INVITED PAPER

Designing Pre-College Engineering Curricula and Technology: Lessons Learned From the Infinity Project

A textbook, computer-based laboratory exercises and teacher training are designed to teach high school students fundamental math, science and engineering concepts.

By Scott C. Douglas, *Senior Member IEEE*, Marc P. Christensen, *Senior Member IEEE*, and Geoffrey C. Orsak, *Fellow IEEE*

ABSTRACT | The importance of mathematics and science education in today's modern, technology-driven society cannot be understated. This paper describes the history of and ongoing efforts in curricular and educational technology development for the Infinity Project, a joint effort between educators, administrators, and industry leaders to establish an engineering curriculum at the high school level. Several issues are considered, including the choice and design of the technology platform used in the curriculum, the curricular and technology development timeline, and the design examples chosen to illuminate important engineering concepts within the curriculum. We also provide a list of key best practices and challenges in developing novel pre-college engineering curricula for future engineers.

KEYWORDS | Education; educational technology; engineering education; engineering profession

I. INTRODUCTION

We live in a technology-driven society. The capabilities of computational devices have grown at an exponential rate over the past four decades, to the point where information processing by electronic devices is central to almost every aspect of modern society. These gains are largely due to the activities of engineers, mathematicians, and scientists who continue to explore new way to design, build, and test computational systems. According to Moore's Law, these gains are likely to continue at their current rates for the near future.

Who benefits most from such technological change? Clearly, those who study an engineering or technology discipline in their college careers will benefit throughout their lives from these advances because of their knowledgeable positions. It is becoming increasingly clear, however, that everyone in modern society requires a basic understanding of technology and how it is created. To reach the widest possible audience, this education must occur at the primary and/or secondary school levels. Much of current engineering and technology education at the pre-college levels is focused on familiarity training with common technological devices, e.g., word processing with computers. What is needed is a broader focus on the design principles behind technology in a structured curriculum. A well-designed, exciting, and relevant engineering curriculum at the pre-college level is also likely to increase the numbers of students who enroll in college engineering and technology programs.

This paper describes the history of and ongoing efforts in educational technology development for the Infinity Project, a joint effort between educators, administrators, and industry leaders to establish a viable engineering curriculum that is taught within the regular high school day. The curriculum teaches students about the design of

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The authors are with the SMU School of Engineering, Southern Methodist University, Dallas, Texas 75275 USA (e-mail: douglas@engr.smu.edu; mpc@engr.smu.edu; gorsak@engr.smu.edu).

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technology-driven systems and motivates them to learn fundamental concepts of mathematics, science, and engineering. While some of the development of the Infinity Project curriculum and its extensions have been documented in various technical papers [5]–[12], careful consideration of the historical development of the curriculum has not been given. Several issues related to the implementation of the curriculum technology are emphasized in this paper, including the choice and design of the technology platform used in the curriculum, the curricular and technology development timeline, and the design examples chosen to illuminate important engineering concepts within the curriculum. We conclude by discussing key best practices and challenges in developing novel pre-college engineering curricula for future engineers as well as extensions of the curriculum to both college and middle-school audiences.

II. DESCRIPTION OF THE INFINITY PROJECT

The Infinity Project consists of several key elements:

1) A textbook with example problems that contains the core content of the course [1];
2) A set of laboratory exercises that are integrated with the textbook content and that are performed by the students in a computer laboratory setting [2];
3) A low-cost software/hardware laboratory kit that each student uses to perform their experiments and gain immediate feedback;
4) Daily lesson plans, a teacher's manual, and in-class lecture slides to support the day-to-day teaching activities of each instructor;
5) Summer training institutes for high school mathematics, science, and career and technology teachers to learn how to teach the curriculum; and
6) A Web-based portal that allows teachers to interact with other instructors and the curriculum designers during the school year and address any day-to-day and week-to-week concerns about their particular course.

During the 2000–2001 pilot school year, 14 schools from the Dallas, Houston, and San Antonio, Texas, metropolitan areas taught the first version of the Infinity Project curriculum to approximately 500 total students. At the time of this paper's writing during the 2007–2008 school year, the curriculum has been offered in over 350 schools in 34 U.S. states with international interest in several countries outside the United States. Demand for the curriculum remains strong, as evidenced by information requests and applications received at the Infinity Project portal and from educational conference presentations.

The Infinity Project curriculum has undergone change over the eight years that it has been offered. A brief description of each component and its development history is now provided.

A. The Textbook

The textbook for the course, entitled *Engineering: Our Digital Future* [1], is effectively the third textbook developed from the course. Its predecessor, entitled *Multimedia and Information Engineering* [3], was developed from spiral-bound notes used in the first two years of the course offerings [4]. All of the textbook versions, including the current one, focus on the design and implementation of information-based technology. While any one of a number of core topics could be chosen for a high school engineering course, we have used multimedia and information technology as the core subject areas for three main reasons.

1) Everyone is likely to benefit from having general knowledge of these areas in later life, no matter what their profession might be.
2) Engineering design principles for these devices can be taught without the need for senior- or college-level calculus.
3) Most students are familiar with and enjoy one or more aspects of these areas, whether they listen to music, go to the movie theater, or communicate using cellular telephones or the Internet.

The textbook has been written with a "top-down" focus on particular problems in the following areas:

- technology projections;
- digital music, audio synthesis, and sound effects;
- digital image analysis and manipulation;
- digital information representation, storage, and encryption;
- communication systems, networks, and the Internet;
- engineering design challenges across a broad range of engineering fields.

Each chapter contains problems to be solved by hand and calculator as well as "just-in-time" in-text pointers to relevant laboratory exercises, to be described shortly. The mathematical prerequisites for the course are Algebra II and one science course with laboratory. No calculus is used or needed.

The 528-page textbook is the result of a multiyear design process. In January 2000, a meeting was held between the textbook authors, twenty high school teachers from across Texas, and members of an advisory board consisting of university faculty, industrial partners, high school administrators, and educational advisors from across the U.S. At that meeting, detailed parameters of the curriculum were specified, including the level of mathematics and science to be taught, the technology for and scope of the laboratory component of the curriculum, and the topics to be covered. During a second follow-up meeting in January 2001, the initial impact of the curriculum was assessed, and a complete redesign of the text was fashioned to better meet all students' needs [7]. In 2003, a revision of the textbook was completed in partnership with Prentice-Hall, resulting in the current textbook version [5].

B. The Laboratory Exercises

Integrated within the course textbook are laboratory exercises that illustrate and apply important engineering design principles concerning the topic at hand. The textbook contains call-outs to these individual exercises in a "just-in-time" presentation approach.

The delivery of the laboratories has undergone change since the inception of the Infinity Project. In the first instantiation of the laboratories used until 2003, each laboratory exercise was given in the form of: 1) an HTML Web page that describes the task(s) to be completed and 2) a software-based design instrument that contains a functional block diagram of the system to be designed and tested or the blocks needed to build such a design from scratch. Thus, no hard copies of the laboratory exercises were specifically created, although the HTML Web pages could be printed easily. In 2004, the laboratory exercises were redesigned to allow the production of a softbound student laboratory manual [8]. The questions for each laboratory exercise are part of a worksheet on which students can "fill in the blanks" to address important issues about their design.

The software environment used for the design instruments is LabVIEW for the Infinity Project, a product of National Instruments (NI), Inc. It is a special instantiation of NI's LabVIEW virtual instrumentation software that is in widespread use in a wide range of industries for test, measurement, control, and monitoring. As a number of laboratories leverage real-time digital signal processing capabilities, it also contains critical software components of LabVIEW DSP to allow the programming of embedded DSP hardware contained in the Infinity Technology Kit. LabVIEW is a flexible software design environment involving only icons as software modules, and students need not learn programming to run existing design instruments nor to build new ones. The programming methodology involves simple rules regarding signal flow graphs that the students quickly master.

The design instruments within LabVIEW for Infinity were originally developed in a software design environment called Visual Applications Builder (VAB), made by Hyperception, Inc. Hyperception was acquired by National Instruments in December 2003, and VAB was maintained as part of the Infinity Technology Kit until 2006, at which point the laboratory design instruments were migrated to the LabVIEW software platform. One of the reasons for the continued success of the Infinity Project is its close partnerships with technology partners, particularly National Instruments and Texas Instruments, who have provided funding or technical design assistance for creating and maintaining laboratory technology and capabilities.

Examples of laboratory worksheets that the students design or build include:

- a waveform synthesizer with a visual "sketchpad" for drawing the sound signal to be heard while it is being played;
- a musical instrument that plays notes from a MIDI file using sinusoids as the instrument sounds;
- a visual object tracker that tracks moving objects in a video stream;
- a coin counter that counts the number of a certain type of coin in a fixed or moving image;
- a "blue-screen" imaging system that allows one to replace colors within a Webcam video stream to mimic the look and feel of a televised weather report; and
- an audio transmitter and receiver that communicates text messages across the room in real time.

Additional details regarding several of these design examples are provided in Section III of this paper. From the above examples, it is clear that the laboratory designs have been chosen to illustrate important real-world applications that most pre-college students have either observed or experienced. We believe that incorporating real-world applications into pre-college engineering curricula is critical to their success. The ease of implementation of such applications depends significantly on the type of technology platform chosen for the designs.

C. In-Class Laboratory Technology

At the time the Infinity Project was conceived, its designers felt it important to bring hardware and software design tools into the classroom that reflected the complexity and richness of the design environments that engineers use in creating technological solutions in companies. Numerous challenges quickly arise in incorporating such tools within pre-college curricula.

1) The design tools have to be easily learned by both student and teacher alike.
2) The design tools have to reflect a complex design process while still being easy to use.
3) The design tools have to be easily maintained, with little to no technical expertise required for this maintenance.
4) The design tools have to be of low enough cost to allow a laboratory station implementation within a school environment, in which:
5) The design tools have to be upgradable as new designs become available.

It was clear that the above concerns necessitated a joint discussion amongst the curriculum designers, pre-college educators, technology experts, and school administrators to obtain an adequate solution. During the January 2000 design meeting, the above issues were considered and discussed, and example technology solutions were explored. The design team quickly settled on a technology solution that has come to be known as the Infinity Technology Kit.

The Infinity Technology Kit is a collection of hardware and software that allows students to implement all of the designs in the regular portion of the Infinity Project curriculum. Just as in the case of the course text, the Infinity Technology Kit has undergone change over the lifetime of

Fig. 1. ***The first version of the Infinity Technology Kit.***

Fig. 3. ***Summer training institutes.***

the curriculum, although the basic components of the kit have remained the same throughout its lifetime. Fig. 1 shows an early version of the Infinity Technology Kit, and Fig. 2 shows the latest version. The kit includes the following.

- *A prebuilt electronic circuit board containing a digital signal processing (DSP) chip, computer ports, audio input and output ports, and power ports:* The first version of this board was a Texas Instruments TMS320C31 Evaluation Module (EVM) that used a parallel port connector for computer interaction and an ac power adapter. This board has since undergone several designs that have improved the processor speed and memory, allowed microphones to be incorporated onto the board, and enabled power to be delivered by the USB data connection. The DSP board is mainly used for audio and data processing experiments involving real-time interaction and was chosen to avoid the variability caused by different computer setups that are likely to be encountered in a classroom setting from one school to another. Later versions of this board added several novel features, such as the ability to flash program the board and use it away from a computer setting with outboard power, the addition of a microphone preamplifier, and the addition of LED status lights that are programmable and accessible through the software design environment.
- *A pair of powered loudspeakers:* As several of the engineering designs within the curriculum involve precise audio processing, these loudspeakers provide a way to listen to the audio signals produced in these experiments. The audio amplifier within the loudspeaker is also useful as a headphone amplifier if the associated headphone port is used with a pair of headphones.
- *A Web camera:* Several of the engineering designs involve the processing of images and video. The Web camera allows students to apply and better understand image and video processing methods through direct experimentation with objects and scenes in their own environment.
- *An optical disc containing the design software and laboratory exercises:* The design software is installed onto each computer once, at which point it is used by the students to complete their designs.

Fig. 2. ***The current version of the Infinity Technology Kit.***

The Infinity Technology Kit requires a computer to work with the software and hardware. Schools that adopt the Infinity Project curriculum are required to have a computer laboratory available for classroom instruction, and access to this lab is expected to be frequent, as about 50% of the instruction is expected to occur while using the Infinity Technology Kit in a laboratory setting.

The software design paradigm used in both VAB and LabVIEW can best be described as graphical programming, in which creating graphs replace writing text as the coding method. Graphs are visual aids that engineers and others use to understand relationships, predict behavior, and deduce outcomes. It is natural to consider graphs as devices to represent instructions, enforce control dependencies, and allow information flow. Graphical programming is represented in a number of software projects and products, among them LabVIEW, VAB, SIMULINK by the MathWorks, the audio processing language MAX, and GraphEdit within the DirectShow SDK from Microsoft. Both VAB and LabVIEW offer rich input and output options for manipulating signals with or without human interaction in real time, from sources such as audio from microphones, video from Web cameras, and stored images. It is this ability to immediately see and hear the results of the program, along with the ability to establish functionality by the study of the programmed graph, that makes these software packages powerful as teaching tools. Engineering offers the chance to see an immediate impact of one's design efforts on a problem at hand, and the impact of a real-time output underscores the utility of the design when it is successfully conceived.

Other issues that have driven the design of the Infinity Technology Kit include the following.

1) How easy is it to set up and take down the hardware in a classroom setting? Many instructors are sharing computer laboratory resources with other instructors teaching other skills, such as writing and keyboarding, and thus the kit may not be permanently set up in all settings. We have found that teachers who need to collect all of the kit's components at the end of each class section can easily do so, and in fact the number of connections and items in the kit have been reduced as the kit has been redesigned. This requirement has also led to a system that requires external power only for the loudspeakers; the first Infinity Technology Kit had an additional ac power transformer for the DSP board and batteries for the microphone preamplifier.
2) How easy is it to learn and use the hardware and software? Leveraging the computer as a communications device to the hardware allows us to use a rich software environment that is both attractive and easy to grasp. The basic rules in using the graphical design environment of both Hyperception's VAB software and National Instruments' LabVIEW software is easily understood by students and teachers alike, as they are quite similar to flowcharts used in logical decision-making. Even so, the software environments are both extensible in that additional blocks or virtual instruments can be introduced and created to incorporate new functionality or to scope existing functionality to help with teaching important concepts and manage overall system complexity.
3) How similar is the software to real-world applications in use in companies today? LabVIEW enjoys widespread use in over 20 000 companies today for various tasks ranging from machine monitoring to space exploration. Despite this fact, the design of the Infinity Project curriculum has always kept its focus on the design challenges and intellectual issues surrounding an engineering solution as opposed to the understanding of a specific software or hardware tool for design. This focus has allowed us to migrate from VAB to LabVIEW without significant conceptual shifts in the issues being taught within the curriculum.

As for the delivery of the laboratories, they are housed within the LabVIEW software and are readily accessible from the splash screen that greets the student when they start the LabVIEW for Infinity software. The instructions for these laboratories are contained with a separate laboratory manual, as described below.

D. Additional Teaching Materials and Aids

The Infinity Project curriculum is typically taught using the course textbook and the laboratory technology, the latter portion through laboratory exercises that involve a series of steps within the software design environment to complete. The first instantiation of the Infinity Project curriculum stored these instructions as text-and-image-based HTML files within the VAB software environment. This delivery was moved to paper form via the publication of a laboratory manual [2] that is in the form of a workbook for students to complete in addition to providing the instructions for the laboratory. The questions to be answered require the student to successfully complete the designs.

Teaching the Infinity Project curriculum involves some choice as to coverage depending on the length of the course. Nominally, the entire text and set of laboratory exercises can be completed in one school year in a single-hour-per-day course; however, it is often the case that instructors choose to include other instructional materials within their course according to personal taste and student interest. Even so, there is great interest from most first-time instructors as to the pacing of the course. For this reason, daily lesson plans were created that describe a typical implementation of the course during an entire school year. In addition, solutions manuals for both the textbook and laboratory manual are available to assist in grading.

E. Summer Training Institutes

It is currently unreasonable to expect that any one school will have a teacher who is both trained as an engineer and available to teach an engineering course. In order to meet the teaching needs for the Infinity Project curriculum, we have developed a 40-hour summer training institute experience for prospective, future, and current instructors of the course. These training institutes have been held at various locations throughout the United States, usually at a university where computing and instruction facilities are often available during the summer period.

The purpose of the summer training institutes is manyfold:

i) To allow the instructor to see the entire curriculum and delve into some of its contents

ii) To provide an opportunity to learn the software design environment within the Infinity Technology Kit under the tutelage of a technology expert
iii) To build camaraderie amongst teachers to carry them forward during the school year

We do not require that the teacher offering the course have prior engineering experience; however, we do require that the teacher has experience teaching a laboratory class. The backgrounds of the teachers who are offering the course currently include those who previously have taught mathematics, physics, computer science, technology applications, biology, and chemistry.

These institutes provide an intense and brief exposure to the Infinity Project curriculum, training in the use of LabVIEW in engineering design, and extended periods for exploring each laboratory within the curriculum. We do not attempt to teach the entire contents of the book in each training period; instead, our goal is to impart the key points of engineering design and the differences between engineering and other common disciplines being taught at the high school level. Starting with two summer institutes in the summer of 2000, we now typically offer six summer institutes at various U.S. locations throughout the summer. These institutes are taught by experienced Infinity Project instructors that are chosen from the cadre of existing course instructors for their expertise and enthusiasm, with assistance from the local facility and personnel. The peer instruction model is one that several educational programs use and has proven to be a successful technique for transferring best practices from teacher to teacher.

F. Web-Based Information Portal

All teachers dynamically adjust their teaching schedule and methods to meet the needs of their students. To make sure our high school teachers have the resources that they need to be successful, we developed a Web portal for information delivery and discussion (www.infinity-project.org). This portal houses:

- discussion groups on curricula and technology issues;
- new laboratories and worksheets;
- sample test questions with solutions; and
- links to relevant Web sites

along with news and general information about the Infinity Project. The discussion group portion of this portal is staffed by graduate students who provide responses to urgent teacher questions, although many of our teachers offer answers to other teachers' questions within the discussion.

III. DESIGN EXAMPLES AND USE OF TECHNOLOGY

A. Overview of Design Strategy

In the initial design of the Infinity Project curriculum, the developers of the curriculum recognized the incumbent position that technology plays as a motivator for engineering education to pre-college students. The ubiquitous and pervasive exposure of our youth to music, movies, video games, cell phones, computers, and the Internet make an educational experience based on multimedia and information-based technologies a natural choice. The challenge in such an educational experience is to transition students' positions from the *users* of technologies to the *creators* of technologies. Achieving this goal required the developers to think about important existing and emerging capabilities within the context of these technologies, to pose how such capabilities could be extended, improved, and further developed. Examples of such designs within the Infinity Project curriculum are:

- an automated movie maker that would create a movie based on a viewer's command input describing the type of movie, the structure of the case, the setting, and key plot points.
- a universal music system that would play any type of music, with any instrumentation and style, based on musical input such as the musical score, types of instruments to be played, and the sound environment in which the music is heard.
- a robot vision system that would calculate the positions of and recognize objects based on attributes such as color, shape, size, and apparent motion.
- a digital yearbook that would serve as an archive of an entire school's yearly experience, and in particular how such information would be represented, stored, digitally protected, and distributed using an appropriate physical medium with limited storage capacity.
- a wireless text communications system using sound as a transmission medium, in which the method of message encoding, the transmission mechanism, the use of physical bandwidth for multiple message passing, and effects of interference and noise play important roles.
- a network-based digital communications system involving message passing, routing topology, and resource allocation as critical factors.

The above designs have clear links to existing technologies such as cell phones, portable music players, industrial robots, and the Internet. The challenge that was addressed in the Infinity Project curriculum is the morphing of these particular design challenges into mathematical and scientific problems and experiments that are readily explored using the chosen laboratory technology and have sufficient impact to engage the student in active learning. Rather than describe the procedure for addressing these design problems, which can be readily surmised from the course text, in what follows we will illustrate how certain important mathematical and scientific concepts are interwoven with experiments that show their importance, validate a student's understanding of them, and lead to engineering designs that have useful outcomes towards the overall design. Each description will take the student's perspective, although advanced terminology will be used where appropriate.

B. Audio: Universal Music Player

Almost everybody listens to music. Music also provides direct links to important concepts in mathematics and science. Some of these concepts include period, frequency, amplitude, spectra, wavelength, time delay, the decibel scale, sinusoidal signals, and exponential decay. The task that introduces a chapter within the course text is easily appreciated:

> Suppose a group of your friends have gotten a band together. Everyone is bringing a different musical instrument to play. You want to join in on the band, but you're not sure which instrument you want to play. In fact, different songs are going to require different instruments, so you want to be able to play a number of different ones. The only problem is, you don't have any of these instruments, and you probably don't know how to play all of them. How can digital technology still make it possible for you to be in the band's spotlight?

One important aspect of the engineering design process is the collection of data relevant to the problem at hand. It is a relatively simple matter to plot audio waveforms as measured by the microphone of the Infinity Technology Kit and study their structure. When one plots the sound waveforms of several different musical instruments at both coarse (several seconds) and fine (several milliseconds) scales, one discovers that they all have to a first approximation two structures to them. The coarse amplitude structure, termed the *envelope signal* $e(t)$, describes the overall loudness of the sound, whereas the fine structure of the sound $p(t)$ repeats over and over. This *periodic signal* has a repeating interval T, called the *period* of the sound, that is connected with how "high" or "low" we perceive the pitch of the sound to be.

Another important engineering tool is *modeling*. Modeling allows one to capture all of the relevant behavior of a system by describing the function of each of its parts as well as how these parts are connected together. Through the power of computation, we can even use models in place of the real-world systems on which they are based, particularly in the case of musical instruments.

Clearly, if one can represent both $e(t)$ and $p(t)$ to high enough accuracy, then one can create an approximate version of the overall sound using the mathematical model

$$s(t) = e(t) \times p(t) \tag{1}$$

Multiplying the two signals makes sense because $e(t)$ does not change much over any one repeating interval, thereby scaling the amplitude of the sound as desired.

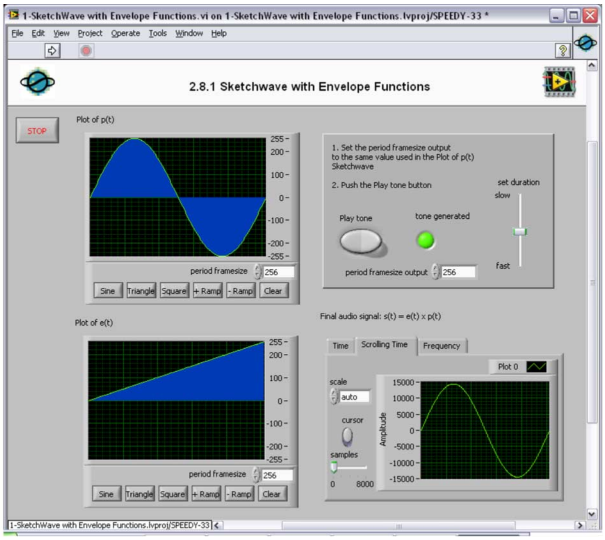

Fig. 4. ***Waveform synthesis using SketchWave.***

The laboratory worksheet that implements this simple waveform synthesis procedure is shown in Fig. 4. Called SketchWave, it has two "sketchpads" where the unique portions of $p(t)$ and $e(t)$ can be drawn using the mouse. Two sliders can be used to adjust the time lengths of each sketchpad. Because all interfaces in the experiment interact with the DSP board in real time, one can fine tune the sound output *while the worksheet is running*, giving a high level of interactivity. Finally, clicking on the "Frequency" button on the multipurpose display on the upper right portion of the worksheet, one can see a new representation of the sound waveform, called the *spectrum*, and through experiment learn the relationship between the period T and the *fundamental frequency* f_0 of the sound.

Musical instruments can "carry a tune" because their waveforms are nearly periodic. Melodies, however, are made up of waveforms with varying fundamental frequency. While a signal with fixed frequency content can be accurately displayed using the spectrum, we need a slightly different display for understanding music—one that adds a time dimension to the spectral plots. We call such 2-D images *spectrograms*. Sheet music is a type of spectrogram, and so are Musical Instrument Digital Interface (MIDI) files, because they store time-varying frequency information in numeric form. To play music, all we need to do is to feed this frequency information into devices that change their fundamental frequency as the melody changes. Sinusoidal signals are examples of simple periodic signals. So, we can create a sinusoidal synthesizer that plays MIDI files by simply connecting the frequency information from the MIDI information stream to the frequency parameters of the sinusoids and adding the resulting waveforms together.

Fig. 5 shows the block diagram for the sinusoidal MIDI player. The yellowish block on the left-hand-side is not a piano keyboard; rather, it simply receives a MIDI data

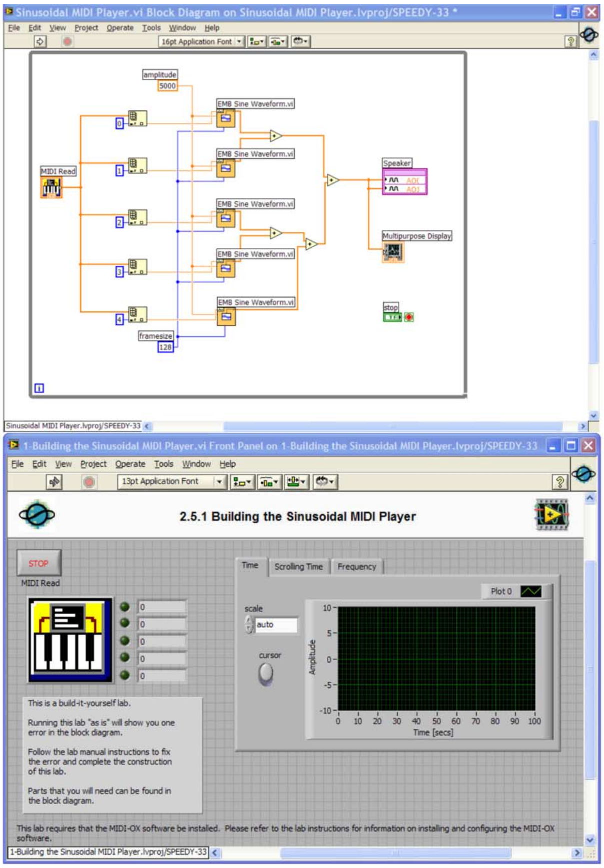

Fig. 5. ***Sinusoidal MIDI Player block diagram (top) and front panel (bottom).***

stream being played by a MIDI player within the Windows environment and extracts its real-time frequency information. The signal flow through this worksheet is easy to understand, and in fact this worksheet is one of the first in the course that the students build themselves. This sinusoidal-based music player is later extended to a universal-instrument music player that uses a sketchpad-generated signal in place of the sinusoidal signal for generating individual note waveforms.

Loudspeakers are simple transducers, consisting of a magnet, a coil, a cone, an enclosure, and some adhesive. They function according to Oersted's Law, which governs the operation of all electromechanical systems. The materials needed to build a loudspeaker are not exotic; hence, they can be built at extremely low cost. Fig. 6 shows one such design, names the Gosney speaker after its inventor, a professor of electrical engineering at SMU. This speaker consists of a button magnet, a coil of insulated copper wire, a paper cone, a Styrofoam salad bowl, and some glue. The total materials cost of this design is about US$0.40 or about the cost of a regular U.S. postage stamp.

High school teachers are encouraged to use sound pressure level measurements from a simple handheld

Fig. 6. ***Gosney speaker.***

sound meter for a given volume setting and signal content to grade each student's design. Depending on the amplification level, volumes of over 100 dBA SPL at the cone's center are possible, and while the low-frequency performance of the overall design is lacking, the sound emitted from the design is clearly recognizable.

C. Video: Chroma Key Imaging System

It is clear that we live in a visual society through our exposure to movies, television, images, and computer displays. Computer manipulation of visual information is mathematically intense. For special effects in movies, very sophisticated algorithms are used to animate, light, and render entire moving scenes that look real to the average moviegoer. This fact alone makes video processing a natural place from which to motivate engineering concepts.

In developing engineering curricula based on manipulation of images, we have focused on applications that illustrate key concepts without requiring significant training in the application of visual arts. These applications treat monochromatic images as matrices of numbers, color images as a set of three matrices, and video as a time-sequence of matrices. Each entry, or pixel, within each matrix is a number that can be manipulated according to its local context or for purposes of an application or useful end. Important concepts that arise in this discussion include

1) representation of brightness, contrast, and color in mathematical form
2) Pixel-by-pixel manipulation using nonlinear functions
3) Thresholding and masking within images
4) Addition, subtraction, and multiplication of pairs of images
5) Shifting of images and convolution

Although these operations are simple to grasp, they can when combined yield visually interesting applications that have important uses.

One of the designs that arises from this development is the chroma key imaging system first developed in the 1940s for film and later adapted to video production. The goal of the chroma key system is to replace a portion of an image

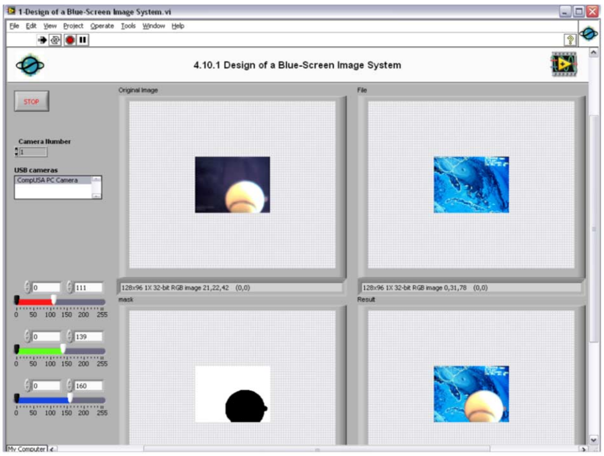

Fig. 7. ***Chroma key imaging system.***

having a known color with portions of an alternate image that can have arbitrary pixel values. Such systems are used every day to illustrate weather patterns in video weather reports, in which the meteorologist appears to stand in front of a weather map. This appearance is achieved by filming the meteorologist in a room with a constant (usually blue or green) color background, in which the background color is dissimilar to any color being worn by the foreground person. The system is tuned by selecting the range of colors to be replaced, which is used to create a masking image that allows spatial selection of portions of images according to their color. The masking image is then used to select which portion of the foreground image is replaced by the background image using multiplication. The background image minus the foreground object is created using an inverse mask, and the two images are combined via pixel-by-pixel addition. The entire process involves simple mathematical operations and a nonlinear thresholding operation and is conceptually simple to grasp.

Fig. 7 shows the LabVIEW front panel for a design that implements the chroma key imaging system within the curriculum. The video feed is taken from the computer's Webcam, so that each student can become the "weatherperson" on screen. The decision on color choices is driven by measurement as well as the availability of a constant background region within the classroom environment. Students quickly realize that uniform illumination is hard to achieve, and that simple color replacement has its limitations in creating an effective foreground-background illusion. These topics are discussion points from which improvements in design are typically sought. Additional applications to three-dimensional scenes are relevant as well—witness the emergence of on-field graphics at televised sporting events, where the first-down marker of a football game or a sponsor's logo can appear in practically any region of the field of view, even if the camera is panning.

D. Communications: Wireless Text Messaging

The ability to send short text messages wirelessly to anyone in the world is a capability that technology-enabled students use every day. Embedded within this technology are a number of important issues, including the following.

i) How is the text information translated into physical form for transmission?
ii) How can several people send text messages at the same time and nearly the same place? What prevents these messages from colliding with each other?
iii) How am I receiving messages? How does the reverse of transmission work?
iv) Why can't I get a good signal sometimes? In more practical terms, why did my bars go away, and how can I bring them back?

We have encapsulated the above issues in a design activity known as the Air Modem. The Air Modem is a wireless text messaging system that uses sinusoidal tones transmitted via loudspeakers and microphones as the communications mechanism. In this system, one Infinity Technology Kit acts as a transmitter, while another Infinity Technology Kit acts as a receiver. The task of the transmitter is to take text information typed into its computer keyboard, turn these keystrokes into sinusoidal waveforms, and play these sounds out of the kit's loudspeakers. The receiver's task is to listen for sinusoidal waveforms at another Kit's microphone, determine which frequency or frequencies were transmitted, and decode this information into correct text information. The main difference between this text messaging system and more common text messaging capabilities in cell phones is the transmission medium, i.e., acoustic waves versus electromagnetic waves. The teaching opportunity in using audible tones as carriers of information, however, is readily apparent.

The primary issues regarding physical-layer system design of wireless communication devices are easily taught using this activity:

1) transmission rate versus signal encoding/decoding complexity;
2) effects of noise, interference, and channel loss on link quality;
3) bandwidth allocation for different users and overall capacity.

It has been our experience that students and teachers alike readily grasp the features and issues surrounding wireless devices when engaged in this design effort. The opportunities for additional exploration in modern-day implementation issues in radio communications are naturally taken, such as the differences between and advantages or drawbacks of analog radio and digital radio.

The LabVIEW front panel for the transmitter design contains a text window where letters appear as they are typed on the computer keyboard, as well as numerical choices for the starting frequency and the spacing between frequencies for a single-tone-per-letter signaling scheme.

By selecting the signal start frequency and spacing between frequencies, the 26 letters of the alphabet along with "space" are mapped to 27 distinct frequencies for transmission. A display window shows the time-domain and frequency-domain representation of the transmitted sound. The LabVIEW receiver front panel contains the same numerical choices as the transmitter: namely, the starting frequency and spacing, as well as a series of controls that are used to tune the detection capability of the system to the volume of the received signals and to try to mitigate effects of noise. The receiver worksheet also has a scrolling display showing what letters were detected.

This experiment allows for careful tradeoffs in communication systems design while providing a tactile way to see the effects of these choices in the design.

IV. BEST PRACTICES AND ONGOING CHALLENGES IN PRE-COLLEGE ENGINEERING CURRICULA

The implementation of the Infinity Project curriculum has given us a general insight into developing engineering curricula for pre-college students. In this section, we highlight several of the issues that surround our design of these curricula, in the form of design and implementation choices, best practices, and ongoing challenges.

A. Design and Implementation Choices

In our implementation, several critical design and implementation choices led to a successful launch of the curriculum in high schools.

1) High school teachers were queried to describe the constraints of the classroom teaching environment prior to curriculum and technology decisions. They also provided important feedback and were kept advised of the developed curriculum. Practical issues such as the typical high school teaching schedule and its relation to other school events such as assemblies and state testing requirements affected the development, as did others such as the number of available electrical outlets in a laboratory or classroom.
2) Laboratory technology was chosen and developed based on a number of factors, including ease of teacher training, relevance to the chosen classroom subject material, and design flexibility. The LabVIEW design environment, part of the suite of graphical design and programming tools offered by National Instruments, gives both teachers and students the ability to simulate and implement complex signal processing systems without a significant training overhead—a critical issue for curriculum adoption and dissemination.
3) Curriculum design was performed iteratively. Three different versions of the Infinity Project text have been used by high schools. In developing each text, feedback from the teachers and students using the materials helped in improving quality. Feedback on the laboratory technology, as obtained through telephone conversations with and Web-based discussion group postings from teachers, helped to identify common problems in the typical classroom environment.
4) Methodologies for growing and scaling professional development and training processes for teachers were identified and pursued. The model adopted—the designation of the most successful high school instructors as Infinity Project master instructors for the summertime teacher training institutes—is scalable to meet a fast adoption rate, and it can be easily expanded geographically.
5) Technology partnerships were leveraged both for financial assistance and laboratory technology development. Texas Instruments and National Instruments have been regularly involved in the development of the curriculum, and the latter entity provided significant amounts of technical support for the Infinity Project.
6) Ease of implementation and use has driven the packaging and delivery of the curriculum. Although the Infinity Project materials are professionally produced, the reasons for the effort to make the curriculum as professional as possible are not simply to gain adoptions. Rather, the most important issue is the robustness of the implementation, which is a by-product of having good business practices in place. One of the goals of the Infinity Project has been to provide a consistent educational experience in every classroom in which the course is taught, independent of other factors that might affect its delivery. This goal not only makes rollout easier; it also is well received by potential funding sources such as government entities, corporations, and philanthropic organizations.
7) Constant improvement of curricular offerings is performed. Just like methods technology corporations use to drive growth in engineering product fields, the developers of the Infinity Project continue to work and innovate within the classroom to maintain the relevance and improve on the curriculum offerings.
8) One of the ways in which these improvements are tested is through offering a one-semester introduction to engineering course at the college level within engineering schools. Today, over 30 different colleges and universities have adopted part or all of the Infinity Project curriculum as part of their first-year course offerings, and in several institutions, this adoption creates a base of engineering talent that can support engineering outreach programs to local high school students and teachers.

B. Best Practices

Best practices are methods that lead to desired results, usually through experience, and that have some measure of transferability to similar problems or contexts. Our past experiences with implementing the Infinity Project curriculum have helped us to identify several best practices that are potentially useful for anyone who is developing pre-college engineering curricula and whose main barrier to effectiveness is widespread adoption.

Best Practice #1: Garner the interest of high-quality, committed pre-college teachers and instructors. A pre-college curriculum must have in-classroom proponents at the high school level to be successful. Presentations at teacher conferences sponsored by the National Science Teachers Association, the National Council of Teachers of Mathematics, and Teachers Teaching with Technology Worldwide, among others, are important to "get the word out" and obtain feedback on the curriculum itself. In addition, a Web-based discussion board is highly recommended to give instructors an opportunity to share ideas and give feedback on the curriculum.

Best Practice #2: Choose a technology platform for any laboratory components carefully, considering all issues relevant to the rollout of the curriculum. Besides overall cost, other important factors in the choice of classroom technology include reliability, extensibility, the ease of teacher training, the support provided by the technology partner, and interface issues with existing classroom technologies like computers and calculators.

Best Practice #3: Develop and provide teacher training experiences for adopters. Pre-college instructors are almost always required to teach multiple subjects, and the amount of time that each instructor has to prepare for these courses is quite limited. Professional development for teachers is a necessity in such circumstances, and this training can be performed in the summertime when pre-college instructors often have time for in-service learning.

C. Challenges

What are some of the common challenges that developers of pre-college curricula face?

Challenge #1: Developing sustainable practices. An innovative educational initiative is relatively straightforward to offer once or twice in a few classrooms where the extent of the impact is limited, with significant involvement of the initiative's creator(s) and developer(s) invested. To have truly lasting impact, however, one needs to develop educational initiatives that can be transferred from expert to novice, that have appropriate documentation procedures in place, and are economically viable for all partners involved.

Challenge #2: Placing a curriculum in an environment that is overprescribed in terms of content and resources. Adding new educational content to a pre-college curriculum inevitably means that existing educational content must be removed or altered to make room. Moreover, students' choices also drive course adoptions at some educational levels (e.g., high school), and to be successful, engineering curricula must be attractive to and fit the overall educational and career goals of these students.

Challenge #3: Getting political and social organizations to support pre-collegiate engineering initiatives. Such support is not necessarily monetary. In fact, the political support provided by state Boards of Education and other educational associations can be critical to widespread adoption of an engineering curriculum. In Texas, the Infinity Project was given course catalog numbers as both a math and a science elective less than one month after the required paperwork was requested by the Texas Education Association.

Challenge #4: Assessment and tracking of pre-college student populations. Because of privacy concerns, it is more challenging to determine and track the impact of educational innovations on pre-college student as compared to college students who can and do typically give consent to such studies. Sample-based studies are one strategy for obtaining such data.

V. EXTENSIONS

The Infinity Project was a seed effort for a number of engineering outreach and educational developments that extend their reach beyond the original concept of a high school engineering course. Two of these developments are now outlined, as well as their relationship to the original program.

A. College Extensions

The original concept of the Infinity Project offered the opportunity for a college version of the course. The inspiration for such an extension was first obtained from the many curricula that are "bridge subjects" from high school to college for which advanced placement tests can be taken. A primary example is calculus, in which high school students in the United States can take before entering college and obtain between one and two semesters of college credit by passing one of several national exams on the subject. Typically, a yearlong course in high school becomes a semester-long course in college for this translation, so the concept of a semester-long Infinity Project course introducing engineering concepts to first-year college students was immediately conceived.

College versions of the course can be implemented by acquiring the materials for the curriculum from the relevant partners—in particular, the textbook from the publisher and the laboratory kit from the technology partner. Many universities have implemented such a course in ways similar to any other adopted course, usually without assistance from the Infinity Project developers, although we have forged partnerships with relevant university partners in order to further our joint goals. Usually, such an implementation extends the course material in either implementation or content. We now describe one way in which the course has been implemented at our home institution, to show how such a model can work.

At SMU, we have developed an approach for implementing material from the Infinity Project that involves several engineering departments within the School of Engineering. This implementation comes in the form of cross-disciplinary design projects between students taking first-year courses in various disciplines, such as Electrical Engineering, Mechanical Engineering, and Computer Science and Engineering. This approach has a number of unique features.

- It can be implemented in universities where course content and requirements are unique for each specific major.
- It does not impose a common interdisciplinary "introduction to engineering" course, in which all students participate in the same lectures and laboratories [5]–[8], thus maintaining the diversity of each department's teaching and scheduling resources.
- It involves course content change only; thus, there is no impediment to implementation caused by administrative changes to degree plans, graduation requirements, and the like.
- It provides a balance between the conflicting needs of: a) offering enough technical content to allow a student to evaluate her or his choice of major and b) showing the student what the content and methods used in another related major are like.
- It can be taught by discipline-specific faculty who normally teach such courses—"superfaculty" that have deep knowledge of multiple engineering fields are not required.
- It shows students what "real engineering life" is like, where the likelihood of engineers with diverse engineering backgrounds working together is high.

The proposed cross-disciplinary design experiences have been implemented with slight variations since Spring 2004. Our strategy employs two design projects. Each design project requires skills that cannot all be acquired in a single discipline or class, such that groups of students from different disciplines must learn to work together in a dynamic problem-solving team typically numbering between five and eight students. The first, less demanding design project is a "dry run" of the longer end-of-semester design project and allows each group to learn how to function efficiently and understand the diversity of skills within the team. The second design project involves a more challenging task to figure out what implementation strategies do and do not work. We believe that this team interaction is one of the most important and rewarding aspects of engineering, and students should be exposed to this interaction as early as possible in their careers.

The first design project involves building a working loudspeaker from ordinary household items. The students are given the chance to each build the Gosney speaker design described previously, after which they are asked to develop a group design that competes against other groups' designs for efficiency, frequency response, and "musicality." Students are given only two constraints in the forms of a standardized piece of wire and a magnet that has to be used in their speaker construction. In each student team, the numbers of engineering students from each discipline are approximately the same. The grade for each student is based on a group report on the final loudspeaker design of each group. This activity is scheduled over two weeks of class time.

The second design project is a five-week activity to construct a nearly autonomous robot capable of finding an object on a playing field—a ball—and moving that object to a designated desired location—a hole. The robot employs an off-board vision system, wireless communication from a separate laptop computer, and onboard computation, physical lifting mechanisms, and locomotion. The constraints are similar to planetary exploration by unmanned rovers, resulting in our calling this project the "Mars Rover" design, although the game is quite similar to "putt-putt golf." Students are scored on how fast the object is located and correctly placed and are penalized in how many distinct commands they send to their wireless robots to achieve the goal. Each team is provided DSP hardware, software, and Web camera identical to that in the Infinity Project, three motors, and batteries. All other materials and design aspects are chosen by the students. Each student is graded on her or his performance in the design project through: i) a group report and ii) individual presentations evaluated by outside faculty.

The vision systems constructed by the student teams in each semester for judging ball-to-hole distance have been similar, being based on graphical software modules that are in use in the course laboratory for the electrical engineering course. The students rely on their understanding of simple image processing concepts as taught in the course to develop a logical strategy for taking an overhead Web camera image of the playing field, determining the ball and hole positions within this image, and calculating distance from the identified locations. Issues of calibration, geometry, and reliability play an important role in these students' designs. One such design is depicted in Fig. 8.

The physical designs of the robots have been varied and have involved devices that impart motion on the ball using pendulums, plungers, ramps with motorized ball lifters, and wheel-based systems, as well as designs that gather the ball and physically move it to the hole. While all robots had to be controlled using digital hardware from the Infinity Project, the programming of the hardware and the shot strategy has involved C++ developed in the computer science and engineering course. An example robot is shown in Fig. 9 along with the student team that designed it.

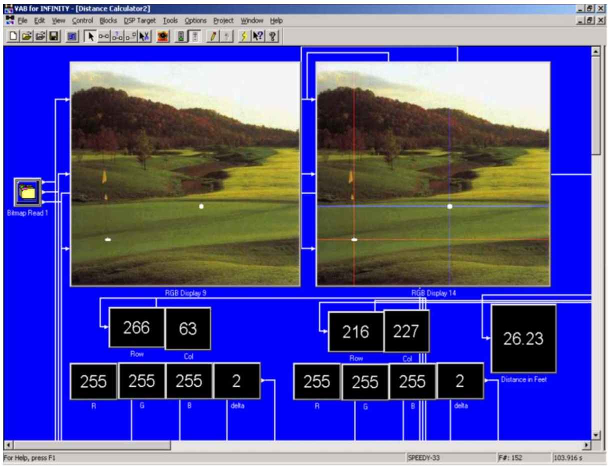

Fig. 8. ***VAB worksheet for an putt-putt vision system using an image captured by a Web camera. This golf image is a simulated bitmap input as opposed to the overhead Web camera data employed in the actual competition.***

Fig. 9. ***A student team with their competitive robot design.***

B. Elementary and Middle School Extensions

The concept of engineering is not age-limited. Almost all young children are exposed to technology from the time they are born in the form of games, toys, music, images, video, and even the Internet. Despite the apparent difficulty and rigor of most college engineering programs, we believe that engineering need not be limited to older students, as young children often possess the creative mind-set and inventive nature that makes a successful engineer. As such, we have begun development of modules that would be appropriate for curricula in the pre-high-school arena.

Our first focus is middle school (grades 6th through 8th), where in 2005 we began pilot-testing engineering modules at a local high school. Like the college extensions, material from these modules also leverage the Infinity Technology Kit and explored the use of sound for separating voice signals and for modifying music to impart the echoes and reverberation of a concert hall or arena. The implementation of these two- to three-week modules is typically done in a mathematics or science class. A key issue in such extensions is linking the material carefully to subject matter already in place at these levels, as it is unlikely that all schools will adopt a technology-based curriculum for all of their students. Developments of other modules for middle-school students is ongoing.

VI. CONCLUSIONS

The Infinity Project is an effort to introduce high school students to concepts, techniques, and knowledge of engineering design, processes, and techniques. This paper outlines some of the history of the Infinity Project, with a focus on technology development and implementation, and indicates how the effort has been extended to other educational efforts at the college and middle-school levels. Laboratory experiments using real-time signal processing hardware and software are described to illustrate important subject matter in practical educational settings. ■

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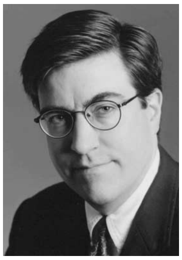
ABOUT THE AUTHORS



Scott C. Douglas (Senior Member, IEEE) received the B.S. (with distinction), M.S., and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, in 1988, 1989, and 1992, respectively.

He is currently an Associate Professor in the Department of Electrical Engineering, Southern Methodist University, Dallas, TX. He is the author or coauthor of two books, six book chapters, and more than 150 articles in journals and conference proceedings. He frequently consults with industry and offers short courses and tutorials in the areas of signal processing and source separation. He has served as an editor or coeditor of several books and conference proceedings, including the *Digital Signal Processing Handbook*, the International Symposium on Active Control of Sound and Vibration, and the IEEE Workshops on Machine Learning for Signal Processing conference records. His research activities include source separation, speech enhancement, adaptive computational imaging devices, and hardware implementation of DSP systems.

Dr. Douglas is the recipient of the 2002 IEEE Signal Processing Society Best Paper Award in Audio and Electroacoustics and the 2003 Gerald J. Ford Research Fellowship. He has served on several technical committees of the IEEE Signal Processing Society and is a Past Chair of the Neural Networks for Signal Processing Technical Committee. He has helped organize several meetings of the IEEE, including the ICASSP and ISCAS conference series, the Digital Signal Processing and Signal Processing Education Workshop series, and the Machine Learning for Signal Processing Workshop series. He is the General Chair of the International Conference on Acoustics, Speech, and Signal Processing 2010 in Dallas. He is also one of the key authors and developers of curriculum and technology for The Infinity Project, a joint effort between educational, civic, and government organizations to implement engineering curricula at the precollege level. He is a member of Phi Beta Kappa and Tau Beta Pi.

Marc P. Christensen (Senior Member, IEEE) received the B.S. degree in engineering physics from Cornell University, Ithaca, NY, in 1993 and the M.S. degree in electrical engineering and the Ph.D. degree in electrical and computer engineering from George Mason University, Washington, DC, in 1998 and 2001, respectively.

From 1991 to 1998 he was a Staff Member and Technical Leader in BDM's Sensors and Photonics group (now part of Northrop Grumman Mission Systems). His work ranged from developing optical signal processing and VCSEL-based optical interconnection architectures, to infrared sensor modeling, simulation, and analysis. In 1997, he co-founded Applied Photonics, a free-space optical interconnection module company. His responsibilities included hardware demonstration for the DARPA MTO FAST-Net, VIVACE, and ACTIVE-EYES programs, each of which incorporated precision optics, micro-optoelectronic arrays, and micro-mechanical arrays into large system level demonstrations. In 2002, he joined Southern Methodist University, Dallas, TX, where he is currently an Associate Professor and Chair of the Department of Electrical Engineering. He has two patents in the field of free space optical interconnections. He has co-authored 27 journal papers and over 60 conference presentations. His current research interests include computational imaging and integrated photonic signal processing.

In 2007, DARPA identified Dr. Christensen as a "rising star in microsystems research" for his development of an adaptive multiresolution imaging architecture, and selected him to be one of the first of the 24 DARPA Young Faculty Award recipients.

Geoffrey C. Orsak (Fellow, IEEE) received the B.S.E.E., M.E.E., and Ph.D. degrees in electrical and computer engineering from Rice University, Houston, TX.

He is Dean of the Southern Methodist University School of Engineering and Founding Director of the Caruth Institute for Engineering Education at Southern Methodist University, Dallas, TX. He designed and created a number of nationally-recognized engineering education programs, including The Infinity Project and Visioneering, that today reach millions of students across our country with innovative engineering curricula and educational experiences.

Dr. Orsak is the recipient of 2001 KPMG High Tech Award and the EE Times 2006 Educator of the Year Award in engineering and science. A noted scholar and expert in communications, signal processing, and information theory, he has been the lead researcher on more than 30 projects funded by public and private grants and contracts. He served on a panel for the National Academy of Engineering's evaluation of the U.S. Marine Corps' science and technology programs and was a DoD Science and Engineering Advisor as a member of the Defense Science Study Group sponsored by the Institute for Defense Analysis.