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CRCD: Wireless Multimedia Communications for Virtual Environments

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Abstract

This project combines research from the areas of wireless communications, very-large-scale integrated (VLSI) circuit design, virtual environments, and human factors in a coordinated interdisciplinary program. This paper gives a brief description of the overall project. Education in the hardware and software of virtual reality (VR) systems will serve as a testbed for training engineers in this co-design philosophy. Part of this project is the creation of three new classes that cover software engineering for real-time software, design of virtual environments, and design of practical wireless devices. The research part of the project will utilize the C6, a three-dimensional, full-immersion, synthetic environment in the Virtual Reality Applications Center (VRAC) at Iowa State to create a new generation of wireless communications devices. This is the first academic program that trains computer engineers and scientists to understand and evaluate the effects of particular hardware and software implementations on human operators.

I. Introduction

Wearable and inexpensive, short-range broadband wireless communications systems are the key to future computing environments. These future information experiences will range from untethered personal computing to totally immersive virtual environments. Engineers capable of designing such devices will need a diverse set of engineering skills in hardware/software integration and human factor issues that are presently treated separately in both curricula and research. This paper gives an overview of a new Combined Research and Curriculum Development (CRCD) project at Iowa State University. This project will integrate upper level teaching and research in communications, radio frequency (RF) and very large scale integrated (VLSI) hardware and software design, and virtual environments in a coordinated interdisciplinary program for simultaneous hardware/software co-design.

Education and training in both communications circuits and virtual environments is difficult because of the rapidly changing underlying technologies and the breadth of necessary multi-disciplinary understanding. Researchers tend to become 'delta functions of excellence' without significant collaboration with others, especially in different fields. This cultural divide is invariably carried into the classroom, where courses and laboratories are only rarely coordinated in a way that will maximize their impact on student understanding and ultimately career opportunities. By providing a framework for both faculty and students to expand their educational and research horizons in an area of critical national need it is hoped that everyone, students and faculty alike, will significantly benefit. Our goal is to bridge this interdisciplinary chasm.

One response to these complex engineering environments, has been a significant increase in attention to design and teaming in engineering curricula, often through a capstone senior design course [1, 2]. This well-tried method has its merits, but in its current form it offers students only an isolated experience in teamwork. Our goal is to give continuity to the students' multi-disciplinary training. We are creating an integrated program in which faculty members in different disciplines will work closely together to mentor larger teams of students and create solutions to complex problems that combine human factors, real-time systems, compact wearable computers, and highly sophisticated graphics. As part of this project, our team will create three new classes that cover software engineering for real-time software, the design of practical wireless devices, and the design of virtual environments. For the research part of the project, we will extensively utilize the C6, a three-dimensional, full-immersion, synthetic environment in the Virtual Reality Applications Center (VRAC) at Iowa State University (ISU). This unique facility is a room where all four walls, the floor and the ceiling are back-projection screens that display stereoscopic images, thus providing total immersion of the participants. More details on the C6 can be found at www.vrac.iastate.edu. We will also use other unique experimental laboratory facilities on-campus for performing related radio frequency (RF) and wireless communications experiments and demonstrations in both hardware and software. These include the new Rockwell Wireless Communications Laboratory, the Microwave and Electro-Optics Laboratory, and the Carver High-Speed Communications Circuits Laboratory with well over $1 million in state-of-the-art instrumentation available for use on this project.

II. Curricular Development

We will create three new courses that pertain to the design of virtual reality environments and adapt several of our existing hands-on laboratories. One of the courses will focus on software engineering aspects of real-time systems that will include various hardware considerations. The second will focus on the design of effective virtual environments while the third will cover information transfer in the microwave frequency range. In addition to these new courses, class laboratories and course content will be adjusted in a number of other related courses as detailed below. Table I summarizes the proposed new courses and curricular development. The software engineering class would be implemented during the first year of the project. The courses in the design of virtual environments and wireless communications will be implemented in the second year. In the third year we will offer all three courses on a rotating basis.

Virtual reality is very hard to teach and learn in a single course, as it is currently at Iowa State University. In the current course, *Introduction to Virtual Reality*, Dr. Cruz-Neira encourages students to research the VR literature and identify specific topics within the field that are of interest to the class. The students "customize" the general syllabus for the course by choosing their own topics. The instructor takes a supporting role to clarify any issue or provide additional information about the topic. Another successful technique is to encourage students, in particular seniors and graduate students to incorporate their research (either thesis or senior design project) into class assignments. In this way, students have a first-hand experience in applying the class contents to their areas of specialization. This particular technique has given excellent results, generating several publications from class work [3,4].

Course (Cr)	Title/Instructor	Enrollment	Level	Req/ Elect	Freq-uency	Innovation
EE 598X (3)	Electromagnetics and Wireless Communications /Weber, Black, Dickerson	15	Senior/ grad	Elect	1/year	Interactive, integrated learning activities. Seminar based.
CE 576X (3)	Design of Virtual Environments /Cruz-Neira, Weber, Dickerson	40	Senior/ grad	Elect	1/year	Hands-on advanced virtual reality hardware and software, evaluation exercises
CE 577X (3)	Real-time Software Engineering for Virtual Environments/Cruz-Neira	45	Senior/ grad	Elect	1/year	Projects on current software challenges for time-critical response of multi-processed environments
EE 422/3 (4)	Communications Systems and Laboratory/ Dickerson	65	Senior	Tech Elect	1/year	New wireless communications experiments, studies in interference
EE 424 (4)	Introduction to Digital Signal Processing/ Dickerson	48	Senior	Tech Elect	1/year	Experiments in adaptive signal processing for interference nulling
EE435 (3)	Analog integrated circuits / Black	20	Senior/ grad	Tech Elect	1/year	New wearable computing interface laboratory
EE/CE 507 (3)	Communication Circuits/ Black	25	Grad	Elect	2 years	New wireless laboratory demonstrations and projects

Table I: The first three courses are new courses that will be developed as part of this CRCD effort. The other courses listed will be enhanced and updated.

A. New Courses

Electromagnetics and wireless communications: This new interdisciplinary course will provide learning opportunities for students in microwave system design. Traditional microwave circuit, field, system, and antenna courses already existing provide background and complimentary instruction for the opportunities to be provided in this course. The course will be an interactive seminar based course with short lectures combined with multiple project emphasis areas. Students from various backgrounds will need only a small common core of required pre-requisite material to work together to learn and solve the system issues. The course will address information transfer in the microwave frequency range.

Several users will typically exist in the same electromagnetic space. Some of these will not be associated with the VR environment but will be nearby users of cellular and wireless phones, aircraft navigation aids, etc. Electromagnetic interference and compatibility (EMI/EMC) issues will need to be addressed. Incorporation of novel antenna technologies will provide opportunity for investigation of neural networks, adaptive and agile antennas (pointing and nulling), real time DSP, and computation algorithm technologies to solve real world communication problems. Interference may be friendly (the same VR environment) or hostile (other adjacent VR environments or other applications such as cellular telephones and navigation aids). The different interference needs to be mitigated. The choice of the transmitting and receiving frequency(ies), data architecture, and system design considerations such as how much of the signal processing can be accomplished with analog hardware (i.e. antennas, multi-receivers, etc.) and how much will be accomplished with digital computation will need to be considered. This course will provide opportunity for a palette of subspecialty projects including analog and digital signal processing in the receiver, the transmitter, and base band as well as opportunity for a student to reduce any of the algorithms to practice by integration in LSI and VLSI mixed mode circuits. The devices will be wearable. The student can investigate circuitry versus battery life as well as looking for other methods of powering the circuits. High-speed data bursts via high power transmission versus low speed low power transmission studies tradeoffs can be done.

Virtual Environment Design: The objective of this course is to provide students with the necessary skills to understand the capabilities of the VR systems that may be available to them and make application design decisions that will lead them to implement effective environments. Students will learn about the fundamental differences between VR systems, the possible options for interfaces, both physical and virtual, how to identify the relevant factors that have an effect on their application, and how to evaluate the effectiveness of their designs. Students will also learn how to select and evaluate interacting hardware systems for VR applications. Ultimately, the course will provide students with expertise on how to utilize a human-centered approach to aid in the selection of an immersive system for a particular application. Several case studies will be given to students to work on them from the concept to the final application.

Courses like this are rarely available in Computer Engineering curriculum. Today's "VR experts" are self-taught professionals coming from a variety of backgrounds: computer scientists, psychologists, engineers, and artists. However, as the field grows and the technology becomes more complex, it is no longer feasible to have this ad-hoc learning approach. There is a strong demand to produce formally trained VR specialists. To date, very few universities in the U.S. offer courses specifically oriented towards virtual reality development. Many of our industrial contacts have expressed a growing need for students with this knowledge.

Real-time Software Development: There are few courses that cover software development issues for real-time (or time-critical) applications and how to design software to survive rapidly changing underlying technology. This knowledge is critical for any Computer Engineering student who plans to continue a career in the development of virtual reality applications, or any other area with rapidly changing hardware. This kind of software requires very different approach on program design and implementation techniques than, for example, a database management environment. A typical VR system integrates a visual display, a tracking system to locate the user and his interactions, several interactive devices, such as wands and gloves, a localized sound system, and graphics and computer hardware. All these components have very different reporting rates, communications protocols, and operation modes. To integrate all these components into a single system, VR developers need expertise in the development of sophisticated software systems that utilize features like multiple processes, message passing, shared memory, dynamic memory management, and a variety of process synchronization techniques.

This course will focus on the design approaches to build software systems that hide the complexity of a virtual reality system. This software system should enable application developers to concentrate their development efforts on the content of the application - not on the underlying technology of the specific VR system. Students will develop practical expertise in these techniques by working in projects requiring encapsulation of the intricate programming issues in reusable library components. There is a need for a VR application development environment in which existing VR applications can be scaled to more distributed and complex VR platforms without effecting the core of specific applications. This will lead to investigations in advanced software engineering techniques, such as dynamic shared objects and runtime linking. We expect this course to be very well received by the students and supported by the potential employers of our students, since the demand for formally trained real-time software engineers is continuously increasing as VR technology is becoming more available.

B. Updates to Existing Courses

The existing DSP and communications courses affected by this project will be linked by large-scale design experiments common to these courses. Each experiment combines basic techniques such as filter design with advanced topics such as interference rejection or adaptive signal processing. The DSP laboratory course emphasizes projects in digital filter design, experiments related to Fourier and time-frequency signal analysis, and signal compression. It will also include projects in digital communication such as the generation of spread spectrum signals and waveform generation, but it will concentrate on DSP implementations. The communications laboratory focuses on modulation, receiver and transmitter design, and coding for complex wireless environments. These courses will build on successful courses developed at the University of Maryland [5] and Virginia Tech [6].

VLSI courses that will be affected by this project include the undergraduate *Analog Design* Course, the graduate level course in *Communication Circuits* and senior design projects. Laboratories and classroom lectures on sensors in the *Analog* classes can easily be adjusted to provide VR emphasis and the graduate communication class can literally feature the short-range wireless problem being addressed in this project.

III. Assessment and Evaluation

An educational assessment program is being developed and implemented in parallel with the engineering course offering as part of this project. In order to provide meaningful project evaluations a range of objectives have been established and we will use multiple metrics to ensure that the objectives are met.

This project includes both student and project performance goals as listed below:

A. Students will gain the needed experience to work effectively in a research and development environment using the concepts of engineering design for hardware/software co-design.
B. Students will be able to communicate effectively and work in diverse multidisciplinary team environments involving simultaneous hardware/software co-design.
C. A new model for educating VR professionals will be established.

A comprehensive evaluation plan is a central feature of this project. The evaluation will consider the resources, techniques, procedures, and strategies employed to accomplish these goals and objectives, as well as the outcomes of the activities and their impact on participants, and will make use of both quantitative and qualitative methodologies. Formative evaluation will gather on-going evidence to suggest how to improve the VR program being developed and implemented. In addition to program performance, we will assess such things as whether assigned tasks have been carried in a timely and satisfactory manner, and whether resources, budget, and project management effectiveness are adequate. ISU's Research Institute for Studies in Education (RISE) will lead the evaluation. RISE has been conducting assessment and evaluation projects for the university, the State of Iowa, and beyond since 1974. RISE has an abundance of experience managing evaluation projects, developing and administering survey questionnaires, conducting focus group interviews, doing data analysis, and assessing the effects of technology.

Summative evaluation (which gathers evidence related to program modification, termination, or continuation) will be undertaken at the end of the project, but involve trends from the beginning of the project to its completion. Multiple measures/indicators of program and student outcomes will be used. Unanticipated program and student outcomes as well as intended outcomes will be identified and assessed. With regard to generic student outcomes such as critical thinking ability, leadership and interaction skills, student retention, academic performance indicators, and careers, participants in the proposed program will be compared to one or more control groups of students as appropriate. The control group will consist of engineering students not participating in the program but otherwise similar to the participants.

Some of the following assessment methods will be used to assess student learning. These methods relate to the specific goals described above.

A1. Faculty evaluation of student ability in software verification through use of interim and final project reports to show how students are working together; student post-survey form self-reports, and student group conclusions obtained through focus group post-interviews.

A2. Observation by faculty of student progress using lab equipment to understand device performance; student post-survey form self-reports on this understanding, and student group conclusions about this understanding obtained through focus group post-interviews.

A3. Faculty observation of student flexibility in modifying their solutions as new information becomes available; student post-survey form self-reports on this flexibility, and student group conclusions obtained through focus group post-interviews.

A4. Evaluation by faculty of student knowledge in the fundamental technologies; student exam scores about such knowledge; student post-survey form self-reports about this knowledge, and student group conclusions obtained through focus group interviews.

B1. Faculty observations about student recognition that narrow disciplinary skills are insufficient; group self-evaluation sheets and interviews to monitor student progress; and student group conclusions about this recognition obtained through focus group post-interviews.

B2. Faculty observations of student familiarity with the use of team-based approaches and skill in maintaining communications between the diverse components of the group; evaluation sheets designed to determine group or team performance in this area; and student group conclusions about this familiarity and skill obtained through focus group post-interviews.

C1. An external expert will conduct observations and analyses of the products and judge their effectiveness within the Iowa State program and their utility in other university programs; surveys will be conducted among other universities that perform research in VR to determine if they have adopted the new approaches and courseware modules and to assess how the new curriculum has affected the design and practice of VR implementations.

C2. Interviews of the industrial partners will be conducted to gauge their response to this new approach for teaching VR professionals; graduating seniors will be surveyed for their overall perceptions of the programs future value to them; graduates working in relevant roles within industry will be surveyed to assess their perceptions of the new program's impact on their job performance, satisfaction, and potential for advancement; the supervisors of those employed graduates will be surveyed.

IV. Research Description

In the past five years, both virtual reality and wireless technology have developed rapidly. While we will focus on the high-end VR systems such as the C6 environment, the research performed with this project will be compatible with more-common environments such as head-mounted displays and distributed virtual environments. Most virtual reality applications developed today are poorly designed and rarely evaluated with their final users. The research in this project is aimed at investigating the relationships between the VR systems, the applications, and the user's performance. The research will help to identify critical factors that affect the use of a VR environment and will provide recommendations and guidelines for the development of virtual design environments.

A. Virtual Environment Research

VRAC has been involved in VR research since the early stages of the field. Currently, VRAC has an extraordinary array of levels of immersion available for its researchers. On the low end are head mounted displays and 3D flat screen displays. At the next level is the C2, a 12'x12' surround screen environment with real time audio and visual display. At the high-end is the C6, a full immersion 10'x10'x10' cube that completely surrounds the user with 3D audio and visual display. The C6 is partly funded by an NSF Grant for advanced computing applications (Award #: DMI9977199). The C6 is the only device of its kind in the United States, and one of three in the world. (The others are in Europe and Japan.) It is the largest device of its kind, and it is designed to be the only wireless surround screen environment.

Dr. Cruz-Neira's group at Iowa State University has been investigating software models to simplify the development of collaborative immersive applications, across hetereogeneous VR and computing systems. We are developing VR Juggler, an operating environment to design, test, and execute virtual reality applications (http://www.vrjuggler.org/). VR Juggler provides a development environment that does not require direct access and use of actual immersive system by using emulators of the different devices and configurations.

The PIs have done previous exploratory work to investigate the impact of VR on a human operator. In 1996 a simple experiment to compare VR systems was performed as part of a summer student project [7]. This study indicated that the C2 environment was more efficient for seeing relationships between objects in virtual space. In 1998, a more formal experiment was performed, which was partially funded by a NSF Research Initiation Grant (DMS-96-32662) to Dr. Dianne Cook and Dr. Cruz-Neira. This work developed VRGobi, an immersive three-dimensional variant of Xgobi [8], an XWindows application designed for analysis of multivariate statistical data. The purpose was to investigate if VR could improve the analysis of complex multivariate data compared to traditional interactive visualization methods [9]. These experiments showed that there is a close relationship between the type of task and the type of VR system used. In addition, factors such as previous exposure to immersive environments, comfort, and the ability to maintain constant visual and auditory contact with other users, play an important role in the overall performance of the operator.

B. Real-time DSP and methods for reducing EM interference

The research also provides an excellent opportunity for the investigators to solve several technical issues associated with wireless communications and interaction in an integrated environment. Untethered movement and communication in a VR environment requires that the user incorporate information transmitters and receivers (T/R) on their person. These T/R units need to be small for unencumbered movement. When the T/R units use the electromagnetic spectrum for data transmission, the units need to be immune or resistant to interference, must be compatible with regulatory codes, and must work in a highly multi-path, rapidly changing shadowing environment. Thus we need to design systems that work at available frequencies and are not susceptible to jamming by cordless phones and other commercial devices [10]. Electromagnetic interference and compatibility (EMI/EMC) considerations will be incorporated in the system architecture. Small size will dictate that the communications take place at wavelengths compatible with the size.

The project provides wide opportunity for a complete system design. The design of the architecture of the complete system includes the impact of human factors on miniature electronics, the incorporation of high speed but low power T/R technologies, and a complete system design. The complete system design will have considerations for anti-jam and anti-threat technology and techniques to provide continuous information transfer for multiple users who cross each other's communication path both physically as well as spectrally. There are many different technologies such as wireless LANs and Bluetooth™ that are available. Research opportunities in an integrated learning environment provide the opportunity for students and investigators from several areas including DSP, communications, VLSI, VR, microwave, human factors, and computer systems to interact to solve technological challenges related to real world applications.

C. Wearable wireless computing

Working with senior design students we have developed a prototype wearable computer running Linux that is approximately the volume of a cigarette pack (based upon a 486 architecture CPU). This system used a combination of commercially available components and custom student designed PC boards. At different times this working device has been used as both a web server and information kiosk type device for the Carver Laboratory High Speed Communications Laboratory. We anticipate extending this device with custom wireless I/O chips and utilizing lessons learned elsewhere on similar small devices (Prof. Pratt's group at Stanford has been particularly helpful: http://wearables.stanford.edu). We also anticipate developing similar devices utilizing more power efficient dedicated processors, such as the TINI and iButton™ Java™ engines offered by Dallas Semiconductor. A small credit-card sized computer built based upon the Cellular Computer CardPC™ has also been extensively used here that is applicable to higher-end but nevertheless still portable applications. This device is approximately the size of a conventional 3.5" disk drive.

D. Analog and Mixed-Signal VLSI Design

Our recent thrusts in VLSI research have been in three major areas: (1) High speed wired communication systems with relatively conventional silicon CMOS technologies, (2) integrated magneto-electronic circuits and (3) high speed data-conversion and signal processing.

We have developed, for example, a number of innovative techniques for transmission of gigabit rate data [11], including design and realization of very low jitter PLL and DLL circuits and computationally simple simulation of these circuits [12]. These techniques are extremely important in this wireless domain where overall system performance is often tied to circuit phase noise. In the magneto-electronics domain, we are the only university group we are aware of that is conducting research into integrated circuits containing on-chip giant-magnetoresistive (GMR) or tunneling magneto-resistive (TMR or SDT) devices. We have devised numerous tools for both simulation of these devices [13; 14] and realizing practical circuits for both interface and nonvolatile memory [15;16] applications. These devices will be very useful for practical wearable position sensors for virtual environments that presently use much heavier and bulkier flux-gate sensors.

We have also recently developed several student-designed integrated circuits that can perform at near GHz rates: (1) a 6-bit A/D conversions that has been demonstrated up to 700 Mega-samples/sec and an analog memory that can record over one hundred points of an analog waveforms at approximately a 1Gs sampling rate, all in a standard digital CMOS process. The high frequency techniques employed in these circuits will almost certainly be of benefit in highly integrated direct down-conversion receivers that are likely to be employed in various projects anticipated here. Indeed, issues pertaining to local interferers have already become evident in testing these circuits as signals from several local FM radio stations are already being recorded by both the high-speed A/D converter and the analog memory. Among the major issues being faced with these chips are: (1) isolation of analog and digital sections of the chip, (2) reduction of bond wire effects (for which we are developing a packageless scheme commonly known as 'die on board'), (3) reduction of interference caused by high-speed output buffers and (4) development of logic and timing methodologies that are insensitive to supply and clock variations. All of these issues will continue to be major design hurdles in the work to be addressed in this project.

V. First Year Efforts

Our current efforts in this project are focused on existing courses in digital signal processing, VLSI, and electromagnetics. We have added new laboratory experiments to enforce the concepts of hardware/software co-design and human factors issues. One example of these first experiments is a laboratory for the communications and electromagnetics course that characterizes the complex electromagnetic environment inside the building that houses the C6 virtual reality environment. This building contains multiple types of wireless devices such as LANs and cordless phones. This work involves efforts in system identification and modeling. A second example is implementation of different methods for interference mitigation such as direct-sequence spread spectrum and adaptive antennas. A formal course in real-time software engineering is also being developed for implementation in Fall 2001. These courses and research projects involve senior-level undergraduate and graduate students working together to create a new generation of wireless devices for natural interactions in virtual environments.

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