

A Photorealistic 3D Virtual Laboratory for Undergraduate Instruction in Microcontroller Technology

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Abstract

In this paper we present a new 3D photorealistic virtual laboratory for undergraduate instruction in microcontroller technology. The web/CD deliverable lab, developed using state-of-the-art interactive computer animation technology, operates and produces results equivalent to the physical laboratory. It is, to our knowledge, the most realistic and advanced computer-simulated laboratory developed so far for microcontroller instruction. The virtual lab solves many of the problems associated with traditional lab instruction by providing: (1) 24/7 access to lab equipment and experiments; (2) effective laboratory training at distance; (3) lab accessibility to students with motor and vision impairments.

Keywords

3D animation, 3D modeling, virtual laboratories, microcontroller technology.

1 Introduction

Laboratory instruction is a major component of the Electrical Engineering Technology undergraduate curriculum at Purdue University and at other peer institutions throughout the United States. In the Electrical and Computer Engineering Technology department of Purdue University, approximately 95% of the course offerings have an accompanying laboratory. The laboratory experiences require students to: interconnect and operate devices, construct sub-system prototypes, and component responses. In general, electrical engineering instructional laboratories follow the paradigm of students spending two or three hours a week in a lab, clustered around work benches learning to use the equipment under the guidance of the faculty or teaching assistant [Mosterman et al. 1996].

There are several problems associated with traditional laboratory instruction. (1) Limited opportunity to repeat the lab assignments, since further practice depends on availability of laboratory space and resources. (2) High lab maintenance/operation time and cost. (3) Very limited accessibility for physically disabled students. Students with a visual impairment and/or impaired motor skills are deprived of a quality laboratory experience as many laboratory assignments require high level of dexterity and good vision. At most, disabled students with reduced motor skills can watch their lab partners perform the experiments [Duarte and Batz 2001]. (4) Complete unavailability to students who do not have access to traditional centers of excellence in education, and thus rely on distance learning.

The object of our research is the development of an interactive, photorealistic 3D computer-simulated laboratory for undergraduate instruction in microcontroller technology. The virtual lab operates and produces results equivalent to the physical laboratory. It includes a highly realistic representation of devices and components, thus providing the students with the mental engagement and immersiveness necessary to successfully complete the experiments.

The hypothesis behind our research is that the 3D virtual lab can solve the majority of the problems associated with traditional laboratory instruction, and can provide students with the same, or higher, level of understanding of the experiments as a real laboratory environment.

2 Background

The value of simulation tools and other multi-media technologies in the learning process has been documented in numerous publications [Chung et al. 2001]. Research shows that the use of simulation tools often reinforces learning and leads to performance improvements in a variety of disciplines [Allwood et al. 2001]. Therefore, recently, there has been significant progress in development of computer-based tutorial systems in many different areas. Though progress has been less evident in engineering education [Mosterman et al. 1996], there are some noticeable examples of engineering virtual laboratories. Del Alamo [Mannix 2000], a professor of electrical engineering at MIT, created a web-based microelectronics lab for his students in 1998. At Johns Hopkins University, Karweit [Karweit 2005] has simulated various engineering and science laboratories on the web. At the University of Illinois Urbana-Champaign (UIUC), researchers have developed a virtual laboratory for earthquake engineering [SSTE 2005]. Oakley, in the department of Electrical and Computer Engineering at UIUC, has developed an interactive tutorial for an introductory circuit analysis course: 'CircuitTutor' [Oakley 1991]. The computer-based tool presents exercises on electronic circuits in a hypertext format. At Vanderbilt University Mosterman et al. [Mosterman et al. 1996] have created and evaluated the effectiveness of a computer simulated lab for use in undergraduate engineering education. Electronicsworkbench.com [Electronics Workbench 2006] has been producing electronics software for education for 20 years. In particular, the MultiSIM 9 software is an electronic lab on a PC that allows for circuit simulation with schematic entry, and includes a few 3D realistic components. At Temple University, Duarte and Butz [Duarte and Butz 2001] have produced the 'Virtual Laboratory for the Disabled' aimed at engineering students who do not have adequate mobility of hands and upper bodies to perform the physical laboratory experiments.

The problem with the majority of computer simulated labs developed so far is that the representation of the virtual environments and their components is very schematic and two dimensional, thus requiring a high degree of abstraction from the user. Because of lack of three dimensionality and representational fidelity, most of the existing virtual labs are just software

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simulations, very far from providing authentic lab experimentation.

In an effort to improve on the current state-of-the-art we have focused on photorealistic interactive 3D computer animation technology for the development of a three dimensional virtual learning environment which provides a true lab experience.

2.1 Benefits of 3D realistic learning environments

A virtual learning environment is defined as a designed information space in which: (a) the information is explicitly represented; (b) educational interactions occur; and (c) students are not only active, but actors, i.e., they co-construct the information space [Dillenburg 2000]. A 3D learning environment is a virtual learning environment which has a unique set of characteristics. Hedberg et al. [Hedberg and Alexander 1994] identify the following features of 3D learning environments that make them different from 2D interactive multimedia: (a) representational fidelity; (b) immediacy of control and higher level of active learner participation; and (c) presence. Representational fidelity refers to the degree of realism of the rendered 3D objects and the degree of realism provided by temporal changes to these objects. Learner control and high level of learner participation refer to the ability to look at objects from different points of view, giving the impression of smooth movement through the environment, and the ability to pick up, examine and modify objects within the virtual environment [Dalgarno et al. 2002]. The feeling of presence, or immersion, occurs as a consequence of realism of representation and high degree of user control and makes the learning environment intrinsically motivating and engaging, allowing the user to focus entirely on the task.

The pedagogical benefits of 3D realistic learning environments have been extensively examined by researchers in the areas of computer graphics, cognitive psychology, visual cognition, and educational psychology. In general, research findings [Dalgarno and Harper 2004; Winn 2002; Shin 2003] show that often 3D learning environments are more effective than 2D interactive multimedia. Dalgarno et al. [Dalgarno et al. 2002] state that '3D realistic environments have great potential in educational contexts as they provide the possibility of rich learner engagement together with the ability to explore, construct and manipulate virtual objects, structures, and metaphorical representations of ideas'.

Both the documented educational effectiveness of 3D learning environments, and the recent advances in the graphics capabilities of standard desktop computers, have motivated the development of our desktop realistic 3D virtual lab.

3. Plan and Overview

This research project involves 2 phases: (1) design and implementation of a prototype photorealistic 3D virtual lab for undergraduate instruction in microcontroller technology and evaluation of realism and functional performance of the simulated hardware components, and (2) assessment of the efficacy of the 3D virtual lab as a learning tool for a course in microcontroller technology. Phase 1 has been completed and the results are the object of this paper; the assessment of the virtual lab is currently being carried out with a group of engineering students and the outcomes will be reported at the conference.

In summary, the design and development of the prototype 3D virtual lab involved the following tasks: (1) photorealistic 3D

modeling and texturing of the laboratory work station equipment and several circuit packs; (2) programming of the microcontrollers' internal behaviors and animation of each board level function (i.e., button pushes, on-off switching, port-pin connections, cabling); (3) design and implementation of the interactive content including learning and testing activities; (4) evaluation of the virtual lab realism and functionality performed by Purdue faculty and graduate students knowledgeable in microcontroller technology.

In section 4 we describe the interactive virtual lab including the 3D models, textures, and animation, the interface, the system architecture, and the interactive content. In section 5 we discuss advantages and limitations of the virtual lab, and future work.

4. The Virtual Laboratory

The virtual lab can be delivered via web or CD-ROM on a standard desktop computer and was implemented using interactive 3D computer animation technology. The platform for the project is based on the highest end in 3D interactive animation. We used Maya 6.5 (Alias™) software to model and texture the 3D lab components and to animate their functionality. Interactivity with the 3D components was programmed using C++ and OpenGL. The OpenGL Utility Toolkit (GLUT) library was used to implement a platform independent interface which works with different operating systems such as Microsoft Windows, Linux, and Macintosh. The microcontrollers' internal behaviors were programmed in C++ and various functions, such as motor rotations, are controlled by different hex files loaded into the virtual microcontroller flash memory at run time. The hex files are machine language files for the microcontroller produced using the CodeVisionAVR Integrated Development Environment (IDE) software development kit [Progressive Resources].

4.1 Models, textures, and animation

The virtual laboratory includes true-to-life replicas of the laboratory work station equipment, consisting of a digital multimeter, an oscilloscope, a function generator, and a power supply (fig. 1), and several circuit boards: an Atmel ATmega16 microcontroller development board, a stepper motor board, a 7-segment display board, an alphanumeric keypad input board, a liquid crystal display board, and an analog to digital & digital to analog converter board. Some of the boards are represented in fig. 2.



Figure 1. Photo of the physical laboratory workstation, left; photorealistic rendering, center; 3D models, right

All 3D objects were modeled in Alias Maya 6.5 as polygonal surfaces, textured using photographs of the real devices, and exported as .OBJ files. To achieve high speed of response in a real-time environment, the poly-count of each model does not exceed 20,000 polygons. In order to maintain a high level of representational fidelity with a relatively low poly-count, we used color and bump maps to simulate several of the photorealistic details.

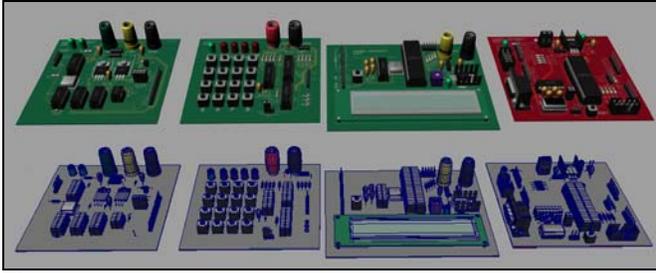


Figure 2. Photorealistic renderings (top), and 3D models (bottom) of (from left): synchronous serial interface board, keypad interface board, LCD interface board, ATmega162 microcontroller development board

4.2 Interface

The interface of the program is graphically very simple. It consists of one resizable window and one toolbox: the window is used to display the 3D objects, the toolbox allows access to a variety of tools (see fig. 3). The toolbox has four frame layouts: 'Camera Controls', 'Load hex files', 'Setup', and 'Command Prompt Controls'.

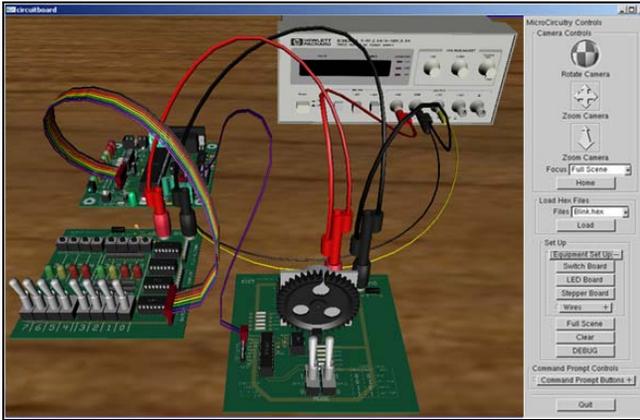


Figure 3. Screen shot of the application: display window, left; toolbox, right

The 'Camera Controls' frame layout, (see fig. 4 top left) contains the tools necessary to navigate the virtual laboratory. The various controls allow for real time functions such as: tumble, zoom-in and zoom-out, track, and pan. In addition, the 'Camera Controls' frame includes a 'Focus' box with a list of all 3D devices displayed in the viewing window, and a 'Home' button. The 'Focus' list box allows the user to instantly shift the virtual camera focus onto a particular device; the 'Home' button is used to reset the default 3D view of the virtual lab.

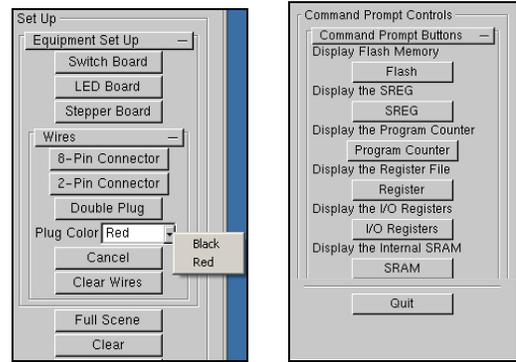
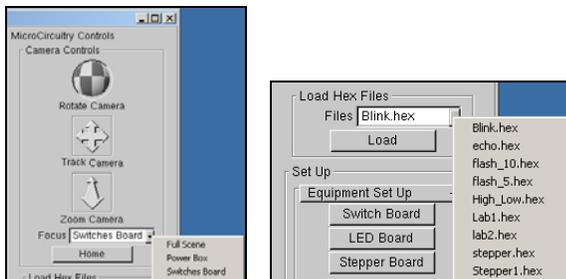


Figure 4. 'Camera controls frame', top left; 'Load Hex files' frame, top right; 'Set up' frame, bottom left; 'Command Prompt Controls', bottom right

The 'Setup' frame layout is used to place different microcontroller boards on the virtual workbench, and to make wire connections (see fig. 4, bottom left). Students create wire connections between microcontroller boards, and between microcontrollers and workstation units, by selecting the desired wire type from the toolbox, and by clicking on the appropriate micro board sockets in the viewing window. The program uses OpenGL picking methods to determine which segments of the micro boards the student is selecting during wire placement. In this way the wires can be placed regardless of what viewing angle and/or zoom factor the user prefers. Picking methods also enable the user to interact with switches, buttons and knobs on each micro board, as well as on each workstation unit, from any point of view. Users rotate knobs by clicking on the knob in the viewing window and by holding the left mouse button down, while dragging the mouse in the direction they want the knob to turn.

The 'Load hex files' frame layout (fig. 4 top right) enables students to load external program files compiled with the CodevisionAVR compiler or any other standard microcontroller compiler capable of generating machine code in the proper hex format. With the current implementation, the program files need to be placed in the script directory of the application. Students can select a particular hex file from a drop-down list and load the file into the program. Upon upload and virtual power-up, the microcontroller simulates the programmed behavior, if the hex file was programmed correctly.

The 'Command Prompt Controls' (fig. 4 bottom right) is used to provide an insight into the internal behavior of the microcontroller. For instance, the Flash, Register, I/O Register and SRAM allow the user to view the internal memories of the microcontroller.

4.3 System Architecture

All graphics data were exported from Maya as .OBJ files and were hard coded into the program using C++. Each microcontroller board model was specified within the program as a separate graphics file, and movable parts were exported separately to provide easy manipulation within the OpenGL framework. Each time the graphics are refreshed, arrays containing the microcontroller board data are checked to determine LED states and other changes that should occur as a result of the microcontroller operations. GLUT functions control keyboard input, mouse input, and window related functions that require communication with the operating system. Currently, (OpenGL User Interface) GLUI and GLUT provide the interface.

Future implementations of the virtual lab will replace GLUT and GLUI with appropriate function libraries that provide the best performance for each individual operating system.

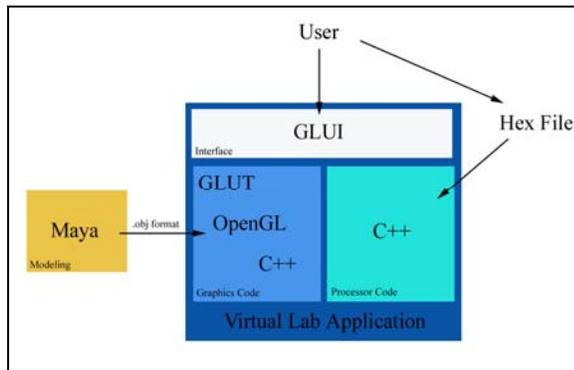


Figure 5. System Architecture

4.4 Interactive Content

The content developed so far allows students to carry out the first five lab assignments of ECET 209, an introduction to microcontroller hardware and software course, focusing on embedded control applications. The virtual laboratory, like the physical one, introduces students to basic concepts related to microcontroller technology such as: interconnections of components and peripheral devices, bus timing relationships, development of structured C-language program control, program debugging, input/output techniques, and use of PC based software development tools.

As mentioned previously, the virtual lab operates and produces results equivalent to the physical one. For example, at the beginning of each lab students need to place the ATmega16 microcontroller board on the virtual workbench and supply it with a voltage of at least 8VDC. Powering the microcontroller board involves setting the power unit to the right voltage, and connecting board and power unit together. In order to set the required voltage, students turn the virtual voltage adjustment knob by clicking and holding down the mouse button while moving up (clockwise knob rotation--voltage increase) or down (counter clockwise rotation--voltage reduction). To connect the Atmega16 board to the power supply, students select the appropriate virtual power cable from the toolbox and click on the correct terminals of the power supply in the viewing window. Students can tumble and/or zoom in/out to better see the components required for the connections. If additional laboratory peripheral boards, such as the lights and switches board, are required to complete the laboratory experiments, they can be placed on the virtual workbench and connected together, and to the power unit, following the same procedure described above. Once all connections have been made, students can load the source files into the virtual microcontroller by selecting them from the pull down menu in the toolbox. After turning on the virtual power, the loaded program starts to be executed. For example, with the program running, students can actuate the virtual toggle switches to provide different input data into the program. The microcontroller turns on or off the virtual lights in response to the input value.

5 Conclusion and future work

In this paper we have described the development of a new photorealistic, interactive 3D lab for undergraduate instruction in microcontroller technology.

The virtual lab presents several advantages. 1) *Portability*: it can be delivered via CD or web on a variety of platforms. Teaching, via the web, laboratory skills requiring dexterity has been, so far, one of the main obstacles to technological training at distance; our virtual lab solves this problem by providing authentic on-line lab instruction to off-campus students who have access to a standard desktop computer. In addition, it gives on-campus students the ability to practice the lab experiments 24/7. 2) *Easy integration of additional content*: adding new lab experiments requires nothing more than writing a few lines of code and the tool is easily customizable to suit different teaching styles. 3) *Customizable interface for meeting the needs of students with disabilities*. The interface can be easily modified in order to incorporate universal software design features such as keyboard equivalents, visual focus indicators, magnifiers, adjustable response time, and specialized input devices to accommodate students with limited dexterity (i.e., expanded keyboards, trackballs, voice input). Creation of a software universal access interface is currently under development.

Furthermore, the virtual lab presents all the benefits of 3D realistic learning environments (listed in section 2.1). It contains true-to life replicas of lab equipment, displayed in real time using realistic perspective and occlusion, photographic quality materials, lights, and motion. It gives the user complete control over the display of devices: students can manipulate, in real time, the orientation of the 3D models (rotation and point of view), the location of the models relative to background, and the zoom factor--For instance, the ability to zoom-in will allow students with limited vision to better interconnect small devices--. Photorealistic representation of components and complete control of the environment make the virtual lab an engaging immersive learning environment that allows for acquisition of new skills by direct interaction and experience, without requiring any abstraction.

Currently, the main limitation of the application is slow real-time performance: the virtual speed is slightly lower than the actual one. For instance, a virtual LED takes longer to turn on than a physical one. Since speed is dependent primarily on models' poly-count, computer system performance, and application design, in future implementations the poly-count of the 3D models will be further optimized and other software design options will be investigated.

Future work will also involve additional programming of more advanced I/O operations, and the integration of a 'digital tutor' to assist and guide the students throughout the experiments.

The application has been evaluated throughout its development by Purdue faculty and students knowledgeable in microcontroller technology who have provided positive feedback on the virtual lab realism and functionality. Assessment of the efficacy of the application as a learning tool for a course in microcontroller technology is currently being carried out with a group of engineering students.

Demos of the virtual lab are available at: <http://www2.tech.purdue.edu/cgt/I3/VL.html>

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