Hands-on Circuit Design and Test Laboratory for Distance Learning in Electrical Engineering

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ABSTRACT

This paper describes the design of the Pandora box, a low-cost laboratory instrumentation that includes a power supply, a signal generator, and a two-channel oscilloscope. In distance-learning environments, the Pandora box, together with a student's personal computer at home, permits a full range of design and test of hardware circuits in the sophomore and junior Electrical Engineering curriculum. Preliminary students' feedback indicates enthusiastic response to this first offering of at-home hands-on experimental laboratory.

1. Introduction and problem statement

Distance learning in engineering is not a new subject, with numerous courses being offered in areas such as computer programming, engineering mathematics, web designs, databases, etc. These courses use either a student's home computer or a network to permit remote access to computer resources on site[1]. Outside the computer-related curriculum, however, the promise of a full 4-year or even 2-year degree via distance learning in a field such as Electrical Engineering has not been achieved due to the lack of a laboratory for students to use to design and test real hardware circuits. Students who live in proximity of the main campus can drive in to use the on-campus laboratory facilities, and students who already have jobs in industry may rely on their companies' instrumentation laboratory to design and test circuits in courses covering introductory circuit analysis, linear systems, basic digital logic design, introductory analog circuit analysis and design. Other students simply have no means to perform hands-on circuit design and test experiments. Some institutions offer "remote design and test" experience to students using the world-wide web[2], but this experience is by no means equivalent to the hands-on experience required of engineering graduates. Operating a piece of equipment remotely is better than nothing, but clicking on a computer screen is not regarded by anybody as real hands-on design and test experience. Circuits do not always work; in fact, students learn more when circuits fail and they have to debug them. Different students make different mistakes in building circuits or designing new circuits, and the diagnosis skills cannot be taught using a central circuit board built by somebody at the main campus. Many aspects of circuit analysis and design have to be taught using real circuit and real equipment: few engineers ever forget the acrid smell or the burning heat of a circuit component the first time they exceeded the operating limit of a

circuit. A worldwide web remote equipment access simply is inadequate in providing this and other extremely valuable experience.
The fundamental obstacle to providing this hands-on experience in circuit design and test to distance-learning students involves the cost and size of laboratory instrumentation. A standard laboratory bench contains a power supply, a signal generator to provide input signals to the students' circuits, and an oscilloscope (having at least two channels) to display signal waveforms. Hand-held multimeters to measure resistance, voltages and currents, are widely available at low cost for individual purchase. Even if we ignore the other costs, the cost of one laboratory bench with the three instrumentation listed above is about $8K to $10K, making it impossible for individual distance-learning students to acquire. Several efforts to provide some capabilities for at-home electronic experimentation have been carried out with various degrees of success:

- Our introductory circuit course uses a "home lab," whose kit consists of a low-cost hand-held digital multimeter, a circuit breadboard, and a set of components. The students can build the experiment at home and use the multimeter to measure voltages and currents at various nodes in a circuit. This home lab has worked very well, despite the fact that there is no visual waveform or no data transfer to a computer for comparison with simulation or for further data analysis.
- Deakin University has also introduced a similar idea in home experimentation kits[3] for distance-learning courses, limited to first-year electronic experiments.
- The electronic test industry has created a wide range of test instruments for the VXI bus or the IEE-488 bus or even the serial bus, from oscilloscope and data acquisition cards to waveform generator cards. These cards plug directly into the PC and provide the various test functions, replacing benchtop instrument. The PC-based instrument has the advantage of integration with the PC, and makes it easier for an experimenter to compare test data with simulated data from the same circuit. A cursory examination of product lines from several manufacturers (see Test and Measurement World magazine for example[4]) reveals that these functions are available as PC plug-in modules: analog I/O, waveform generator, digital I/O, oscilloscope, logic analyzer, multimeter, spectrum analyzer, counter, timer, frequency measurement, timing measurement. The unit price, which targets industry test engineers as buyers, is the real impediment in providing these equipment as part of an at-home laboratory for distance-learning students. A single card costs anywhere from $400 to $4000; even a handheld version, with the lack of PC integration, still costs about $300 for a simple oscilloscope. An instrumentation toolbox with a waveform generator (for at least sine and square waves) and a 2-channel low-frequency oscilloscope would be at least $800, not including the associated software cost and user-interface programming to integrate them.

This paper describes one solution to this laboratory instrumentation issue: the design of the Pandora box, which provides all three instrumentation (power supply, signal generator, and oscilloscope) and, in conjunction with a student's personal computer (PC) at home, permits the full range of hands-on circuit design and test for sophomore and junior Electrical Engineering courses. Section 2 presents the curriculum needs and our design approaches to meet these needs, section 3 shows the design of the box from three perspectives (hardware design, software and user-interface design, and design of laboratory experiments for use with the box), section 4 discusses the initial feedback from students who have used both the on-campus laboratory and the Pandora box, section 5 looks ahead to dissemination to other institutions, section 6 considers the merits and limitations of the design, section 7 is a brief explanation of the box's name (Pandora), and section 8 concludes the paper.

2. Curriculum needs and design goals

Our design of the Pandora box within the distance-learning context addresses three specific needs:

- Critical hands-on experience (as opposed to "virtual" experience) in an asynchronous on-line two-year EE or computer engineering curriculum.
- A systematic two-year EE curriculum deliverable in three formats: on-site, on-line (synchronous and asynchronous), and at-home. The at-home format (asynchronous on-line) is a special component targeted to meet the needs of students who must take courses from home due to a variety of reasons (full-time jobs, young children, disabilities, etc.), who live in remote communities.
- A possible cost reduction in laboratory equipment, both to the institutions offering the curriculum and to the students.

The design goals to meet these needs and address larger issues in curriculum design include:

- Create an instrumentation toolbox for four-year universities and community colleges (CCs) to include hands-on hardware-based laboratory experience. The toolbox may be used on-site (e.g. at a four-year university) or by distance-learning students who have no access to any laboratory instrumentation. Hereafter, we will refer to these students as "at-home" students since they literally have to do their entire course work at home.
- Establish a laboratory-driven curriculum development methodology, common to two-year and four-year institutions, to provide hands-on laboratory experience at a reasonable cost. In developing a solution to the problem, we have to ensure that the methodology is transferable and replicable at many institutions, and that cost constraints are met, especially in the case of at-home students.

3. Design of the Pandora box

The design approach to provide hands-on experience is to exploit the combination of available low-cost instrumentation designs[5,6,7], off-the-shelf integrated circuits and components, and a home computer. An example of a low-cost instrumentation design is from Maxim[8], showing how a function generator can be realized quickly using their integrated circuits (ICs). Figure 1 shows the overall topology of the system when it is being used by a student to build and test a circuit. The omnipresent home computer provides the necessary instrument control, the monitor used as the oscilloscope display, and an environment to integrate the laboratory experimental results with simulation results (e.g. from a circuit simulator such as SPICE or a mathematical modeling tool such as MATLAB), thus enhancing the students' learning. This very simple yet effective approach was followed in our creation of the Pandora box, whose design is described in depth in this section.

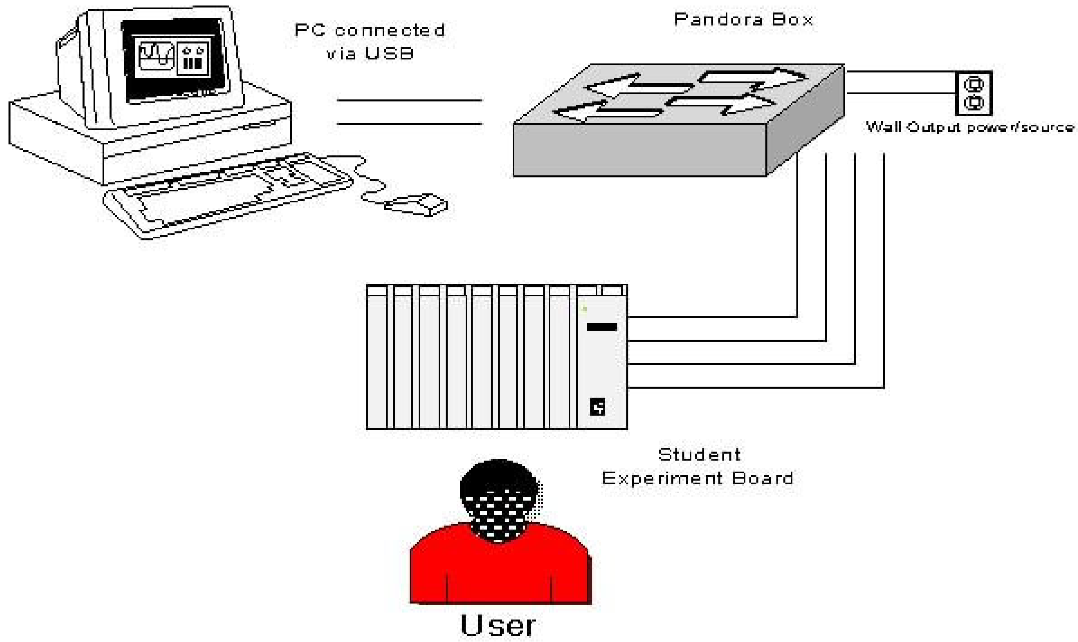

Figure 1. Pandora box in use.

3.1 Hardware design

The hardware design consists of five subsystems:

a. The power supply. To provide a +/- 5V DC and ground to the student's circuit board, we begin with a low-cost AC-to-DC converter frequently used for portable electronic components. This converter plugs directly into any AC outlet and supplies 12 VAC at 1 Amp to the Pandora box. The internal circuitry of the Pandora box converts this power into the +/- 5V DC at a 500 mA maximum (more than sufficient for sophomore and junior circuit experiments) to be used by the student and also the power supplies (+12V DC, -12V DC, and 3.3V DC) necessary to operate the other circuits internal to the box.
b. The function generator. The function generator provides signals as inputs to the student's circuit board. The signal types include sine or cosine, square, and triangular signals. Note that a DC signal is already available via the power supply. The signal frequencies are selectable from 10 Hz to 1 MHz. The signal amplitudes are selectable between 0 V to 5 V. The function generator design is based on the Maxim integrated circuit (MAX038), and the overall schematic is shown in Figure 2. The selection of signal type, amplitude and frequencies is digitally controlled with several banks of digi-potentiometers, as opposed to the conventional mechanical control using knobs and switches. This electronic control makes it possible for the home computer to be used to operate the Pandora box.

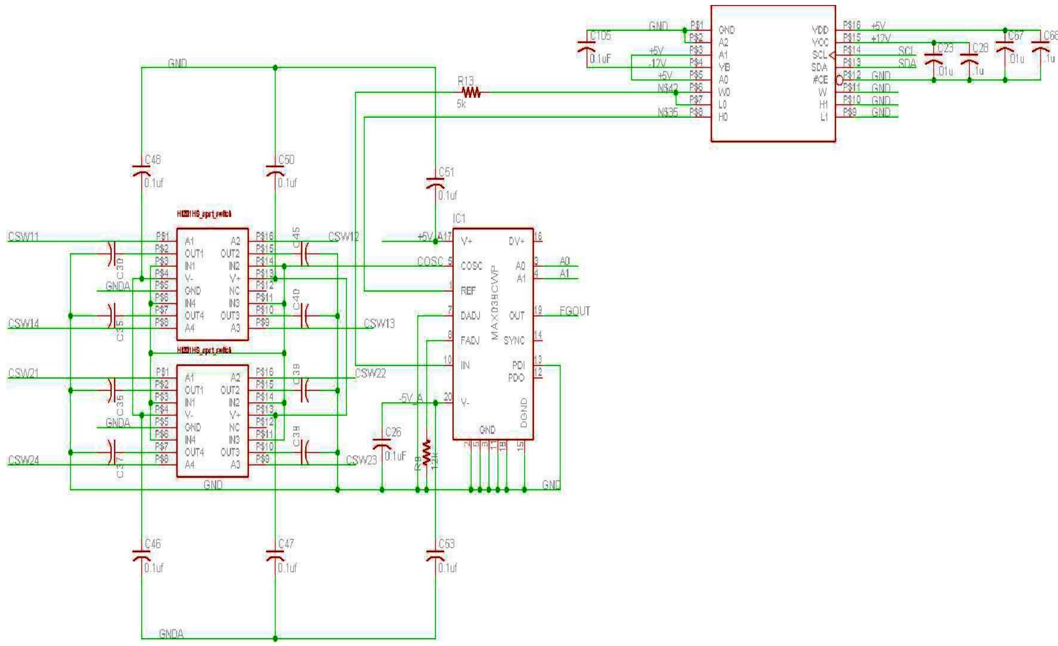

Figure 2. Function generator schematic.

c. The oscilloscope. The oscilloscope design has two channels and can operate up to 1 MHz. The design in Figure 3 uses an Analog Devices analog-to-digital converter (AD 9281) with dual channels to sample one input signal and one output signal from the circuit at the same time. To prevent over-voltage at the oscilloscope input, a simple circuit for scaling, windowing and zooming is implemented to let the student focus into one specific region of interest in the signal waveform. The 8-bit digitized data is first stored in the ADC internal memory and then transferred to the personal computer via the USB bus for display and other analyses.

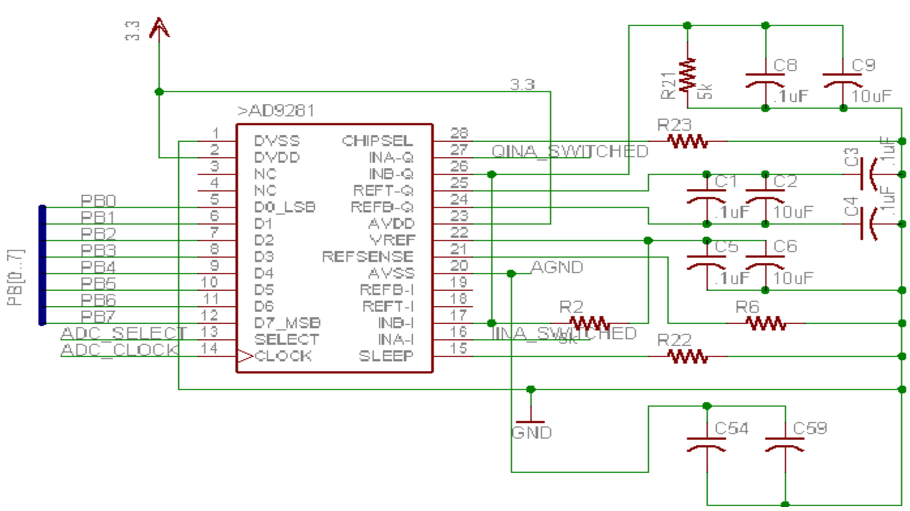

Figure 3. Oscilloscope design schematic.

d. The controller of the Pandora box is implemented using a Cypress programmable controller (CY37128P100) in Figure 4. The design requirements are to control the settings of the function generator and the acquisition of waveform data from the oscilloscope circuit. The logic design is quite simple and can be programmed on the Cypress chip from the computer. We intentionally choose this re-programmable architecture for possible later enhancements of the box functions without having to re-design or replace any hardware component in the system.

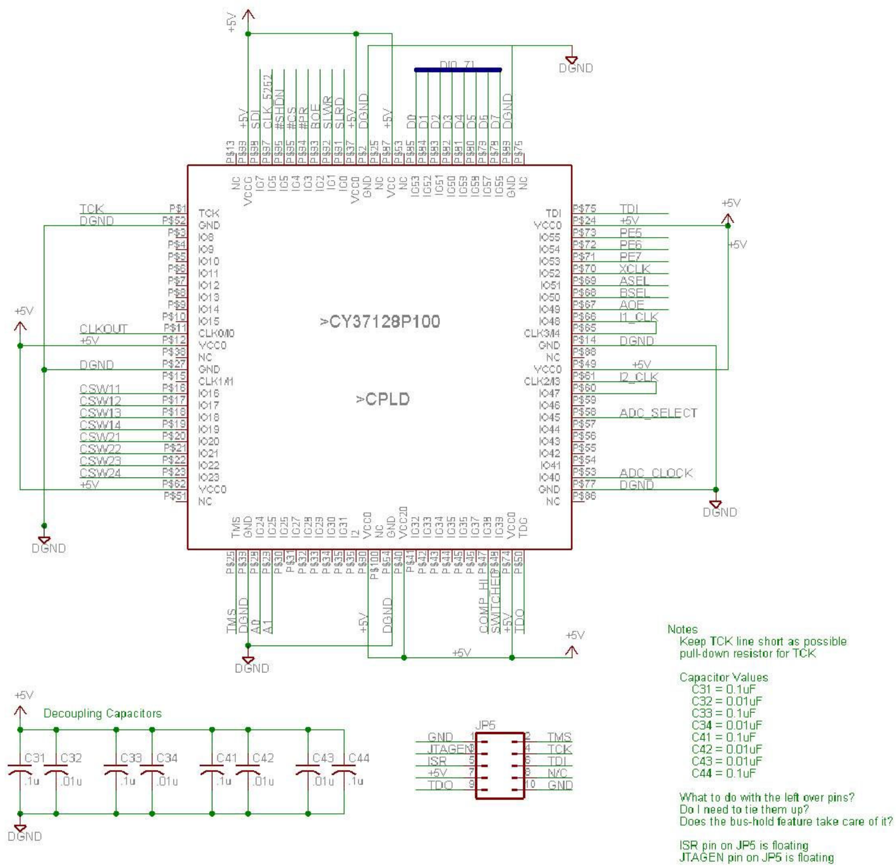

Figure 4. Pandora box programmable controller design.

e. The communication between the Pandora box and the computer is handled by the Cypress USB microcontroller (CY7C64613), a standard component used in the industry for USB devices. The Pandora box is effectively a USB device connected to the computer (Figure 5). The USB microcontroller handles the tasks of transferring user commands from the computer to operate the box and signal data from the Pandora box back to the computer. From the computer (as we will discuss later in the software and user-interface design), the student can set the signal type, frequency, and amplitude to apply to his circuit, and collect oscilloscope data from two signals for viewing on the computer monitor. The USB communication is transparent to the user.

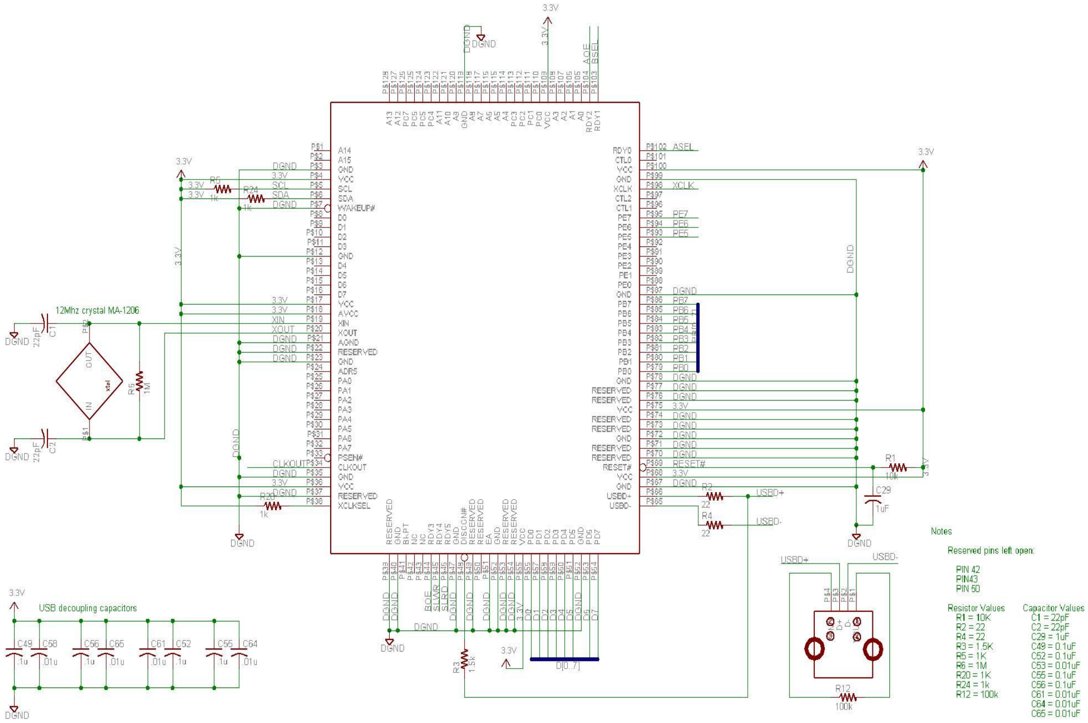

Figure 5. USB controller design.

The entire hardware design of the Pandora box, whose front panel is shown in Figure 6, achieves adequate functionality for use by students in building and testing circuits in low-level electronic courses. The physical size of the box is 2.5” H x 6” W x 8” D, which makes it portable and fits very well on a desktop as a computer peripheral. The simplicity of the design also makes it more robust and easy to improve in the future.

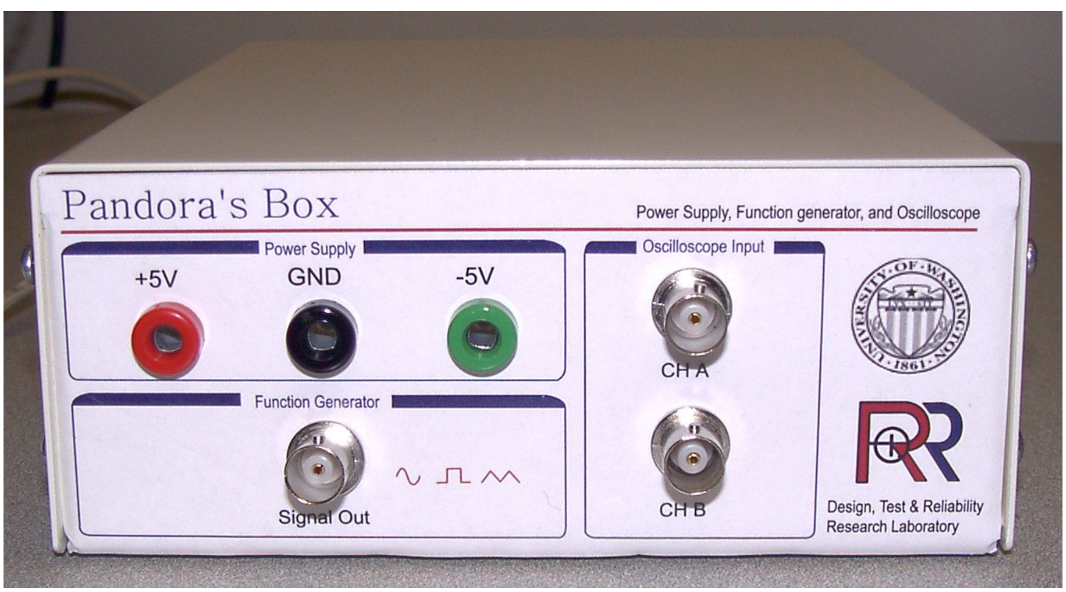

Figure 6. Pandora box showing front panel functions.

3.2 Software and user-interface design

The software design of the Pandora box uses the industry-standard LabView tool for instrumentation control. The user interface in Figure 7 permits to the student to set the signal type, amplitude, and frequency, and to operate the oscilloscope to collect waveforms from two signals. These two signals are usually one input and one output signal from his / her circuit board, but of course can be any signals on the student's circuit board. The waveform display on the computer monitor is scalable in both the time axis and the voltage axis, just like in an oscilloscope. As described in the hardware design, we include a capability to zoom into a specific region of a waveform to see it in more details and the student can set this zoom using the computer user interface as well. We note that this interface design is much more user-friendly than the current use of benchtop instrumentation: these equipment have so many knobs and push-buttons and switches, each with many levels of menus, and students spend more time struggling with equipment settings than with their circuit testing. The communication to the Pandora box is embedded into the user interface design and the waveform data can be saved on the computer for later analyses using tools such as MATLAB or SPICE. Examples of data analyses include: to perform a Fourier transform on the signal data to see its spectrum using MATLAB, and to compare the experimental signal data with the simulated signal using SPICE. Since the experimental data collected from the Pandora box is already in the computer, the analysis and comparison with simulation are very simple and well integrated, thus helping to enhance students' learning in circuit design and test.

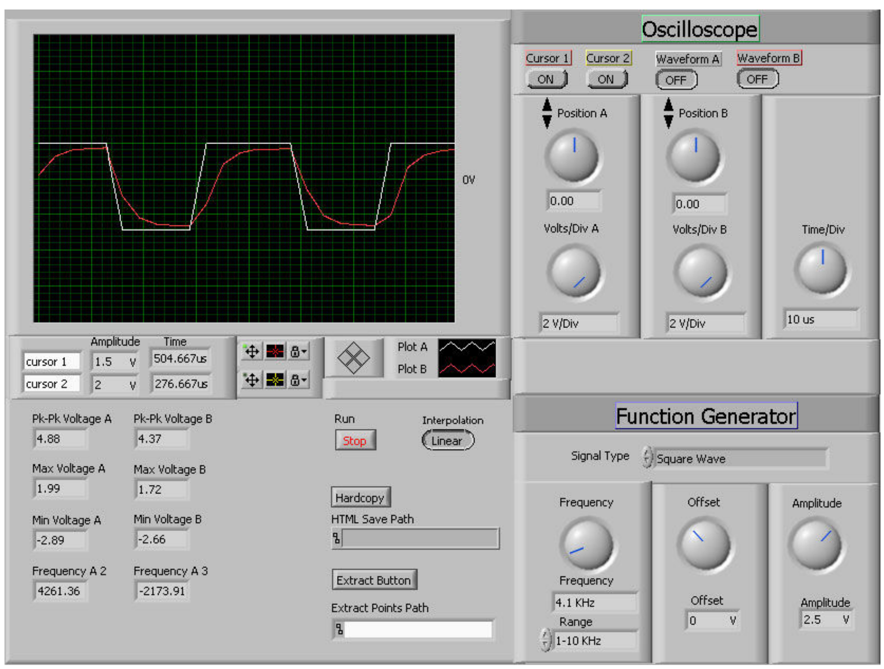

Figure 7. User interface design on the computer.

3.3 Experimental laboratory curriculum design

The Pandora box permits a full range of laboratory experimental designs for low-level circuit courses in topics such as circuit theory (DC and steady-state), linear systems, digital logic designs, analog circuits, analog electronics, and simple filter designs. The experiments currently used in our curriculum do not need any re-writing to adapt to the Pandora box if the signal frequencies used in the experimental circuits are lower than 1 MHz, which is the case for more than 85% of our current freshman, sophomore, and junior Electrical Engineering courses. For the remaining experiments, minor re-writing makes the laboratories suitable for the Pandora box. Of course, this first prototype is limited in frequencies but we already have a plan to improve the design to address this issue.

We emphasize that the Pandora box provides a hands-on laboratory experience, as opposed to "virtual" or "remote" laboratory experience in other distance-learning laboratory implementations. The student at home has a full instrumentation capability connected to his computer, he can build and test his own circuits, he can debug circuits just as students on campus do, and he actually can work in a better environment since his experimental results are already on the computer, directly available for analysis with MATLAB and / or comparison with SPICE.

4. Initial feedback from students

The first prototype of the Pandora box was used by four student groups who have taken courses using standard benchtop laboratory instrumentation. The assessment tool is a survey that includes specific questions to compare the laboratory experience using the Pandora box and using the laboratory instrumentation, capabilities, ease of use, and open-ended questions about possible other applications. The focus group conductor first briefed each student group (2 or 3 students each) about the Pandora box and the purpose of the study. The students were then given a circuit experiment in a sophomore course, which they built on a superstrip circuit board and tested using the Pandora box. Student responses were enthusiastic and suggested that the Pandora box was much easier to use than current instrumentation in the lab. They also made several suggestions for improvement of the toolbox that will be incorporated in its ongoing development. A sample set of responses includes:

- Ease of use: excellent to very good, much better than laboratory instrumentation.
- Size and weigh: just right.
- Effectiveness for use in testing circuits: very good.
- Use at home: strong favorable response, which includes students' plan to use the box for other purposes as well, outside class work.
- Enhancement of learning: definitely enhancing laboratory skills since students can use the box more often (no access limit as in the case of laboratory instrumentation), and can experiment with other circuits and hobby circuits at home.
- Cost: preferably less than $200 (compared to an average cost of $100 per course textbook, especially when the Pandora box can be used in many courses). Note that one of the design goals of the Pandora box is to limit the user cost to $200 or less, to make it affordable to students and institutions.

An interesting anecdote illustrates other unforeseen benefits of this laboratory toolbox. A student taking the Pandora box home to work on circuit experiments reported the next day: "My parents said this was the first time they could see what I did in school and what they were paying for."

We of course are continuing to conduct focus groups to collect more student feedback, both on campus and in distance-learning courses, and expect to have more results to report at the conference.

5. Dissemination strategy

The first prototype of the Pandora box is being used in our distance-learning courses, and will soon be used by our partners (two local community colleges and the University of Alaska – Fairbanks) to evaluate its performance, benefits and impact with regard to providing hands-on laboratory experience to undergraduate electrical engineering students in remote locations. Since we do not have automatic manufacturing equipment, the time to build one box is two to three weeks, and due to low volume (the prototype run targets only dozens of boxes for use by distance-learning students in our initial study), the cost per unit is closer to $200. To disseminate the box widely to other institutions (2-year community colleges, 4-year universities, and other distance-learning programs), we are exploring a cooperative effort with an electronic manufacturing company with access to automatic surface-mount technology so that the box can be fabricated at higher volumes (in the thousands during the first year) and at much lower per-unit cost. It is anticipated that the dissemination will also reach out to international schools where budget constraints and lack of expensive laboratory facilities make the Pandora box an ideal instrument for teaching electrical engineering experiments.

6. Merits and limitations of the Pandora box

The Pandora box meets three key design goals stated in section 2 above:

- Providing hands-on laboratory experience to students. The box is a direct replacement for the instrument required in testing circuits, and the students can build and test circuits in real life, not using "virtual" instrument on the web or tele-operation to run instrument at a distance.
- Reducing the cost of laboratory instrumentation, both for students and for institutions. With the cost range about $200 (comparable to a portable CD player that many students possess), it is feasible for each student to acquire the toolbox and use it not only for class experiments but also for electronic hobby and other experimentation at home. A university can reduce the cost for laboratory equipment by replacing the bench instrument with the toolbox, and in the process, recovers the laboratory space that can be used for other purposes. Space recovery and cost reduction are two very important parameters in an institution resource planning, especially in offering courses with intensive equipment requirement to a large number of students.
- Flexibility in using the toolbox in school, in a remote location, or at home. The Pandora toolbox is portable and together with a laptop PC, provides an "instant" laboratory to test electronic circuits anywhere anytime. With lower-cost desktop PCs now available in school or at home, the box can be used at many locations with ease.

The unforeseen advantage of space recovery for the academic institutions, together with cost reduction both in terms of instrument cost and maintenance cost, is a significant factor that would not be possible using the industry offerings of benchtop instrument.

Compared to handheld instruments marketed by the electronic industry, the Pandora box scores several key advantages:

- An intuitive graphical interface to use the instrument. The Pandora box interface is straightforward to learn in a few minutes while each handheld instrument has its own user's guide which nobody reads. Pushing various buttons or trying to figure out the complex hierarchy of menus for each instrument (benchtop or handheld) has been a source of frustration to students.
- Integration of test functions in one single portable box, with a small DC converter, instead of several handheld instruments.
- The total cost is lower for the Pandora box, even when including the DC converter. Of course the performance for the Pandora box might not be comparable to expensive industry instrument targeting the commercial test market, but the essential factor is that the Pandora box provides sufficient performance for laboratory experiments as part of the standard electrical engineering circuit curriculum. We note that the existing expensive equipment in our laboratory are not used to their full capability anyway, thus the extra performance in a sense is wasted.

As an electronic system, the Pandora box of course has limitations. Possible improvements, while keeping the cost low, include:

- Better frequency control and settings in the function generator.
- Better amplitude control and settings in the function generator.
- More memory for the oscilloscope to store longer waveform segments.
- Robustness and reliability.

At present, we are working on these improvements as part of the transfer of the design to an external company for manufacturing and dissemination.

7. A note on the name Pandora

In Greek mythology, Pandora was the first woman on earth and was given a box as gift from the gods, with the warning not to open it. Impelled by her natural curiosity, Pandora opened the jar, and all evil contained escaped and spread over the earth. She hastened to close the lid, but the whole contents of the jar had escaped, except for Hope. In creating this laboratory toolbox for distance learning and at-home experimentation, we believe that it will greatly enhance access to electrical engineering at low cost, but at the same time, there is a real concern that it will reduce the face-to-face interaction between faculty, teaching assistants, and undergraduate students. Engineering is not just about science and technology; it is also about working with people, and we sincerely hope that the opening of this Pandora toolbox will benefit engineering education as a whole, but not at the expense of human interaction.

8. Conclusion

This paper reports for the first time an instrumentation toolbox designed with the specific goals of providing hands-on circuit design and test experience to students in distance-learning programs or at remote locations with no access to expensive benchtop instrument as part of their study. The first prototype has been completed and initial feedback indicates enthusiastic response from the students. While the box of course can be improved significantly in the next revision, both in terms of improving performance and reducing per-unit cost, it is the key ingredient to help achieve the promise of a true electrical engineering degree program offered via distance-learning.

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References

1. Remote Dynamical Systems Laboratory, Electrical Systems, Stevens Institute of Technology, http://dynamics.soe.stevens-tech.edu/, 2004.

2. Remote Electrical Engineering Laboratory Home Page, St. Cloud State University http://condor.stcloudstate.edu/~tawele/, 2004.

3. J. Long, J. Florance, and M. Joordens, "The Use of Home Experimentation Kits for Distance Students in First-Year Undergraduate Electronics," Proc. ASEE 2004 Annual Conference, June 20-23, 2004, Salt Lake City, UT.

4. Test and Measurement World magazine, http://www.reed-electronics.com/tmworld/, 2004.

5. D. Anzaldo and J. Inkpen, "3.3-V Supply Taps Power from the -12V PCI Bus," Electronic Design, pp. 134-146, February 7, 2000.

6. K. Levine, "Low-Cost Function Generator," Electronic Design, pp. 153-154, April 3, 2000.

7. A. Bindra, "On-Chip Processors Turn Monolithic ADCs into Data-Acquisition Systems," Electronic Design, pp. 79-86, April 3, 2000.

8. Application Notes on Signal Generation Circuits, Maxim Semiconductor Corporation, http://www.maxim-ic.com/.

Biography

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