AC 2010-2156: PORTABLE CYBER-LABORATORIES FOR ELECTRICAL ENGINEERING EDUCATION

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Portable Cyber-Laboratories for Electrical Engineering Education

Abstract

Laboratories that address Electrical Engineering (EE) concepts often require expensive bench-top equipment, and numerous students can be difficult to accommodate in these crowded spaces. Additionally, static laboratory tools are increasingly incompatible with the lifestyles of today's students, who are accustomed to mobile resources like laptop computers and cell phones that host multimedia interfaces which enliven the user experience. This paper describes a new collaboration between the Kansas State University (KSU) Electrical & Computer Engineering (ECE) Department and the East Carolina University (ECU) Department of Engineering, General Engineering whose overall goal is to develop mobile hands-on learning experiences for EE concepts and then formally assess whether laboratories performed at home are effective supplements for traditional lecture- and laboratory-based courses.

To this end, the project team is developing an affordable, portable circuit prototyping kit whose primary component is a printed circuit board that hosts a National Instruments (NI) myDAQ data acquisition module (which includes a ±5 V power supply, a function generator, and a digital multimeter), a large breadboard, and numerous multimedia connectors. The carrying case that holds this board also contains a desktop power supply and a parts/tools storage area. The myDAQ module communicates over a USB interface with LabVIEW virtual instruments (VIs) that run on either a laptop or handheld computer. This kit design is an upgrade to a Rapid Analysis & Signal Conditioning Laboratory (RASCL) unit that has already demonstrated promise for courses that address circuit theory, signals, and systems.

Initial development and assessment activities target (a) upper-level KSU undergraduates that enroll in *ECE 512: Linear Systems* and *ECE 772: Biomedical Instrumentation* and (b) upper-level ECU undergraduates that enroll in *ICEE 3014: Electric Circuit Analysis* and *ICEE 3050: Instrumentation and Controls*. The VI-based modules address fundamental learning objectives identified by ABET and the Sloan Foundation in the cognitive, affective, and psychomotor domains. Selected objectives from these three domains are being assessed via student surveys, concept inventories, Fundamentals of Engineering exam performance, and laboratory observations. Higher-level learning is designed into each module, and biomedical applications are emphasized to increase student interest.

I. Introduction

Laboratories are integral to engineering education. They authenticate theory, deepen understanding, sharpen hands-on skills, and promote enthusiasm for the profession.[1] Laboratories that address Electrical Engineering (EE) concepts require expensive benchtop equipment, and numerous students are difficult to accommodate in crowded laboratories. Static laboratory tools are also increasingly incompatible with today's students, who are accustomed to mobile resources like laptop computers that give them lifestyle flexibility and host multimedia interfaces that enliven the user experience.

The **overall goal** of this collaboration between the Kansas State University (KSU) Electrical & Computer Engineering (ECE) Department and the East Carolina University (ECU) Department of Engineering, General Engineering (GE), is to develop mobile hands-on learning experiences for EE concepts and then formally assess whether laboratories performed at home are effective supplements for traditional lecture- and laboratory-based courses. Innovative virtual instruments (VIs) on laptop and handheld computers will interact with custom, low-cost prototyping kits integrated with plug-and-play data acquisition units to offer a portable alternative to traditional benchtop work spaces. Six **technical objectives** support this goal:

- Develop and replicate affordable, portable circuit prototyping kits useful either inside or outside of a traditional laboratory context.
- Create laboratory experiences (hands-on protocols and software interfaces) enabling students to learn EE concepts in their preferred environment.
- Develop lecture demonstrations with these prototyping kits.
- Integrate these lecture and laboratory modules into four existing courses
- Assess the ability of these modules to engage students, enhance learning, and facilitate participation of a larger, more diverse student base.
- Disseminate research products and findings to the broader engineering education community.

II. Motivation

A. The Lecture/Laboratory Disconnect

In curricula that teach EE concepts, hands-on laboratories that accompany circuit theory, signals & systems, and digital design courses are often scheduled separately, partly because textbooks often adopt a written-work and software paradigm. Additionally, organizing students and topics in laboratory-only environments is more efficient than interspersing hands-on assignments with lectures, so unless lecture and laboratory courses are paired, laboratories can be *separated in time* from their corresponding lecture material, making it difficult for students to retain knowledge before they put it into practice.

B. Scalability and Overcrowding

Scalability is also an issue for lecture versus laboratory courses. Lecture courses can more easily accommodate enrollment increases. Per-student resource needs for laboratories are comparatively high and nearly constant on a per-student basis, so enrollment increases will cause overcrowding and scheduling issues in laboratories before they cause similar issues in lectures. For example, in the *ICEE 3050: Instrumentation and Controls* laboratory course offered by Dr. Yao at ECU, each work area has a full equipment suite and can accommodate only two students (see Figure 1). Laboratory overcrowding has been a recurring problem, and student numbers in the ECU GE curriculum are expected to double in upcoming years. The KSU ECE Department has a similar situation.

Figure 1. Crowded ECU laboratory space.

C. Traditional Pre-Laboratory Experiences and Higher-Level Thinking

Most traditional EE laboratories require pre-laboratory work to make students more effective during the laboratory session. However, even if students study theoretical concepts, lack of early access to equipment can hinder their ability to adequately prepare. Additionally, the laboratory session may be extremely inefficient because students can spend most of the period building or debugging a circuit, a task which could be done before they arrive. This leaves little time for the reflection and analysis required for higher-level learning,[2-4] and this ***lack of higher-level learning translates to poor retention and often poor performance*** on semester exams and Fundamentals of Engineering (FE) exam problems.

D. Open Laboratories

Temporal course/laboratory separation, overcrowded laboratories, inefficient laboratories, and a desire to move hands-on experiences into lecture courses,[5, 6] have led to a desire for *"*open laboratories:*"* [5, 7-10] rooms of equipment where students can work on laboratory exercises any time. However, besides resource allocations required to maintain equipment laboratories and hire staff to oversee them, open laboratory traffic can be problematic when large lecture courses or service courses for other departments decide to implement hands-on exercises as part of the learning experience.

E. Challenges for a General Engineering Curriculum

General engineering programs must cover material from multiple sub-disciplines, so their courses must each cover a broad range of topics.[11] The ECU GE program (B.S. in Engineering) supports four concentrations (Biomedical, Bioprocess, Industrial Systems, and Mechanical Engineering). Students in all concentrations take common core courses before starting courses in their major area. Two electrical courses (*ICEE 3014: Circuit Analysis* and *ICEE 3050: Instrumentation and Controls*) form part of this core, addressing electric circuits, electricity, instrumentation, and controls. A new *ICEE 4305: Electromechanical Systems* course was offered in Fall 2009 based on feedback from the department's industrial advisory board. Such courses are designed with three purposes: (1) to prepare students for their concentration of study; (2) to help students prepare for the FE exams; and (3) to meet practical industry needs.[12] In a GE program, creative course design is needed to meet these constraints. For example, *ICEE 3050: Instrumentation and Controls* must cover topics usually addressed in at least two separate courses in a specialized EE curriculum. A project-based teaching approach was therefore adopted to improve efficiency.[13] As illustrated in Figure 2, controls-related topics are tied to a larger 5-week course project entitled *Design of a Coupled-Tank Level Control System*. A separate multi-week design project covers instrumentation topics.

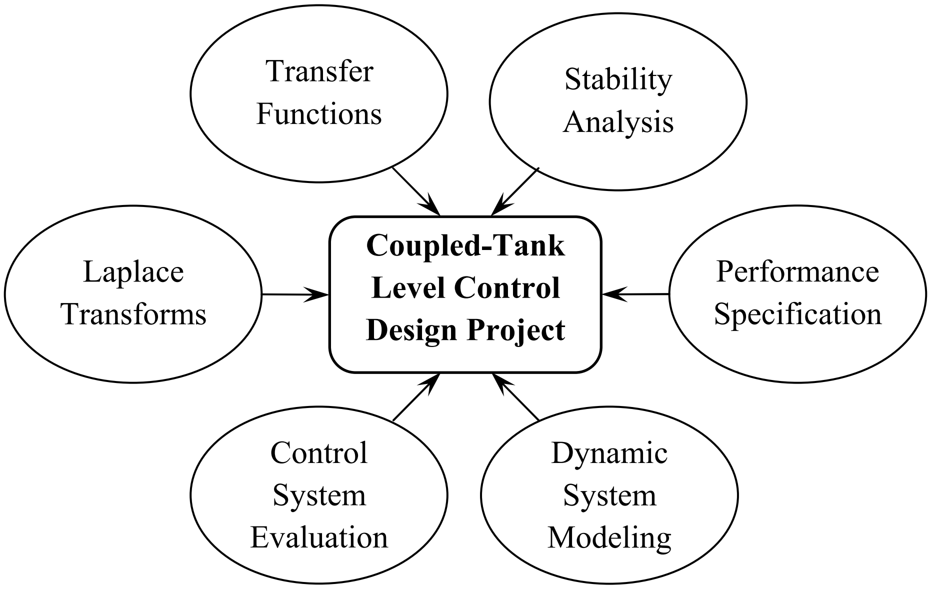

Figure 2. Course topics associated with the coupled tank control project.

F. Laboratories with Virtual Instruments as a Sensible and Forward-Looking Solution

Given the issues addressed in the previous paragraphs, engineering curricula that teach EE concepts could benefit from VI-based laboratories that allow students to build and test circuits at home as a supplement to their work with 'real' equipment on a laboratory bench. Most students use cell phones and have home access to laptop computers (e.g., all enrolling freshman at ECU must purchase a laptop). Assuming connected students will migrate toward mobile tools that support their living model, it seems sensible to supplement these cell-phone and laptop interfaces with low-cost, portable hardware specialized for electric circuit prototyping. This approach is scalable and somewhat independent of traffic problems associated with overcrowded laboratories, catalyzing the use of these hands-on experiences in both lecture and laboratory courses. Students that use these tools with traditional laboratory courses could more effectively build and debug their circuits prior to coming to the laboratory, allowing more time for higher-level discussions with the instructor.

Other benefits could be gained from the availability of such tools. First, EE educators desire associations between consecutive courses as a means to retain knowledge and connect old knowledge to new concepts. A laboratory kit that a student could purchase for a textbook price (or better yet assemble as an introductory project) could be used in multiple consecutive courses. At KSU, this platform could be a common thread through *ECE 210: Intro to EE*, *ECE 410: Circuit Theory I*, *ECE 511: Circuit Theory II*, *ECE 512: Linear Systems*, and *ECE 530: Control Systems*, where a variety of VIs could accompany the bread-boarding functionality and data acquisition capability to meet these subject needs. Second, as students learn circuit, system, and processing concepts, they can test and implement them in hardware (on the breadboard) and in software (via LabVIEW interfaces), leading to better concept retention. VIs with audio, video, and other multimedia enhancements could assist with higher-level learning.

III. Background

A. Previous Work – Technology Development for the Classroom

Rapid Analysis and Signal Conditioning Laboratory (RASCL). The investigators on this project have a history of creating effective learning tools for engineering education.[14-26] One recent product, a RASCL unit,[24] is an analog/digital prototyping tool that forms the initial hardware and software technology base for the learning modules proposed here. It was designed to allow students to complete hands-on laboratory assignments off-campus. RASCL version 1.0 is pictured in Figure 3 along with a sample LabVIEW VI and a student user. A RASCL unit, at a cost of ~$250, consists of a carrying case that contains a printed circuit board (which hosts a National Instruments (NI) USB–6009 data acquisition (DAQ) module, a function generator, and a large breadboard), a desktop power supply, and a parts/tools storage area. The DAQ module communicates with LabVIEW VIs through a computer's USB interface. The following requirements drove this design:

- The breadboard should be large enough to accommodate reasonably complex circuits.
- The portable toolkit should have a case, a power supply, a DAQ board (for analog and digital input/output), and a software interface to view waveforms and to provide output control signals.
- A stand-alone LabVIEW license should accompany the DAQ hardware at no additional cost.
- The board and case must be durable enough to survive trips to campus in a backpack.
- The kit should be affordable and flexible enough for use in several classes.

This low-cost RASCL unit has limitations (e.g., sampling frequency and instrument fidelity) relative to benchtop laboratory equipment, but it offers the potential for students to address hands-on homework assignments in their own living environment.

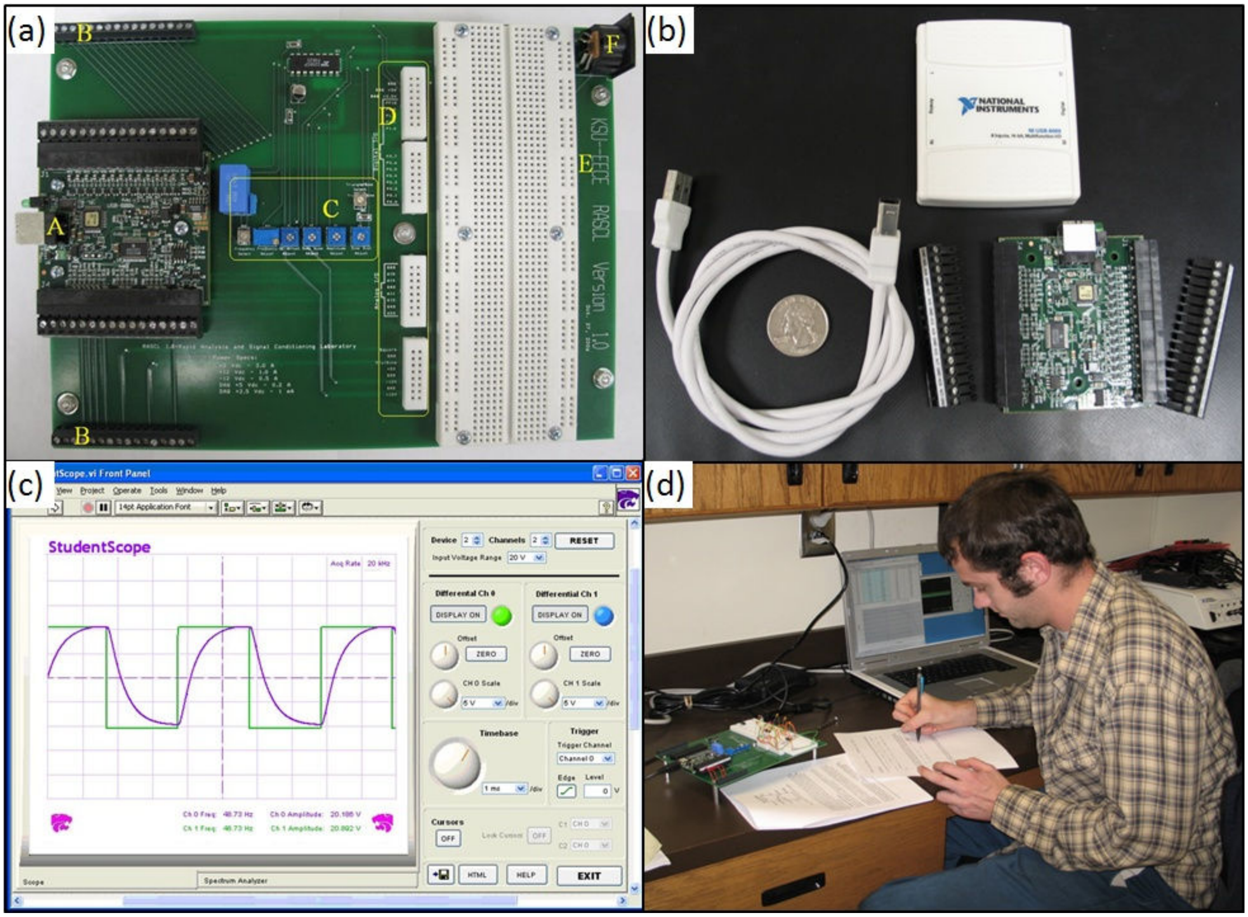

Figure 3. Virtual prototyping tools: (a) KSU RASCL Version 1.0 prototyping board, (b) USB data acquisition card, (c) LabVIEW StudentScope virtual oscilloscope, and (d) student using the unit.

To assess the potential of such a tool, one learning module was created and evaluated: a 2nd–order lowpass voltage-controlled-voltage-source filter laboratory for the Fall 2006 KSU section of *ECE 512: Linear Systems* (38 students). [24] The exercise, intended to take two hours and driven by learning objectives, required students to build a predefined circuit and assess its properties by applying different input signals and analyzing the respective output signals. Students were asked to experimentally determine the filter transfer function, compare the transfer function to theory, analyze the effect of this filter on different time-domain waveforms, and investigate how the DAQ unit and sample parameters affect frequency spectra. Questions were interspersed during the exercise to assess student understanding of laboratory concepts. Each student was asked to complete a survey to summarize their learning experience. Student responses were highly positive: they felt that similar hands-on exercises would be effective additions to lecture courses. While students acknowledged the importance of theoretical learning, they expressed a preference for coursework that combined theory and hands-on learning. An important observation was that students with no prior experience in building circuits found this exercise to be especially effective and that it increased their desire to learn. Students would be willing to invest $200-$400 on this type of tool. Given this feedback, KSU moved ahead with RASCL version 2.0 (see Figure 4), which incorporated twice the prototyping area, better function generator controls, an optimized layout, and audio input/output jacks.

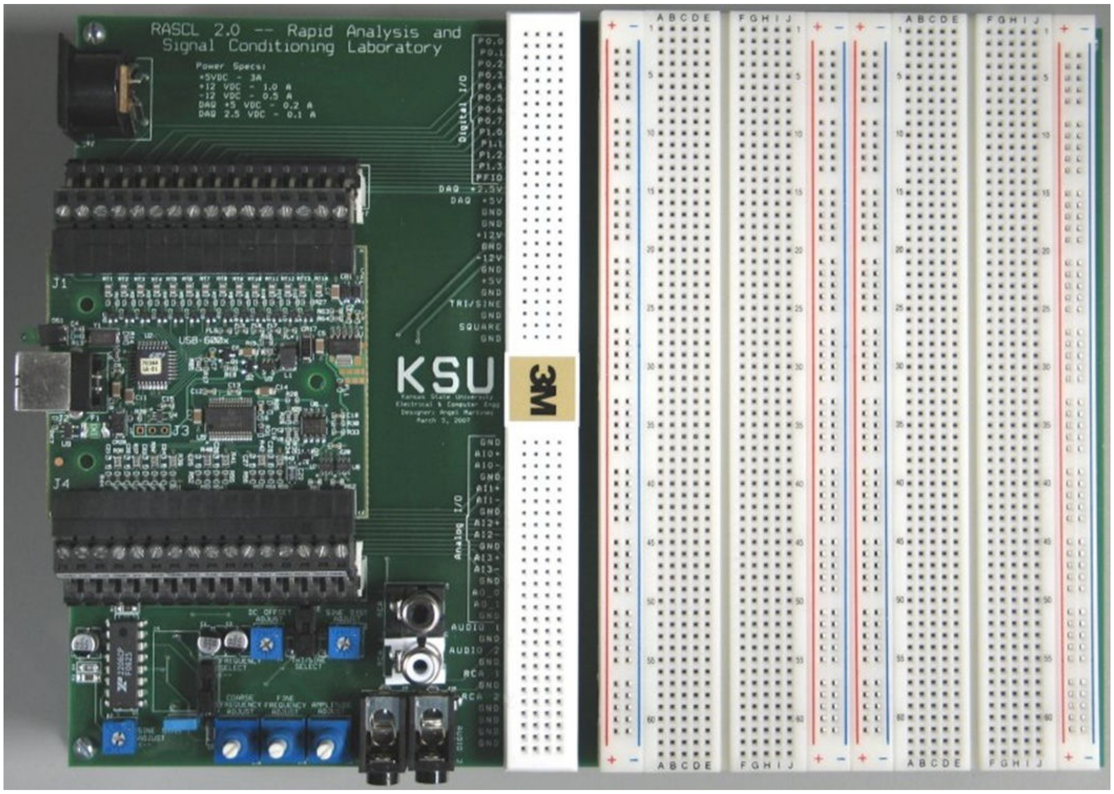

Figure 4. KSU RASCL Version 2.0

B. Existing Breadboard-Based Products for Circuit Prototyping and Education

One would surmise that low-cost tools already exist for circuit prototyping at home, but options are quite limited; this drove the development of the RASCL platform. In light of the requirements listed in the previous section, a precursory search for suitable existing products (a search which included the ASEE publication database[27] and the IEEE XPlore search facility[28]) was surprisingly unfruitful, affirming the educational niche such a tool would fill.[24] This is illustrated in Figure 5, where the picture on the left shows a minimal breadboard for home audio projects designed by William Durfee (University of Minnesota). This NSF-funded mini-kit, which partly inspired the early KSU RASCL work, is a simple but forward-thinking tool designed to "pilot an innovative approach to system dynamics and control laboratories that incorporates proven hands-on learning principles to improve student learning."[29] The kit includes software written in Visual Basic that allows students to communicate with the board via the left and right channels of the Line-In port on a computer sound card. The resources on such a board are restricted when one considers broad use in an EE curriculum. The basic design, however, is consistent with several research and commercial products that use a sound card or USB-DAQ interface to turn a PC into an oscilloscope.[30-34] Other portable data acquisition devices exist,[35-38] but like the oscilloscope emulators, they do not by themselves meet the requirements for in-home laboratory kits. Two academic collections[39, 40] also come close in spirit, but these are not commercially available and do not have the level of integration desired for large-scale course adoption. On the other end of the spectrum, the NI EVLIS modules[41] (Figure 5, right) are highly functional, including a power supply, functional generator, oscilloscope, digital multimeter, and large breadboard. Given an external data acquisition (DAQ) card and a LabVIEW virtual instrument, they offer ample functionality for EE student use at home but are much more costly than a textbook even at educational prices. Some systems under $1,000 are shown in the center of Figure 5. Of these units, the NI SC-2075 is useful but requires a separate DAQ card and LabVIEW Interface. The Global Specialties Analog Circuit Trainer,[42] offers multiple input signals, a prototyping area, and a portable power supply, but it does not include a connection to a PC. Freescale offers an evaluation board to prototype digital systems that employ the MPC555 microcontroller,[43] but it has limited breadboard space. Finally, microEngineering Labs, Inc. offers a similar board,[44] but the board is designed for operation with a Microchip PIC microcontroller and does not support the breadboard and visualization features seen as important for off-campus, hands-on circuit learning experiences.

In contrast, the KSU RASCL version 2.0 kit costs $250 with minimal markup and includes NI USB-6009 DAQ unit access to LabVIEW VIs. National Instruments has agreed to work with KSU and ECU on this effort. Their newest version of the USB-6009 portable DAQ unit (now called a "myDAQ" unit) will be linked with KSU RASCL version 3.0.

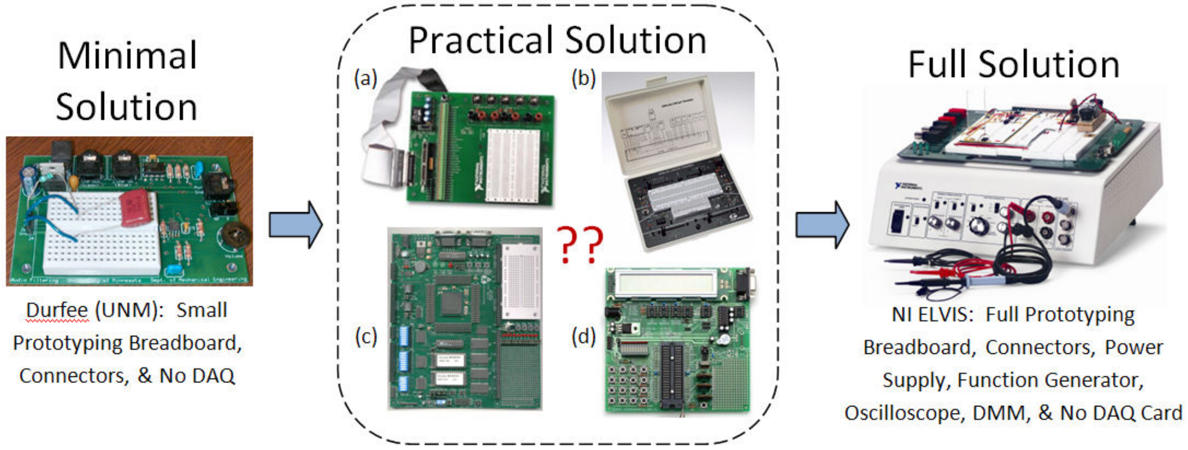

Figure 5. The search for a prototyping solution for home use: (a) National Instruments SC-2075, (b) Global Specialties Analog Circuit Trainer, (c) Freescale evaluation board, and (d) microEngineering Labs, Inc. development board.

C. Learning Levels and Assessment

Bloom's taxonomy is a broadly accepted classification scheme for the cognitive learning domain that relates to the first 5 of the 13 laboratory objectives identified by ABET[45] and the Sloan Foundation[46] to cover the three knowledge domains: cognitive, affective, and psychomotor.[47] This taxonomy arranges intellectual behavior into six levels of increasing abstractness or complexity: [3] *(Questions in parentheses are based on the updated Bloom's taxonomy [2, 48])*

1. **Knowledge**: arrange, define, duplicate, label, list, memorize, name, order, recognize, relate, recall, repeat, reproduce, state (***Remembering:*** *Can the student recall or remember the information?*)
2. **Comprehension**: classify, describe, discuss, explain, express, identify, indicate, locate, recognize, report, restate, review, select, translate (***Understanding:*** *Can the student explain ideas or concepts?*)
3. **Application**: apply, choose, demonstrate, dramatize, employ, illustrate, interpret, operate, practice, schedule, sketch, solve, use, write (***Applying:*** *Can the student use the information in a new way?*)
4. **Analysis**: analyze, appraise, calculate, categorize, compare, contrast, criticize, differentiate, discriminate, distinguish, examine, experiment, question, test (***Analyzing:*** *Can the student distinguish between the different parts?*)
5. **Synthesis**: arrange, assemble, collect, compose, construct, create, design, develop, formulate, manage, organize, plan, prepare, propose, set up, write (***Evaluating:*** *Can the student justify a stand or decision?*)
6. **Evaluation**: appraise, argue, assess, attach, choose, compare, defend, estimate, judge, predict, rate, core, select, support, value, evaluate (***Creating:*** *Can the student create a new product or point of view?*)

Various assessment tools that map to the three learning domains (cognitive, affective, and psychomotor) have been developed and distributed[49-51] that rely on learning theory[52, 53] and established methods for teaching engineering.[54-57] For example, concept inventories help to identify student misconceptions and measure the impact of interventions.[58, 59] Student surveys are also frequently applied to collect opinions on teaching approaches and their effectiveness. Turns et al.[50] reviewed 12 different instruments (concept maps, interviews, focus groups, laboratory/classroom observation, etc.) that can be utilized for different purposes. Information regarding these instruments can be readily obtained through various channels.[60] The ASEE 2006 workshop paper prepared by NSF engineering-education program directors also provides helpful assessment guidance.[49] Resources that specifically target assessment of laboratory-based education, however, are lacking. As noted by Feisel et al.,[1] objectives for laboratory-based education have not always been clearly defined, and effectiveness assessments for laboratory-based education remain an open research area.

IV. Methods

The work to be completed for this effort is guided by these major themes:

- **Development** of mobile, hands-on laboratory tools that provide inexpensive personal alternatives to crowded laboratory experiences
- **Creation** of engaging multimedia protocols that promote higher-level thinking
- Formal **assessment** of the impact of these laboratory experiences on learning
- **Dissemination** of these tools into the broader engineering education community

A. Learning Tool Development

KSU learning tool development will initially focus on **upgrades to the RASCL version 2.0 unit**. The most impactful of these will be the migration to the new and yet unreleased version of the NI USB-6009 DAQ unit. Dubbed the NI myDAQ, it adds a ±5 V power supply, a function generator, and a DMM. The unit will ship with drivers and VIs based on the NI ELVISmx software[61] used to control the NI ELVIS II units.[62] This VI collection includes an oscilloscope, a waveform generator, a digital multimeter, a power supply, a digital I/O interface, and a frequency-domain Bode analyzer. Other functional upgrades will include briefcases with bays for the RASCL components, better function generator knobs, improved audio/video connectivity, and a more robust design. The NI myDAQ, which will include a student LabVIEW license, is targeted at a $250 retail price point, so the cost of the entire upgraded toolset will be ~$350.

At the same time, ECU and KSU will begin to design **new learning experiences and the LabVIEW VIs that accompany them**. This will be the primary development activity for this effort. When possible, academic VIs from National Instruments or other contributors will be used as starting points. The protocols that utilize these VIs may be supplemented with learning videos (e.g., created with Adobe Flash[63] or Dreamweaver[64]) that students can play while they work with the RASCL unit, assemble their circuits, etc. This is a powerful aspect of the proposed effort, as numerous Internet videos already exist that address EE topics.

B. Learning Experiences

Anticipated Process. Students will prototype their circuits and use these tools on, e.g., their kitchen tables at home to (a) complete hands-on homework assignments for lecture courses, (b) attend to pre-laboratory work prior to coming to campus, or (c) address unfinished work from a prior laboratory. Their laptop computers or PDAs will help them visualize their work, and online resources will address student questions. When students arrive to scheduled laboratories, their circuits will be ideally built and tested, so the instructor can spend more time interacting with them, more time on higher-level learning, and less time debugging circuits. Upon completion of the scheduled laboratory, students can then take their circuits home and do parameter tradeoffs for the post-laboratory follow-up and report-generation process, leading them to a deeper understanding of the principles addressed in the laboratory session.

Target Classes/Populations. These activities will target (a) **upper-level KSU undergraduates** that enroll in *ECE 512: Linear Systems* (40 EE & CmpE students/semester) and *ECE 772: Biomedical Instrumentation* (15 EE & non-EE students/semester) and (b) **upper-level ECU undergraduates** that enroll in *ICEE 3014: Electric Circuit Analysis* (40 GE students/semester) and *ICEE 3050: Instrumentation and Controls* (40 GE students/semester). In ECE 512, modules will supplement the lecture and programming course, whereas in ECE 772, ICEE 3014, and ICEE 3050, modules will supplement/replace existing labs.

Module Development Strategy. The investigators have adopted a strategy where KSU and ECU researchers will each develop eight learning modules for their respective courses, with the goal that at least half of the modules will also be used by the partner institution. These VI-based modules will highlight the following fundamental objectives identified by ABET and the Sloan Foundation:[1]

- Cognitive Domain: Instrumentation, Models, Experiment, Data Analysis, and Design
- Affective Domain: Learn from Failure, Creativity, Safety, and Ethics in the Laboratory
- Psychomotor Domain: Psychomotor and Sensor Awareness

Higher-level learning[3] will be planned into each module (see *Section III.C.*). The 'Learn from Failure' area will be addressed via built-in failure experiences, where students will be provided just-in-time help to address a problem. Audio/visual elements will be added to target the Sensory Awareness area and therefore positively increase the impact of these experiences o the affective and cognitive domains.[49] Biomedical applications will be emphasized to increase student interest, optimize module re-use in ECE 772, and maximize the likelihood of female-student engagement, since educators are generally aware that female students migrate toward topics such as biomedical engineering because they address societal benevolence.[65-67] In addition to the learning modules created by the investigators and their graduate students, other modules will likely be created by honors students and students that enroll in special topics courses. This model has worked well in the past for ELVIS-based learning experiences.

Planned Modules. Table 1 lists the anticipated learning experiences to be developed for this effort. The *Learning Kit Introduction* module will be the first module employed in each course, as it will familiarize the students with the kit features. Modules to be shared between KSU and ECU are marked with an asterisk. Note that ECE 512 and ECE 772 may also share modules between them, depending on the makeup of the ECE 772 student population.

Table 1. Learning Modules. (ECE 512: Linear Systems; ECE 772: Biomedical Instrumentation; ICEE 3014: Electric Circuit Analysis; ICEE 3050: Instrumentation and Controls)

KSU ECE	ECE 512 – Complex Numbers and Sinusoids* ECE 512 – Natural Response of RLC Circuits* ECE 512 – 2nd-Order Butterworth/Chebyshev Active Filters; Audio Filtering* ECE 512 – Fourier series ECE 512 – Signal sampling and aliasing; Discrete Fourier Transforms ECE 772 – Sensor calibration and Measurement Theory* ECE 772 – Amplifier design; Instrumentation amplifiers (Electrocardiography) * ECE 772 – Biosignal spectra; Filtering (Photoplethysmogram; Electrocardiogram; Audio) *
ECU GE	Learning Kit Introduction* ICEE 3014 – Thevenin/Norton Equivalent Circuits ICEE 3014 – Voltage/Current Division ICEE 3014 – Single-Time-Constant Circuits; RC Filters* ICEE 3014 – Op-Amps 1* ICEE 3014 – Op-Amps 2* ICEE 3014 – Temperature Alarm Design. MATLAB Model of a Wheatstone Bridge Circuit; Wheatstone bridge circuit linearization; Temperature alarm circuit integration and test* ICEE 3050 – Oil level sensor design. Parallel copper plates calibration; 555 oscillating circuits; LabVIEW data acquisition, processing, and display; Sensor characterization and specification

*Modules to be shared between KSU and ECU.

C. Learning Assessment

Laboratories with portable kits such as those described here can potentially address all of the 13 fundamental laboratory objectives laid out in the ABET/Sloan Foundation colloquy. However, assessing all of these objectives would be overwhelming for an NSF CCLI Type I study. Therefore, selected objectives from the three domains will be assessed to evaluate the effectiveness of this approach. The objectives assessed and the means of assessment will depend on the subject matter for a given laboratory, but in general the following assessment approaches will be applied: student surveys, concept inventories, FE sample questions, and laboratory observations. Planned instruments and their respective outcomes are summarized in Table 2.

Table 2. Assessment instruments for outcomes in the three knowledge domains.

Learning Outcomes		Student Survey	Concept Inventory	FE Sample Questions	Laboratory Observation	Modified Pittsburg Survey
CD	Knowledge Level (BL1,2)	X	X			
	Model, data analysis, and design (BL3-6)	X		X		
AD	Students attitude towards engineering	X				X
	Learn from failure	X			X	
PD	Psychomotor	X			X	
	Sensory awareness	X			X	

Student surveys will be developed and administered to collect feedback for all three knowledge domains, including (1) students' opinions regarding each individual laboratory module, (2) self assessments of how well they met the learning objectives, (3) students' changes in attitude towards these courses, and (4) students' attitudes with respect to engineering as a profession. Existing assessment resources from NSF's knowledge base will be adopted if possible when the surveys are developed. For example, the team plans to use the questionnaire from the *Student Assessment of Learning Gains* web site (http://www.salgsite.org/) to measure student perceptions of learning gains due to their experiences with the proposed laboratory modules. A modified Pittsburgh Freshman Engineering Survey[68] will also be used to collect attitude information (last column, Table 2). Pre- and post- surveys will be administered to collect student attitude information and information about levels of understanding in EE topics. For example, a modified Pittsburgh Freshman Engineering Attitudes Survey will be administered twice for each class to monitor student attitude changes. Similarly, students will be required to work on FE problems before and after laboratories to gauge improvements in cognitive understanding.

Other instruments will be used to assess specific objectives within the three domains that are best supported by the new learning approach:

1. Cognitive Domain. Concept inventories will be used to measure improvements in student understanding for specific topics taught in specific classes; this can usually be considered acquisition and comprehension of knowledge (BL1 and BL2; "BL" = Bloom's Level). FE questions will be embedded into midterm and/or final exams to assess high-level thinking. FE sample questions usually evaluate a student's critical thinking, which includes thinking skills such as analysis, evaluation, induction, deduction, and inference.[69] These skills are combinations of the data analysis, models, and design areas as specified in the 13 Fundamental Objectives and can also be generally mapped to multiple Bloom's levels (BL3–L6). Many resources are available to locate sample questions for topical areas covered by the classes proposed here.

2. Affective Domain. In addition to evaluating student attitudes toward engineering as a profession, the team will assess the "Learn from Failure" fundamental objectives. For each class, students will be asked to work on erroneous problems and will be observed to see how they approach these problems and how they learn from their mistakes. The investigators expect to see a greater number of simple mistakes at the beginning of the semester and fewer simple mistakes near the end of the semester, demonstrating students' relative achievements for this objective.

3. Psychomotor Domain. The psychomotor and sensory awareness objectives will both be measured in this domain. For a given subject area, the investigators will develop a rubric to evaluate a student's ability to perform a task and observe how proficiently they can set up the equipment and visualization tools. For sensory awareness assessment, questions will be designed into a laboratory module to measure how the extended laboratory experience has helped a student develop this skill.

V. Concluding Remarks

The merit of this approach is clear. First, the technology is timely and apt. Mobile students need mobile tools, and the textbook price point of these planned kits makes them suitable for adoption by individual students, which means the approach is scalable to any number of students and has the potential for **transformative change** in curricula that have limited physical laboratory resources. The use of VIs, coupled with mobile, hands-on hardware, provides a rich opportunity for unique, multimedia-intensive learning experiences that would be difficult to implement effectively in a static laboratory with limited space and a meager selection of instrument interfaces. Additionally, not only are appropriate, textbook-priced prototyping solutions unavailable on a broad off-the-shelf scale, but few previous efforts have attempted to formally assess the insertion of hands-on cyber-technologies into classrooms; published assessments and assessment methods for the insertion of tools into *laboratory* environments are even more difficult to find.

This effort has the potential to dramatically and positively impact both engineering pedagogy and the physical resources that facilitate learning. From a pedagogical viewpoint, this project will help to develop new assessment methods for hands-on learning experiences that employ virtual instruments, whether these experiences are paired with a lecture or laboratory parent course. As noted earlier, these tools are in short supply. An important part of this process will be the development and assessment of higher-level-learning experiences such as those alluded to earlier in this document. This research will also help to move hands-on engineering education into a more distributed model that relies on cyber-enabled tools which are more in line with the mobile, plugged-in lifestyles of today's students. The beauty of this approach is that the proposed tools and methods have the **potential** ***to address individualized, hands-on education without requiring substantial updates to the already-existing educational laboratory infrastructure***. From a tools viewpoint, hardware at textbook prices will open up entirely new curriculum options to engineering education programs that lack additional laboratory space or are trying to incorporate greater numbers of distance-learning students into their programs. Also, since these hardware tools and their associated VIs are generic, cross-course projects and multi-semester projects (e.g., to study learning trajectories) are now more viable possibilities.

From a dissemination viewpoint, it is important to restate that academic efforts which have attempted to address these types of portable learning kits do not have efficient means to scale delivery of their hardware products to the entire engineering community. Because of the investigators' relationship with National Instruments, all research products (hardware, learning protocols, virtual instruments, and assessment methods) generated through this work have the potential to be manufactured in large quantities and broadcast to a worldwide engineering education base, which makes this project unique. The nearer-term dissemination plan will start with a web site jointly maintained by KSU and ECU that provides (a) order information for RASCL hardware, (b) downloadable LabVIEW VIs and videos (cross-posted on YouTube) for various learning subjects (including non-EE curricula), (c) assessment tools (either custom or third-party) relevant to hands-on cyber-laboratories integrated into lecture and laboratory courses, (d) links to relevant tools on the National Instruments education site, and (e) links to similar research endeavors. Research results will also be disseminated through more traditional venues: journal publications, conference papers/presentations, and book chapters.

With respect to broadening participation, these mobile hands-on-learning kits can have an immediate impact on distance learning, K-12 students that demonstrate early interest in science and engineering, students in developing countries, and under-represented groups, including inner-city and rural students. These mobile stations can be used anywhere in the world where electricity is available, making engineering education accessible to students without access to benchtop measurement instrumentation. This might include junior-college students that wish to align with university-level teaching efforts, or perhaps non-engineering students to whom faculty wish to teach circuits principles but do not have the local laboratory resources to support.

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