Center for Mobile Hands-On STEM

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Kenneth Connor is a professor in the Department of Electrical, Computer, and Systems Engineering (ECSE) where he teaches courses on electromagnetics, electronics and instrumentation, plasma physics, electric power, and general engineering. His research involves plasma physics, electromagnetics, photonics, biomedical sensors, engineering education, diversity in the engineering workforce, and technology enhanced learning. He learned problem solving from his father (ran a gray iron foundry), his mother (a nurse) and grandparents (dairy farmers). He has had the great good fortune to always work with amazing people, most recently professors teaching circuits and electronics from 13 HBCU ECE programs and the faculty, staff and students of the SMART LIGHTING ERC, where he is Education Director. He was ECSE Department Head from 2001 to 2008 and served on the board of the ECE Department Heads Association from 2003 to 2008.

Prof. Kathleen Meehan, University of Glasgow

Kathleen Meehan earned her B.S. in electrical engineering from Manhattan College and her M.S. and Ph.D. from the University of Illinois under the supervision of Prof. Nick Holonyak, Jr. She worked as a member of technical staff at Lytel, Inc., following graduation. At Polaroid, she was appointed a Senior Research Group Leader, responsible for the design of laser diodes and arrays. After leaving Polaroid, she was employed at Biocontrol Technology. She moved into academia full-time in 1997 and worked at the University of Denver, West Virginia University, and Virginia Tech. She is currently the director of the University of Glasgow-University of Electronic Science and Technology of China Electronics and Electrical Engineering programme. While at Virginia Tech, she collaborated with Dr. Robert W. Hendricks, with assistance of a number of undergraduate students, to develop an instructional platform known as Lab-in-a-Box, which is used in a number of courses within the Virginia Tech B.S.E.E. program. She continues to be actively involved in the development of mobile hands-on pedagogy as well as research on other topics in STEM education, the synthesis and characterization of nanoscale optical materials, and fermentation processes.

Dr. Bonnie H. Ferri, Georgia Institute of Technology

Dr. Bonnie Ferri is a Professor and the Associate Chair for Undergraduate Affairs in the School of Electrical and Computer Engineering at Georgia Tech. She performs research in the areas of active learning, embedded controls and computing, and hands-on education. She received the IEEE Undergraduate Education Award and the Regents Award for the Scholarship of Teaching and Learning. She received her BS in EE from Notre Dame, her MS in ME/AE from Princeton, and her PhD in EE from Georgia Tech.

Prof. Aldo "Al Ferri" A. Ferri, Georgia Institute of Technology

Al Ferri received his BS degree in Mechanical Engineering from Lehigh University in 1981 and his PhD degree in Mechanical and Aerospace Engineering from Princeton University in 1985. Since 1985, he has been a faculty member in the School of Mechanical Engineering at Georgia Tech, where he now serves as the Associate Chair for Undergraduate Studies. His research areas are in the fields of dynamics, controls, vibrations, and acoustics. He is also active in course and curriculum development. He is a Fellow of the ASME.

Dr. Deborah Walter, Rose-Hulman Institute of Technology

Dr. Deborah Walter is an Associate Professor of Electrical and Computer Engineering at Rose-Hulman Institute of Technology. She teaches courses in circuits, electromagnetics, and medical imaging. Before joining academia in 2006, she was at the Computed Tomography Laboratory at GE's Global Research Center for 8 years. She worked on several technology development projects in the area of X-ray CT for medical and industrial imaging. She is a named inventor on 9 patents. She has been active in the recruitment and retention of women and minorities in engineering and currently PI for an NSF-STEM grant to improve diversity at Rose-Hulman.

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Remarkable progress has been made in the development and implementation of hands-on learning in STEM education. The mantra of *See One, Do One, Teach One* overly simplifies the idea but does provide a helpful structure to understand how many engineering educators are attempting to change the learning experience of our students. Until recently, this effort has been faced with a major limitation. We can easily incorporate traditional paper and pencil and numerical analysis, synthesis, and simulation in our classrooms. However, the remaining key aspect of doing the job of an engineer – experimentation – has only been included through the use of expensive and limited-access lab facilities. Small, low-cost Mobile Hands-On STEM (MHOS) learning platforms (e.g., mobile personal instrumentation and control devices like *myRIO*, *myDAQ, Analog Discovery* and *ADALM1000* and processors/microcontrollers like *Arduino, Raspberry Pi, PSoC, ARMmbed, LaunchPad …*) provide almost unlimited opportunities to solve this remaining problem in engineering courses. Pedagogy based on these tools has been implemented and studied in many institutions in the US and in other countries, impacting thousands of students each year. In all cases in which hands-on learning has been studied, the pedagogy has been successfully implemented. This has occurred even in traditionally theory-only courses, resulting in more engaged students and instructors. Although the initial assessments of this new approach to STEM education argue for broad application, the definitive case for its adoption has yet to be documented so that all STEM educators can fully appreciate its merit.

Goals of the Center for Mobile Hands-On STEM

The Center for Mobile Hands-On STEM is pursuing activities that gather strong evidence of the effectiveness of Mobile Hands-On STEM (MHOS) pedagogy on student learning and develop an effective and pro-active dissemination strategy for the entire STEM educational community. To achieve these goals, we have recently focused on:

1. Creating and implementing new standardized assessment tools that measure student learning, especially through the development of new experimentally focused concept inventories, as well as measure ease of adoption by instructors.
2. Identifying implementation barriers for wide-spread adoption and how these might be overcome by applying the business start-up methodology of the NSF I-Corps program, working with faculty who have recently received funding to implement the mobile pedagogy, and holding focus groups among different constituencies.
3. Delivering a set of workshops for faculty and administrators on effective use of Mobile Hands-On Learning. The first was held at the 2012 ASEE Conference in San Antonio, the second at Georgia Tech in conjunction with the 2013 ASEE conference and there were two workshops the following year, one at ASEE and one at the American Control Conference. Other workshops were offered jointly with collaborative projects, like the HBCU ECP project.

The focus of the most recent activities of the center has been in the delivery of these workshops (goal 3) to spread the best practices of the early adopters of the MHOS pedagogy. We have been hosting a series of online practitioners' workshops rather than the usual physical face-to-face workshop, because of the potential for wider and longer-term impact. The Center for Mobile Hands-On STEM conducted a series of three virtual workshops for educators who already use hands-on learning, that is, the practitioners of the pedagogy. The expected outcomes of the workshops were: 1) to share ideas, 2) examine challenges, 3) determine best practices, and 4) give feedback to NSF and to vendors who build the supporting technologies.

The workshops targeted participants who have experience developing and using portable experiments on one of the following platforms: National Instruments *myRIO,* microcontrollers, and data acquisition/instrumentation boards such as the Digilent *Analog Discovery* board or the *myDAQ*. In each of the cases, students can own the measurement device or the embedded processor unit (the *myRIO* or microcontroller) and couple their own device with an experimental platform. The portability of the platforms could fall into one of three categories: 1) completely portable and student-owned so that the lab or project could be done outside of the classroom or lab environment, 2) experimental platform that is fully portable but not student-owned and can be brought into a classroom, and 3) an experimental platform that is modular with part of it being portable so that is can be used outside the classroom and part that would remain in a laboratory environment.

Flipped, on-line workshop methodology

Each workshop was conducted using an online virtual meeting site where participants discussed the specific applications presented. The format was a *flipped workshop* where the presenters posted 3-5 minute videos of their applications and experiences. Participants were asked to view each other's videos before the workshop, so that the workshop time was devoted to discussion of the various applications and consensus building to form recommendations.

Each workshop lasted three hours spanning over two days, 1.5 hours each session. The first day's session concentrated on a discussion of the submitted videos, and the second day focused on determining a consensus on several issues: best practices and challenges logistically and pedagogically, recommendations to the vendors of the platforms, and recommendations to NSF for future funding on Hands-On Learning initiatives. Participants were remunerated a small stipend for their efforts.

There are 34 videos produced for the workshops that are available on the YouTube Channel "Mobile Hands-On STEM". The videos were posted well ahead of the workshop and attendees were encouraged to post comments and questions on each video's site. The presenters responded in the comments section on YouTube or respond during the online workshop. Thus, the workshops had an asynchronous and a synchronous component.

One workshop was devoted to *myRIO* projects, one to microcontrollers, and the final one to data acquisition/instrumentation boards. While both *myRIO* and microcontrollers are embedded platforms, they are applied in quite different contexts. The *myRI*O is a packaged embedded system that uses a graphical programming language that does not require students to know how to program in a traditional language. Microcontrollers require users to know how to program and how to do more detailed hardware integration. As a result of these distinctions, they are used differently in projects and their targeted audiences are unique. The *myRIO* is a second-generation version of the *CRIO*, which was given to high school students who worked on First Robotics. Thus, the *myRIO* is better suited to students without a strong electrical engineering or computer engineering or computer science background.

Best Practices

The list of topics below reflect the discussion and general consensus of the workshop participants on the use of portable labs.

1. <u>Pedagogical approach</u>

The level of open-endedness of the experiment or project depends on the purpose. The pedagogical approaches observed by the practitioners can be categorized as: directed experiments, open-ended programing tasks, and mobile labs. The best practices of experienced practitioners are summarized below.

Directed experiments use straightforward labs that instruct students to explore and demonstrate basic theoretical principles. Some examples use predefined *LabVIEW* VIs (for the *myRIO* or *myDAQ*) and prebuilt physical platforms, where students can adjust parameter values. Personal instrumentation Workspaces (*Analog Discovery*) or Configuration Files (*ADALM1000*) can also be predefined and, user interfaces can be set up for microprocessors. The first two options are generally much easier to develop. The experiments should have some sort of reflective activity or exploratory activity. The concepts that are introduced into the project/lab should be clearly related to the course content. If there are tests in the course, then some short questions can be added to the test that are on topics that were reinforced by the experiment or project.

Labs and projects that have a prebuilt physical apparatus and include **an open-ended programming task** are useful for control design courses. Various control design methods can be explored as well as real-time implementation issues such as sampling and aliasing and sensor noise. To simplify the physical apparatus, electrical op amp circuits can be built that are analogous to mechanical systems yet behave similarly. In those cases, the components can be chosen to have low natural frequencies, e.g., a few Hertz which are commonly found in mechanical systems, and which the students can easily relate to and are compatible with the sampling rate capabilities of the *myRIO*. The *myRIO* allows students who do not have a strong background in structured programming languages to implement sophisticated control laws. Skeletal code or a basic working VI with limited features can be given as a starting point to shorten the learning curve. Some projects are completely open ended, where students are free to design and build both the physical apparatus and to program the embedded device teach higher-level problem solving, analysis, and design.

Feisel and Rosa, 2005[1], conducted a colloquy where they determined by consensus 13 desired features of engineering labs including comparing theory to experiment, perception, learning by failure, safety, sensory perception, and design of experiments. **Mobile labs** can be designed to utilize as many of these as possible within constraints that may be dictated by size and cost constraints. When students have the flexibility to work on the devices/projects/labs in their own time and in an environment of their choice, they are more likely to explore concepts more deeply and spend more time being creative.

Simple, inexpensive and completely portable labs, especially circuit-based activities, can be used to represent a more sophisticated physical system. Some reconfigurability (such as changing component parameters) makes them more flexible. These lab kits can be purchased by students and used remotely by distance learning students. Creative lab platforms that show a variety of physical phenomena are often harder to release to students for use on their own time. However, it is possible to develop robust, portable apparatus that can be checked out by students. Complete portability versus sophistication of the experimental platform might be compromised by making part of the experiment portable, such as the Georgia Tech RC car or the *myRIO* portion being programmed and run outside of the lab using models of the real system. Haptics experiments may fall into this category as well.

2. Scaffolding of Skills and Concepts

Students learn by relating new knowledge/skills to existing knowledge/skills. Multiple experiences with a platform can be gained in one course or over a sequence of courses, and the skills learned in the early experiences can provide scaffolding for the more in-depth skills learned in later experiments and classes. It is therefore desirable use the same platform over multiple courses. Students can be reminded of how the platform was used before (what features used and why) and how the new experience builds upon that or is different from that usage.

A complex systems can be broken into subsystems for analysis or design. Understanding task/system decomposition and subsystem integration ties together skills needed for the subsystems with the skills/knowledge needed for integration. Students have the opportunity to develop debugging and troubleshooting skills. To develop independence, students are encouraged to read and interpret data sheets, and possibly to select their own parts from a catalog based on project requirements. In true tinkering fashion, the best projects provide opportunities for students to learn through hands-on activities where they are free to fail and try again. The complications they encounter in this process will help them to identify areas where they lack understanding, and to improve and reinforce their understanding through practice. Testing and verification should be an integral part of the design process. In some examples, automated testing, either virtual use of a simulation of the code or using a testing circuit, can help provide formative assessment so that students can have a chance to improve their performance before the project is graded.

3. Motivation

Students are motivated when they see value in the exercise and have an expectation that if they put in sufficient work that they will learn the knowledge or skill. They are also motivated if something looks fun. **Simple experiments** should show a clear relationship to a real application. (for example, an ECG experiment is directly applicable to real life). There is a lot of value in **open-ended projects** and many practitioners try to include them whenever possible. Students tend to always go above-and-beyond in open-ended projects, and take more vested interest. Students can earn credit by helping to design the experimental platform with design criteria of making the platform fun/engaging while being able to convey fundamental concepts. These activities are facilitated by the availability of maker space equipment and resources. It is possible to over-emphasize open-ended projects, while fun for students, they can take a toll on faculty in support and grading.

4. Logistics

The most successful implementations have a department level strategy and an embedded systems team within the department making decisions to build a cohesive sequence of classes, which push students to use the hardware and software as often as possible. To reduce the learning curve or overhead, use standardize tools (such as *myRIO* and *LabVIEW*, a particular personal instrument, an inexpensive microcontroller) across courses in the curriculum. Students should be taught to use the appropriate tools for the job/course (e.g., use the *myRIO* when you need the real-time closed-loop performance, use personal instruments to characterize voltages and currents, etc.). Flipped classes work great for this. Resources are needed to build the experimental platforms or projects (equipment, staff, supplies, tutorials). A good deal of this work can be done very well by students.

It is not clear that all schools can assume students own their own laptops. There are also a lot of problems with software on different laptops and faculty may spend a lot of time troubleshooting all those different machines; alternatives include using a cloud compiler or having the software on university machines but that defeats the purpose of anytime/anywhere. Smaller programs often have an adequate number of desktops as backups for laptops. All of the software for all of the assignments can be made available on the desktops and a majority of students can then do their work on the desktops. It is important to give nauseatingly detailed instructions as to how to load the software, but after that, it is usually not necessary to provide any additional laptop support. If students are required to purchase a laptop, schools should provide an image maintained by their IT department to ensure uniformity in students' ability to use and install software.

5. Sharing Ideas Across Schools:

Practitioners recommend that an archive or library of projects and resources would be useful for a network of practitioners to share their ideas and projects across schools using means such as a Dropbox or a YouTube Channel. Some of the experiments presented can be implemented with alternative platforms, such as microcontrollers versus *myRIO*s. In order to make these resources translatable to different schools, they should clearly identify the assumptions on the student background and resources available when implementing the course. This information would help others determine if the experiment is appropriate or how they might need to supplement the materials.

6. Challenges and Barriers

A significant barrier exists in the dearth of resources and information for students or instructors. Varying levels of student preparation (knowledge of programming, modeling, hardware integration) when trying to use a project developed elsewhere remains a challenge. Common boards for common uses might be helpful. There are also varying levels of fabrication resources and support staff at different schools which makes it difficult to use an experiment developed elsewhere. There exists a lack of repair and replacement infrastructure for widely distributed platforms, especially student-owned.

The mobile technology is much cheaper than dedicated lab spaces, but it's unclear what business models should be used to fund the acquisition of required equipment for student learning. Models range from, university purchased equipment where students check-out or rent devices, to completely unfunded where students buy equipment and keep it for the class or subsequent classes like they might buy a textbook. Early adopters have benefited in many cases by donations or grant funding, but it is unclear if this is a sustainable or can be widespread.

Students have a hard time making connections between courses. There is a need for broad application throughout the curriculum, probably in combination with other inexpensive tools, but sometimes other faculty are barriers. Series of courses that use this approach could address these issues.

7. Feedback to NSF

NSF funding priorities play a huge role in establishing the priorities that our university engineering departments place on research directed toward novel applications of science and engineering as opposed to research directed toward identifying and establishing the best practices when it comes to engineering instruction. The workshops' participants have in common their commitment to the addition of a substantive hands-on-with-hardware experience to the threads within their departments addressing mechatronics and control system design, circuits and electronics design, embedded systems design, etc. NSF's commitment to the same principals should be increased.

A variety of issues are embedded in the list of best practices that should get some priority for funding. Some examples:

1. Automated testing using both software and information from hands-on hardware.
2. Effective pedagogy for students with widely differing background and capabilities in all areas of student instruction: fundamental theory, simulation and experimentation. The small, generally inexpensive and portable hands-on tools addressed in these workshops enable a level of integration of all types of STEM educational experiences not seen in the past.
3. Funding joint projects between industry and the academy on product/resource development.
4. How to best enable effective sharing of resources between universities.

8. Feedback to Vendors

Hardware and software vendors should have a good track record of long-term support. Much like the automotive market, academia tends to use and reuse their work for 4-6 years. Obsoleting hardware or significantly changing IDEs is brutally hard on professors and cheats students.

Equipment prices tend to still be too high and are not sufficiently stable to enable effective planning, especially with respect to how costs are split between universities and their students.

Vendors should work to develop more student friendly training materials. A practitioner with 15 years in the semiconductor industry says that their technical literature is written by experts for experts. It is nearly impossible for 95% of the students out there to learn from the material provided by vendors. This is doubly true for embedded systems where a 20 pin microcontroller may have a 100 page data sheet, a 600 page user manual, and a 500 page compiler/IDE manual. Vendors do sometimes work with individual schools to develop more student friendly materials, but there does not seem to be a concerted effort to drive this material to other schools. Most vendors do not try with even one school. Instructors are encouraged to get in touch with contacts at their vendors to see if they would provide more support in this area. Some instructors are reluctant to transition to a newer microcontroller because the data sheet increases from 300 pages to 600 pages.

Conclusions

The online workshop format, with participant-produced videos viewed and commented on before the meetings, worked very well and is a cost-efficient method for collaborating and disseminating ideas. Everyone got a good idea of what other active practitioners were doing and discussions were lively and far-ranging. An archive of the participants' videos and comments remains accessible on YouTube and can reach a wider audience of educators. More workshops are being planned for 2017 and will address issues identified by the participants. While the individual workshops were focused on specific classes of portable learning platforms, nearly all participants use more than one type and many use several. There is a very active community of practitioners who are generally too busy to travel to a meeting like this and all are interested in finding ways to share information more effectively.

There was essentially universal agreement that student engagement in the learning process is enhanced through the practical application of course theory. Professors can structure exercises for personal exploration, so that students become self-directed and practice tinkering. Access to lab equipment for students is easier because of its mobile nature and lower cost. The mobile learning platforms provide more opportunities for students, without the limitations of space and cost, therefore ECE enrollment can increase.

[1] Feisel, L.D. and Rosa, A.J., 2005, "The Role of the Laboratory in Undergraduate Engineering Education," *Journal of Engineering Education*, Vol. 94, No. 1, pp. 121-130.