

## **Web-based Labs for Cyberphysical Systems: A Disruptive Technology**

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### **Abstract**

The paper discusses a solution for fully web-based but still hands-on software engineering labs for cyberphysical systems. A cyberphysical system is understood as a computer system that is embedded in a larger system whose functions are not necessarily computational, and which is accessible via a network. Incorporating online labs into the teaching process involves not only remote operation and experimenting with the device, but primarily remote software development, uploading this software to the device, and then remote testing of its operation, with observing the device via a webcam. A couple of lab stations for conducting web-based laboratories are discussed, and respective lessons learned are outlined. This type of web-based labs have been offered for the first time in the U.S., in a fully online undergraduate course on Embedded Systems, in the Spring 2013.

### **Keywords**

online education, engineering education, cyberphysical systems, embedded systems, web-based labs, online labs, software engineering.

### **INTRODUCTION**

Cyberphysical systems (also spelled Cyber-physical) are a fairly recent computing research area (CPS Steering Group, 2008), with strong roots in real-time and embedded systems. Due to combining computational aspects with access to the real, physical devices and connectivity to the Internet, they are considered critical to the nation's wealth and security. With this in mind, education and curriculum development should be an integral component of cyberphysical systems development and applications.

Several conference activities have been launched recently (WESE 2012; First CPS Education Workshop 2013) to address issues of cyberphysical systems curricula. Both researchers and educators began offering related courses (Shin 2008; Lee 2010; Li 2011; Marwedel 2012), started publishing papers on curriculum development (Lidström 2011; Bauer 2012) and related textbooks (Lee 2012).

Various concerns have been addressed in discussions, several of them stating that education in this new discipline is very challenging. For example, on the Panel "How to Teach Cyber-physical Systems" (WESE Panel 2010), it was stated that "Educating students about cyber-physical systems is itself a challenge due to the broad array of topics required." In a talk on curriculum challenges in cyberphysical systems, another researcher stated that (Pappas 2010):

- "It is conceivable to develop an undergraduate major on cyber-physical systems;
- It is probably impossible to institutionalize it within any university;
- But it may be a lot easier to achieve this across universities with open access educational materials."

Examples of cyberphysical systems, such as modern software intensive embedded systems, are applied in the most demanding real-time safety-critical applications, for example, flight control, particle accelerator control, road vehicle control, etc. They are all distributed and for proper operation require very different programming techniques than traditional systems. Typical software engineering curricula, however, rarely include respective methodologies of software development. If they do, related courses mostly concentrate on the specification and design aspects of cyberphysical systems, but stop short of including thorough treatment of implementation and testing. Possible major reasons for this situation are:

- difficulties with acquiring, operating, maintaining hardware and system software;
- necessity of acquiring specific knowledge of device architectures and low-level programming techniques for this hardware and system software, and
- need of significant attention to the technical support, rarely available in colleges.

Thus, there is unquestionable need to create a software development education laboratory to apply methodologies for implementation and testing of cyberphysical systems, as well as to enable web-based development and testing (as opposed to traditional local development), by expanding remote access to operation. The purpose of a respective lab, described here, is to provide a platform for remote access to embedded devices in a cyberphysical system, to allow software development, implementation and testing, including remote experimentation. This objective is different from traditional online laboratories, which only allow conducting remote experiments. A review of the development of web-based engineering labs reveals that, although there have been multiple developments over the last two decades (Salzmänn 1999; Ammari 2006; Bochicchio 2009; Zubia and Alves 2011), the primary function of these labs is to conduct experiments via the web in respective engineering disciplines: electrical engineering, control, mechanical and chemical engineering, as well as in physics, chemistry, biology and other sciences.

What is different in the project described here, is that the web-based lab enables remote software development with uploading the executables to the remote embedded device and testing its operation by remotely observing the test results. Although the concept of a lab operating this way is not extremely new, to the author's knowledge there has been no single course offered, yet, in the U.S. universities, which would involve using such a lab on a full scale basis. This paper presents a fully operational lab that allows students to conduct hands-on labs from a distance, never physically coming to the lab. The term hands-on is not in contradiction with web-based or online. The confusion may be related to the proximity of equipment and student, implied by the word "hands-on". Then, of course, the terms are contradictory. But when one talks about functionality, functions of a hands-on lab can be provided equally well by a web-based lab, as noticed before by other authors (Bochicchio 2009).

The rest of this paper is organized as follows. First, a brief description of an existing laboratory is presented. Next, a number of findings are discussed from the experimental operation of the lab. Then, the significance of the lab is outlined in broader terms, as a disruptive technology, followed by a conclusion.

## **LAB DESCRIPTION**

The lab has been set up and developed in response to both students' demand and current trends in technology. A general organization of the lab and some details of lab stations have been discussed previously (Zalewski 2010). In this section, we only present the lab overview and setup.

A general architecture of the lab is very typical (Figure 1). A number of lab stations, interfaced to the Internet through various technologies, are accessible from web clients. Students obtain access to the stations according to schedule via a

course webpage. Lab stations are diversified to offer various technological platforms, to help meet the criteria what lab is best suited to learn specific concepts.

The assumption in selection of equipment and software for lab stations is that the platform clearly articulated computing concepts important in cyberphysical systems:

1. Hardware Architecture
2. Interconnecting Bus Architecture
3. Operating System (OS)
4. Programming Language(s)
5. Integrated Development Environment (IDE)
6. Network Protocols
7. Web Technologies
8. Typical Applications.

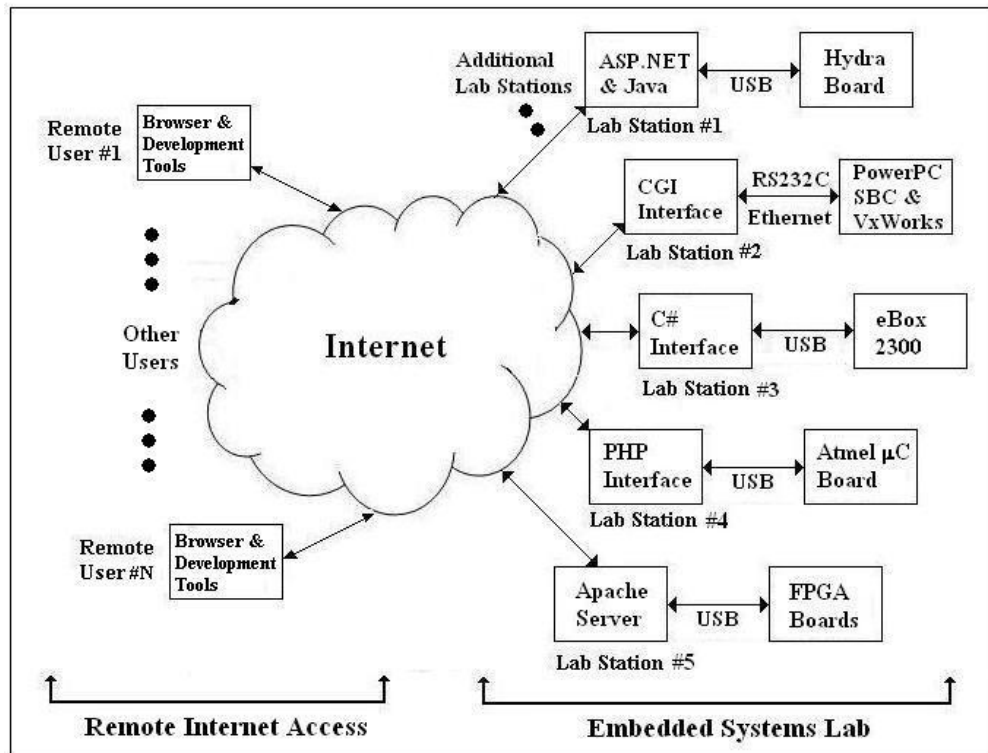


**Figure 1:** Overview of the cyberphysical systems lab access

Two examples of lab stations, which are designed that way, include: network game programming station and remote robotics station. They are described briefly below.

The design of the game station involves the following components corresponding to the list above: (1) multicore ARM processor, (2) USB bus, (3) bare machine without OS, (4) TinyBasic for programming, (5) vendor specific IDE, (6) HTTP protocol, (7) ASP.NET web technology, and (8) GUI application.

Sample interface seen by a student is shown in Figure 2. It consists of two parts: User Interface and Developer Interface. User Interface (left hand side) corresponds to playing a multi-player network game and can be more or less sophisticated, depending on the type of lab assignment. This is what the student sees when the game uploaded to the station is run. Developer Interface (right-hand side) allows uploading the compiled code, zipped image files for graphics, and user manual.

The design of the lab station for remote robotics follows the same principles of making it available to experiments for learning eight aspects of cyberphysical systems, but the nature of the station differs from the game station. Respective components of the design involve: (1) Vortex86 processor, (2) Windows CE 6.0 OS, (3) C#

for programming, (4) Visual Studio IDE, (5) USB bus, (6) TCP/UDP protocols, (7) .NET Framework web technologies, and (8) control application.

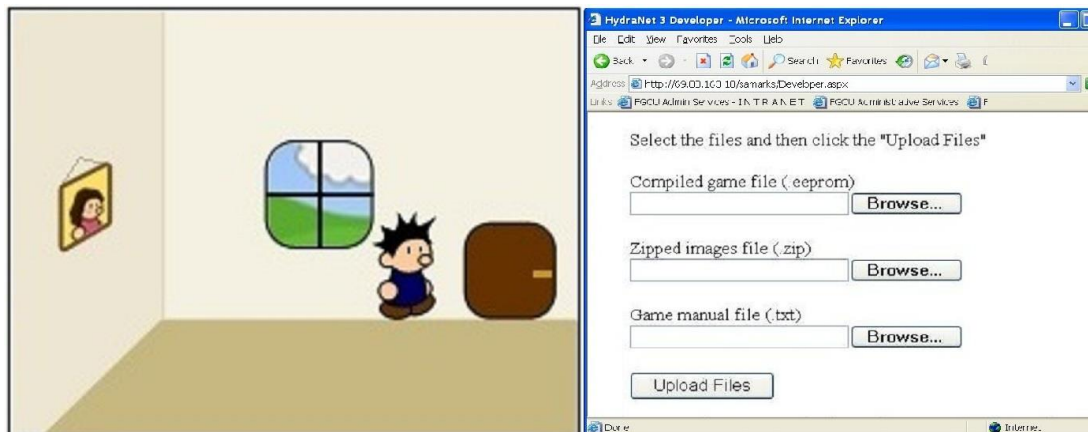


**Figure 2:** Typical interface to the network game programming station

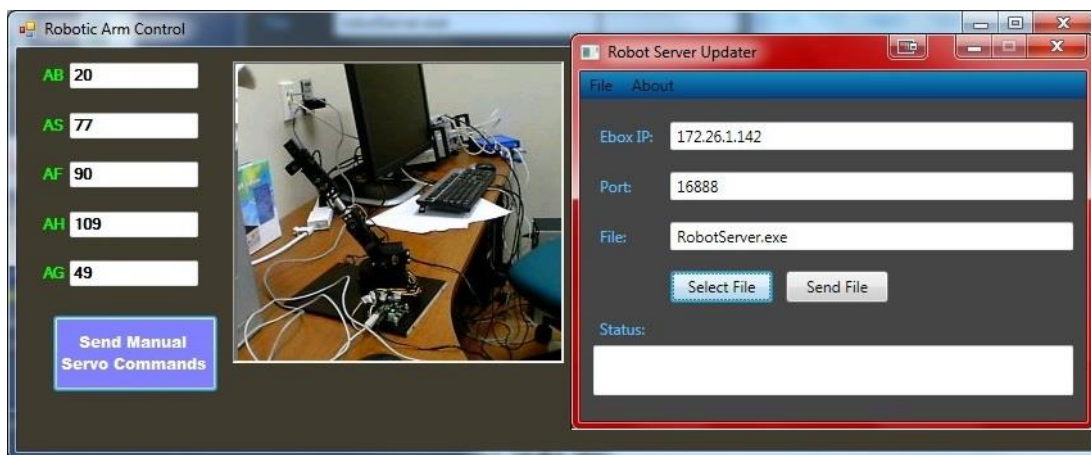


**Figure 3:** Typical interface to the remote robotics station

The interface seen by the students is shown in Figure 3. As opposed to the game project, where all GUI is virtual, here the camera shows the physical movements of the robotic arm to allow testing (left-hand side). Uploading of software to control the robot is done in three steps: connecting to the robot, sending the executable to it, and running it (all handled by separate modules).

## LESSONS LEARNED

The lab has been in operation for the last 3 years on an experimental basis, with lab stations being used as needed in various upper level project courses. For example, teaching lower level concepts, in a course on Embedded Systems, is well served by the labs covering hierarchical items from (1) to (5), while teaching concepts of cyberphysical systems in a Computer Networks course is well covered by items (6) through (8). During this period, a number of issues came up and experiences have been gained, which can be roughly divided into three categories: pedagogy, technical issues, and administrative and organizational challenges.

### Pedagogy

Pedagogy is a crucial factor in offering and use of all engineering labs, not only those accessible online. In this regard, many different issues come into play due to the fact that the remote labs are unsupervised and asynchronous.

First, it must be made clear that including the labs in a course enhances the learning process. This seemed to work for two reasons: (1) the remote labs speed

up the process of acquiring knowledge of concepts and techniques, and (2) the remote labs broaden the horizons of knowledge in software development, because students are forced to include into the picture elements of interactions with multiple additional components, such as networks and people.

Second, emphasis on the later phases of the software development cycle, implementation and testing, via the web makes the learning process more attractive, because of the opportunity to make actual observations in real time how the developed software performs.

Third, elements of pedagogy which work in teaching embedded systems with conventional labs, that is, enforcing knowledge by a sequence of demo, exercise, assignment and project, do not seem obstructed by the move to web-based labs.

Several other observations related to pedagogy include the following:

- For effective acquisition of knowledge, user manuals and other documentation for the lab have to be carefully developed and maintained.
- The question of intellectual value of each project has to be addressed before it is included in the course: what is the contribution of a lab to the course objectives?
- Impact of lab units on teaching effectiveness has to be assessed: will student's understanding of problems and solutions addressed by the lab be increased?
- Similarities and differences between traditional and non-traditional populations have to be addressed (with non-traditional being usually more mature): to what extent succeeding in lab projects depends on physical proximity to campus?
- It has to be made clear to the course audience that web-based software engineering labs go two levels above online courses: not only the use of lab equipment is offered over the Internet (one level up), but also software development and uploading it to this equipment is taught (second level up).
- The uniqueness of these labs lies in the fact that they cannot be replaced by hands-on labs, since due to the necessity of web-based software development, they are hands-on labs themselves; both types of labs converge.

### Technical issues

Numerous technical issues have been identified, which fall into two major categories: availability of network connections and continuity of operation.

Multiple embedded devices with Internet connectivity, which are essentially additional computers on the university enterprise network, constitute potential vulnerability, which can be exploited by malicious users. For security reasons, most software ports except port 80 are blocked. The significance of this problem has not been anticipated when the project started, and depending on the project's scale and scope they must be appropriately addressed sufficiently early in the life cycle.

To provide the continuity of operation of such a lab is an enormous challenge, due to the (non)-availability of technicians. One solution is to designate students from senior level courses to become station custodians. This costs less than full-time technicians and is potentially even more practical regarding responsiveness, however, can be considered only as a temporary solution, since students who graduate have to be replaced by the next generation, and this requires additional time and extra funds for training.

Additional observations related to the technical issues include the following:

- Technical problems with specific labs can be related to mistakes regarding device or software capabilities. In one particular instance, devices running on a wireless network were connected with sensors on a 1-wire bus, which did not allow uploading software via the network, thus defeating the purpose of the lab.

- Several platforms (e.g., Labview, RFID) that were initially eliminated from inclusion in the lab, because they did not provide a capability of remote software uploading, have been upgraded by their vendors to offer respective features. This fact should be taken into consideration when planning for expansion.
- With today's advanced web technologies, web-based labs should be considered parts of the entire online offer of related courses. This means that designing respective courses should be significantly changed to become integrated with the lab projects. This had not been anticipated when the project started.

### **Administrative and organizational challenges**

Administrative problems are also significant and are by nature mostly beyond the control of the lab offerors. The major problem is course enrolment and tuition payment. The nature of remote labs is to make them available for access from remote locations worldwide. This fact multiplies the number of potential users by a factor hard to estimate, because anyone with respective prerequisites or academic credentials can become a legitimate user. However, due to the university regulations, students who want to take a course offered with such remotely accessible lab may face multiple difficulties. There may be many years to come before this issue will find some satisfactory resolution. Another significant problem appears to be the training of faculty to include these labs in their courses. This is related to compensating faculty who want to participate in the development of such labs. Whether developing or adopting the lab, the process is challenging and involves additional burden on instructors who are willing to face the changing world. It is certain, that both governments and universities have to find ways to fund faculty development to follow such inevitable trends.

Other administrative and organizational aspects of web-based labs can be summarized as follows:

- One of the main advantages of web-based labs, opportunity of sharing equipment, is raising a question of paying for maintenance.
- If the lab is initially playing well its anticipated role, there is an essential question on sustainability: how to continue operation when the funding period expires.
- One of the most crucial factors in building and expanding the lab is faculty motivation, which becomes critical when external universities are involved.
- Educating faculty about the benefits and logistics of web-based labs seems to be necessary. One vehicle to achieve this goal is Faculty Workshops.
- Offering web-based labs to other universities and spreading them around has to be done gradually, first introducing the labs to courses at other institutions, and if this works well, implementing the lab in this particular institution.

### **SIGNIFICANCE**

In addition to the local perspective at the educational institution, where such labs have tremendous impact on course offers and actual delivery, the labs have great significance from a broader perspective due to their innovative nature.

Generally speaking, a disruptive technology, the term introduced in the mid-nineties (Bowen & Christensen, 1995) means the technology that has a potential to disrupt the markets, because they have not been prepared for its introduction. The term does not mean just innovation, but innovation that has a disruptive impact on the markets. Bowen & Christensen (1995, p. 43) give the following examples:

IBM dominated the mainframe market but missed by years the emergence of minicomputers, which were technologically much simpler than mainframes. Digital Equipment dominated the minicomputer market with innovations like its VAX architecture but missed the personal-computer market almost completely.

In a broader perspective, such a disruptive technological event was the introduction of print by Gutenberg, although it took years to change the markets, but that was proportionate to the slow pace of adopting innovations. The same observation can be made about invention of a steam engine, which ultimately led to the industrial revolution. A less obvious example, not necessarily perceived as a disruptive technology, was the introduction of a clock, which drastically changed our lives. As was noticed in one of major works (Mumford, 1936):

[...] the clock is not merely a means of keeping track of hours, but of synchronizing the actions of men. [...] one ate, not upon feeling hungry, but when prompted by the clock; one slept not when one was tired, but when the clock sanctioned it.

Non-computer companies that missed the boat when newer technologies became to appear include: Sears giving a way to Walmart, Blockbuster that gave a way to Netflix, newspapers that are getting collectively bankrupt giving a way to digital media, and so on. What we do not realize is that the same may happen to traditionally viewed universities, which are one of the most conservative institutions on earth, still enjoying their structures shaped centuries ago. Well entrenched in their academic positions, college educators may not realize it, yet, that perhaps in twelve to fifteen years the universities, as we know them, may disappear from the face of the earth. Even though this may seem a statement too dramatic to say, it is certain that the digital generation will take over.

Both on the earth and in the sky there are clear signs of this threat. In the sky, that is, in cyberspace, there are very distinctive examples, such as coursera.com, of a forthcoming overturn in effective teaching on-line. Thousands of libraries around the world are converging towards a single huge library named google.com. There are clear signs of the rapidly growing phenomenon of online learning. Even though schools are traditionally resisting change, if there is someone with a vision, web-based labs will catch up and rapidly transform the education as we know it.

## CONCLUSION

As the data of the U.S. Department of Labor indicate, the expected growth of the demand for software engineers, for the next decade is at the level of 10-15% a year. A large part of the profession will have to deal with cyberphysical systems, because of their significance to the nation's wealth and security. Thus, it makes a big difference whether we educate these engineers with old or new technologies. The real question we should ask ourselves, as educators, is: How can we make the existing and forthcoming Internet-based technologies beneficial in transferring knowledge? How to make sure that they create lasting cultural values? Finding the answers becomes more urgent every day, since with the advent of mobile phones it appears like the entire world collapsed into the fifth dimension, the cyberspace. With the pervasive nature of web technologies and their proliferation, web-based labs can make a dramatic change in our lives as engineers.

This project is original in software engineering and cyberphysical systems education, because it allows students and developers not only to operate remotely the lab devices via web interface, but also program the devices from remote locations and remotely test the software (with a webcam) without ever entering the lab physically. Thus, the project is game changing, because if such labs proliferate, this will ultimately cause a significant expansion of the ways students of engineering and computing disciplines can learn online. If the education market happens to respond to this challenge, web-based labs may become a new disruptive technology, causing a real breakthrough in education.

There are, of course, several unknowns in the entire endeavor. For example, it is unclear from this project whether, in addition to learning specific skills for cyberphysical software development, web-based labs help in acquisition of problem solving

skills and application of critical thinking. A more targeted research is needed to lead to specific observations and respective conclusions.

Finally, one important aspect of developing such labs must be emphasized, but has been neglected, thus far, in the lab design and implementation: teaching security of cyberphysical systems. In this view, several aspects of respective curriculum have been analyzed and related work initiated. A two-step process has been proposed: curriculum for foundations of security in cyberphysical systems and advanced security curriculum. Tentatively, each component of the curriculum has been allocated eight modules and related work started.

In summary, there is no doubt that the significance of such labs is being recognized more and more widely in the engineering and computing education community. Both the interest of the US military (Keefe 2007) and establishing of an IEEE Working Group 1876 with a mission to develop a standard for online laboratories (IEEE Standards Association 2012) testify to this fact.

## ACKNOWLEDGMENTS

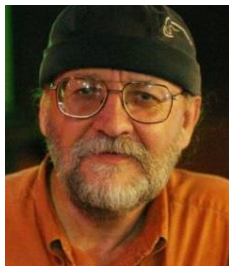
This work has been done under grants from the National Science Foundation, Award No. DUE-0632729 and Award No. DUE-1129437. Views expressed herein are not necessarily those of the NSF. Additional support has been provided by a grant SBAHQ-10-I-0250 from the U.S. Small Business Administration (SBA). SBA's funding should not be construed as an endorsement of any products, opinions, or services. Supplementary funding has been provided by NASA through the Florida Space Grant Consortium.

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## Biography



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