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Significance of Online Laboratories in Modern Engineering Education

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Summary: This paper briefly reviews online laboratories used in engineering education around the world, focusing on their advantages, disadvantages and current trends. Labs in various engineering disciplines are covered, including electrical, chemical, mechanical, control, computer engineering and others. Some common characteristics of such labs are discussed and latest developments presented, with emphasis on the significance of online labs in modern engineering education and to the society, in general. Based on this review and on author's own experiences in using online software engineering labs important points in lab development and significance of their emergence and usage are touched upon from a broader perspective.

Keywords: Online labs, remote labs, web-based labs, engineering education

1. Introduction

An online laboratory for engineering education can be characterized after (Orduña, 2014) as a remote laboratory forming "a software and hardware solution that enables students to access real equipment located in their institution, as if they were in a hands-on-lab session." This type of labs gained popularity over the recent years, mostly due to technological trends, but also because of several advantages in operation. Its overall architecture is presented as a generic system shown in Fig.1 (Gonzalez & Zalewski, 2014).

Historically, the first known attempt to access lab experiments remotely dates back to 1991 (Aburdene et al., 1991). A review of the development of online engineering labs reveals that there have been multiple developments growing over the last two decades (Salzmann et al., 1999, Ammari & Ben Hadj Slama, 2006), with the primary function of these labs to conduct experiments via the web in many different engineering disciplines: electrical engineering, control, mechanical and chemical engineering, as well as in physics, astronomy, chemistry, biology and other sciences. Traditionally, such labs allow students to perform experiments using real laboratory equipment from a distance via the Internet (Nedic et al., 2003, Mergl, 2006). Multiple survey papers on online and remote labs have been published over the years (Ma & Nickerson, 2006, Gravier et al., 2008, Cooper & Ferreira, 2009, Guimarães et al., 2011, Tawfik, 2012) and two recent volumes of related articles describe current status of remote labs (Zubia & Alves, 2011, Azad et al., 2011).

From the point of view of using such labs in engineering education, a number of issues arise that can be roughly categorized into three primary groups: technical, pedagogical and organizational (also called administrative) (Zalewski & Gonzalez, 2014). While technical issues are always a significant part of the entire endeavor, due to the nature of the Internet and its related shortcomings, and organizational details require a lot of attention due to the institutional challenges and unpreparedness of staff to conduct such endeavor, it is the pedagogy, which ultimately determines the quality of education using any sort of labs.

In this view, the paper addresses the problem of significance of online labs, concentrating primarily on their mutual relationships with pedagogy. The rest of the paper is organized as follows. Section 2 presents an overview of issues related to pedagogy across the domain of online engineering labs, which is followed, in Section 3, by a discussion of broader impacts of such labs from the social and international perspectives. Section 4 ends the paper with conclusion.

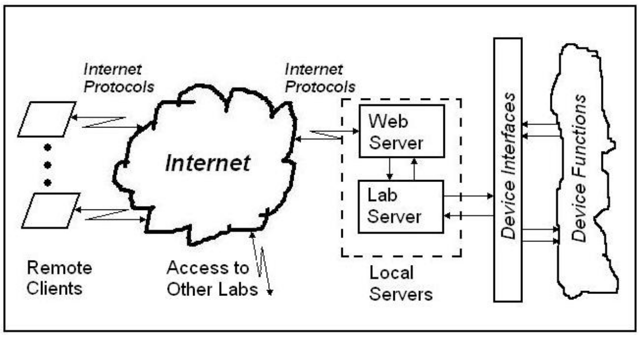

Figure 1. Architectural components of a remote lab (Gonzalez & Zalewski, 2014)

2. Overview

2.1. Essential Motivation for Online Engineering Labs

First, let's try to answer the basic question: Is there a real need for online engineering labs and, if so, why is that, what is the motivation? We look into the following four aspects of the motivational context (Zalewski, 2013): professional, educational, innovational and societal. Professional motivation for developing such labs comes from a combination of two different perspectives: needs of the engineering programs and trends in the design and application of computerized systems. The need for workforce with respective type of skills has been well documented in professional practice.

The most spectacular case had actually occurred as long ago as in 1997 during the Pathfinder mission to Mars (Reeves, 1997). In brief, a robotic device, which landed on Mars, got stuck due to an unidentified software problem, later during the mission recognized as, so called, priority inversion. Then, engineers at the ground control center corrected the software and re-uploaded it remotely to the device. This example gives an incredible boost to the need of acquiring respective knowledge and skills by engineers, in general, and software engineers, in particular.

Educational motivation comes both from the earth and from the sky. In the sky, that is, in cyberspace, there are very distinctive examples, such as coursera.com, of a forthcoming overturn in effective teaching online. Scores of libraries around the world are converging towards a single huge library named google.com. On the earth, on the other hand, one can quote numerous articles, from the newspapers, professional magazines and research journals, on the rapidly growing phenomenon of online learning. Online labs have to become an integral part of this trend.

As far as societal motivation is concerned, it may not be immediately obvious, but it should be made absolutely clear that the World Wide Web, as we know it now, has been created exactly for the purpose of remote access to the labs. The very first paper published on this technology was written, as an internal report, by two scientists from the European Organization for Nuclear Research, CERN, in Geneva, proposing the creation of a protocol, which would allow sharing data and equipment usage among physicists around the world, working on high-energy physics experiments (Berners-Lee & Cailiau, 1990). The Large Hadron Collider (LHC) built and operated at CERN, and known from recent discoveries of the tiniest elementary particles known to the humankind, has remote control centers, from which one can design and control high-energy physics experiments.

There is also an innovational aspect of the need for creating online engineering laboratories. Among two recent Top Ten innovations predicted by IEEE Spectrum for 2012 (Top Tech 2012) and 2014 (IEEE Spectrum Special Report: 2014 Top Ten Tech to Watch) to likely have the biggest impact in the forthcoming years, there were a number of significant technologies, among them: civilian UAV's (drones) for commercial markets, Oculus virtual reality headset with smartphone, U.S. brain initiative, DARPA's rescue robot, and others. Several innovations that made it to the 2012 top technologies list, were also included in the 2014 list, for example, exoskeleton for paraplegics, which would retire a wheelchair solution, bionic eye that allows the blind to see just with a pair of sun-glasses, 3-D printing, 3-D chips, 4G Long Term Evolution (LTE) networks, and more.

What is amazing, however, and sad, is that none of the lists of technological hits does include a single entry, which would be closely related to education. This fact must prompt some response from educators to both verify the accuracy of the claims and take respective action.

2.2. Literature on Online Lab Effectiveness

There is a multitude of papers published recently trying to address the effectiveness of online engineering laboratories. The contents and findings of some of them are reviewed in this section.

Tsiatsos et al. discuss the network of remote labs in, what they call, technologically low-readiness countries (Tsiatsos et al., 2014). The advantage of having such labs relies on enabling "the implementation of a training system at the international level and the creation of a new generation of versatile graduates able to adapt to a changing global context." The following factors are studied to evaluate effectiveness of such labs: (a) usability of remote labs; (b) learners' attitude towards remote labs; (c) technical evaluation of remote labs operation; (d) evaluation of the e-learning content (teaching units previously described); and (e) learning outcomes.

Nafalski et al. (2009) describe a multi-partner intercontinental collaboration in developing remote engineering labs, focusing on the following major stages: (1) scoping to guide the formation focal points in development; (2) aligning existing systems; (3) development of the framework; and (4) refining the framework. Their initial experience was only marked as positive, with several key observations, among them a unique one that none of the participating students "felt confident enough to work individually with students from other countries." So multiple-to--multiple student teams had to be created.

Sundarajan and Dautremont (2014) describe preliminary results of a study on evaluating remote thermo-fluids laboratory. They conclude that "laboratory experiences where the focus is on data collection and analysis can be ported to a remote or online mode without sacrificing the student learning experience." However, they conclude that where troubleshooting was required, the remote experimentation suffered from an inability to observe the exact process as compared to the in-lab students.

Aliane et al. (2010) list a more comprehensive list of limitations of online labs, based on their experiences with control engineering education. The primary deficiency of online labs, as compared to true hands-on labs, is the inability of handling lab instruments, such as oscilloscopes, function generators, power supplies or digital multi-meters, which constitute an added value in control engineering. The authors also argue that true hands-on experiences in the lab "increase student motivation and help create a learning environment that permits students to develop general competencies, where they can learn to work in teams, meet deadlines and work schedules, communicate effectively, manage conflicts, as well as many other skills that are applicable across a broad range of engineering professions."

Gravier et al. (2012) describe results of their study on collaborative online labs, including participants' survey. The responses valued the collaborative aspect of such labs, stressing that the overall idea of a collaborative online lab was very good (82% of respondents), and that it is useful in facilitating to help one another. One particular observation is important that using this lab instead of "local laboratory helped them significantly when writing reports, particularly when reproducing graphs and their results." Additional positive comments were received from tutors, who also stressed that among disadvantages of a remote platform is a lessened ability to distinguish between strong and weak students. This seems to be compensated, however, by a much greater suitability for cooperation than in a local lab.

In an earlier study, Nickerson et al. (Nickerson et al., 2007) used a three-phase approach to introduce online labs. In the first phase, the students were tasked with familiarizing themselves with the underlying physical principles, in the second phase they were briefly guided by instructor in a traditional hands-on lab, and finally, in the third phase, they conducted full experimental studies in a remote fashion.

Many other online engineering lab projects could be discussed, had enough space been permitted. Some of the most recent projects and related references can be found in (De la Torre et al., 2013)-(Sancristobal et al., 2014). They emphasize similarities and differences between hands-on, online and virtual labs, with examples from international and national collaborations.

3. Considerations on significance

3.1. Sociological Perspective

In a broader perspective, beyond that of an educational institution, where this sort of labs has a tremendous impact on course offers and their actual delivery, online labs have also broader significance. One of the attractions of online labs is their innovative nature, which makes them a potential candidate to become a disruptive technology. Generally speaking, a disruptive technology, the term introduced in the mid-nineties (Bower & Christensen, 1995), means the technology that has a potential to disrupt the markets, because the markets have not been prepared for its introduction. The term does not mean just innovation, but innovation that has a disruptive impact on the markets (Bower & Christensen, 1995, 43).

One can give several examples from the computing domain. For instance, 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. From a broader perspective, such a disruptive technological event was the introduction of print by Gutenberg. The same observation can be made about the invention of a steam engine, which ultimately led to the industrial revolution.

Observing the speed and pervasiveness with which modern computing technologies penetrate the society, what immediately comes to mind is the unprecedented scale of their usage. The number of Facebook users, according to company's quarterly report, recently reached 1.11 billion per month (March 2013 data), with 665 million active users each day on average in March. As reported by Digitaltrends, the number of active mobile phones will exceed the world population in 2014, reaching 7.4 billion devices (Pramis, 2014). From the perspective of embedded and cyberphysical systems, according to the Chief Scientist of the U.S. Air Force, by 2025 there will be 7 trillion IP enabled devices in existence (Maybury, 2013), all forming a humongous ecosystem that would need a well educated workforce.

But it's not only the growing population of devices or users, which is astonishing and unprecedented. It is also the size of certain individual devices, which is reaching amazing proportions. To an extent, this issue has been quantified around 70 years ago by Lewis Mumford, with his concept of a megamachine (Mumford, 2013). Mumford, himself an inventor, used this term to describe the size of some large-scale endeavors, with an example of building the pyramids. Referring to this concept he termed it "a shorthand reference to the entire technological complex", one that the Egyptians invented for harnessing the manpower to erect and maintain the pyramids.

Incidentally, Mumford quantified the size of a megamachine, using the prefix "mega", to reflect the machine's size, not intending it but adhering to its meaning as 10^6 components. What was hard to count back then, and could be only estimated for the pyramids, is much easier to account for in contemporary societies. When one speaks of the Internet based endeavors, such as social networks or mobile phones, the term one could use is gigamachines, and with the advent of cyberphysical systems it goes into the teramachines territory. This is where online labs have to be placed regarding the size of the venture, maybe forming a lab cloud, and have to be judged in this context.

Viewing these phenomena from even broader perspective, one must quote Marshall McLuhan who wrote in (McLuhan, 1964) and later reformulated it in (McLuhan & Fiore, 1967) that:

Today, after more than a century of electric technology, we have extended our central nervous system itself in a global embrace […]. Rapidly, we approach the final phase of the extensions of man – the technological simulation of consciousness, when the creative process of knowing will be collectively and corporately extended to the whole of human society, much as we have already extended our senses and our nerves by various media.

In his analysis, glasses are extending our vision, vehicles extend our legs, printing extended our speech, telegraph, telephone and newer media extend our nervous system, and electronic media extend our consciousness.

In relation to these observations he coined the phrase *the medium is the message*, arguing that the separation between the content of the medium and the medium itself is disappearing. What is actually in the contents is not important, it's the medium that contains, conveys, and is the message. What led McLuhan to this observation is his previous study on the printing press (McLuhan, 1962). This is where he formulated the essential thought on the impact of the invention of printing on the evolution of modern society in western civilization. The advent of the printing press gave rise to the revolution in communication. Following this, the emergence of a rational thought in Enlightenment was actually a consequence of introducing the printing press. Relating this to online labs, one could argue that they would easily become a part of the engineering education's nervous system.

In a strict engineering perspective, the historical analogies are even more compelling. As some of the authors argue, it is unquestionable that online labs are gradually becoming a part of the civilizational change (Lindsay & Wankat, 2012): *The slide rule became obsolete because new technology could achieve the most important of its outcomes, but quicker, easier and cheaper. An analysis of remote laboratories shows that many learning outcomes are able to be achieved more easily and more cheaply in the remote mode, and additional learning outcomes are also possible, with only a small number of non-fungible outcomes preventing remote laboratories replacing the face-to-face experience.*

3.2. Potential for International Cooperation

With the pervasiveness of online laboratories and ease of access, one particular consequence is worth discussing: potential for international cooperation. However, it is rather difficult to find examples of effective international collaborations in engineering education, especially over the Atlantic. On the other hand, there have been suggestions that certain educational areas are particularly suitable for inter-university cooperation, because of the breadth of topics involved. One example is cyberphysical systems education, which is claimed to be a challenge due to the broad array of topics required. However, in a talk on curriculum challenges in cyberphysical systems, Pappas (2010) made a statement that:

- *It is conceivable to develop an undergraduate major on cyberphysical 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.*

One of a few attempts to establish a U.S.-E.U. collaboration in education areas related to engineering, known to the author, is the ILERT/DeSIRE2 project (Kornecki et al., 2009)-(Kornecki, 2014). These programs involved six universities, 2 from the U.S., and 4 from E.U., sponsored by corresponding grants from the U.S. Department of Education and the European Commission. This particular collaboration was at the graduate level and did not involve online labs or even online courses, but is worthwhile analyzing in a view of potential issues that may arise when online education is started.

The project was well-planned and involved two major stages: initial stage and implementation stage. The initial stage, described in (Kornecki et al., 2009), involved three essential phases:

- preparatory, which relied on searching for partner institutions interested in such collaboration, as well as exploration of potential for financial support in the Research phase. As a result of this phase, an initial consortium was formed and the project focus areas have been determined;
- research, which consisted of formalizing the activities, surveying industry needs, defining learning objectives, and developing framework for the curricula. As a result, the curricular proposal has been developed, credit transfer methods have been analyzed, and memoranda of understanding finalized,
- pilot implementation, which relied on offering experimental courses with limited student engagement, evaluation of progress, and exploration of financial support. Results of this phase were numerous and included, among others: assessment of readiness of the consortium to offer exchange programs, assessment of technical challenges and technology transfer to support related courses, and leveraging differences in educational backgrounds.

Successful completion of this stage led to the second stage addressing a number of objectives, with three primary goals in mind (Kornecki, 2014):

1. Provide exposure to the students to work in international settings with foreign university partners.
2. Provide an opportunity to the students for exploring the host country language and customs (culture).
3. Provide instruction in the areas not available in the home institution.

The first goal was accomplished by addressing student mobility and staff exchange. In case of online engineering labs, the exchange factor does not play a significant role, while work in the international setting is relatively transparent. The second goal does not seem to be much relevant when online engineering labs are involved, perhaps except transfer of credits, but this issue needs to be resolved at the administrative, not technical, level. And the third goal, which is crucial for online engineering labs, was met in the DeSIRE2 project by development, and dissemination of innovative curricula and web-based technologies.

In summary, such educational needs as expressed by Pappas (2010) and experiences in international cooperation in software engineering education, as described by Kornecki et al. (2009, 2014), are of great value for initiating collaboration in the use of online engineering labs. Some success has been already reported in cooperation between European and Australian universities. As Ku et al. discuss in their paper (Ku et al., 2011), online labs are especially welcome and successful in sparsely populated areas, where students can take advantage of remote access to school facilities.

4. Conclusion

The significance of online laboratories in engineering education is enormous and unquestionable. The current paper covers this issue only to a limited extent, but points to a number of important aspects to consider when building and evaluating such labs: (1) What is the actual motivation to create online labs? (2) How can one measure lab effectiveness compared to other types of labs? (3) What are the societal consequences of introducing such labs? (4) Is there an increased chance for international collaboration in the global educational market?

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Znaczenie zdalnych laboratoriów w nowoczesnym kształceniu inżynierów

Streszczenie

Słowa kluczowe: zdalne laboratoria, laboratoria internetowe, kształcenie inżynierów

W artykule omówiono zdalne laboratoria stosowane w kształceniu inżynierów na świecie, ze szczególnym uwzględnieniem ich zalet, wad i aktualnych tendencji w dziedzinach inżynierii elektrycznej, chemicznej, mechanicznej, komputerowej i innych. Omówiono niektóre wspólne cechy takich laboratoriów i najnowsze osiągnięcia, z podkreśleniem ich znaczenia w nowoczesnym kształceniu i ogólnie – dla społeczeństwa. Przedyskutowano też najważniejsze aspekty przyszłościowe.