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Review

Virtual and remote labs in control education: A survey

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ABSTRACT

Virtual and remote labs have been around for almost twenty years and while they have been constantly gaining popularity since their appearance, there are still many people in the control education community who either do not know many details about them or do not know them at all. What are their benefits? Which examples of virtual and remote labs for control education can be found in the Internet and how spread and popular are they? What are the current trends and issues in the implementation and deployment of these tools? And the future ones? These and others are some of the questions we answer in this paper, trying to bring the attention of the control education community to these tools which, we believe, are meant to have an increasing importance and relevance for the 21st century students.

1. Introduction

Automatic control is mainly based on two streams of thought (Kheir et al., 1996): one stream is based in practical experience while the other stream is based in theory and mathematics. Nowadays, control engineers need to have both a deep understanding of the mathematics behind the concepts in the automatic control field and a wide experience implementing these theoretical solutions in real problems and plants. The stream based in practical experience relies on the idea that *something* needs to be controlled and so, the control systems engineering curricula must be hands-on and practice-based. This has been the traditional vision of engineering until one hundred years ago, when the second stream, based in theory and mathematics, started to gain importance (Froyd, Wankat, & Smith, 2012). This one, relies on abstract concepts such as the four identified by Kheir et al. (1996) as the major ones on control systems: *dynamic system, stability, feedback* and *dynamic compensation*, which are best modeled mathematically. As a consequence, enabling a balance between excessive theoretical proofs and emphasis on physical intuition is a major challenge in control education. In this sense, lab experimentation plays a key role to connect theory and practice. Among others, control labs fulfill the following goals (Antsaklis et al., 1998):

- Demonstrating/validating/motivating analytic concepts.
- Introducing real world control/modeling issues, such as saturation, noise, sensor/actuator dynamics, uncertainty, etc.
- Providing facility with instrumentation and measurement tools.
- Exposing students to broader design issues from problem specification to hardware implementation and economic considerations.
- Exposing students to professional practice that includes maintaining engineering notebooks and report writing.
- Team learning and problem solving.
- Comparing theoretical results with real world results, thus validating the theory.

Traditional hands-on labs involve high costs associated with equipment, space, and maintenance staff (Gomes, 2009). A line of research, which has been growing for the last twenty years, looks for reducing lab costs by taking advantage of the Internet, i.e., by substituting traditional labs with online labs.

To characterize the different modalities of experimentation environments and thus provide a precise definition of online labs, two criteria were proposed in previous work (Dormido, 2004):

1. According to the way resources are accessed for experimental purposes, environments can be *local* or *remote*.
2. According to the physical nature of the lab, environments can be *real* or *simulated plants*.

By combining those criteria, there can be the following types of experimentation environments, depicted in Table 1:

1. *Local access-real resource*. This combination represents traditional *hands-on labs*, where the student is in front of a computer connected to the real plant.
2. *Local access-simulated resource*. The whole environment is software and the experimentation interface works on a simulated, virtual and physically non-existent resource, which together with the interface is part of the computer.

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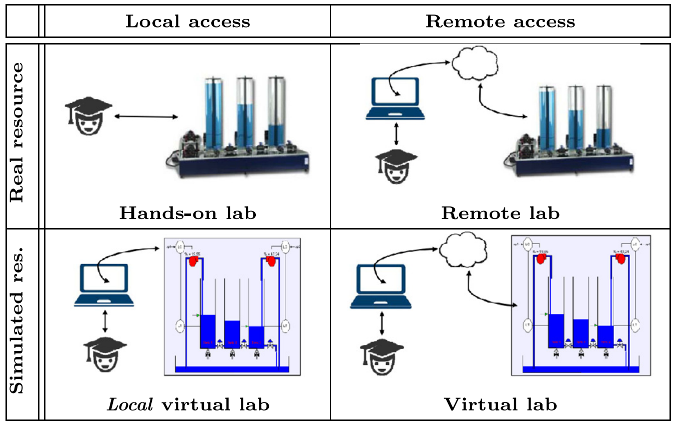
Table 1
Types of experimentation environments.



3. *Remote access-real resource*. Real plant equipment is accessed through the Internet. The user remotely operates and controls a real plant through an experimentation interface. This approach is named *remote lab*.
4. *Remote access-simulated resource*. This form of experimentation is similar to the one above, but replacing the physical system with a mathematical model. The student operates with the experimentation interface on a virtual system reached through the Internet. As it is a simulated process, it can be instantiated to serve anyone who asks for it. This is what is usually known as *virtual lab*. In comparison with local simulated resources, virtual labs allow: (i) a decoupling of the model (which can run on the server) and the view (which runs on the client), which supports the immediate introduction of control experiences with unknown time-varying delays, and (ii) online collaborative work.

The importance and use of *Virtual and Remote Labs* (VRLs) has been growing over the years (Heradio et al., 2016; de la Torre, Sanchez, & Dormido, 2016) as the technology has progressed and some of their major concerns have been solved. From the initial conception of VRLs, one of these concerns has been assessing whether VRLs were able to provide learning outcomes comparable to traditional hands-on labs. As we will see, most empirical studies have shown that VRLs and hands-on labs are equally effective (Brinson, 2015). Moreover, VRLs provide additional advantages as the following ones (Gravier, Fayolle, Bayard, Ates, & Lardon, 2008):

1. *Availability*: VRLs can be used from anywhere at anytime, thus they support students geographically scattered, who besides are conditioned to different time zones.
2. *Observability*: lab sessions can be watched by many people or even recorded.
3. *Accessibility*: labs can be accessed by handicapped people.
4. *Safety*: VRLs can be a better alternative to hands-on labs for dangerous experimentation.

While there are a fairly amount of works addressing the assessment of VRLs and many more about particular implementations and general architectures for them, there are few papers that study their history and evolution. This survey tries to overview the past, present and future of VRLs in control education. To do so, it is structured as follows. Section 2 provides a catalog of VRLs for control engineering currently available on the Internet. Section 3 outlines the most common approaches to develop VRLs and deploy them through the Internet. Section 4 reviews empirical studies on assessing the VRLs educational effectiveness compared to hands-on labs. Section 5 tries to foresee the future trends in the area. Finally, Section 6 summarizes the conclusions of our work.

2. Online labs for control education

In 1998, the National Science Foundation and the Control Systems Society Workshop on “New Directions in Control Engineering Education”, held at the University of Illinois at Urbana-Champaign, produced, as one of its outcomes, a report summarizing the major conclusions and recommendations that emerged from the workshop (Antsaklis et al., 1998). A shorter version of such report was published in the IEEE Control Systems Magazine (Antsaklis et al., 1999). In both documents, the authors recognize the potential value of remote labs and state that *“students can gain practical laboratory experience over the Internet”* and that *“remote or eyes-on laboratories can serve a valuable purpose in several ways”*, particularly *“as a way to maximize the use of expensive laboratory equipment”* and *“as a way to provide laboratory exposure when hands-on labs are not possible”*. However, they identify a problem on how WWW-based control systems educational materials could be found in the Internet back on those days, arguing that websites were scattered and their material lacked documentation and quality evaluation. Thus, they stand up for a cooperative effort among professional control organizations to develop and coordinate WWW-based tools for control education. Among other recommendations, they come up with this one:

“Improve information exchange by creating a centralized Internet repository for educational materials. These materials should include tutorials, exercises, case studies, examples, and histories, as well as laboratory exercises, software, manuals, etc.”

The documents then clarify that *“this repository can also contain links to remote sites, especially sites that provide virtual laboratories for control”*. While the authors explicitly mention virtual labs and omit remote labs, this must be understood from the perspective of what they considered doable at the time. Back in 1998 it was difficult to think about the possibility of sharing remote laboratories and so, writing down an explicit recommendation encouraging control organizations to create, deploy and share remote labs would probably have been too daring. Still, they wrote a recommendation on how to promote the appearance of WWW-based tools for control education, whether these tools were exercises, tutorials, virtual labs or remote labs:

“Promote the development of a set of standards for Internet based control systems materials and identify pricing mechanisms to provide financial compensation to Internet laboratory providers and educational materials providers.”

Unfortunately, eighteen years later, we can not say that these particular recommendations have been addressed by the control organizations and, therefore, virtual and remote labs are not of-

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