Challenges in Remote Laboratory Sustainability

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Abstract **- Remote experimentation facilities have been accessible from the Internet for more than a decade. However, sustainability of such services is not adequately ensured in many academic institutions. The major challenge lies in moving from a single research setup available occasionally to a professional remote laboratory infrastructure with many setups accessible worldwide and 24/7. Not only are the technical aspects demanding but also the usability of the solutions and the support of the customers are to be considered. On the technical side the solution should be robust to students and external malicious attack. It should be fully autonomous and capable of self-diagnosing. In case of problems it should be able to set itself back to a known stable state and report problem to the administrator. On the educational side, the learning environment should be reworked to consider the drawback inherent to the distance to make the student interaction with the distant system as close as possible as the actual work on the real equipment and enable collaborative work.**

Index Terms – Remote laboratory, remote experimentation, sustainability, engineering education.

INTRODUCTION

Remote laboratories can be of many kinds; we focus on remote laboratories where the users mainly access physical equipment for remote experimentation purpose. Remote experimentation is typically introduced to complement hands-on laboratory sessions in traditional higher education settings, to avoid travelling to the training centers in distance learning or to offer live demonstrations in classroom sessions. Remote laboratories are often used in control, robotic and mechatronic education to illustrate theoretical principles and deployment methodologies. As an example, the different control design and implementation steps taught to students in control courses (system identification, controller design, real-time control, performance validation, etc.) can be efficiently carried out remotely on mechatronic systems as they exhibit visually observable dynamical behavior. In addition, comparison between simulation and actual implementation results is an important element of the educational methodology [1].

The objective of a remote experimentation solution is to make the student interaction with the distant system as close as possible to the actual work on the real equipment. In other words, the best possible feedback has to be provided to a user action so that the drawbacks inherent to the distance between the user and the physical equipment are minimized. The first drawbacks is the transmission delay for the information to travel from the client to the server and back. The second undesirable effect is the difficulty to reproduce, at the client side, the state of the distant equipment, its dynamics and its conditions of operation. The specific aspects that define the quality of service for remote experimentation are presented in [2].

Physical experiments have been made available to the Internet community for more than 10 years. In 1994, one of the first online experiments permitted the remote control of the ASEA-Irb-6 robot. Users could control the robot arm gripper in order to manipulate wooden blocks on a table. The server read the user commands entered in an HTML form, performed the required operation and returned a page containing an updated image of the setup [3]. The interest for remote experimentation has never diminished over the years. More research setups were proposed and the question of sharing state-of-the-art laboratory equipment arose. At the same time, the numbers of students taking hands-on laboratory sessions at the Ecole Polytechnique Fédérale de Lausanne (EPFL) – and in other institutions as well – increased to such a point that even splitting the class in groups was not sufficient to accommodate simultaneously all students in the laboratory premises on campus. The remote access hence became mandatory.

This paper presents some of the challenges faced when moving from a single research experiment available online to a professional quality remote laboratory with many experiments accessible worldwide 24/7 (Fig. 1). The technical agreements that permit the sharing of physical equipment among laboratories are also challenging. To ensure effective remote experimentation, pedagogical aspects and learning modalities have also to be considered carefully.

This paper is organized as follow: First, an historical timeline describing the evolution of the remote laboratory facility available at the Ecole Polytechnique Fédérale de Lausanne (EPFL) for automatic control hands-on education is given. Then, technical and educational challenges faced regarding the development and the maintenance of such a remote laboratory are presented. Finally, future directions in remote laboratory evolution are proposed in the conclusion.

FIGURE 1
THE REMOTE LABORATORY FACILITY FOR AUTOMATIC CONTROL HANDS-ON EDUCATION AVAILABLE AT THE EPFL.

HISTORICAL TIMELINE

This section provides some milestones regarding the evolution of the students' control laboratory at the EPFL.

- ~1980: The measurements are made on physical equipments with oscilloscope and are captured using a Polaroid camera. Controllers are made with discrete analog components. Reference signals are generated with external signal generators.
- ~1990: The measurements, the signal generators and the controllers are implemented as software components on a computer equipped with a data acquisition (DAQ) board.
- 1992: Control of the physical equipment is standardized on LabVIEW using a homegrown real-time kernel.
- 1995: First remote experimentation tests, including an image and a single measurement.
- 1996: Remote control of physical equipments was carried out on a regular basis over the local LAN during classroom sessions for live demonstration purposes.
- 1997: Remote control over the Internet was successfully presented during a transatlantic demonstration conducted during the NIWeek'97 keynote.
- 1998: Development of an integrated environment to manage access rights for remote experimentation carried out by students. Static learning material was provided online.
- 1999: Physical equipments were shared among education institutions within the context of the Relax IST project.
- 2000: The existing remote experimentation client software was integrated into the eMersion collaborative experimentation environment which included a shared laboratory journal, a contextual protocol, an analysis toolkit and awareness support [4].
- 2002: The first official batch of students took regularly the automatic control lab sessions remotely.
- 2004: A mobile client application for remote experimentation including bandwidth adaptation was deployed. The eMersion environment started to be shared for standardization purpose within the ProLEARN Network of Excellence on professional learning.
- 2005: The physical equipments were renewed after 15 years of use. More than 40 new setups were made available locally and remotely 24/7.
- 2006: The collaborative space for supporting remote experimentation has been enhanced towards its usage in communities of practice in the framework of the Palette integrated project.
- 2007: A new remote experimentation framework is under development for supporting a more autonomous learning paradigm and for simplifying the integration of external applications. It relies on the standardization of a remote experimentation exchange protocol.

CHALLENGES IN PHYSICAL EQUIPMENTS

The physical equipment considered for remote experimentation are mainly mechatronic systems with mobile parts as they exhibit visually observable dynamical behaviors [5][6]. Other equipment such as chemical systems, heat flow systems or coupled tanks systems [7] that have less or no visually observable behaviors need to be enhanced to enable remote visualization. For example, a simple strand of wool has been placed at the exit of the heat flow system available at the EPFL to permit the visualization of the air stream. If such an artifice cannot be made on the physical equipment, it can generally be added to the client software in the form of augmented reality [8].

This physical equipment may be accessed locally in addition to the remote access and therefore needs to be robust to careless manipulation by students. Students will try their utmost to break, intentionally or not, the physical equipment. Such behavior seems to be part of the learning process or at least part of the appropriation of the system. In addition, security measures may be required to protect users from system failure. Question such as *what happens to the moving parts if the system is suddenly unplugged?* should be answered prior to granting access to the system. The worse case scenario will always happen. For example there are three levels of security at the EPFL for a remotely accessible inverted pendulum. First, a software security sets the output of the controller to zero if the cart reaches predefined boundaries. Then, an electrical switch shunts the actuator power if the predefined boundaries are crossed. Finally, mechanical shock absorbers are place at both ends of the track. The shock absorbers were installed after we discovered that the first two security measures were not sufficient to stop the cart running at full speed with a badly selected sampling period.

This physical equipment must be fully observable remotely. Not only the state of the physical equipment of interest for the experimentation protocol is to be considered but also the surrounding environment should be observable. The redundancy in the remote inspection is welcome. For example, if the physical equipment main switch is within the camera field of view, the distant user may better understand the unexpected results acquired when the system is not powered.

FIGURE 2
THE REMOTE LAB ELECTRICAL DRIVE SETUP.

The physical equipment should be fully controllable at distance (Fig. 2). All the aspects should be remotely controlled, while some of them may not be controllable from the distant user interface, the administrator interface should allow their control, for example, to reset the distant equipment. Similarly, diagnostics information should be available to the administrator.

CHALLENGES IN SOFTWARE

The software that control the physical equipment as well as the client interface software must be robust and written using a defensive approach toward unforeseeable usage [9][10]. Security concerns must also be considered. The developer of the remote experimentation software must guarantee that maliciously crafted information sent to the server will not interfere with the control of the physical equipment and induce damage. The received information must be cautiously validated prior to being used. These requirements generally necessitate major software revision when developing the professional-quality solutions students are expecting.

The developed software should also be adaptive to easily integrate and/or adjust to new components. The software written to control physical equipment tends to get as old as the controlled equipment. Remote experimentation software relies on a client-server architecture [11]. While the software on the server side runs on a known environment, this is not the case for the software used by the client to control the remote setup. Specific attention needs to be paid to the client application to properly handle unknown environment. This is especially true for software that relies on Web browsers to run the client interface (GUI).

Robustness toward hardware faults or unavailability is also a key issue for the acceptability of the remote experimentation paradigm by the students. If at connection time they are not able to access the chosen experiment, they may lose motivation and interest. At the EPFL, a dynamic allocation mechanism has been implemented to route students to an available and working experiment. Prioritization among both users and equipments is also handled by this mechanism. The mechanism tries to always route user to the same equipment. In the same way, it accommodates possible collisions between students experimenting in the laboratory premise and the ones accessing the equipment remotely.

Physical equipment is often shared among educational institutions. Thus, the client applications should be made available for various environments. The common denominator between these environments is the communication protocol. A well-documented user-defined protocol on the top UDP/TCP ensures a wide availability and a straightforward porting to new environments.

CHALLENGES IN MAINTENANCE

Remote laboratories maintenance is a difficult and time-consuming task when a 24/7 availability is targeted. The first step in providing a wide availability is to detect problems; this implies that the physical equipment and its associated software are capable of self-diagnoses. If the remote experiment is not able to set itself back in a known stable state it should send an alarm to the administrator. A watchdog mechanism [12] sending heartbeats to a local resetting device automates system crash detection and recovery [13]. Likewise sending heartbeats to a centralized monitoring server permits the supervision of the whole laboratory infrastructure at once. The various components of the remote experimentation servers sent, at a regular pace, information regarding the physical equipment and its remote usages to the monitoring servers.

These informations are summarized (Fig. 3) and stored in a database for further statistical and historical analysis [14].

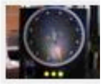
128.178.5.201	eELab (01)	14 d v.42 - 5.04.2007	14 d v3.0.11b - Nov 2006	128.178.5.71	3 / 11	0 / 0	0 / 0	
128.178.5.202	eELab (08)	13 d v.42 - 5.04.2007	13 d v3.0.11b - Nov 2006	< OffLine >	1 / 4	0 / 0	0 / 0	
128.178.5.203	eELab (20)	14 d v.42 - 5.04.2007	14 d v3.0.11b - Nov 2006	128.178.5.203	2 / 4	0 / 0	0 / 0	
128.178.5.204	eELab (21)	14 d v.42 - 5.04.2007	14 d v3.0.11b - Nov 2006		0 / 4	0 / 0	0 / 0	
128.178.5.205	eELab (12)	02.05.07 11:04 v.42 - 5.04.2007	14 d v3.0.11b - Nov 2006		0 / 7	1 / 1	0 / 0	
128.178.5.206	eELab (18)	14 d v.42 - 5.04.2007	14 d v3.0.11b - Nov 2006		0 / 2	0 / 0	0 / 0	

FIGURE 3
THE REMOTE LAB MONITORING CONSOLE.

The same information can be synthesized before being presented to remote users for awareness purposes (green circle, the upper-left part Fig. 4).

To avoid repetitive maintenance operations such as software updates, the control of the remote experimentation servers should be possible for administrators at a distance using screen-sharing software.

CHALLENGES IN DEPLOYMENT

Similarly to the maintenance, the deployment should be as automated as possible. Administrators should perform deployment once instead of manually performing the installation on each machine in the remote laboratory. Nowadays, many solutions exist to deploy a software package on many machines at the same time. Problems arise when multiple versions of the software must be run at the same time or when the software must be modified according to the connected physical equipment. A rigorous versioning strategy is important due to the longevity of the physical equipment. The source code, the information related to the equipment and the various configurations should be stored on a versioning server such as CVS or SVN.

Another aspect that is often discovered only in the deployment phase is security. By definition remote laboratories are connected to the Internet and thus prone to malicious attack. Brute force attacks have been monitored on every single machine in our laboratory. A not so trivial password has been discovered after 6 months of brute force attempts on a badly protected server. The antidote is a well-configured and up-to-date operating system, as well as a solid firewall. There are actually two firewalls, one for the LAN access and another one on each server to avoid in-LAN attack. Nominative VPN access also increases the security.
The remote experimentation server must be configured to promptly block and report suspicious activities.

Students may also use remote experimentation servers during hands-on laboratory sessions to locally control the physical equipment. This access must be granted within a distinctive session with limited rights. At the EPFL, a hidden session runs the real-time data acquisition and control software, the remote experimentation server and the video broadcasting, while a foreground session lets the user access the remote experimentation environment through a Web browser. Hence, both the local and the remote students use the same solution.

EDUCATIONAL CHALLENGES

Personal satisfaction and educational benefit are the major challenges from a student's point of view. Not fulfilling users' expectations will result in clients not using the proposed solution. Students using remote laboratories are demanding and expect professional quality solutions since the work they perform during laboratory sessions is generally graded. They are also used to high quality game interfaces, so they do not accept any compromises in GUI quality.

The additional flexibility provided by remote connections is highly appreciated and permits the students to manage the laboratory session at their own pace and from their own location. The drawback is that the learning modalities found on campus should be emulated. Collaborative learning support should be provided, as well as some form of tutoring and assistance. Diagnosis tools regarding the operating conditions of the laboratory resources and awareness regarding the progress of the class and the other students are also essential for sustaining the motivation for learning at distance.

The Hexagon tool from Open University (UK) has been integrated within the EPFL eMersion environment to fulfill the above requirements.

FIGURE 4
THE HEXAGON INTERFACE FOR ONLINE SUPPORT.

Figure 4 shows the Hexagon virtual room in which students can chat, have video conferences and meet with the teaching assistants during office hours. Virtual participants added in the room display awareness data (number of available laboratory experiments in light green for example in the upper-left part of the figure).

CHALLENGES IN SUSTAINABILITY

An effective remote laboratory facility is costly to develop and to maintain for a single academic institution. Commercial trials have also shown that the economical value of such a settings is not high enough for establishing a viable business model. As a consequence, an effective model for sustainability is the sharing of the investments and the laboratory resources between different universities. However, there are still technical and human barriers to overcome before such a paradigm could be effectively implemented. The envisioned distribution of the eMersion environment as an open source or freeware platform is one of the first steps in this direction. Due to the complexity of the environment, different universities have contributed to the development of the different components. As example, EPFL has contributed to the development of the eJournal that provides the collaborative support features for experimentation, the University of Murcia has provided the EasyJava component that enables the integration of interactive simulation of the physical equipment actually controlled, and the Open University (UK) has provided the Hexagon component mentioned previously.

Having online tutoring and assistance solutions available 24/7 is not enough. Teaching assistants should also be available outside regular hours to answer student questions. One interesting paradigm resulting from the networking of resources and institutions is that, on an exchange basis, some institutions can provide human assistance as a compensation for access to laboratory resources that may not be available at their location and conversely. This scheme is especially interesting for exchanges between industrialized and developing countries where the human resources are expensive and the laboratory ones abundant on one side, and where the human resources are abundant and the laboratory ones sparse on the other side. Taking advantage of time lag between different countries is also an valuable scheme for an efficient usage of the online resources.

CONCLUSIONS AND FUTURE WORK

Many institutions have developed and are still developing remote experimentation resources as an added educational value. However, many of them have been or will be offline in the future. This paper highlights the challenges to tackle and proposes some solutions to avoid the worst-case scenario described above. The remote experimentation paradigm, despite being demonstrated as feasible and effective a decade ago, is still not widely spread because of these challenges. The authors hope that, through this short but important list of potential difficulties, the engineering education community will establish successful and win-win partnerships to ensure sustainability for providing the next generation of future engineering students with the learning resources they deserve.

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