Remote Laboratories Extending Access to Science and Engineering Curricular

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Abstract—This paper draws on research, development, and deployment of remote laboratories undertaken by the authors since 2000. They jointly worked on the PEARL project (http://iet.open.ac.uk/pearl/) from 2000 to 2003 and have worked on further projects within their own institutions (the Open University, United Kingdom, and the University of Porto, Portugal, respectively) since then. The paper begins with a statement of the rationale for remote experiments, then offers a review of past work of the authors and highlights the key lessons for remote labs drawn from this. These lessons include 1) the importance of removing accessibility barriers, 2) the importance of a pedagogic strategy, 3) evaluation of pedagogic effectiveness, 4) the ease of automation or remote control, and 5) learning objectives and design decisions. The paper then discusses key topics including assessment issues, instructional design, pedagogical strategies, relations to industry, and cost benefits. A conclusion summarizes key points from the paper within a review of the current status of remote labs in education.

Index Terms—Information interfaces and representation (HCI), user-centered design, virtual labs.

1 Introduction

Remote experiments for teaching and learning in the science and engineering subject areas have been around for over 20 years now. Their widespread penetration across the curricular at higher education level, as their proponents have predicted, has yet to be achieved. However, the authors maintain there is still a significant potential here. This paper highlights key lessons learned from the authors' work in this field over the last 10 years. Key to this is the move of the focus from solving the technical issues of how to make remote control of teaching experiments possible to addressing the pedagogical challenges of doing so in a way that is effective in teaching and learning.

The paper restates the rationale for remote experiments. Fundamental to this rationale are issues of access. This means access for all students to lab facilities in a way that is effective in their learning, including the case of students with disabilities. The paper gives an overview of the various projects that the authors have led and been involved in, the lessons and the issues that surfaced from them. Promising research and development directions that will shape the future generations of remote laboratories in the authors view are outlined.

2 Rationale for Remote Experiments

Providing remote access to practical experiments may seem like a straightforward idea within distance education [1], [2], [3], [4]. It appears to offer a simple solution to problems of distance, collaboration, expensive equipment, and limited availability. In this section, we consider whether these provide sufficient reasons; for the control issues, the software and learning design challenges mean that providing remote access is not a prospect to be entered into lightly; rather analysis should identify where the benefits really can be. Remote access is not enough; there should be better learning provided to otherwise disadvantaged learners [5], [6], [7].

Practical work is universally recognized as being a key part of science and engineering education. However, there are challenges to making practical work available to students in today's higher education environment. There are diverse reasons for considering the provision of practical work remotely in a given context but these all revolve around issues of students' access to the equipment and facilities they need to undertake teaching experiments.

2.1 Access to the Laboratory Equipment

There are three particular circumstances when the provision of experimental work remotely can enable experimental work to be more readily offered to students [8], [9], [10]:

1. when the students are studying at a distance from the institution;
2. when the equipment required for the desired experimental work is considered prohibitively expensive;
3. when it is difficult to cope with large student numbers given the lab space available.

In the first case, distance learning, traditionally experimental work has been offered by simple "home experimenter" kits and intensive residential schools as part of a distance learning course. The home experiment kits obviously have limitations on the range of experimental work that can be undertaken. The residential schools can offer access to high quality laboratory facilities but here most of the practical work associated with a particular course has to

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be grouped into an intensive week say. Remote experiments in a distance learning context offer the possibility of access to exciting experimental facilities and the undertaking of particular experiments at the point in the course when they are most relevant to what the students are studying.

Increasingly there are demands on engineering and science courses to give their students experience of state-of-the-art laboratory facilities. These demands may come from accrediting bodies or key prospective employers of the students on the course. Now this can be prohibitively expensive especially in the cases where this equipment would only be used for a small part of the year. One solution here offered by the remote experiment approach is the possibility of sharing expensive equipment between different institutions.

The third case can be addressed by providing experiments on something like a 24/7 basis remotely over the Internet. In this way, the same physical space can cope with much larger student numbers and a greater flexibility can be offered to the students as to when they undertake their practical work.

2.2 Extending Access to Students with Disabilities

Universities may wish to consider the additional potential benefit of remote experiments of providing access for students with disabilities who may not be able to access a laboratory, or who cannot operate laboratory equipment. Universities who wish to develop remote experiments may find this a useful tool in making science and engineering courses more accessible. This may be particularly relevant in countries which have introduced legislation to reduce discrimination against people with disabilities, in particular students with disabilities. US and United Kingdom (and many other countries[1]) have such legislation. Clearly, whether it is the primary aim of a university to adopt the practice of using remote experiments to make courses more accessible for students with disabilities or not, it is important to provide ready access and to assure that the user interface is usable to students who need to interact with their computer environment in variety of ways. This includes students with disabilities.

3 An Overview of PEARL and Its Successors

I keep six honest serving-men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who.
.....
Rudyard Kipling

The authors' experience in remote laboratories begun in the late 1990s and led to a first project entitled Practical Experimentation by Accessible Remote Learning (PEARL), at a time when a very significant effort was still required to overcome the technical difficulties that hampered remote access to laboratory workbenches. Additional projects followed, as the research effort focused successively on technical, educational (content development and delivery), and pedagogical issues. The next sections summarize the objectives and scope of these projects.

3.1 PEARL

The PEARL project ran from 2000 to 2003 and the authors were partners in it. PEARL researched and developed a system to enable students to conduct real-world experiments as an extension of computer-based learning (CBL) and distance learning systems. The objectives were to give high quality learning experiences in science and engineering education by bringing the teaching lab to the students; offering flexibility in terms of time, location, and special needs. This rationale extended Internet course delivery to include enabling students to work collaboratively on practical elements of their courses that would be traditionally lab based. The project developed a modular system for flexibly creating diverse remotely controlled experiments, integrating this with a collaborative working environment and accessible user interfaces. The project evaluated the pedagogic impact of this approach, validating its developments in different educational contexts and subject areas. These included foundation level physical sciences (as part of an open and distance learning introductory course); cell biology (as part of a final year undergraduate course); manufacturing engineering (postgraduate training); and digital electronics (as part of undergraduate courses in design and testing). Further information about the pedagogical strategies developed in PEARL and their outcomes may be found in [11].

The overall budget for PEARL was US $2 million with an effort of 30 person-years. It was coordinated by the Open University (the first author being project director) with the other partners being: University of Dundee; Trinity College Dublin, Faculty of Engineering of the University of Porto; and Zenon S.A. of Athens.

3.2 MARVEL

MARVEL was an education and training project funded by the European Commission's Leonardo da Vinci programme [12]. MARVEL aimed to implement and evaluate learning environments for Mechatronics in Vocational Training, allowing students online access to physical workshops and laboratory facilities from remote places. The project merged real and virtual, as well as local and remote worlds in real time, and led to evaluated working examples of remotely accessible practical environments, together with supporting e-learning and student assessment material, in robotics, modular production systems, and process control. With a duration of 30 months (ended in April of 2005), MARVEL brought together partners from Germany, Portugal, Scotland, Greece, and Cyprus. Instead of focusing on technological aspects, MARVEL concentrated on the development of learning content (remote experiments), which shared the following modules embedded into a Moodle[2] e-learning platform:

- a Flash Communications server to support collaborative learning via videoconferencing;

1. See a list at http://www.w3.org/WAI/Policy/.

2. See http://moodle.org/.

- a proprietary scheduling/booking application that enabled the students to reserve one-hour slots in the remote labs;
- an underlying e-learning package that integrated the modules referred above and all pedagogical contents that were necessary to carry out the required remote experiments.

The typical MARVEL remote experimentation scenario might be summarized as follows:

- The teachers drafted a metascript description (used by the students to start their work) and built a corresponding *workshop* activity within Moodle (including the definition of deadlines and grading schemes).
- The remote lab equipment was set up to support the practical tasks required from the students and the corresponding interface panels were brought together (e.g., using a set of PXI modules and the corresponding LabView scripts).
- The teacher presented to each group of students the work to be done and the milestones and expected deliverables.
- The work of the students was initiated and the teacher supported and supervised its development, assessing the intermediate documents and deciding when to move on to the next phase of the *workshop*.

The two last steps could either take place face-to-face or online, using the videoconferencing server. All the background theoretical contents were made available within the same Moodle site in the form of other resources/activities, such as lessons, quizzes, assignments, a forum, etc.

The sequence described above was perceived by the students as a *learning activity with an embedded remote experiment*. The learning goal was stated in the metascript provided by the instructor and the social constructivist approach ensured that at the end the students *provided evidence* of achieving the intended learning goal. The prototypes developed within MARVEL are all presented online at http://www.marvel.uni-bremen.de.

3.3 LABS-ON-THE-WEB

The Labs-on-the-web project was prepared in response to a call for proposals aiming to improve pedagogical success in higher education degrees [13]. The project rationale was that web access to lab workbenches would facilitate experiments and other practical assignments proposed to engineering students, enabling them to better understand and consolidate the underlying theoretical knowledge. The project comprised three main areas:

1. the technical work needed to set up a range of remote labs in various engineering degrees;
2. teacher training, to ensure appropriate perception and use of the technology;
3. pedagogical evaluation (knowledge and skills, learning processes, peer cooperation, teacher interaction), including the development of the methods and instruments to be used on field trials, data gathering, and analysis.

Tasks 1 and 2 proceeded simultaneously, and so did the development of the pedagogic evaluation methods and instruments involved in task 3. Halfway through the project, field trials were initiated, and data started to be gathered. Analysis and reporting closed the project, which lasted from November 2006 to June 2008. The project consortium included the Faculty of Engineering and the Faculty of Psychology and Educational Sciences of the University of Porto (Portugal), and several other schools from Coimbra and Lisbon that offered their students remote access to the experiments.

The technical work package included in the project work plan played a minor role, and was basically intended to provide maintenance capability for the remote workbenches. The real aim of the project consisted of dealing with teacher training and with the evaluation of pedagogical effectiveness. A training program comprising three $5 \times 2\text{h}$-session training actions was developed to address *Pedagogical principles*, *E-learning via Moodle*, and *Online labs*. The attendants to each session were proposed homework tasks estimated to require approximately the same time as the in-class presentations. The *Pedagogical principles* and the *E-learning via Moodle* sessions were interleaved, to enable the "practical" application of the "theoretical" concepts presented in the pedagogical presentations. Teacher training took place between February and June 2006, involving 103 teachers, who were allowed to build individual training plans, according to their knowledge profile and application goals. Interviews with the trainers and questionnaires filled by the trainees (teachers) were used to evaluate these training actions.

The evaluation of pedagogical effectiveness led to very interesting results, and supported the conclusion that students recognize the pedagogic benefits of remote labs. We also concluded that comprehension of the learning process is an important dimension in the use of remote experiments, which is in itself worthy of consideration as a research direction. The Labs-on-the-web project has shown that there is still room for improvement, concerning development and usage of remote labs to support practical assignments in engineering courses.

3.4 Lego Mindstorm-Based Remote Labs

One of the findings of the stakeholder research undertaken at the end of the PEARL project was that cost was a major factor likely to influence the widespread adoption of remote labs in higher education. Many educators considered making facilities such as the remote controlled optical spectrometer and electron microscope remotely available as appropriate for learning but prohibitively expensive. Because of this, the work since PEARL at the OU has concentrated on realizing low cost remote experiment facilities. The approach adopted is to build diverse lab jigs implemented with Lego Mindstorm and basic webcams. Mindstorm consists of a programmable microcontroller embedded within a Lego brick that can be connected to a range of sensors and actuators. Examples of jigs created include:

- Programmable Robot;
- Light bench (not really sufficient precision);
- Principals of flight;

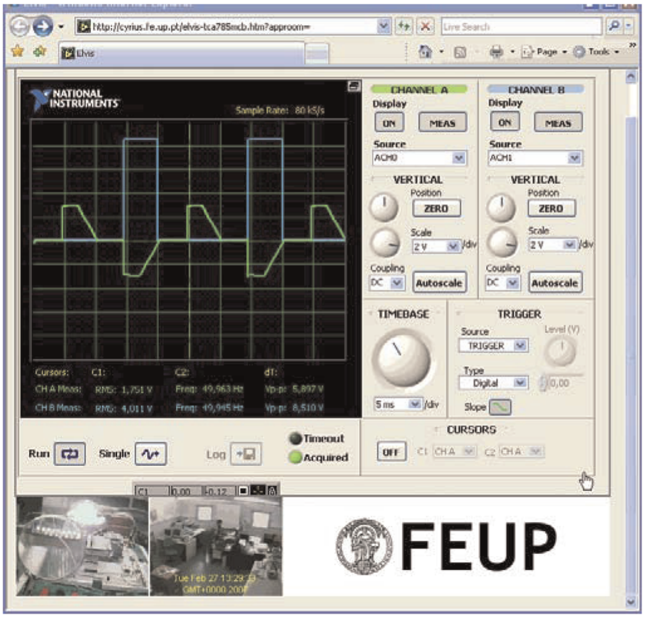


Fig. 1. A remote electronics workbench interface panel.

- Newton's laws of motion;
- Measurement of g by falling/pendulum;
- Angles of refraction/refractive index.

The Lego Mindstorm is connected to a PC that acts as a web server exposing its functionality to the world. Dedicated remote clients are implemented in JAVA.

4 Key Lessons

The example projects that were summarized in the previous sections were a valuable source of experience with regard to technical, functional, and pedagogical aspects. A summary of the lessons learned will now be presented, focusing on what the authors consider to be the most relevant conclusions derived from those projects.

4.1 Lesson #1: On the Importance of Removing/Minimizing Accessibility Barriers

The need to account for accessibility requirements when developing remote laboratories is a key lesson that deserves to be considered first and foremost. Real barriers in virtual worlds are unfortunately too common, and particularly so in this application domain [14], [15]. Instrument control panels are normally designed to replicate the buttons and displays found in standard workbench equipment, meaning that interaction with the users is largely based on visual information and positional control. The example shown in Fig. 1 represents the interface to a remote electronics workbench with live video streaming from the workbench desktop and from the laboratory where it is located.

Graphical programming languages such as LabView [16] are not necessarily an obstacle to the inclusion of accessibility features in the implementation of a remote lab, but their inclusion is largely left to the designer/programmer. The end result is in most cases highly unfavorable to users with visual impairments or other special needs. National Instruments is aware of this problem and provides documentation to advise developers with this respect [17], but many remote laboratory environments designed with LabView suffer from this problem. An accessibility test done with the *Watchfire WebXACT*[3] tool [18] signaled a variety of quality and accessibility issues that are listed in Tables 1, 2, and 3, and grouped according to the three levels of priority defined by the W3C *Web Content Accessibility Guidelines* (WCAG). Note: these relate to WCAG v1.0 which pertained at the time this work was undertaken. Since December 2008, these have been superseded by WCAG 2.0 (http://www.w3.org/TR/WCAG).

Notice that many of the errors and warnings indicated in these tables are not a consequence of the graphical programming environment, and were instead due to bad programming practices. Addressing such problems may be perceived to effect time-to-market and other cost performance factors. However, addressing them is also often a market acceptance issue as well as an aspiration and legal obligation for many educational institutions.

TABLE 1
Priority 1 Errors and Warnings

	Errors		
	Guidelines	*Instances*	*Line*
1.1	Provide alternative text to all images	1	38
12.1	Give each frame a title	3	21, 28, 33
	Warnings		
1.1	If an image conveys important information beyond what is in its alternative text, provide an extended description.	1	38
2.1	If you use color to convey information, make sure the information is also represented another way.	1	38
4.1	Identify any changes in the document's language.		
5.1	If this is a data table (not used for layout only), identify headers for the table rows and columns.	1	40
5.2	If a table has two or more rows or columns that serve as headers, use structural markup to identify their hierarchy and relationship.	1	40
6.1	If style sheets are ignored or unsupported, ensure that pages are still readable and usable.		
6.3	Provide alternative content for each SCRIPT that conveys information or functionality.		
6.3	Make sure pages are still usable if programmatic objects do not function.	2	8, 42
7.1	Make sure that the page does not cause the screen to flicker rapidly.		
8.1	Provide accessible alternatives to the information in scripts, applets, or objects.	2	8, 42
11.4	If you can't make a page accessible, construct an alternate accessible version.		
14.1	Use the simplest and most straightforward language that is possible.		

3. This tool was acquired by IBM in February 2008 and is no longer available since that date.

TABLE 2
Priority 2 Errors and Warnings

Errors			
	Guidelines	*Instances*	*Line*
3.2	Use a public text identifier in a DOCTYPE statement.		
3.4	Use relative sizing and positioning, rather than absolute.	15	18, 20, 21, 27, 28, 32, 33, 37
Warnings			
2.2	Check that the foreground and background colors contrast sufficiently with each other.	1	38
3.1	Where it's possible to mark up content instead of using images, use a markup language.		
3.2	Make sure your document validates to formal published grammars.		
5.3	Avoid using tables to format text documents in columns unless the table can be linearized.		
5.5	If this is a data table (not used for layout only), provide a caption.	1	40
6.4	If objects use event handlers, make sure they do not require use of a mouse.		
9.2	Make sure that all elements that have their own interface are operable without a mouse.	2	8, 42
10.1	If scripts create pop-up windows or change the active window, make sure that the user is aware this is happening.	2	8, 42
11.1	Use the latest technology specification available whenever possible.		
12.2	Add a description to a frame if the TITLE does not describe its contents.	3	21, 28, 33
12.3	Group related elements when possible.		
13.1	Make sure that all link phrases make sense when read out of context.		
13.3	Provide the user with a site map or table of contents, a description of the general layout of the site, the access features used, and instructions on how to use them.		
13.4	Provide a clear, consistent navigation structure.		

TABLE 3
Priority 3 Errors and Warnings

Errors			
	Guidelines	*Instances*	*Line*
4.3	Identify the language of the text.	1	1
5.5	Provide a summary for tables.	1	18
Warnings			
4.2	Use the ABBR and ACRONYM elements to denote and expand any abbreviations and acronyms that are present.		
9.4	Consider specifying a logical tab order among form controls, links, and objects.		
10.3	If this is a layout table used for formatting text in columns, provide a linear text alternative.		
11.3	Allow users to customize their experience of the web page.		
13.5	Provide navigation bars for easy access to the navigation structure.		
13.8	Provide distinguishing information at the beginning of headings, paragraphs, lists, etc.		
13.9	If this document is part of a collection, provide metadata that identifies this document's location in the collection.		
14.2	Where appropriate, use icons or graphics (with accessible alternatives) to facilitate comprehension of the page.		
14.3	Use a consistent style of presentation between pages.		

One of the lessons indicated by the results shown in Tables 1, 2, and 3 is that the programmers frequently skip the introduction of alternative text to images to shorten the development time (the error indicated in the beginning of Table 1), therefore, preventing audio transcriptions that would be vital to visually impaired users.

4.2 Lesson #2: On the Importance of a Pedagogical Strategy

Remote observation and control can be fun, but care must be taken to ensure that its enormous potential for constructivist and collaborative learning strategies is not wasted. Lab scripts may offer the students a much richer learning experience, if their teachers are aware of the plethora of pedagogical benefits offered by remote experiments. Leading the students to realize that the lab session can adapt to their pace, instead of forcing them to work on a predefined schedule; that they can continue an experiment from home, if it was not possible to complete it at the lab; that they can rehearse the lab assignment before going to the workbench; that they can repeat part or a whole experiment to confirm doubtful data; and that they will not necessarily miss the assignment if illness or other reasons prevented them from going to the lab, will likely lead to much better knowledge retention rates and more satisfactory learning experiences.

Lab assignments are an important activity within any social constructivist learning model, not only because they represent an exploratory approach to knowledge acquisition, but also due to the fact that in most cases they are carried out by groups of students, where collaboration supersedes individual work. The design of remote experiments as embedded learning objects within an e-learning platform is, therefore, highly recommended. Moodle, which has become a leading learning management system worldwide, is based upon a social constructivist learning model, and by that reason offers resources and activities which have the potential to maximize the learning effectiveness of remote experiments. The *workshop* activity[4] constitutes a

4. See http://docs.moodle.org/en/Workshops.

perfect example to illustrate how a remote experiment can be transformed into an embedded learning object that serves an educational purpose [12]. This activity uses peer review techniques to take the students through various stages during the development of educational content. The teacher sets the time line underlying a sequence of tasks that lead to a final outcome delivered and evaluated according to a predefined grading strategy.

The lesson to learn with this respect is that remote experiments should not be seen as a goal in themselves, but rather as a building block within a much wider instructional design context. Laboratory work, be it on-lab at the workbench or done remotely, is meant to complement the knowledge acquisition process, where e-learning platforms and blended learning strategies play a vital role.

4.3 Lesson #3: Evaluation of Pedagogical Effectiveness

A fundamental question when considering remote experiments to support any science or engineering degree is—do remote laboratories offer an added value in pedagogical terms? It is not trivial to answer this question, and many remote experimentation projects were carried out over the years without the participation of educational science partners. This is not necessarily a mistake, but any technical project that seeks an educational objective will never reach a real validation stage, if the evaluation of pedagogical effectiveness is under the responsibility of the engineering team.

An appropriate framework to evaluate the pedagogical effectiveness of remote laboratories comprises a set of instruments and procedures for capturing evaluation data, including questionnaires, interviews with students and teachers, and the observation of how students interact and collaborate when carrying out remote lab assignments. Their application to selected case studies provides a wealth of information that must then be processed in statistical and interpretative forms. The results obtained are likely to contain some surprises, particularly when seen through the eyes of academic staff that are not related to educational sciences.

The evaluation framework developed within the LABS-ON-THE-WEB project comprised an online questionnaire that was applied to the students *before* and *after* doing each remote experiment. This questionnaire comprised seven possible choices (1-7 with the highest value indicating strongest agreement) that were used to grade the following dimensions:

1. knowledge and skills (e.g., acquisition of new knowledge; development of ICT skills, including Information and Communication Technologies; possible development of new alternatives/solutions);
2. learning process (e.g., understanding the theoretical concepts underlying the remote experiments and the cause/consequence relationship that explains a given result);
3. peer cooperation (assessing the importance, the existence, and the possibility of collaborative interaction among students);

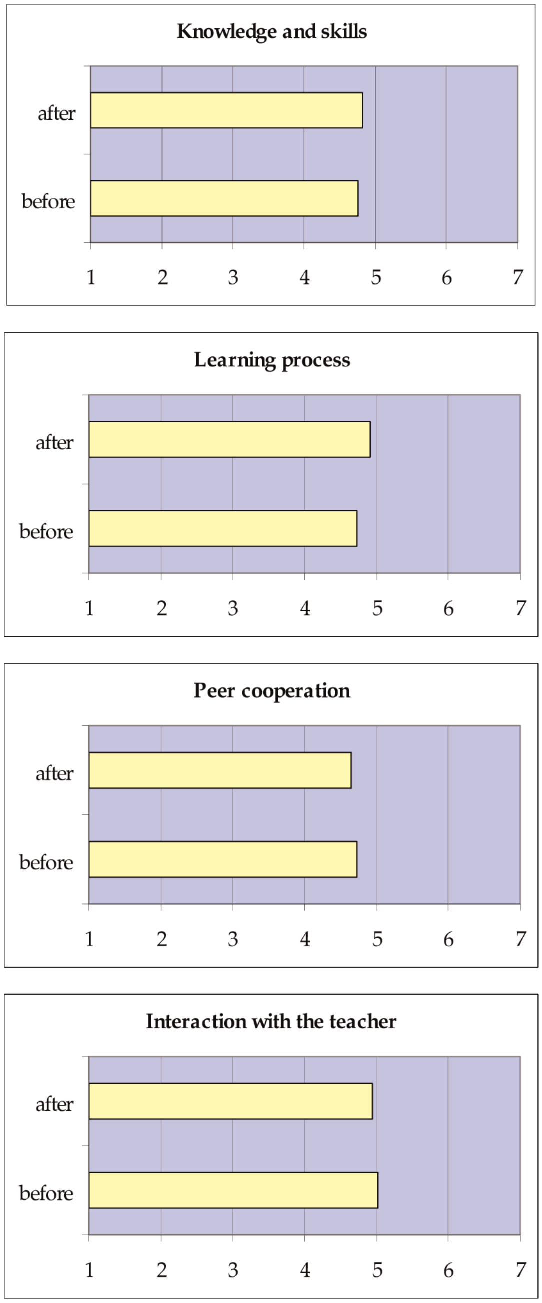


Fig. 2. Average values obtained for the evaluation dimensions, *before* and *after* the remote experiments (153 valid questionnaires before, 169 after, in a total of five courses).

4. teacher interaction (including items related to the importance of collaborative work between students and teacher and the availability of the latter).

This framework was used to evaluate the pedagogical effectiveness of a set of remote workbenches used in five courses, involving a total number of students that ranged from 153 (concerning the first stage, *before* the experiment) to 169 (*after*). Fig. 2 shows the average results obtained for each of the four evaluation dimensions referred above.

The results showed small positive effects from the introduction of remote experiments on the Knowledge and Skills and Learning Processes dimensions. However, the surprise findings were that there was actually a small but significant negative effect on Peer Cooperation and Interaction with the Teacher. This was considered particularly important, because one of the beliefs associated with offering remote experiments, is that they will promote collaborative learning practices. A possible explanation for these results lies on students' over expectations concerning teacher interaction. Many students that are online most of their day (and night . . .) look at remote laboratories as a 24-hour link to their teachers, and become somehow disappointed when they realize that teacher support is not going to experience a major upgrade under this new umbrella.

The need for realistic management of expectations, concerning interaction among students and between students and teachers, is therefore a key lesson that will benefit both sides alike. Much like the relationship between e-learning and in-class lectures, remote labs should not be seen as a replacement for in-lab assignments, but rather as a complement that facilitates access to educational activities, while preserving much of the asynchronous nature of e-learning, when it comes to teacher support. Chat rooms and other synchronous communication resources can be excellent in helping students, but they are also terribly time consuming, and this affects their acceptance by academic staff pressed by many other duties.

4.4 Lesson #4: Ease of Automation or Remote Control

One of the key lessons learned in PEARL and other projects is that one cannot necessarily automate processes or make them remotely controllable in an easy or cost effective manner. We found that processes that are very easy for a human to conduct are sometimes the most difficult to automate. This affects decisions about what experiments to offer remotely and thereby puts restrictions on particular experiments that support part of the curriculum being made accessible remotely.

4.5 Lesson #5: Learning Objectives and Design Decisions

Another key lesson is that the remote experiment team needs to consider learning objectives of the activity during the process of considering remote implementation. It is necessary to weigh up the costs of implementation against the benefits of offering a facility. For example, in PEARL, the Open University found that implementing a facility to allow students to insert the grating into the spectrometer, which involve highly accurate robotic systems, would not be worth the cost because this part of the activity was not central to the learning objectives of the activity: students needed to learn that it needs to be done, but it was not necessary for them to actually do it to learn this.

5 Discussion

A major conclusion derived from the authors' experience is that *remote laboratories do not have to replicate their real counterparts*. Most remote laboratories are developed to resemble the real workbench hosting the experiment, and there is nothing wrong in doing so, as long as we understand that *physical* resemblance does not implicate an exact replica of *functional* aspects (e.g., in the sense that it is possible to envisage functional features embedded into the interface panels, which do not exist in the real workbench equipment). This section will discuss a number of issues that are seen by the authors as relevant improvements to be expected in future generations of remote laboratories.

5.1 Discussion #1: Embedded Assessment Features

Students in a real lab are normally accompanied by a teacher that observes their work and provides help whenever necessary. The teacher divides his/her attention within the whole class, meaning that each group will sometimes have to wait, or eventually follow a trial-and-error path while trying to solve a problem (be it with the equipment or with the experiment), until succeeding or receiving help. Even when this trial-and-error process leads to a catastrophic error, there's not necessarily a problem in this approach, which is in fact at the very core of any exploratory learning model. However, a price has to be paid when the teacher's attention is shared by say eight or more groups in a lab class. There's a wealth of formative assessment information that may be collected just by observing how a student adjusts an instrument. The problem is that a teacher will only be able to observe one group at a time, meaning that only a small fraction of that information will actually be captured, when a single teacher accompanies a class with eight workbenches. However, if formative assessment features are embedded into the experiment interface panels, ubiquity of the observer becomes possible. If ethical and transparency rules are properly addressed, remote lab assignments of this type will offer the students a much richer learning experience.

Embedding formative assessment features into experiment interfaces raises a number of problems that extend from data capturing to data mining. A reference model comprising success spaces and rules to identify meaningful student actions will have to be defined, requiring a close cooperation between software and education science teams. The example represented in Fig. 1, showing an experiment interface that includes a two-channel oscilloscope, might be used to illustrate this discussion. A teacher observing how a student adjusts the oscilloscope would easily assess if the he/she is familiar with the instrument, whether the student seems to handle the buttons randomly without achieving his/her goal and be able to advise or provide help. When using interface panels to a remote oscilloscope automated assessments can potentially achieve the same thing, regardless of the number of online workbenches in use at any moment, and without depending on the availability of the teacher.

A fundamental question will, however, have to be addressed to enable embedded assessment features—what student actions are relevant for assessment purposes? The answer to this question involves the concept of *success spaces*, where it becomes possible to map student actions against specific skills or knowledge objects. In the case of the oscilloscope shown in Fig. 1, if the student is asked to adjust the time base (to avoid a mismatch between the frequency of the signal under observation and the selected time scale), one possible success space is represented in Fig. 3a [19].

Fig. 3b represents a sequence of student actions, captured from a *start point* (time base and amplitude) and including six

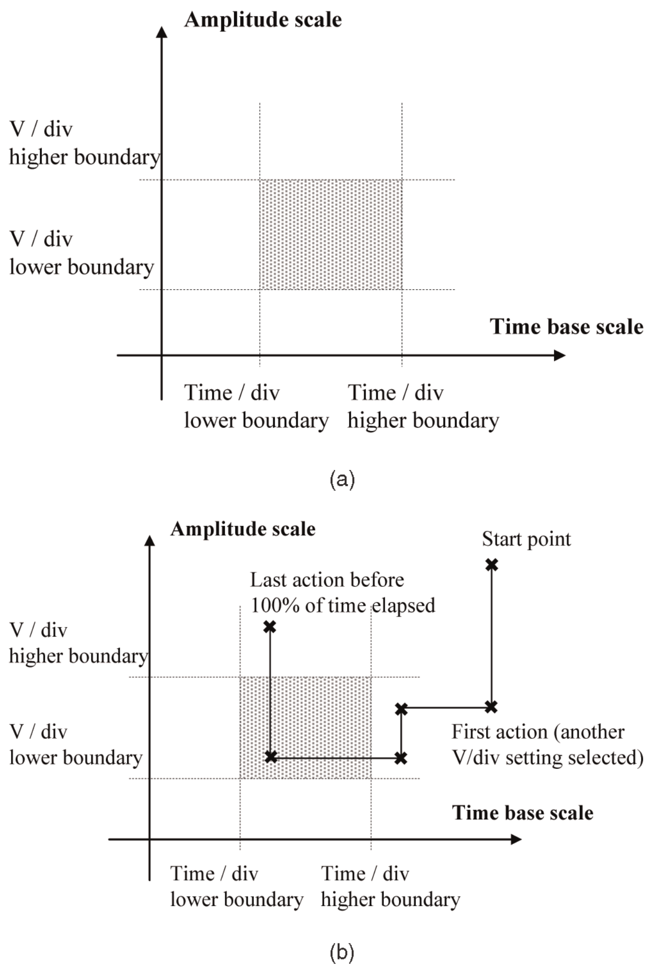


Fig. 3. Success spaces used to plot student actions. (a) Success space for adjusting time or amplitude. (b) Student actions mapped into the success space.

settings, until the time available for the assessment of this knowledge object has expired. The boundaries of the success space, for this specific example, were defined by the maximum and minimum time and amplitude settings needed to ensure an acceptable visualization of the input signals. This example is also useful to trigger some important questions that are still open to discussion.

What student actions are relevant and deserve to be logged into the assessment report, to be made available to the student and to the teacher? If the student completed the adjustment exercise within a standard time interval, there is nothing to log and no special action needs to be taken. However, if he/she hadn't yet entered the success space within the time limit set for this exercise, we're likely in the presence of a student that is not yet sufficiently familiar with the operation of the oscilloscope, and this is meaningful formative assessment information that deserves to be logged. The same happens if the student has proven his/her knowledge in a very short time (e.g., <20 percent of the time limit), since we're likely in the presence of a student that may need a more challenging goal in order to feel motivated by the tasks proposed.

The reader may have noticed that in the case of Fig. 3b the student had actually entered the success space within the time limit set for this exercise. It is questionable if he/she noticed that and just wanted to try something else, or simply failed to realize it and continue to try out different settings randomly. Various other situations may be envisaged where it is possible to question if the conclusions derived by this method are meaningful. However, we should keep in mind that a very large number of such atomic assessment exercises may take place during a lab assignment lasting for one or two hours, so it will be possible to look at the assessment results from a statistical point of view for validation purposes.

Embedded assessment features are still far from reality, particularly because there is a great deal of research needed to define feasible sets of success spaces, meaningful knowledge objects, and validation procedures. To complicate things a little further, it quickly becomes clear that they will vary widely from one remote experimentation area to another. They may also vary dynamically within a given experiment, if the challenges posed to the students evolve in real time as the experiment progresses. The definition of a framework for embedded assessment in remote laboratories used within science and engineering courses is an open field where much research and discussion will take place in the following years.

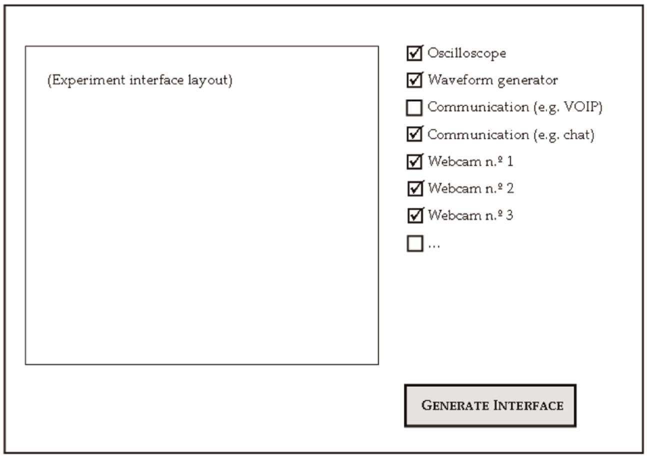
5.2 Discussion #2: Instructional Design Support

Designing a lab assignment, and particularly the experiment script, is no longer what it used to be. Offline workbenches were far easier to set up, and the technical skills required from the teachers and lab technicians were largely restricted to the instruments present and the experiment itself. Preparing the workbench was essentially related to defining how to stack and lay out the necessary instruments and equipment. The interface to an online workbench must be equally simple to set up, or otherwise teachers and technicians will have to master Internet and firewall technologies, JAVA programming, web page development, etc. Most of them will not be interested to take that step. Specific technical training for academics and technicians is unavoidable, but remote laboratories will not convert teachers into web programmers. Instructional design support will have to be devised, namely in the form of experiment interface design and production, integration into e-learning platforms, etc.

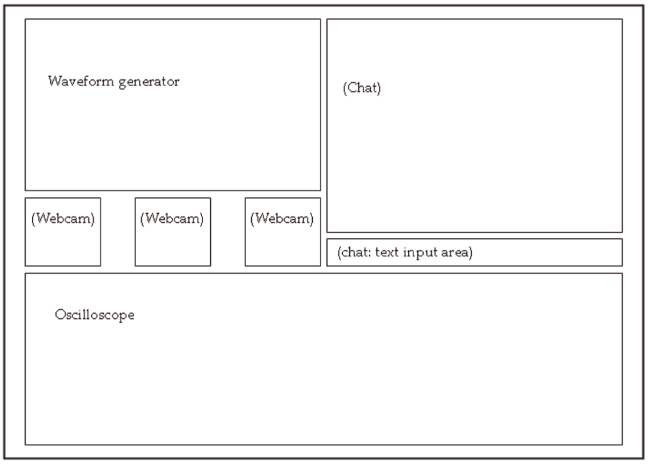
The case of interface design and production is particularly interesting for discussion within this context, since it is relatively simple to envisage a library of instrument panels, communication gadgets (e.g., chat or videoconferencing windows), file transfer tools, etc.

A library manager tool might be offered to the teacher as represented conceptually in Fig. 4a. The standard experiment interface, generated automatically when pressing the "Generate interface" button, would ideally correspond to the layout represented in Fig. 4b and might be customized by dragging and dropping the rectangles corresponding to each component.

Figs. 5 and 6 show two examples of experiment interfaces generated by a prototype implemented from this conceptual specification [20]. The case study represented here corresponds to a remote experiment dealing with structural fault detection on mixed-signal boards supporting the IEEE 1149.1 and 1149.4 standards [21], [22]. The test program is specified in SVF [23] on the right side of the



(a)



(b)

Fig. 4. Experiment interface panels: Conceptual design support. (a) Specification of the interface components. (b) Experiment interface generated according to (a).

panel shown in Fig. 5, and the test setup and test results are shown on the left. The oscilloscope, voltmeter, waveform generator, and videoconferencing channels are provided in a separate window to minimize vertical scrolling, as shown in Fig. 6.

Instructional design support in the form described in [20] is yet in the research and development stage. One of the reasons for this delay derives from the lack of de facto standards concerning technologies and platforms to support the development of remote laboratories. Contrary to the wider e-learning scenario, where enabling technologies,

Fig. 5. Test program specification, test setup, and results for the remote test experiment.

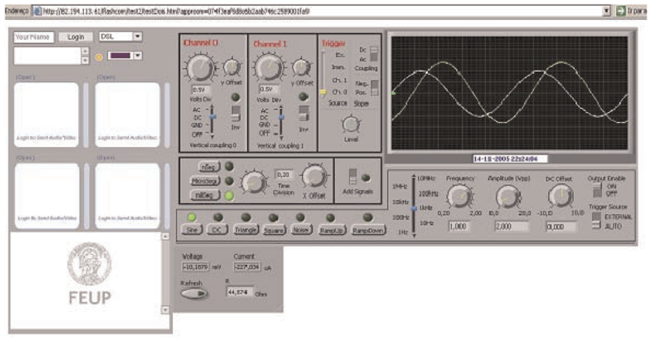


Fig. 6. Instruments and videoconferencing modules for the remote test experiment.

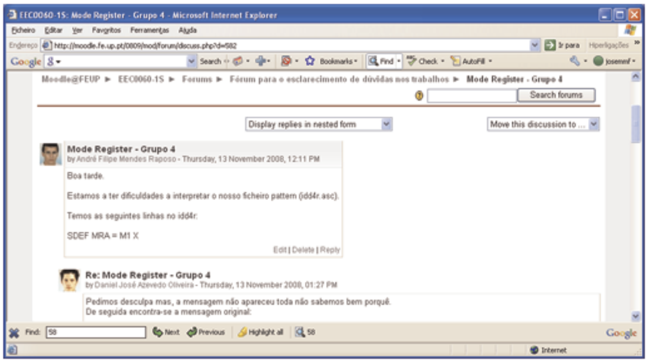
and functional and portability issues, are reasonably standardized, there is a wide variety of remote laboratories. The development of tools for automatic generation of experiment interfaces will not only facilitate the work of teachers and technicians, promoting the widespread adoption of the remote laboratories, but will also simplify the development of remote laboratory grids, and content sharing (of remote experiments) among institutions in similar science and engineering areas.

5.3 Discussion #3: Pedagogical Strategies for Collaborative Learning Based on Remote Labs

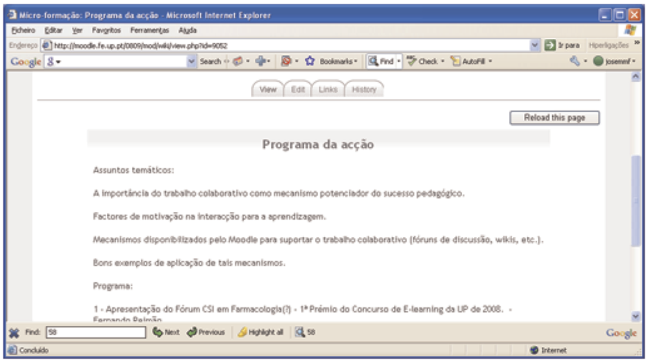
Remote laboratories and collaborative learning are not necessarily linked. However, lab assignments (local or remote) are usually carried out as group work, and therefore offer an excellent opportunity to support collaborative learning strategies. Their potential to support exploratory learning models is also worth mentioning, since the lab script may be explicitly designed to trigger group discussion and the acquisition of knowledge needed to explain the experiment results. This social constructivist vision explains why some Moodle resources and activities (e.g., the *workshop* activity referred in a previous section) simplify one of the main challenges faced by teachers—how to convert a remote experiment into a meaningful learning object. Pedagogical strategies play a key role in what concerns the learning effectiveness of remote laboratories, but satisfactory solutions/frameworks are still lacking. The fundamental problem is that remote experiments are still very frequently offered as stand-alone activities, ignoring the potential that derives from being able to include in the same browser window such powerful resources as the online workbench, the e-learning platform, search engines and online resources, chat and videoconferencing, etc.

The development of a good pedagogical wrapper for remote experiments calls for the cooperation of education scientists and e-learning experts. This work is yet to be done, particularly in what concerns the collaborative features and how to embed them effectively into the remote experiment script. Fig. 7 shows two examples of Moodle activities that illustrate what we're discussing in this section.

- The *forum* provides a discussion area where students and teachers may discuss experiment procedures or results, clarify doubts, query each other, etc. A forum is one of the simplest collaborative activities



(a)



(b)

Fig. 7. Collaborative learning activities supported by Moodle. (a) A Moodle Discussion forum. (b) A Moodle wiki.

within Moodle, yet few teachers will associate a forum to each experiment, and those that do so will frequently find the results disappointing for lack of interest from the students.

- A *wiki* is another example of a powerful collaborative activity supported by Moodle. Slightly more complex than a discussion forum, a wiki stores a shared document that can be modified by the authorized participants. All modifications are automatically registered, showing how the document evolved. If the experiment script asks the students to present a theory explaining the observed results, a wiki is an excellent choice for doing that work collaboratively, and enables the teacher to follow the participation of each group member. However, students will tend to ignore this activity, if they don't perceive a coherently integrated overall pedagogical strategy.

Collaborative activities offer an excellent framework to improve the learning effectiveness of remote experiments, but very little pedagogical research has been done so far in this area. Remote laboratories are still very much a technological subproduct of the Internet revolution, and most of them result from projects that addressed technical challenges, leaving the pedagogical aspects in the background. The development of e-learning platforms suffers less from this problem, not only because it started much longer ago, but also because some such platforms have an explicit underlying pedagogical vision (the social constructivist learning model of Moodle, for example, binds technological and pedagogical aspects and is partly responsible for the widespread acceptance of this platform).

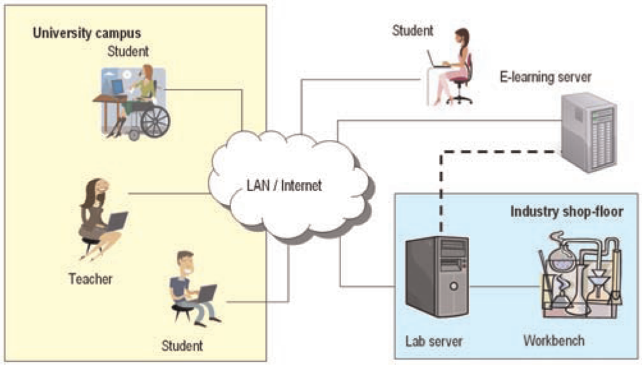


Fig. 8. A remote lab located in the factory shop-floor.

5.4 Discussion #4: Remote Labs @ Industry

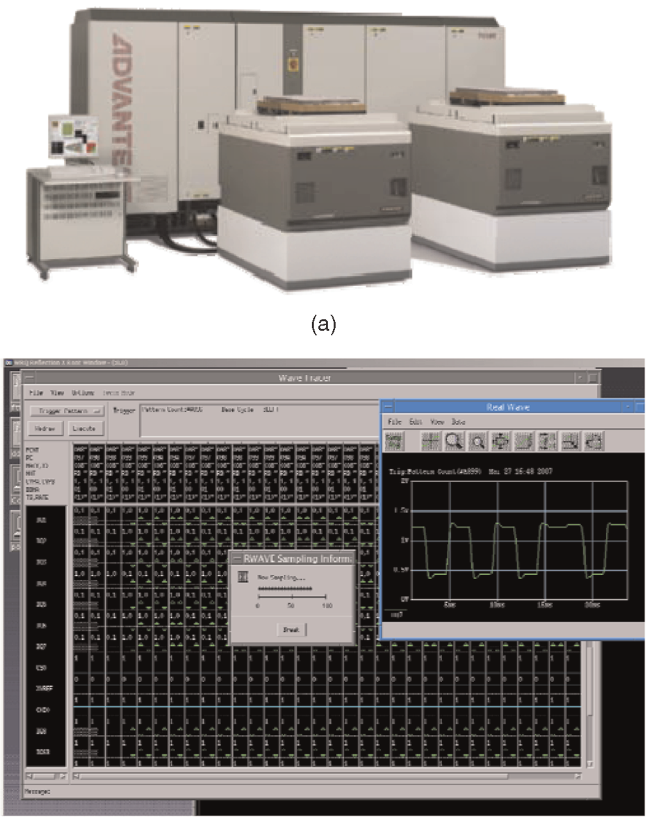
Remote labs are usually seen as online workbenches that are located in the university campus, offering access to students from their homes. However, there are other scenarios that can be envisaged, offering pedagogical and other benefits that go beyond the limitations of a strictly academic setting. Remote access to sophisticated equipment located in the factory shop-floor is a good example of such scenarios, as illustrated in Fig. 8.

In many cases, remote access to shop-floor equipment may already be in use inside the company. The SDRAM test system illustrated in Fig. 9 is a good example of what has just been said. Test engineers, particularly those working in test program development, work from their desks instead of walking to the factory shop-floor.

Due to their very high cost, SDRAM testers are an excellent example to illustrate the advantages of remote labs to industry [24]. Generally speaking, the benefits of envisaging remote access to shop-floor equipment may be summarized as follows:

- offers the students access to specialized knowledge that may not exist within the university;
- represents an opportunity to work with sophisticated equipment that may be too expensive or too specific to exist in a university;
- improves employability of the students, by offering them skills that are directly relevant to companies, and enabling the company to assess and select the students;
- enables the companies to have a say concerning academic curricula and required student skills;
- offers the students a glimpse of their future professional life before they leave the university (organizational and cultural habits, time and activities management, etc.);
- last but not the least, remote labs at industry bridge the gaps with academia and facilitate the deployment of joint educational and research programs.

In spite of the many advantages in this form of cooperation between academia and industry, good examples of remote labs located at industry premises are still very scarce. There is yet a significant amount of work that



(a)

(b)

Fig. 9. SDRAM test equipment and the test engineers working environment. (a) Advantest SDRAM tester. (b) Advantest development tools.

needs to be done in this area, not so much in terms of pedagogical or organizational research, but rather in terms of disseminating good practices, identifying good opportunities, establishing the necessary cooperation channels, and developing the corresponding educational programs.

5.5 Discussion #5: Cost Effectiveness

In most cases it is more costly to offer an experiment remotely than face-to-face in the lab. This additional cost needs to be justified. The justification normally comes from meeting issues of access. This may be:

- access to expensive or safety critical equipment;
- access any time form anywhere to limited lab space and equipment;
- improved access for disabled students;
- integration into distance learning programs;
- sharing of lab facilities between institutions or across sites at an institution.

So, the additional cost of making any lab facility available online can, normally at least, be offset by the number of students that can use it in a given period. Many institutions are finding it increasing difficult to provide comprehensive labs to all the students on their courses. Remote labs can offer a solution to this maximizing the number of students that can use an item of equipment. Cost effectiveness is one criteria to evaluate in deciding what specific experiments to offer remotely and in their design; not just the adoption of the overall approach.

There is a pedagogic advantage of remote labs in that experiments can usually be offered at the time the students undertake the related areas of study. This may be difficult to quantify as a cost benefit but funding is often linked to student completion rates and grades, so it may be possible.

6 Conclusions

In summary, this paper has given a case for the role of remote experiments in extending access to teaching labs and other practical work as part of principally science and engineering education. Remote laboratories have come a long way since their introduction in the late 1980s/early 1990s. The last decade witnessed a move from breaking technological barriers to the enhancement of pedagogical features, and the next generations will undoubtedly include embedded tutoring and personal assessment features that will improve their pedagogical effectiveness still further. In spite of 20 years of activity and accumulated experience, it is remarkable that some obstacles remain to the widespread adoption of these solutions. The public perception of remote laboratories has improved, but it is still important to stress that in most cases we are talking about a complement to lab classes, and not of their replacement. They enable the students to rehearse, complete, repeat, or extend their lab work, offering flexible access to lab spaces that would otherwise remain out of reach when the lab is closed. At the same time, they represent an extension to e-learning technologies, and in this way prevent Moodle and other learning management systems from dying at the laboratory door. The integration of remote experiments with the remaining e-learning contents offers an enormous potential for improving the pedagogical success of science and engineering students, and their contribution with this respect will be even more important, as the next generations depart from near-replicas of workbench equipment and evolve into adaptable learning companions, assessing and tutoring students as they do their lab work. This paper has also highlighted the potential for remote labs to give comprehensive access to practical work that might otherwise be denied them including students with disabilities.

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References

[1] J.V. Nickerson, J.E. Corter, S.K. Esche, and C. Chassapis, "A Model for Evaluating the Effectiveness of Remote Engineering Laboratories and Simulations in Education," *Computers & Education,* vol. 49, no. 3, pp. 708-725, Nov. 2007.

[2] E.D. Lindsay, S. Naidu, and M.C. Good, "A Different Kind of Difference: Theoretical Implications of Using Technology to Overcome Separation in Remote Laboratories," *Int'l J. Eng. Education,* vol. 23, no. 4, pp. 772-779, 2007.

[3] J. Ma and J.V. Nickerson, "Hands-On, Simulated, and Remote Laboratories: A Comparative Literature Review," *ACM Computing Surveys,* vol. 38, no. 3, Sept. 2006.

[4] D. Gillet, A.V. Nguyen, and Y. Rekik, "Collaborative Web-Based Experimentation in Flexible Engineering Education," *IEEE Trans. Education,* vol. 48, no. 4, pp. 696-704, Nov. 2005.

[5] E.D. Lindsay and M.C. Good, "Effects of Laboratory Access Modes upon Learning Outcomes," *IEEE Trans. Education,* vol. 48, no. 4, pp. 619-631, Nov. 2005.

[6] J.E. Corter, J.V. Nickerson, S.K. Esche, and C. Chassapis, "Constructing Reality: A Study of Remote, Hands-On, and Simulated Laboratories," *ACM Trans. Computer-Human Interaction,* vol. 14, no. 2, Aug. 2007.

[7] T. Abdel-Salam, P. Kauffman, and G. Crossman, "Does the Lack of Hands-On Experience in a Remotely Delivered Laboratory Course Affect Student Learning?" *European J. Eng. Education,* vol. 31, no. 6, pp. 747-756, Dec. 2006.

[8] F. Biocca, J. Burgoon, C. Harms, and M. Stoner, "Criteria and Scope Conditions for a Theory and Measure of Social Presence," *Proc. Presence,* 2001.

[9] B. Fraser and H. Walberg, "Research on Teacher-Student Relationships and Learning Environments: Context, Retrospect and Prospect," *Int'l J. Educational Research,* vol. 43, pp. 103-109, 2005.

[10] Z. Nedic and J. Machotka, "Remote Laboratory NetLab for Effective Teaching of 1st Year Engineering Students," *Int'l J. Online Eng.,* vol. 3, no. 3, 2007.

[11] M. Cooper, A. Donnelly, and J.M. Ferreira, "Remote Controlled Experiments for Teaching over the Internet: A Comparison of Approaches Developed in the Pearl Project," *Proc. 19th Ann. Conf. Australasian Soc. for Computers in Learning in Tertiary Education,* 2002.

[12] J.M. Ferreira and D. Mueller, "The MARVEL EU Project: A Social Constructivist Approach to Remote Experimentation," *Proc. First Remote Eng. and Virtual Instrumentation Int'l Symp. (REV '04),* Sept. 2004.

[13] J.M.M. Ferreira, E.M. Almeida, I.M. Figueiredo, and C.F. Leite, "Labs-on-the-Web: A Multidisciplinary Project to Evaluate the Pedagogic Effectiveness of On-Line-Labs," *Proc. European Distance and E-Learning Network Ann. Conf. (EDEN '08),* June 2008.

[14] L. Nevile, M. Cooper, A. Heath, M. Rothberg, and J. Treviranus, "Learner-Centred Accessibility for Interoperable Web-Based Educational Systems," *Proc. 14th Int'l World Wide Web Conf. (WWW '05),* May 2005.

[15] M. Cooper, "Making Online Learning Accessible—The Role of the Educator and Issues for the Educational Institution—Reflections on Experiences at the Open University," *Assoc. of Learning Technology J.,* vol. 14, no. 1, pp. 103-115, Mar. 2006.

[16] NI LabView—The Software That Powers Virtual Instrumentation, http://www.ni.com/labview, 2009.

[17] National Instruments, Accessibility Requirements Compliance Matrix, www.ni.com/pdf/gsa/en/labview-508-accessibility-requirements-compliance-matrix.pdf, 2009.

[18] J. Faias, J.M. Ferreira, and C. Leite, "Accessibility and Usability of Online Labs: Real Barriers in a Virtual World," *Proc. Int'l Conf. Remote Eng. Virtual Instrumentation (REV '07),* June 2007.

[19] M. Conradi, R. Langmann, A.M. Cardoso, and J.M.M. Ferreira, "Embedding Formative Assessment Features into LabView Interfaces," *Proc. Int'l Conf. Remote Eng. Virtual Instrumentation (REV '07),* June 2007.

[20] J.R. Alves, G.R. Alves, P.A. Ferreira, and J.M.M. Ferreira, "REXIB: Remote Experiments Interface Builder," *Int'l J. Online Eng.,* vol. 2, no. 3, 2006.

[21] *IEEE Std 1149.1-1990, IEEE Standard Test Access Port and Boundary-Scan Architecture,* 2009.

[22] *IEEE Std 1149.4-1999, IEEE Standard for a Mixed-Signal Test Bus,* 2009.

[23] Serial Vector Format Specification, www.jtagtest.com/pdf/svf_specification.pdf, 2009.

[24] J.M. Ferreira and A.C. Leão, "An SDRAM Test Education Package that Embeds the Factory Equipment into the E-Learning Server," *Proc. Int'l Conf. Remote Eng. Virtual Instrumentation (REV '08),* June 2008.

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