

ReLOAD: Real Laboratories Operated at a Distance

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Abstract—Remote laboratories are increasingly being developed to provide students with Web-based access to real laboratory experiments. The demonstrable advantages (e.g., increased accessibility) are tempered by concerns that remote access will be substituted for “hands-on” practical work, and reduce interaction between students. We argue that these concerns can be avoided if remote labs are used appropriately, as with any other pedagogical method. We review studies that have made direct comparisons between remote and hands-on labs, and analyze the important similarities and differences by considering the students’ physical and psychological experiences. A case study is presented: “ReLOAD”, which has been in operation since 2001 providing remote operation of dynamic experiments in Mechanical Engineering, featuring personalized experiments, immediate automated grading and feedback, and collaborative learning. We present results from online surveys and from focus groups of students’ opinions and experiences with hands-on and remote labs. Drawing from this experience, the characteristic properties of remote-access labs are investigated from a pedagogical perspective. We find that many of the differences and similarities between the modalities are controllable factors, to greater or lesser extents, and provide examples of remote labs offering some valuable educational advantages which are not possible with traditional labs.

Index Terms—Engineering, collaborative learning, distance learning, personalized e-learning.

1 INTRODUCTION

WITHIN the disciplines of engineering and physical sciences, laboratory work is considered to be “at the heart” of learning [1] and can have a strong impact on students’ learning outcomes [2], [3]. Laboratory-based sessions are widely used in order to provide physical evidence of theoretical principles and to teach practical skills. When used appropriately, they can enthuse, motivate, and inspire students.

Laboratory teaching requires commitments of time, space, and finance to purchase, install, and maintain equipment, and then to host the students. As the size and diversity of cohorts increase, so does the pressure on resources; this has been one likely factor driving research into technological alternatives to the traditional methods of laboratory teaching.

Simulations of the lab experience have been created, using computer interfaces and prerecorded data; however, this removal of the “live” element has received criticism from students and educationalists [3]. Simulations certainly

have value (e.g., in providing animations of dynamic physical processes), when they are provided supplementary to existing teaching, as originally intended [4]. However, if simulations are used *in place of* experimental work, where uncertainties occur (“serendipity” [5]), then simulation is fundamentally inappropriate since the results are predetermined.

Fig. 1 shows an example of measured data from a real experiment, exhibiting noise, uncertainty, and imperfections—important characteristics for students to see.

Creating a simulation is not simple: In a recent colloquium on Internet teaching [6], experienced developers of the technology agreed that they had found it more difficult to create a computer program to try to simulate a process realistically than it would have been to simply run the real process. Accordingly, the scope of this paper will include only experiments with real hardware.

An alternative approach is to provide remote access to real laboratory experiments. Proponents of this technique are keen that it is distinguished from simulated experiments so it is important to define the terms. Fig. 2 shows the general structure of a remote lab, comprising:

- **apparatus** (real experimental equipment)
 - from which data (measurements) can be recorded;
- a **Remote Link** for bidirectional transmission;
- an **Interface** that allows students to
 - submit requests for an experiment (providing experimental parameters)
 - receive data (measurements).

Three vital components are indicated in bold type. The specific implementation of these three is left undefined;

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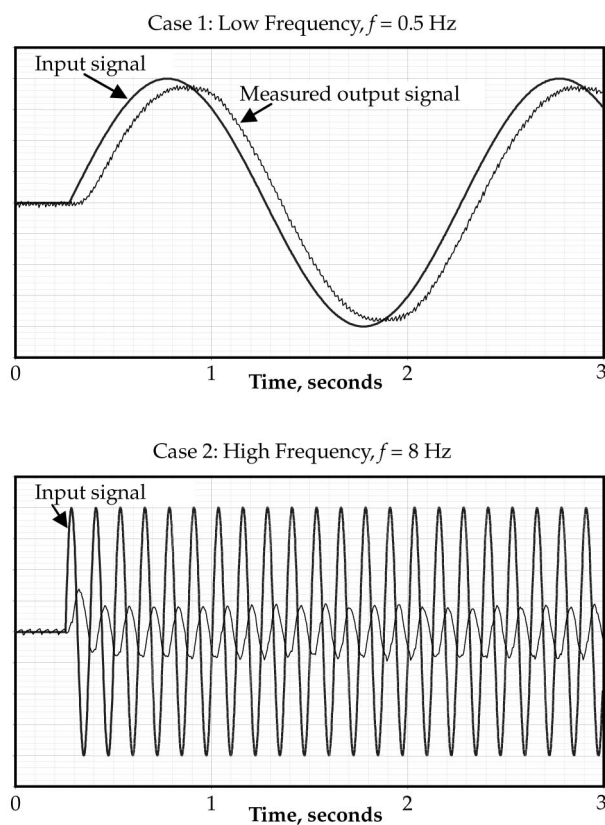


Fig. 1. Examples of measured experimental data showing noise, imperfections, and nonlinearity that are commonly found in real experimental equipment.

while the increasing use of remotely operated laboratories has been facilitated by the increasing availability and capability of personal computers and the Internet, other implementations of remote operation are also possible.

Remote labs have been applied in a range of disciplines including environmental and ecological science [7], but are mainly found in engineering departments: chemical (e.g., [8]), electrical (e.g., [9]), and mechanical (e.g., [10]). The technology is being developed in an increasing number of higher education institutions and is branching out to new subject areas and to other levels of education.

Many remote labs can already be accessed by anyone with conventional generic Web-browser software [10]; this feature provides the opportunity for institutions across the world to access experimental equipment. Some small user groups are forming and have provided evidence of successful collaboration and sharing of resources over international boundaries [8], [11]. There is enormous potential for much wider collaboration and sharing of resources nationally and globally. But before remote laboratories can achieve their

potential, several fundamental logistical issues still require urgent attention: how will facilities be funded and maintained? Who will have access and when? More debate is required to resolve these issues and to reach a consensus on the strengths and weaknesses of the remote lab modality, and its place in the curriculum. Currently, there is not even an agreement on the technique's name: "Web labs, virtual labs, or distributed learning labs" [5].

There are ongoing disputes over the effectiveness of remote labs at delivering learning outcomes, and their overall effects on students' experience. Most examples to date are simply remote versions of traditional labs and some researchers have attempted to make direct comparisons between learning outcomes with hands-on versus remote labs. However, there has been little work that addresses how the specific characteristics of the remote modality can be exploited to reinforce learning. Now that the technical feasibilities of various approaches are being increasingly understood and proven, it is time to consider the best use of the remote lab modality from an educational perspective.

To that end, this paper begins by investigating the real similarities and differences between hands-on labs and remote-operated labs. We then present a detailed description of our work on remote labs, comprising several different experiments that have been operated by students in institutions across the globe. Drawing on this experience, we highlight several characteristic features and affordances of remote operation of laboratories and make some suggestions for best practice.

2 REMOTE LABS AND HANDS-ON LABS IN COMPARISON

2.1 Presence and Context

The fundamental difference imposed by remote operation is the physical separation of student and apparatus. This, by definition, means that it is impossible for students to perform tactile, physical interaction with the remote device. Hence, remote labs have very limited ability to teach a practical skill or craft. On further investigation of remote labs, it becomes apparent that other aspects of the physical and virtual environment experienced by the students are not so straightforward.

Considering the physical and social environment: with hands-on labs, students may work individually or in groups, using one piece of apparatus or several duplicated sets, and the lab may be led by just one teacher or there may be assistants. In each case, the ratio of student:apparatus:teacher is fixed before the lab, and during the experiment, the teacher will be in control of the learning environment. For remote labs, that is not necessarily the case: If a teacher

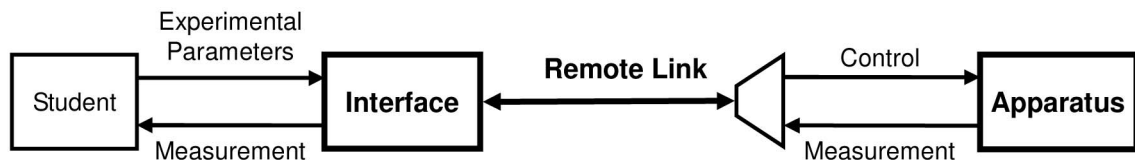


Fig. 2. The generalized structure of remote laboratories.

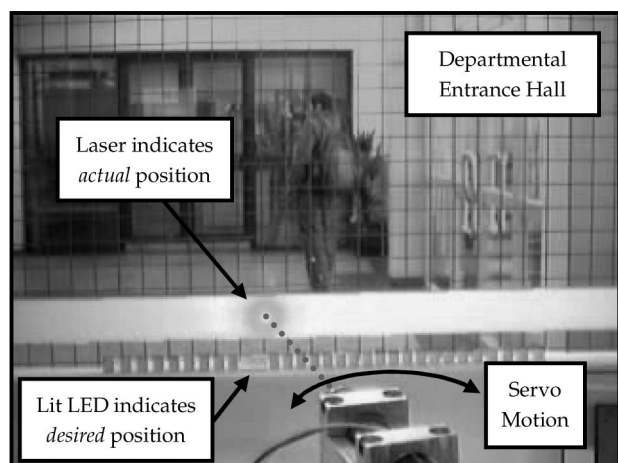


Fig. 3. Example frame from a video clip used in a remote lab, showing the experimental setup. NB: Students do not see the annotations; these have been added purely for this paper.

is not actually present with a student, then the physical environment in which the student conducts the lab may be variable; this issue is expanded later, in Sections 3 and 4.

Physical presence, however, is only one element in the “perception of reality”: a student’s “subjective mental reality” [12], [13]. Though physically remote, a student can still feel a sense of immersion within the concepts and themes of a lab: a “psychological presence.” This immersion can be enhanced with a high-fidelity interface [14]. Remote labs often incorporate photographs or even a video clip of the experiment; this is described in the case study in Section 3. Fig. 3 shows an example video frame from the Real Labs Operated At Distance (ReLOAD) case study.

When considering the physical environment of labs, disciplinarity becomes an important factor; the remote labs discussed so far have been within the discipline of engineering, but, in medical education, the physical and social environments are much more relevant to the learning process. In medicine, the human interaction with patients is a very significant learning outcome of practical sessions [15]. Furthermore, the learning environment—the ward—is the same as that encountered later, in practice. By comparison, engineering labs and experiments can be quite different (often simplified) environments to industrial labs or workplaces.

This concept of presence has relevance to the issue of the “environmental context of learning”: Studies have shown that a same-context advantage is observed for recall of information, for example, information received in a classroom may be more easily recalled within that same classroom (see, e.g., [16], for a review). It should be noted that this advantage primarily applies to memorizing facts and data, rather than the application of knowledge or problem-solving. As with presence though, physical context is not all: the “internal context” is perhaps more relevant for a student who is engaged in introspective study. “Same context” can then be used to refer to any situation where a student is studying that particular subject, depending on the depth of their psychological immersion in the concepts and theories.

A student is not necessarily more psychologically “immersed” in a subject during a lab session: There can be any number of other distractions—examples are presented

in Section 3.4 and discussed in Section 4.5. Physical presence does not guarantee psychological presence when concentration lapses: A teacher might well ask of a student: “Are you with us?” Depending on the cognitive nature of the experiment, the degree of psychological immersion is not necessarily greater in either remote or hands-on labs. The degree of psychological presence with either modality is actually very hard to quantify or control. This undermines attempts to compare remote and hands-on modalities directly, as they are likely to have many uncontrolled degrees of freedom.

2.2 On the Assessment of Efficacy

The ability to perform direct comparison between modalities is further limited by the lack of standard criteria with which to evaluate the effectiveness of lab work [5]. The traditional assessment method for performance in laboratory work is to grade a student’s report; however, it has been pointed out that in many cases, the resulting grade represents to a large extent the student’s ability to write a report, rather than their grasp of a particular concept or development of a skill [17].

Despite these issues, the creators of some remote labs have attempted to demonstrate their efficacy by directly comparing learning outcomes between remote and hands-on versions of the same experiment. Lang et al. [9] attempted to quantify learning outcomes by applying a knowledge test of 120 true/false questions on the specific subject to students before and after carrying out an experiment. One group of students participated in a traditional lab (on electric circuits) and the other experienced an online version. The researchers thus attempted to investigate any difference in learning outcome attributable to delivery method. The knowledge test did not show any practically significant differences between the methods; however, all the measured differences in knowledge were very small, and in some cases, average knowledge of the subject was actually found to be higher before participating in the experiment. Lang et al.’s conclusions from that study were that either the tests were not effective at measuring the outcomes of the practical work, or that the practical course was not effective at increasing knowledge.

Lindsay and Good [18] canvassed students who had taken either a hands-on experiment or simulated or remote access versions of the same experiment and found several differences in their perceptions and experiences. The experiment had several learning outcomes which were assessed individually through systematic grading of the students’ written reports on their work. After a series of detailed studies, Lindsay and Good found that it was impossible to conclude that any access mode was ultimately superior to any other, because the modes exhibited multiple differences across different learning outcomes [18].

After reviewing remote lab technology, Ma and Nickerson [5] also questioned the validity of like-for-like comparisons and noted that controlled trials are not possible when there’s no way to standardize instructor ability. Furthermore they warned that it would not be relevant to compare across different disciplines. When reviewing published studies of the effectiveness of remote technologies versus hands-on labs, it is noticeable that research has very rarely been conducted by workers without a strong allegiance for either method.

TABLE 1
The Experimental Rigs Available on ReLOAD

| Apparatus | Investigation Purpose |
|----------------------------------|--|
| <i>University of Leeds</i> | |
| Vibrating Beam Rig | Adjustment of damping Adjustment of amplitude Variation of beam mass |
| Smart Lumped-Mass Beam Rig | Adjustment of added mass Adjustment of damping |
| Servo-Motor Rig | Step response analysis Frequency response analysis Adjustment of controller parameters |
| Wind Tunnel Rig | Adjustment of flow speed Adjustment of angle of attack |
| <i>University College London</i> | |
| Structural Dynamics Rig | Adjustment of added mass Investigation of modes of vibration |

In conclusion, the two modalities are fundamentally and significantly different; thus, direct comparison is not appropriate or productive. In making these comparisons, some published work appears to be seeking to justify remote learning as a suitable like-for-like replacement for face-to-face experience. There could then be a danger that remote labs would be viewed by some as “a convenient way to include lab experience without having to actually run a real laboratory.” Instead, the authors propose and advocate an alternative approach: that there are differences compared to hands-on labs, but these can be acknowledged, accepted, and exploited in order to make the most appropriate use of each different teaching method.

In Section 4, we investigate the general characteristics of remote labs with respect to learning and teaching, but first let us examine a specific case study.

3 CASE STUDY: THE “ReLOAD” SYSTEM

Remote laboratories have been in operation at the University of Leeds, UK, since 2001, under the acronym “ReLOAD.” The current remote lab system now includes the experimental rigs listed below in Table 1, with further experiments being developed at other sites.

This system is part of the undergraduate engineering curriculum at the University of Leeds (typically, this has approx. 120 students per year group), at the University of British Columbia in Vancouver (typically approx. 100 students), and at University College London (typically approx. 30 students). In this section, we describe the operation of the system and present results of usage statistics, of questionnaires on students’ opinions and outcomes, and quotes from focus group studies.

3.1 Architecture

The system allows connection of multiple experiments at multiple locations, all connected through a central server. The architecture is shown in Fig. 4.

The ReLOAD system is operated entirely via a Web-based front-end. It comprises two core component types; a central ReLOAD Web server and remote experiment PCs that control the physical experiments through data acquisition hardware. Industry-standard technologies are used throughout to ensure reliability and consistent operation.

The ReLOAD server is used to administer and coordinate the system as a whole. A Web server (Apache v2.2) drives the Web front-end to ReLOAD and manages remote connections to a central database. The database (MySQL v5.0) is used to

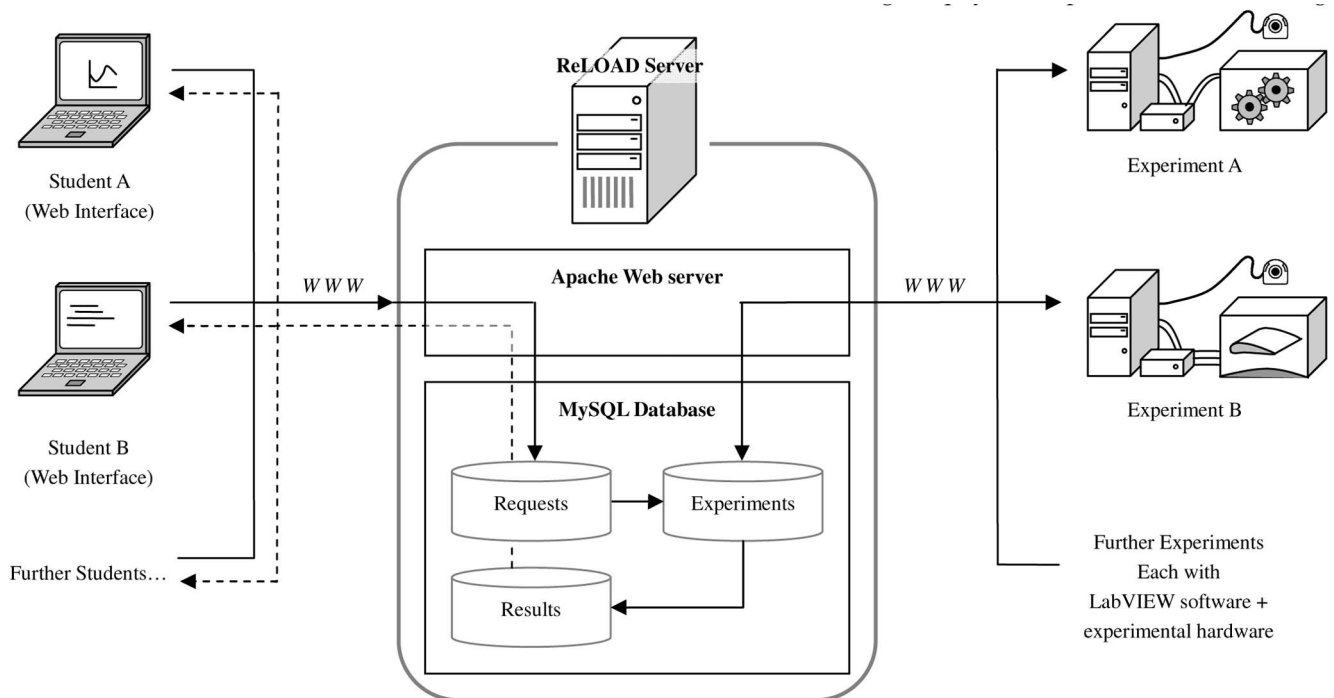


Fig. 4. Overall architecture of the ReLOAD remote-operated lab system, showing connections of multiple students to multiple items of computer-controlled experimental hardware, with communication over the Internet.

maintain the status of the system including a list of currently active experiments, queues of pending experimental requests, and experimental results to be returned.

The database provides each user with a personal profile that provides access to previous results and a customized list of experiments relevant to them. The process of conducting an experiment is described in the following section, but will result in numerical parameters being entered into a Web page which submits the information to the ReLOAD database via the Web server. To manage multiple requests from multiple students, each experiment has a queue which is processed sequentially.

Experiment PCs are controlled using LabVIEW (National Instruments, Austin, Texas), a widely used software environment which provides a powerful and rapid means of developing measurement and control applications. A generic ReLOAD-Link program coordinates communication with the server, and invokes experiments as and when requested. The experiment PC advertises to the server the experimental apparatus it is controlling which is then used to maintain the list of currently active experiments. Thus, the experiment PC is in control of running the physical experiment and recording relevant results to a file on the local machine. These results can be individual values, graphs of data varying over time, images, or any other form of digitizable data. In particular, for dynamic experiments, a Web cam is often used to record the motion of the experiment, saving a short video clip to file. The experimental data are then returned via the Web server.

Communication with the ReLOAD server is via an HTTP web link. This standard is pervasive and enables experiments to be easily deployed in a multitude of different environments, secured behind firewalls/proxies and even make use of mobile Web connections. In the event of an equipment malfunction (e.g., a power cut to an experiment PC), the experiment is automatically removed from the list and the support team is alerted.

3.2 Typical Operation of a Remote Lab

There are four sections to the ReLOAD Web site: a Visitors section for general information including an interactive demonstration, a Students section for users from the University of Leeds, a Guests section for users from other institutes, and a Staff section for tutors. A specific example of a vibrating-beam experiment is described elsewhere [17]; the general operation is described as under.

3.2.1 Lab Protocol

Prior to running a lab, the teacher will decide on the lab protocol, and produce explanatory notes and instruction documents. These are typically presented and discussed in class, and are also placed on the ReLOAD Web site for reference. The students may already be somewhat familiar with the actual laboratory equipment since it is displayed prominently within the department. In some cases, the students are introduced to the laboratory apparatus in real life with a demonstration before they commence their online tasks. This scheduling flexibility may enable the theoretical material presented in lectures to be more closely linked to the laboratory experiments, increasing the students' immersion in the concepts being taught.

A list of student names is used to create individual usernames and passwords for each student, allowing them to

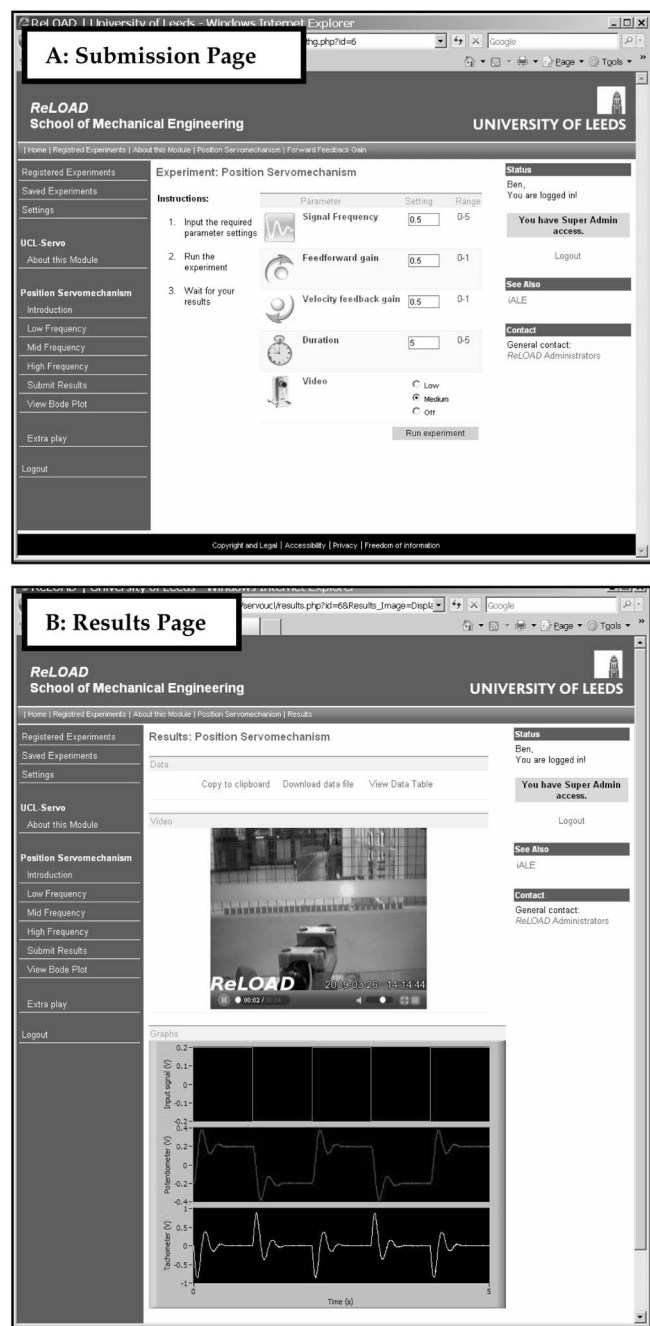


Fig. 5. Screenshots of the ReLOAD Web interface. (A) How experimental parameters may be entered. (B) Typical results with graph, video clip, and links to download results

log in to personalized experiments as defined by the tutor. Operational parameters for the experiment may be defined by the tutor for each user beforehand (and may be hidden from the user), or the tutor might ask that students design the experimental protocol themselves, choosing their own parameters, as appropriate. An example Web interface is shown in Fig. 5A. The student will then click a "submit" button and the request is processed and the real experiment is conducted at a remote location, as described above. When the experiment is complete, results are returned to the student's Web page. The delay in returning will depend on the duration of the experiment and the number of students attempting to operate it at the time. The experiments in dynamics typically have a

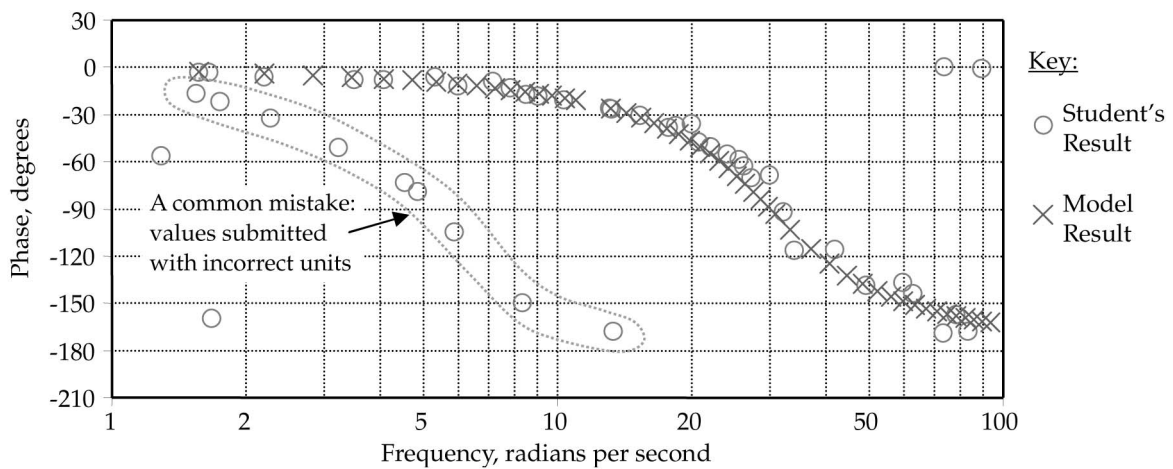


Fig. 6. Example results from a whole lab class. Compiling every student's result produces an overall plot of a system's behavior, which would not be achievable by one individual student.

quite short duration of 5-20 seconds, and the students very seldom have to wait for more than 30 seconds.

An example of the results returned is shown in Fig. 5B. The numerical results data can be downloaded in a number of formats, the most popular being a preformatted Microsoft Excel worksheet. From this data, users are able to take relevant measurements from the experimental results and/or perform mathematical analysis, as required, for the class assignment.

3.2.2 Students' Submission of Their Findings

Having conducted a number of experiments to gather data, a student's calculated or measured results can then be submitted by the user back to the ReLOAD database directly, online. The numerical values resulting from their calculations are entered in text boxes within an online form. When submitted, the form is then processed for errors using PHP scripts and, on satisfactory input, the data is stored in an MySQL database.

3.2.3 Assessment of Student Performance

In the Staff section, class group results can be displayed in tabulated and graphical form and various analyses and assessment functions are available. The tutor may choose to assign a mark to each student manually, but several automated processes are also available. Knowing each user's experimental parameters, a quantified grade can be calculated by comparing their values against a "model" answer, which could optionally be verified by rerunning the experiment using the same parameters. In assigning a grade, the tutor may choose to vary the emphasis placed on any particular part of the assignment.

3.2.4 Feedback to and From Students

A popular function of ReLOAD is the ability to provide immediate, quantified feedback to the students on their performance. If an automated marking scheme is applied, the student can receive a grade immediately, and depending on the experiment, an option may be provided to display a combined graph showing a user's own data points (highlighted in one color) compared to their peers (all in a second color to provide anonymity). This facility can be used to provide formative feedback that is targeted and

timely; the potential educational benefits of this are discussed later in Section 4.8.

Evaluation and feedback are also collected from the students via online questionnaires which users are encouraged to fill out before they see the peer group results. The questionnaires take the form of a number of "tick box" response questions and a freeform text box. Results from the evaluation are anonymized prior to being returned to tutors via simple tools available in the Staff section. As well as facilitating the teacher's development of the lab, asking for feedback can make the students feel valued (increasing motivation), and the feedback process can make them reflect further on their exercise.

3.3 Collaborative Learning Mode

As well as being able to provide individualized experiments, remote operation has facilitated online collaboration for a whole class of students. As an example, we will consider an investigation of a motorized servo-positioning system, as shown in Fig. 3. The highest priority learning outcome was that students were able to observe the features of the response of a real-life servo system at a wide range of input frequencies (example responses at two different frequencies are shown in Fig. 1). However, in order to capture such a complete representation of the servo system's performance, a student would have to repeat measurements at perhaps dozens of frequencies. This would not be an efficient use of their time and would distort the learning outcomes as the student would be spending a disproportionate amount of effort measuring values from the traces, rather than thinking about the theory.

With a class of several students, there was an opportunity for collaboration, where the individual results are compiled to construct a complete "frequency response" of the servo system. Some of the combined students' results are shown in Fig. 6. Compared to the "model" results, errors can be clearly picked out. In a number of cases, a "common mistake" is identified and is illustrated in the figure. These common mistakes can be easily identified by an automated grading routine which could therefore provide that formative feedback immediately to the student. A planned future development is for cases where if a student's results

are badly wrong, the student could be presented with a button to request help from the teacher.

Once they have submitted their own results, students were then able to view the cumulative graph of all results submitted so far. They could thus compare their performance against that of their peers, providing useful feedback of their relative performance in the class. The remote system enabled students to assess their relative performance in private, without fear of being embarrassed in front of their peers; this could be beneficial for the motivation of students, and hence, their engagement with the subject. Students could then revisit the compiled results graph to see how the data submitted by the whole class built up to form a complete frequency response. The students were also able to see the types of mistakes made by their classmates and learn from these mistakes without individual students suffering any embarrassment.

At the same time as protecting the self-confidence of less-able students, the more-interested students had unlimited opportunity to investigate the system in depth, without feeling restricted by time or by fear of making embarrassing mistakes.

3.4 The Students' Experiences

Providing the students with an online feedback questionnaire has provided the authors with data that have been invaluable during the development of the ReLOAD system. We have also used the outcomes of focus group interviews conducted by the independent Royal Academy of Engineering since March 2008: Groups of five to six engineering students at the University of Leeds, the University of Manchester, and the University College London (UK) were interviewed in an informal setting; a facilitator asked open-ended questions on the students' experiences with hands-on labs and remote labs. Interviews were recorded and later transcribed. Over 50 students have been interviewed to date. We present some of the numerical results here, with verbatim quotes from the interviews.

Including a video clip of the experiment was primarily done to demonstrate the behavior of the physical system and to allow the students to relate the results graphs to real dynamic behavior. The video also seemed to have important benefits for student motivation and engagement, with the results below indicating that they are linking the online presentation of results with the real physical hardware.

Q 6. I am convinced the data I received is from a real experiment and not just a simulation.

| Agree strongly | Agree | Disagree | Disagree strongly |
|----------------|-------|----------|-------------------|
| 28% | 72% | 0% | 0% |

Q 7. Being able to see a video clip made the experiment appear more realistic.

| Agree strongly | Agree | Disagree | Disagree strongly |
|----------------|-------|----------|-------------------|
| 46% | 51% | 0% | 3% |

The questionnaire result shown below indicates the students appreciated being treated individually. This has

very positive implications for motivation and engagement, discussed in Section 4.6:

Q 3. I liked having my own personalized experiment on ReLOAD.

| Agree strongly | Agree | Disagree | Disagree strongly |
|----------------|-------|----------|-------------------|
| 44% | 56% | 0% | 0% |

The students unanimously appreciated the 24/7 access, confirming this widely published benefit of remote access labs. The ReLOAD system logs show evidence of its use during all 24 hours of the day.

"I live a long way from Uni... I was using it between lectures."

"It was nice being able to do the work when you wanted."

To date, we have chosen not to prescribe that the students specifically conduct the lab on their own, or in groups; instead, they may choose to work alone or in groups to suit their own preference.

"I worked with my housemate who was on the same course, that was really helpful"

"It really helps to bounce ideas off each other"

We have found significant differences in the students' preference:

"...when you get it right it is just awesome, I get really geeked out when I get things right without any help"

"[to] have the instructors there in the lab that can answer your questions, that helps a lot"

Thus, the remote lab can provide flexibility in learning style, and is not necessarily more "prescribed" than a hands-on lab; this reinforces the conclusions reached in Section 2 when comparing remote and hands-on labs. The focus group interviews also canvassed opinions and experiences with hands-on labs for comparison with the students' experiences with ReLOAD:

"In real life things go wrong and you don't get to learn that experience if you just use [the remote lab]"

"[the hands-on labs] are not teaching us the engineering as we do not get the opportunity to play with the equipment and take it to extremes"

Despite the traditional views that "real" hands-on labs must offer a better learning experience, we encountered a surprising number of negative experiences described by the students:

"...you go into the lab with the focus being on the assessment and because of that you are not really thinking about the engineering side of it, you are just thinking 'I need to get written down what I need for my lab report'"

"...having to set it up and then being frustrated that it didn't work"

"As an engineer do we need to operate all the kit in a workshop?"

"Trying to cram everything into two hours is too much concentration and stress"

These frustrations could distract the students from their learning, thus decreasing their engagement and motivation.

To avoid this, care is taken to ensure that the online experiments run smoothly and that students' tasks are clearly defined. The questionnaire results below indicate that the students using ReLOAD generally found the remote lab comprehensible (note: despite the absence of teaching staff/demonstrators).

Q 2. Compared to other "hands on" experiments I've done, it was easy to understand the ReLOAD experiment.

| | | | |
|----------------|-------|----------|-------------------|
| Agree strongly | Agree | Disagree | Disagree strongly |
| 33% | 59% | 5% | 3% |

Q 4. Analyzing the data downloaded from ReLOAD was straightforward.

| | | | |
|----------------|-------|----------|-------------------|
| Agree strongly | Agree | Disagree | Disagree strongly |
| 46% | 51% | 0% | 3% |

The continued refinement of the ReLOAD system through student feedback has resulted in a set of online laboratories that are well-liked by students and teachers. For the final section of this paper, we consider how some of the attributes of remote operation can be specifically exploited to improve teaching and learning.

4 CHARACTERISTIC PEDAGOGICAL PROPERTIES OF REMOTE LABS

4.1 Accessibility

Remote access offers tremendous benefits for those students who are physically unable to attend a conventional laboratory (due to limited mobility or other medical restrictions, for example). Furthermore, in many cases, the process of automating an experiment for remote access—removing the need for human operators—results in an experiment that can be accessed 24 hours a day. This provides further support for students who are unable to attend a particular timetabled lab session due to other commitments, for example, childcare, or religious holidays. Read et al. [19] presented evidence of students accessing the Leeds University ReLOAD lab from many different countries, during religious festivals and at all 24 hours of the day.

In traditional labs, it is generally not possible for students to return to repeat data measurements if they realize later that they have made a mistake. Remote access can provide the opportunity to repeat whenever necessary, and hence, imposing less pressure to record data correctly within a given time frame. This is seen as beneficial by many students: flexible access provides them freedom to carry out work at their own pace, fitting the different learning styles identified in their interview responses previously. This access mode may be less suitable for students who are poorer at governing and planning their study time; however, if that is a concern, it should be remembered then that remote labs are equally capable of running on a time-restricted, strictly scheduled timetable just as with hands-on labs, and that the students' individual access logs can be observed by teachers, if required.

If the remote lab is based at a different institution, then the students will only have remote experience, but if the equipment is local, then a mixed-access-mode approach can be used. As mentioned in Section 3.2.1, for some ReLOAD experiments, the students are able to see the real equipment in action, and then, later have the freedom to access it whenever they choose. Thus, they experience some of the benefits of both access modes.

4.2 Standardization, Quality Assurance

In recent years, there has been pressure from governments and student organizations to increase standardization of teaching. Within Europe, this has manifested, for example, as the "Bologna Process" which aims to standardize the higher education experience within the EU. Remote operation of some labs could address this issue, providing disperse student groups with access to the same items of equipment and learning experiences.

In general, homogenizing the students' experiences is not viewed in a positive light by educationalists [20] who feel that education is a personal process of development, and that a learner's motivation is dependent on their feeling individually recognized and valued [21]. If remote labs are applied arbitrarily, the learning process could suffer. However, that is by no means necessary, and if used appropriately—as frequently reported in the literature—student motivation and interest have been maintained and often increased through the use of remote technology. As demonstrated in the previous section, the student's individual login IDs on the remote lab system can be readily used to personalize their experience, with positive outcomes.

4.3 Human Interaction

While students are physically separated from the laboratory, that does not necessarily mean that they must perform the experiment in isolation. Remote delivery affords several strategies for learning environments. The physical environment might be an informal dorm room or Internet café, but it need not be: remote labs can still be conducted in a classroom equipped with computers. Compared with hands-on labs, there is greater scope for variation of the psychological environment: the degrees of the virtual presence of peers and of teachers are controllable factors, through optional provision of online chat rooms, email support, or even video links.

In traditional hands-on labs, various ratios of student: apparatus:teacher are encountered, depending on the total number of students, the nature of the experiment, and the resources (time, financial, space, and staffing) of the institution. Therefore, unfortunately, the teaching environment is frequently determined by logistical and resource limitations instead of educational requirements. The ReLOAD case study has shown that students have the option to select a working mode that best suits their learning style, be that working alone or in small groups in a computer room. This flexibility has been seen as advantageous in supporting the needs of increasingly diverse cohorts of students where peer group dynamics can impinge on individual learning [19].

4.4 Collaborative Learning

Section 3.3 presented an example of collaborative learning that was enabled through remote operation. The authors envisage that one of the most important uses of remote

operation will be to provide large groups of students with access to large, expensive items of equipment. Institutions inevitably have to be selective in choosing which experimental apparatus to purchase and maintain on-site, but remote access offers the possibility to share equipment between institutions, as demonstrated by the ReLOAD case study.

As mentioned, the nature of collaboration between students can take many forms including personal face-to-face discussions, Internet chat rooms, or telephone communications. We have so far left the choice up to the individual students; however, the opposite case is also possible: the students' working mode can be enforced, if that is deemed suitable. Read and Sarmiento [22] presented a pedagogical technique to develop modern communication skills by requiring that groups of students only conducted their meetings online, in a professional manner.

4.5 Control of Learning Outcomes

Prior to running a hands-on lab, it is necessary to ensure that the starting conditions for the equipment are always returned to a consistent state, as far as possible. Depending on the laboratory in question, many experimental setups will have their own peculiarities and teachers might be familiar with explaining "Where the lab instruction sheet says 'connect the blue wire' instead you should connect the red wire." These realities are a nontrivial, valuable part of the student's overall experience, and following conclusions from Section 2, the most appropriate lab delivery method should be selected depending on the desired learning outcomes. However, the practical nonidealities should not be allowed to interfere with the designed learning outcomes to avoid frustration and distraction of the type reported by the students earlier.

Magin and Kanapathipillai [3] report of a degree course which has completely separated the teaching of practical lab skills into a year-long module "engineering experimentation" to ensure that students have hands-on experience. This option may not be suitable for other degree courses though, where lab experiments are often more closely linked to the understanding of theories and would benefit from being delivered concurrently.

4.6 Motivation of Students and Teachers

While well-planned labs can be enjoyable and engaging, there are undesirable aspects to hands-on labs that were described during focus group interviews which can be stressing, demotivating, and counterproductive for learning.

Elton [21] recommended that to enhance the intrinsic motivation of students they should be:

- "Treated as individuals;
- Expected to show individuality, originality, and creativity;
- Allowed choices and preferences in their learning;
- Allowed to negotiate the means by which they are assessed."

These recommendations were made several years before remote labs became available; however, each point is certainly attainable using remote access: the ability to individualize experiments has been reported [17], as has the provision of choice in their learning method [19]. Any experiment can promote motivation of students through these routes, if it is thoughtfully designed in the first

instance and then kept up-to-date. Maintaining course materials for a remote lab in an up-to-date state can be easier than a hands-on lab, since:

- Updating apparatus and instruction documents only needs to be performed once (as opposed to many duplicated sets of apparatus)
- The 24/7 accessibility offers increased opportunity for a teacher to test and update the protocol.

It is quite possible that the popularity with students of the ReLOAD labs is due to the considerable effort made by developers and lecturers to design the experiments, the course material, and the feedback questionnaires. The successful running of the experiments is continually investigated in detail, including student feedback from the online questionnaire, and work has been published throughout. Thus, the delivery of this lab features an unusually high level of reflective practice [23].

In this case, the development and use of remote labs cannot be seen as an easy option compared to sticking with the traditional lab, raising the question: why do the creators of the technology go to all that effort? It could well be the case that the remote lab increases the motivation and engagement of the teachers as well as the students. By facilitating the reflective cycle, as described above, the technology could be said to encourage the teacher to take an interest in investigating the process, evaluating the students' learning, and even publishing the results. This can be viewed as an example of teaching and learning being integrated through the common theme of "enquiry," as described by Rowland [24].

4.7 Student Independence

The degree of control provided to a student will influence their motivation, and it will fundamentally affect their learning. With a tightly prescribed laboratory protocol, students may simply follow instructions robotically and gain very little deep understanding. Conversely, open-ended structures allow more-interested students to investigate to a deeper level, and to learn about effective experimental design.

In some ways, remote labs are more prescribed—for example, students cannot accidentally connect up the apparatus incorrectly. Also, the lack of the immediate presence of an instructor (in some cases) could mean that written instructions have to be more specific. However, in other ways, remote access provides much greater freedom to explore: to make mistakes without embarrassment, to repeat experiments and to proceed at their chosen pace. Once the students have carried out the "core" tasks, presented in a straightforward manner, they are free to investigate further to their own satisfaction, either on their own or in discussion with peers. This differentiation was viewed positively by students using the ReLOAD system and it is further suggested that this additional freedom could be exploited to develop the students' skills in critical thinking and experimental planning, helping to increase the research element of laboratory work.

4.8 Reflective Cycles, Formative Assessment

The traditional method of providing feedback on students' performance in a laboratory has been the submission of reports which are then graded and returned. Apart from the

time required to grade these reports, there exists a necessary further delay in that no reports can be returned until the whole class has completed the laboratory (some schedules can run over months). This severely limits laboratories as a tool for providing formative feedback within a course, impinging on student learning and motivation [25]. The ReLOAD case study demonstrated that assessment of remote labs can, sometimes, be performed automatically, allowing immediate feedback [26] which can be used formatively or summatively.

Laboratories are often used to demonstrate theoretical concepts in practice. To link theory and practice, the student should have access to theoretical material while carrying out the experiment; here “access” means physical access to books and notes, and also cognitive access—that the relevant concepts are “fresh in the mind.” Due to scheduling restrictions of hands-on labs, it is often not possible to coincide the teaching of a particular concept with the relevant laboratory. This can lead to the laboratory work being seen as conceptually separate from the theory. In contrast, the ReLOAD system has enabled students to operate experiments much nearer to the time of the relevant lecture.

The more flexible access options afforded by remote labs mean that students are able to learn in reflection cycles: referring to the theory, performing an experiment, and comparing and then repeating this cycle, as required. They can even return to the experiment while writing a report, for example, to check a particular detail or verify an unusual/unexpected result.

The experiences above suggest that remote access could, in some cases, promote deeper, better-linked understanding, and make more effective use of the laboratory experiment.

5 CONCLUSIONS

There are fundamental differences between hands-on and remote labs, beyond the mere format of their interfaces, which result in differences in the learning experience, and for this reason, remote labs should not be directly substituted like-for-like for hands-on laboratory work.

Nevertheless, the only *necessary* difference between hands-on and remote labs is the physical separation of student and apparatus. Other differences and similarities in the student’s learning experience can be controllable factors, to greater or lesser extents. Remote labs have the potential to offer some valuable educational advantages if, like any other teaching technique, they are used appropriately within the curriculum (and not advocated purely on a cost-saving basis, for example).

The authors have experienced several specific affordances provided by the remote laboratory format:

- Personalized experiments;
- Collaborative work
 - Ability to learn from peers’ results
 - Anonymity, if so desired;
- Flexible access (often 24/7);
- Immediate feedback, which can be either
 - Purely formative
 - Assessed;
- Flexibility of learning environments;

- Physical environment
- Social environment.

We suggest that these can be exploited to promote:

- differentiated learning;
- deeper learning (for more-interested students);
- greater student control of their learning;
- more inclusive, accessible teaching environments;
- better linking of practical and theoretical work.

Since each educational discipline and course will have its own learning objectives, with different priorities, the incorporation of the technology will have to be tailored to each specific laboratory. The “best practice” is to recognize that there is no universally suitable approach to the use of remote labs. We suggest that the means to ensure the labs are applied appropriately is “reflective practice” [23]: the practice of continually evaluating and reflecting on features of the course which are successful, and those which need addressing.

The largely successful use of remote labs published in literature to date may be due to the high prevalence of reflective practice adopted by teachers. Publications on the subject are indicators that the novelty of the technology has engaged the teaching staff to the extent that they are motivated to research and investigate the students’ learning. The ReLOAD project has produced international collaborations between institutions, in-depth discussions and theorizing of best educational practice in consultation with large numbers of students, and has increased accessibility to high-quality laboratory equipment, which has been of measurable benefit to those involved.

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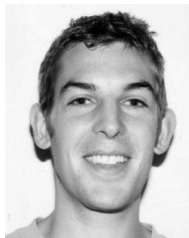
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