Remote laboratories in teaching and learning – issues impinging on widespread adoption in science and engineering education

Remote laboratories in teaching and learning – issues impinging on widespread adoption in science and engineering education

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***Abstract*— This paper discusses the major issues that impinge on the widespread adoption of remote controlled laboratories in science and engineering education. This discussion largely emerges from the work of the PEARL[1] project and is illustrated with examples and evaluation data from the project. Firstly the rationale for wanting to offer students remote experiments is outlined. The paper deliberately avoids discussion of technical implementation issues of remote experiments but instead focuses on issues that impinge on the specification and design of such facilities. This includes pedagogic, usability and accessibility issues. It compares remote experiments to software simulations. It also considers remote experiments in the wider context for educational institutions and outlines issues that will affect their decisions as to whether to adopt this approach. In conclusion it argues that there are significant challenges to be met if remote laboratories are to achieve a widespread presence in education but expresses the hope that this delineation of the issues is a contribution towards meeting these challenges.**

***Index Terms*— Educational technology, Remote sensing, Remote control, Science education, Engineering education.**

I. Introduction

The author led a major European Union funded project on remote controlled teaching experiments, PEARL[1] that concluded in July 2003. This project developed four remote experiments in the fields of foundation level science (basic chemistry and physics), biochemistry (electron microscopy); manufacturing engineering (automated visual inspection) and electronic engineering (analogue and digital electronic design and test). These were then evaluated in real educational contexts. The details of these developments are not described here but have been fully reported elsewhere [1], [2], [3]. This paper draws on the experience and results of the PEARL project and reflects on developments in the field since then and discusses the key issues that have to be addressed if this approach is to be widely adopted in education. This paper deliberately does not discuss the technical issues of realizing remote controlled experiments but expounds those issues that impinge on the specification and design of the experiments and the way they are offered remotely. These must be understood so that the technology serves the teaching and learning in its context.

In this paper the terms 'remote laboratories' and 'remote experiments' are used interchangeably; 'experiments' means teaching experiments and is used interchangeably with 'practicals'.

II. The Rationale for Remote Experiments

In the first phase of the PEARL project a review of the literature on engineering and science education and a survey of educators in these subject areas within the four universities participating in the project were undertaken. This work is available in public deliverables of the project [4], [5] and has been summarised in previous publications [6], [7]. This confirmed that experimental work is a vital part of science and engineering teaching at all levels. There were no dissenting voices from this. However there was debate about whether the current provision of practical work best served the educational objectives of the courses reviewed. Criticisms included that many teaching experiments had not been updated for years, that there was insufficient provision of up to date equipment for the students to use and insufficient space within teaching establishments to provide adequate practical work for the student numbers. In summary practical work was highly valued by educators and professional bodies accrediting courses but there were significant challenges in many institutions in making adequate provision of practical work for their students. Central to this challenge is the issue of access to practical work.

A. *The access rationales*

The provision of remotely controlled experiments accessible over the internet or campus intranet can potentially address the issue of access to practical work in a number of ways:

- By giving access to experiments over a longer time frame and at times preferred by students
- By sharing expensive resources between institutions
- In giving access to safety critical and expensive equipment with reduced risk
- By offering improved access for disabled students
- By facilitating greater access to experimental work in distance education

Making experiments accessible remotely creates an opportunity for educational institutions to make laboratory

[1] Practical Experimentation by Accessible Remote Learning, EU project IST-1999-12550. See http://iet.open.ac.uk/PEARL

work available to students out of normal office hours. Whether 24 hour, 7 day a week access is cost effective mostly depends on decisions about whether tutor feedback synchronously with the experiment is deemed pedagogically important and whether technician support at the remotely accessed laboratory is required. The remote digital and electronics design and test facility developed by FEUP[2] in the PEARL project was made available for students to book online at anytime. It was frequently accessed by students during the night hours and they reported that they preferred this to fit round other work and study commitments.

The remote control of an electron microscope achieved by the University of Dundee within the PEARL project is an example of an expensive facility that by being remotely controlled can be shared between institutions. It further exemplifies where safety constraints could readily be achieved. This was done by only offering the students control over the features of the microscope that they needed to undertake their tasks and not those features that required specialist training and that could be potentially damaging to the equipment if misused. If students were physically present with the microscope they could accidentally or maliciously cause damage. It should be noted that technician support physically with the microscope was a prerequisite for this facility and they were responsible for these other controls, which were only needed at the set-up stage.

Disabled students are grossly underrepresented in science and engineering disciplines at university level. The reasons for this are complex and include significant factors from primary and secondary level education. However access to experimental work is identified as a key barrier in analysis of this problem both in North America and Europe. Much work has been done over the last 30 years in making the computer accessible to disabled people. Virtually anyone, irrespective of disability can be enabled to use a computer. Thus if experimental work is computer controlled it can be made accessible to disabled students in a fully participatory way. If the experiment is computer controlled it is largely immaterial whether the computer is located with the experimental apparatus it controls or remotely. Access for disabled students can thus be promoted provided the interface that mediates the remote control is accessible (see section V. B.). Remote experiments also offer a possibility of overcoming problems of physical access to the laboratory that may exist in certain premises or facilities for some disabled people.

In distance education, traditionally experimental work has been offered by simple "home experimenter" kits and intensive residential schools. 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 then most of the practical work associated with a particular course has to 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.

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In considering the access rationales it is important to remember that when implementing remote experiments one is seeking to give access to the learning experience not primarily the remote apparatus. Thus how the student is guided though the experiment, how encouraged to reflect on what they are doing and observing, if and how they can access a remote tutor and collaborate with remote peers are key issues that need to be addressed if the access rationales are to be justified.

B. *A pedagogic rationale*

The core pedagogic reasons for wanting to offer students remote controlled experiments as part of their courses are those of wanting to include practical work generally and these are discussed in section III. A. However there may be additional pedagogic reasons for wanting to do this remotely. One view of the role of practical work is that it is important in introducing students to the world of scientists and engineers in practice, often referred to as the community of practice by educators [8]. Today the reality for many professional engineers and scientists is that they work collaboratively mediated by computer. This may also include the remote control of equipment. Remote controlled experimental work, so long as it is undertaken by pairs or small teams of students, provides an excellent context for developing remote collaboration skills that will be important in their future careers.

III. PEDAGOGIC ISSUES

Having established a set of rationales for why one might want to include remote experiments in a course or programme of study this section discusses the pedagogic issues that impinge in the detailed selection and design of such experiments.

A. *Importance of Learning Objectives*

Clear learning objectives for planned remote experiments need to be established from the outset. This may seem an obvious statement but objectives for practical work can be diverse, as discussed below, and are often not well delineated. However these objectives directly inform decisions about:

- What experiments are chosen to offer remotely
- Interface design
- Scheduling within the course
- Implementation compromises
- Accessibility accommodations
- Collaboration tools
- "Scaffolding" for the experiment (e.g. on-line tutor, multimedia documentation, online help, etc.)

Different educators have researched the reasons for the inclusion of practical work on courses [9], [10] and have variously categorized the aims of practical work. Building on the two cited works it can be stated that practicals are often included in courses for the following groups of reasons:

(a) to illustrate the principles behind a subject using experiments that introduce, illustrate or reinforce concepts and theories taught in other parts of the course, thereby acting as a focus for reflection;

(b) to enable the teaching of procedures or skills training, and to teach skills in experimental design, planning, observation, data analysis;

(c) to introduce students to the world of professional scientists and engineers (sometimes called the community of practice by educators),

(d) to provide a focus for student-student and student-tutor interaction;

(e) to motivate students, with the premise being that practical work can be important in influencing the development of positive attitudes to the subject;

(f) to familiarize students with the use of important instruments, equipment, and techniques such as the use of a microscope or an oscilloscope.

Some general comments are offered here about the validity of remote experiments and the issues for their design against this classification of objectives. Remote experiments can certainly be used to meet the objectives listed against (a) but if this is the sole objective then the question has to be asked is there a more cost effective way of achieving the same objective based on simulation or another interactive multimedia application?

The objectives in (b) can be achieved in remote experiments. The case of skills training depends a lot on what the skills in question are. Manual manipulation skills are particularly problematic to achieve in a remote experiment and this may have a big impact on the decision on what is offered remotely. However many relevant areas of skills training are readily offered in a remote experiment. In the early stages of the PEARL project an approach was considered that would enable students to have significant impact on the design of experiments in a remote laboratory by configuring apparatus. This was set aside as being overly complex for the then state-of-the-art. However even given a fixed remote apparatus a range of experiments can be achieved, parameters changed and thus opportunities for students to undertake experimental design created. The requirements for observation will dictate the design but is rarely a fundamental barrier. Remote experiments offer an excellent context for collecting real world data for subsequent analysis. Indeed some approaches in this area extend what is possible in the face-to-face lab by remotely collecting data from multiple distributed sources. A common example finding increasing interest at school level is collecting data from multiple remote weather stations and using these as a context for teaching analysis and graphing techniques.

The case for the role of remote experiments in introducing students to the community of practice and thereby meeting the objectives labeled (c) has already been made in section II. B.

Remote experiments can provide an excellent focus for both student-student and student-tutor interaction, the objectives given against (d). However decisions about how experiments are organized and what communication tools are used to facilitate these interactions are of key importance to how effectively this is achieved.

The PEARL evaluations yielded some interesting perspectives on this issue. Ahead of the evaluations some of the educators associated with the project anticipated that students working remotely may miss the sense of being part of a larger group doing practical work together but no evaluation subjects reported this. Indeed a few reported the converse with the major advantage of the remote experiments identified by one subject being the ability to work more individually, *'Because I'm not very good in groups of people.'* She preferred working remotely in a pair from a room of her own because *'I think when there's a whole group of people doing the same thing you feel more pressurized to go at their speed. … It's just you and the person you're working with here isn't it?'*.

In the case of the PEARL experiment using an optical spectrometer hosted by the Open University a direct comparison was made between students undertaking the same experiment face-to-face at a residential school and remotely. When asked about their tutors the residential school students were overwhelmingly positive. The tutors were *"excellent"*, *"very enthusiastic and patient"*, and *"very good at explanations of the equipment"*. The PEARL students were positive but more measured. The tutor was certainly needed and the students were reassured by his presence. It seems the tutor continued to fulfill his technical support/guide role in the remote activity but was no longer in a position to communicate their *"passion for their subject"* as they did to the residential school students. The tutor, in fact, played a very different role in the two cases. Residential school tutors are very proactive, keep a close eye on students' progress, and engage them in dialogue to monitor and assess their progress and understanding. In contrast, the PEARL tutor generally only reacted to queries raised by students in the text chat facility provided. In this case he was located with the remote laboratory but unable to monitor students' progress by sharing their interface view or listen in to their audio dialogue. Technically both of these would have been possible and the desirability of these facilities and different modes of remote interaction between students and the tutors needs careful consideration in designing remote experiments.

Student motivation (e), was one of the specific aspects looked at in the evaluation work in the PEARL project. Students in each of the four universities and in the cross-institutional evaluation undertaken in PEARL were positive about the remote experiment experience. They completed or came near to completing the experimental tasks, made observations, processed data, etc. Where comparisons were possible these were roughly equivalent to the experiences of students in the face-to-face laboratory. There was however some frustration reported by students in the sessions due to lack of control or delays in feedback (for example from remote tutors).

Familiarizing students with important instruments was a key objective of three of the four PEARL experiments. This is more readily achieved when the instruments have interfaces that can be directly replicated remotely. This was certainly the case with the oscilloscope and the controls to the electron microscope. Although even in the case when an optical spectrometer, normally operated manually, was motorized for remote control and mediated to the students buy a bespoke computer interface, most students felt they had been introduced to new equipment and some were confident in being able to use the equipment in the future if they met it in a laboratory. Thus in many cases but not all the objectives grouped against (f) can be achieved in remote experiments. This impinges on the decision as to whether it is appropriate to offer a particular experiment remotely.

B. The virtual science versus remote real experiments debate

One response to the difficulty of providing adequate access to experimental work is the increasing use of simulations whether delivered online or on DVD/CD-ROM. These are often referred to as virtual science approaches but are as equally prevalent in engineering subjects. The author has argued since the conceptual thinking that led to the PEARL project that while simulation approaches have a valuable educational role they are not a replacement for much practical work [11]. Others have questioned why the objectives of the educational use of remote experiments cannot equally as well be achieved by simulations? "*Whether a remote laboratory or a remote simulation, it is all bits and bytes down the wire*".

The key challenge for the virtual science approach that is directly addressed by remote experiments is the issue of credibility. Through art and computer games most students today have extensive experience of virtual worlds realized in a computer simulation. They are fully aware that the laws of physics in these worlds, for example, can be very different from those we experience in the real-world. Thus they will, possibly only subconsciously, know that a simulation will behave as programmed and this may or may not be a faithful representation of the behavior it is seeking to model from the real-world. Thus a virtual experiment will not confirm or refute a hypothesis. This being said these approaches can be a good aid to understanding of complex ideas as an animated, interactive illustration and a focus for reflection but they cannot replace real-world experimentation in science or engineering education.

This view of the value of the distinction between remote and virtual experiments was confirmed in the comments of subjects participating in the evaluation of the PEARL project's developments. For example, some identified an advantage of the PEARL experiments as knowing that what they were doing '*was actually happening*'. They preferred this to using a CD-ROM '*I know it's hard to explain, but I know what I mean. When you're doing it on CD, its doing what it's supposed to be doing isn't it?*'. The students also stated that they wanted to be able to see any mistakes that were made and contrasted this with not being able to make mistakes in simulations they had used.

Remote controlled experiments have a particular advantage when real-world conditions are important to the learning. This could be where observations of non idealized data is important; where the subject of study is complex that would inevitably be simplified in a simulation and where simulation is not possible in real time because of limitations of processing power. Virtual science approaches have a particular advantage when being able to distort the natural laws enables difficult concepts to be illustrated. Examples of this include distorting time so that simulation of very rapid events can be observed (e.g. shock waves as an object goes supersonic) or events that occur over long time scales can be compressed (e.g. plate tectonics).

It is argued here that remote controlled experiments can bridge the gap in many cases between work in a laboratory and that which can be achieved with simulations. It thus provides an additional tool for educators to incorporate into the mix of educational experiences that make up a course. The decision about what is best achieved by remote experiments and what by simulation is primarily one that should be determined by the learning objectives as discussed above. Remote experiments give another "line of defense" where there are pressures towards the replacement of pedagogically valued experimental work with simulations, whether for economic, accommodation, modes of delivery, or other reasons.

IV. WHAT EXPERIMENTS TO OFFER REMOTELY IN WHAT CONTEXTS?

An informal review of the remote experiments reported at educational conferences since 2000 has shown a wide range of experiments that can be offered over the internet in diverse subject areas have been developed worldwide. However the field is dominated by the electronics engineering discipline. The author suggests there are two key reasons for this. Firstly many practical activities valued by educators in this subject area can be readily offered remotely based on established technologies. Examples of such technologies include LabView™ the remote instrumentation software from National Instruments and the various standard instrumentation busses developed primarily for the industrial test world. These are readily adopted in the educational context to offer remote access to instruments that the educators need to implement their practical work. Secondly educators in this discipline often have, or have ready access to, the technical skills needed to integrate the various technologies that enable the implementation of a remote experiment. Many remote experiments are still being produced "in-house" and major educational technology suppliers of systems for remote experiments are yet to emerge. This accentuates this bias towards subjects with educators with appropriate expertise.

The rest of this section looks forward to prospective remote experiments and highlights the areas for consideration by institutions and individual educators weighing the *pros* and *cons* of adoption of these in their courses.

A. Course Context

Teaching experiments do not sit in isolation but are integrated into the curriculum of a course and that course is usually further integrated into a programme of study leading towards a particular qualification. A big challenge to be addressed, if remote experiments are to move from isolated examples to being the means by which a significant proportion of practical work is offered across a programme of study, is that it is often difficult to do this by incremental development. Many of the advantages put forward for remote experiments (e.g. increased access to practical work) are not achieved if only one or two experiments on a course are offered remotely. However to move a course's whole programme of experimental work to remote delivery at one time will often demand prohibitively high levels of investment. Further the risks of not adequately achieving the remote delivery or the specified learning objectives are increased in such a "bigbang" approach rather than an incremental introduction where lessons can be learnt between successive implementations.

This challenge having been stated there are points of opportunity when introduction of remote experiments may be particularly apposite. For example, when a new course is being created or when the mode of delivery of a course is being changed. Recent years has seen a blurring of the distinctions between face-to-face and distance learning with many institutions now offering what is termed blended learning. This is in part associated with the increasing adoption of Virtual Learning Environments (VLEs) by what were previously face-to-face institutions. This evolution in the modes of interaction between the institution and its students and the increased investment in educational technology provides an opportunity for the introduction of remote experiments. It further sets a probable requirement that the remote experiments should be integrated into the institution's VLE. This was demonstrated in the case of the analog and digital electronics test facility developed in PEARL.

Remote experiments are not limited to any particular subject domain or curriculum and could probably be extended outside the science and engineering fields that have been the focus for this paper. However, in all the background research in PEARL, and in the workshops organised to reflect on the results of the project and the potential of the approach, it was the chemists that had most reservations. This was because they put a high value on developing good laboratory practice and manual skills (e.g. assembling of glassware) in the objectives for students' practical work and because the sense of smell (which is difficult to replicate remotely) was important to them. In determining whether remote experiments are appropriate in a given curriculum the role of experimental work needs to be examined in line with the discussion of objectives given in section III. A.

Most courses and programmes of study are accredited by professional bodies that oversee their subject area. Such accreditation in science and engineering subjects often makes detailed stipulations about the types of practical work students should undertake and the range of skills they should develop through this. Thus the introduction of remote experiments will impinge on accreditation and this may have to be the subject of negotiation between educational institution and professional body. The author is not aware of any specific cases of this to date.

B. Technical Realisability

The ease with which an experiment can be implemented so that it can be undertaken remotely has a major bearing on how readily the educational objectives can be achieved and the cost-benefit analysis discussed below. In general simple manual tasks are often complex to offer remotely and apparatus that is by design computer controlled is relatively easy to extend to remote operation. For example in the PEARL spectrometer experiment students in the face-to-face version undertook simple flame tests with various metal salts as a precursor to using the spectrometer. In the remote controlled version, after extensive consideration, it was decided to replace this with presenting the students with set of video clips of these flame tests being undertaken. This was in part a safety consideration but also because any robotic implementation of this task remotely was going to be unreliable and prohibitively expensive.

C. Cost benefits

Cost benefit issues were raised in all of the focus groups conducted towards the end of the PEARL project to enable educators outside of the project team to reflect on the potential of its developments. Some commented that if remote experiments were to cost them more than providing experiments face-to-face it would be very difficult for them to introduce them into their institution. Economic constraints are going to have a big impact on the future adoption of remote experiments. A cost benefit analysis is very specific to the details of a particular case and many of the benefits are difficult to quantify. A brief summary some key issues that will impinge on such an analysis is given here.

1) Student Numbers and Scalability

Student numbers are an important consideration in analyzing the cost-benefit of a remote experiment. For example the spectrometer experiment at the Open University is associated with its foundation level science course which is studied by most students who go on into the science degree programmes. This has typically 3000 students registered per year. The experiment typically lasts 4 hours. If we wish students to work in pairs to undertake the experiment within a 10 week period and say operated a remote laboratory 12 hours/day, 5 days/week, the minimum number of remote controlled spectrometers and associated apparatus required would be 10. In this case the prototype cost of the apparatus was about €30,000 each. Thus this represents a case where a huge initial investment would be required if the decision was taken to offer this experiment remotely to all students.

Conversely small student numbers can also lead to the situation where the move to remote experiments is prohibitive. This arises when significant investment has to be made in equipment which is only used for a small proportion of the time. However the very fact that the experiments can be conducted remotely potentially provides an amelioration of this problem. If the experiments are shared between institutions then they can be in use for a much higher proportion of the time and the costs can be shared. There are plans to create "grids" of online experiments from many institutions but the organizational problems in this approach should not be underestimated.

2) Tutor and technician support

The cost of apparatus may principally determine the capital outlay to introduce a remote experiment but it is the staff costs of tutor's and technician's time to support it that are going to be the major component of the running cost. These may then need to be compared with the corresponding costs for face-to face provision.

3) Opportunity Costs

The costs of introducing remote experiments do not sit in isolation but need to be compared with the alternatives. This may include the costs of providing multiple sets of new equipment for a face-to-face laboratory when fewer sets of apparatus would be necessary if the experiment was offered online on a 24 hour basis. Other examples would be the costs of overcoming accommodation problems or commissioning the development of a simulation package.

V. Usability and Accessibility

A. Usability

It is the user interface that mediates to the student the practical activity designed. The user interface needs to enable the student to carry out all the tasks and make all the observations that are necessary to achieve the learning objectives of the experiment. It is important that students focus on performing the activity rather than on the use of the software. In most cases the students will not have much time to learn to use the interface, and may only use it once to complete a particular experiment. Students will be provided with some instructions, but it is essential that the user interface 'affords' the purpose and operation of the controls. Thus a high priority has to be put on the interface design and its usability. Usability requirements need to be established at the specification stage of the development of remote experiments. Then the design features implemented to meet these specifications and whether they have successfully achieved this evaluated. It is important to note that usability is not just a function of interface design but may also impinge on the overall system design. For example some usability features may require particular feedback from the remote laboratory.

1) Issues of remote control over the internet

When remotely controlling equipment via the internet it is probable that there will be human perceivable delays between the issuing of a command at the user interface, the command being executed at the remote laboratory, and then seeing the result of the execution in the user interface. The actual delay will depend on the network configuration, bandwidth, routing, and traffic at the time; it is therefore unpredictable. This potentially creates a situation for control instability and user frustration. Consider the case when a student makes a command, believes erroneously that what he/she is observing is after the system has responded to that command and then executes a further command. This will often lead to the situation where the remote equipment does not perform in line with the student's expectations and it takes them longer to achieve their intention.

In response to this the PEARL spectrometer interface design included buttons, rather than knobs or sliders, to support students in making discrete commands and the system provided both visual and auditory feedback that confirmed when a command had been executed.

2) The importance of usability testing

The importance of usability testing in the development of remote experiments cannot be over stated. It provides insights into the way in which students will interact with the software and the experiment, which cannot be foreseen by developers or educators. This should be undertaken as soon as possible in the development cycle so that there is opportunity to amend the experiment design, the nature of the feedback from the remote lab, the interface design and the instructions to the student as necessary.

There is often a mystique around usability testing but simple observations of the performance of even a handful of students performing the experiment will provide useful feedback. They can be observed and the problems they encounter noted, and then be interviewed to get their opinions of the experience and to gauge to what extent the learning objectives have been achieved. The types of observation that yield useful feedback include:

- Where students make mistakes with the user interface (for example, click one button instead of another)
- Where students perform unexpected commands, or do things in an unexpected order
- Where students appear to be confused about what they should do next
- Where the information / feedback from the laboratory is not clear or confuses to the student
- Whether the students are comfortable using the interface, and whether it does what they expect it to, as they interact with it.

B. Accessibility

The argument that remote experiments can create greater access to the practical elements of courses for disabled students is predicated on the fact that the software that mediates the experiment has to be accessible to them. Software can be made accessible to nearly all users irrespective of any disability but this is only achieved by intent and design.

There are well established principles in how to promote accessibility in software design and electronic content [12], [13]. Then there are specific guidelines how to implement these principles in different programming languages. The various accessibility features that were built into the PEARL client software for the spectroscope are listed and briefly described below. This was implemented in JAVA and it was the JAVA accessibility guidelines that informed the implementation issues here [14], [15], [16].

1) Inheritance of Windows properties

Some disabled users require or prefer specific settings within the operating system in order to use the computer. For example, people may require certain colour combinations, font style and size, or to use utilities such as StickyKeys[3].

2) Text labels on all controls

The screen-reading software used by visually impaired users for speech output requires all user interface elements to have text labels which can be read out.

3) Keyboard operable

Many disabled users cannot or prefer not to use a mouse and therefore need to be able to operate all user interface elements via the keyboard. The PEARL application provides two methods of keyboard operation. The Tab and Enter keys respectively can be used to navigate between, and operate, the controls. In addition, keyboard shortcuts enable the user to operate all controls quickly by reducing the need to navigate between controls.

4) Reminders of shortcuts included in labels

Users are supported in learning the keyboard shortcuts with the inclusion of the shortcut in the label of the control.

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[3] StickyKeys is a function provided in the accessibility options of most operating systems whereby functions that are normally accessed by simultaneous pressing of multiple keys can be achieved by sequential pressing. This is advantageous for some people with manual manipulation difficulties.

5) Auditory indication of command progress

To provide visually impaired users with feedback on the progress of commands, non-speech sounds are provided to acknowledge the system's receipt of a command, that it is being executed, and that it is complete. This information is also provided visually for other users in the form of progress bars located beneath each control.

6) Status bar

The status information provided in the progress bars is also presented in a status field. The application focus can be temporarily moved to this field using a shortcut. This enables visually impaired users to query the current status in case they missed the auditory indication.

The PEARL project demonstrated that a high level of accessibility can be achieved even in complex interfaces to remote experiments.

VI. Conclusion

Remote controlled experiments for educational purposes have existed for over 10 years and there has been a rapid increase in developments in this field since 2000. However most of these developments have been isolated examples of what can be achieved. Some have been integrated into courses but as far as the author is aware no courses currently exist with a comprehensive range of remote experiments across their presentation. This paper has outlined key issues that need to be addressed if remote controlled experiments are to become widely adopted in science and engineering education. In summary these issues are:

- The importance of learning objectives in determining what experiments to offer remotely then in informing the design decisions in implementing them and constructing the educational framework in which they are offered to the students
- The issue of when is a face-to-face experiment, or a remote experiment, or a software simulation most appropriate
- How remote experiments need to fit into the wider educational context
- Cost-benefits
- The importance of usability of the system and its user interfaces in meeting the educational objectives
- The importance of accessibility if this approach is to realize its potential for extending practical work to disabled students

The rationale for remote experiments is clear and is stated at the beginning of the paper. However significant challenges are faced in moving forward from the current state-of-the-art towards the vision of a widespread, and appropriate, adoption of remote laboratories in teaching and learning. It is hoped that this paper has made a contribution to that envisioned progress.

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