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Remotely controlled laboratories: Aims, examples, and experience

Sebastian Gröber, Martin Vetter, Bodo Eckert, and Hans-Jörg Jodl

Department of Physics, University of Technology Kaiserslautern, Erwin-Schrödinger-Straße, D-67663 Kaiserslautern, Germany

e-mail: eckert@physik.uni-kl.de

ABSTRACT

Remotely controlled laboratories are real experiments that can be controlled by users from their computers via the internet. We present an overview of technical and pedagogical developments, describe the diversity and potential of our experiments, and comment on their acceptance by physics instructors.

I. INTRODUCTION

The introduction of electronic learning, blended learning (merging of on-campus and internet based approaches to learning), self-paced learning, and distance education has changed the teaching of physics. These tools and techniques have been made possible with the advent of personal computing in the 1970s, multimedia in

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the 1990s, and the internet, which is now almost universally accessible. However, we believe the potential of internet technologies, such as broadcasting video lectures, collections of contributed (non-peer-reviewed) multimedia material, and web portals for teachers, has not been fully exploited for educational purposes. In particular, remote control over the internet is now practical and we have recently evaluated electronic learning projects that use this technology to study how remotely controlled labs, virtual labs, and internet experiments have been used in teaching science and engineering.[i1] Most of the experiments currently being offered are in engineering education and about 20% are in physics. These experiments include remote-control telescopes, microscopes, and robots.[2]

In this article we describe the Kaiserslautern implementation of real experiments in electronic learning via remote control and comment on our technical solutions to programming and interfacing problems.[3] In a separate publication we will present in detail the Millikan oil drop experiment as a remote-control laboratory.[4]

II. THE CONCEPT AND TECHNIQUE

The purpose of remotely controlled labs (or, "remote labs" for short) is to allow users with a computer to remotely control an experiment from a separate location (see Fig. 1). Remote control has been used for many years in research, including large particle accelerators, space science, and telescopes, and in tech-

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nology development, including robotics, manufacturing processes, and control. The reasons that they are used include lack of equipment at the local institution, cost, insufficient time for data collection or too much data, and danger to the experimenter. Only recently have instructors in engineering, physics, chemistry, biology, and other disciplines begun to apply this technique as a teaching aid.[1]

On the basis of our experience with remote labs and our familiarity with available technologies, we discuss here the requirements for developing such laboratories. The selection of the topic or phenomenon is important and we recommend choosing an experiment that is covered in the standard course of study. The operation of the remote lab must be intuitively clear, and the performance of the experiment should not require the reading of additional texts. Users must be able to observe the progress of the experiment via a web camera and receive their data for further analysis. The experiment must work round-the-clock over periods of weeks. The material at the website should be readily available to implementation the experiment, and the graphical user interface should be flexibility and functionality to make the labs interesting. The use of remote labs should also be free of charge and in a common language.

It is also important that users are not required to install special software, drivers, or plug-ins. Because the remote labs have to be accessible by a broad audience (with various browsers and operating systems), we have chosen standard internet and open-source technologies. In particular, we require only a web

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browser with the Java runtime environment. The graphical user interface is provided by a web server that delivers the html pages of the remote experiment. The interface between the web server and experiment is realized by a programmable microcontroller unit (Fig. 2). PHP modules running on the web server operate in two directions: A client user request (e.g., clicking a button) leads to the transmission of control parameters to the microcontroller interface, which then converts the values into commands (e.g., signals or voltages) for the experiment (e.g., switch a power supply on or off). The PHP modules also dynamically update the laboratory website, which contains control buttons and displays of the status and current values of parameters (e.g., the message “power supply is on”). Once the PHP modules have been programmed, they can easily be adapted to a new experimental set-up thanks to standard routines and implemented commands. Programming the microcontroller via the in-system-programming interface is simple and necessary to do only once. An important advantage of this architecture is that the experiment is safe against hijacking, preventing unauthorized users from changing the possible range of the experimental parameters.

III. TEACHING ATTRIBUTES

The Kaiserslautern remote laboratory collection presents each remotely controlled experiment in the same manner and in a way similar to student labs: introduction, set-up, theory, exercises and problems, lab, analysis, discussion, and reference

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material (see Fig. 3). We also present an instructive analysis of a particular experiment as a remotely controlled laboratory. In some cases we provide complete lesson plans contributed by teachers; this section will grow in the future. The third element is a set of extensive collections of problems with detailed solutions. See for example, the Millikan oil drop experiment, Rutherford's scattering experiment, and electron diffraction.[3] Besides the physics of the experiment, these problems cover historical aspects, derivations, working principles of all relevant technical components, and error analysis issues (see Fig. 3).

Each remote lab is presented in German and English, and two of them are additionally offered in French and Italian. Users are invited to translate the content of all websites (about 10 pages each) into their native language. With our support these translated pages may also be implemented in the future.

The simultaneous use of the same remote lab by several users is not possible. However, a waiting user can watch the live images of the web camera(s) of the ongoing usage and view the time left until the lab will again become available. We are working to allow users to schedule specific experiments in advance. (This user-time management system will be ready in a few months.)

From our experience producing twenty remote labs we recognize that the selection of a new experiment as a remote lab is most essential. One has to consider questions such as: "How central is this experiment?" and "Why is it not performed in class?" In addition, the benefits of each remote-control experiment

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should meet or exceed those of a traditional lab. For Millikan's experiment it is necessary to measure many droplets to achieve statistical significance. For Rutherford's scattering experiment it is necessary to measure carefully the number of scattered particles in a limited range of scattering angles. To study radioactivity it is necessary to deal with hazardous radiation for many hours. For interference and diffraction studying a variety of slit configurations (single, double, and multiple) is necessary to find a relation between the intensity pattern and the geometry of the diffracting objects.

After the teacher has discussed the real experiment in class, students can perform their own experiments remotely as homework. If each student performs his or her own variation of one experiment, then the students can submit and communicate their results electronically, allowing them to discuss their results online. Some remote labs are very flexible. For example, in the experiment on radioactivity there are about 50 absorbing samples of different thickness and different materials. The experiments on interference and diffraction can incorporate any of about 200 different apertures and obstacles as well as laser light of various wavelengths. Measurements may take a matter of minutes or they may require several hours, thus users must define their research interests or goals and develop their own research plan before performing their measurements. Some of the remote labs are complex, such as those on Optical Computed Tomography and on

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Order/Disorder (in progress).[3] Because these topics are well suited for self-study, we offer an additional tutorial for those labs.

The implementation of an experiment as a remote lab is simple and transparent using our approach. As a result, teachers and students may wish to build a remote lab on a new topic. We have developed a tutorial that describes how to build an interface and to program the microcontroller.

IV. LEARNING OBJECTIVES

One important issue in the successful operation of remote labs is interactivity: number of actions, their quality, and complexity. These actions do not consist merely of clicking buttons. Users of a remote lab not only must possess traditional lab skills (e.g., tabulating and graphing data, operating an oscilloscope), they must also be able to perform and control a diverse array of actions. Depending upon the experiment, users must learn to select and arrange light sources, align optical or scattering components, and perform realignments as necessary. They must be able to position radioactive samples and absorbing matter, or connect signal generators, semiconductor devices, and meters. Users must also be responsible for making decisions, such as choosing time intervals and durations for measurements, setting voltage or current values from proposed ranges, and executing troubleshooting tasks. Finally, users must learn how to record and export experimental data for further evaluation.

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All of these capabilities and skills are typical for tasks given to students in an on-campus lab course. Of course, we recommend real on-campus laboratory experiments as a first choice. However, remote labs can be particularly useful for part-time students, students enrolled in distance-learning courses, and students in less developed countries.

V. FIRST EXPERIENCES AND ONGOING DEVELOPMENT

The following list of remote-control laboratories demonstrate that our approach works. Most of the remote labs are physics oriented, though some are designed for students in other science disciplines or for interested lay people.[3]

The physics topics include electron diffraction, the photoelectric effect, radioactivity, diffraction and interference (two variants), Millikan's oil drop experiment, Rutherford scattering (see Fig. 4), voltage-current characteristics of semiconductor devices (two variants), the speed of light, the oscilloscope, order/disorder in crystal structure, order/disorder by optical scattering and Fourier transformation, and the magnetic field of one or two parallel currents. The projects include a wind tunnel, optical computed tomography, a toll system, "hot wire" (a game), a robot in a maze, optical tweezers, and a "world pendulum" (see Fig. 5).

The expense of developing an experiment as a remote lab include: cost of the actual experimental setup; cost of the remote control specific hardware (inter-

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face/microcontroller, computer, and web camera(s); total cost about $1000); cost of the remote-control variant of the experiment such as stepper motor, *x*-*y* positioning, and electronics; and the cost of programming (1-2 person months). Because we have a standard solution for the microcontroller interface and programming, the cost of an additional remote lab is acceptable.

Most of the remotely controlled laboratories were built by students as part of their master thesis projects (each of 4-6 months duration). These projects were supervised by two post-doc co-workers, with one supporting technical requests and programming and the other giving advice on physics content and pedagogy. Four remote labs were built from scratch by high school students during a one-week summer camp in 2005 at the University of Technology of Munich. The successful work done by the students showed that, despite the time limitations and early technical challenges in refining user interfaces, our approach made for excellent student projects. After the summer camp, these remote labs were sufficiently polished in content and appearance that we deemed them ready for public use.

Our plan is to deliver all our remote labs to foreign institutions and instruct a technician or physicist at each site to maintain the experiment. The weekly maintenance needed to check each of our remote-control experiments is less than one hour. Since 2003 we have not had massive technical problems; occasionally we have had to activate the “reset” function. After having protected the central server and the web server of each remote-control experiment at each location, we have had no attacks or misuse of any kind.

We have installed tracking and monitoring devices for all remote labs so that we can capture relevant data of visitors, including IP addresses and user-provided information. We also record the way in which a visitor makes use of a remote-control experiment (whether in play or research mode), the parameters that each visitor changes in using a lab, and the duration of use. This tracking is done in observance of the privacy laws. We differentiate visitors and users: a user is defined as a visitor who changes several parameters of the experiment. All visits from members of the remote lab project are discarded.

We have been collecting data since 2003. Approximately 15,000 people visited our web portal in 2007, which means an average of 3-4 visitors per remotely controlled laboratory per day. The numbers of both visitors and users have increased by 50% since the first half of 2007 resulting from announcements and broader publicity of the project. About 70-80% of the visitors manipulate one or more controls of an experiment.

We have received feedback from a variety of users, including individual teachers whose classes performed remote-control laboratories as homework, instructors of teacher training courses, and interested lay people sending questions via e-mail. The fact that remote labs are increasingly in demand demonstrates their acceptance. One aim of Ref. 1 and the present publication is to achieve

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broader use of the remote labs. We will then expect to be able to answer obvious questions such as: "Does this method actually produce learning gains that are similar to (or greater than) actual labs?" and "How exactly are students engaged when doing a remote lab experiment?"

VI. CONCLUSIONS

In the future we plan to offer in-service teacher training courses to help teachers use remotely controlled experiments in class and to develop new ones with students. So far, we have received positive, but not systematic, feedback from teachers who made use of individual remote labs in their teaching. One of the next steps is to gain insight into how teachers use the remotely controlled laboratories in teaching and how students accept these new methods of teaching. In the meantime we are developing teaching materials for the remote labs realized so far. We wish to encourage the creation of a cluster of remotely controlled laboratory experiments worldwide. We consider science students at universities in developing countries as a possible target group; these institutions have good communication channels but lack equipment for student labs. Other topics such as the world pendulum (Fig. 5) might promote real-time collaboration on experiments for students in geographically separated regions.

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Figure captions

Fig. 1. A sketch of a remotely control laboratory for experiments on the photo-electric effect.

Fig. 2. The interface design (middle) and the communication channels (arrows) between the interface and experiment and between the interface and web server. The terminal function of the computer is needed only when programming the microcontroller using the in-system-programming interface (dashed boxes).

Fig. 3. Remote-control experiment on electron diffraction. Shown are the navigation menu of the experiment, the video stream of the diffraction pattern at the fluorescence screen of the electron tube at a voltage of 4.5 kV, and the controls of the experiment.

Fig. 4. Remote-control experiment on Rutherford scattering. (a) Setup showing the web camera, vacuum chamber, interface, and some electronic devices (vacuum pump not shown). (b) Image of the web camera showing the heart of the scattering experiment. Shown from left to right are the Am-241 source of α-

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particles, thin gold foil, and detector. The Am-241 source is moveable on a circular path in a range of ±50° with respect to the beam axis. The user can also choose from two foils (gold or aluminum) or a 1 mm slit. The numbers of registered counts per time interval set by the user is displayed.

Fig. 5. Remote-control experiment on a world pendulum. (a) The origin of the dependence of the surface gravitational field g on the latitude φ, the oblation of Earth due to rotation, and the resulting radial component of the centrifugal acceleration g_{cr}, which reduces g as one moves from the pole to the equator. The quantity g_0 is the acceleration due to a spherical Earth at rest. (b) The calculated gravitational fields $g(\varphi)$ for the spherical Earth at rest (g_0 = constant) and a rotating spherical Earth, as compared to that determined from the world geodetic system, WGS84.[5] The data are collected from towns where we have placed string pendulums to measure g with an accuracy of $< \pm 0.002$ m/s^2. For Kaiserslautern, Germany ($\varphi \sim 49°$) we determined $g(49°) = 9.8097$ m/s^2, which fits the data provided by the German National Metrology Institute (PTB Braunschweig) when taking into account the gravitational anomaly for the Kaiserslautern region and the correction due to the height above sea level.

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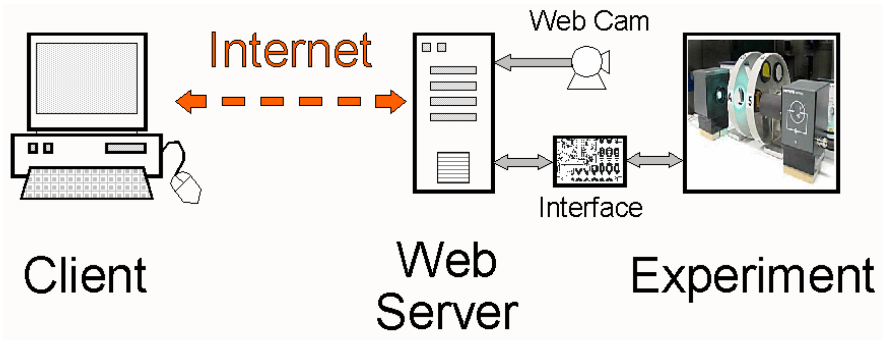

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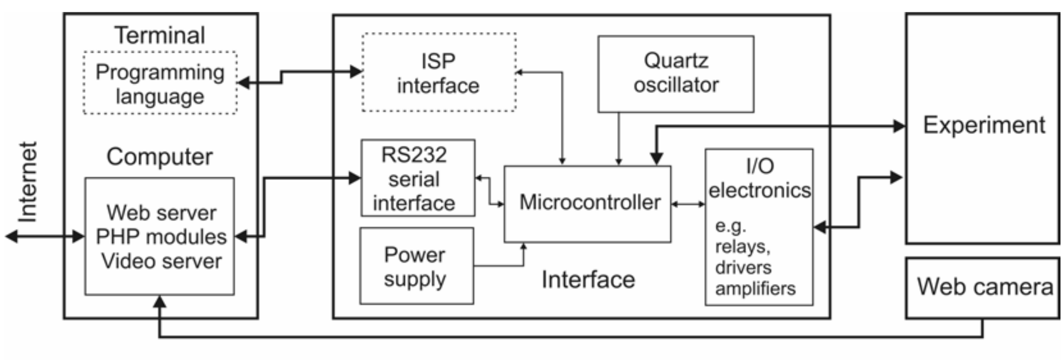

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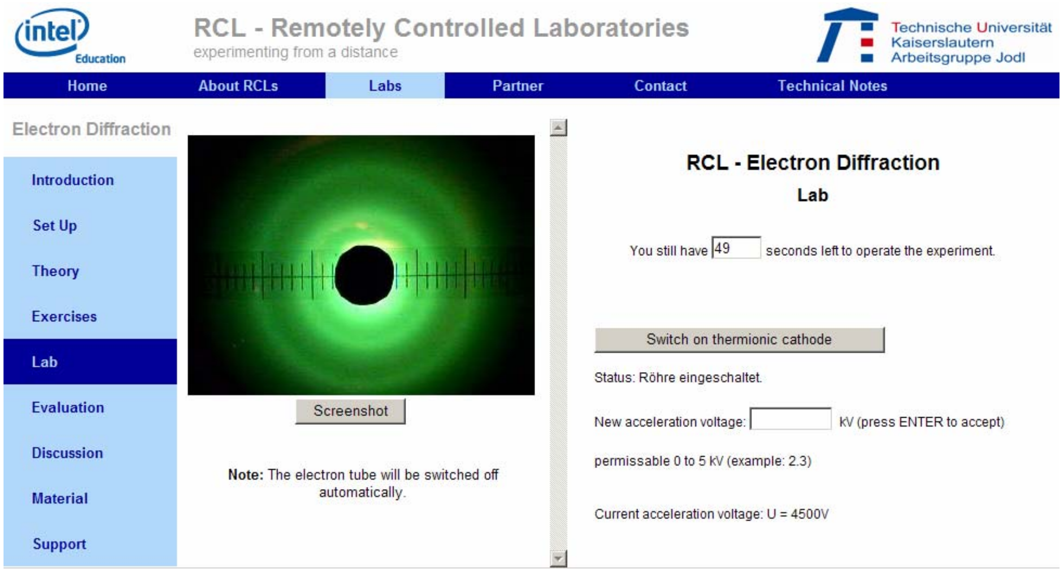

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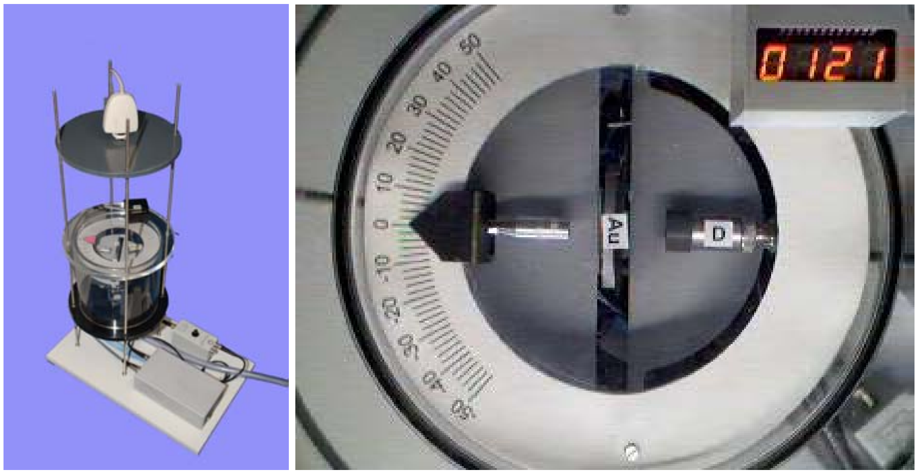

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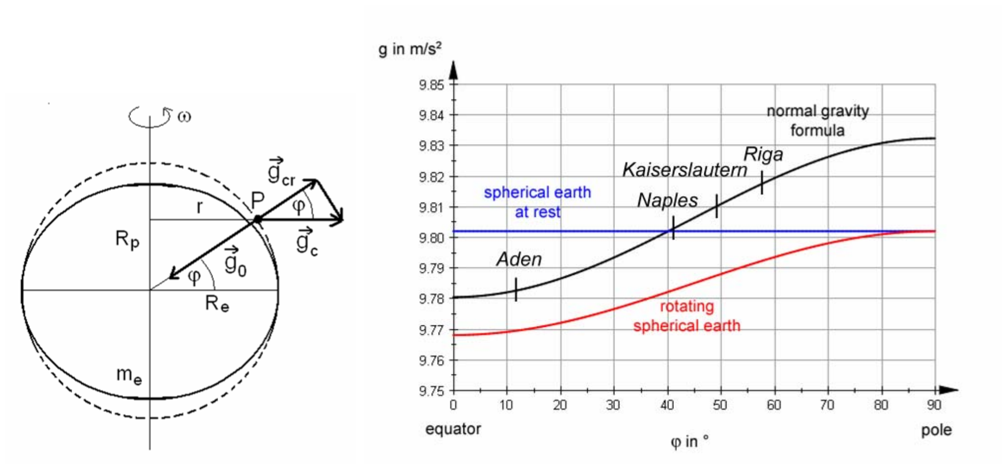

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[1] Sebastian Gröber, Martin Vetter, Bodo Eckert, and Hans-Jörg Jodl, "Experimenting from a distance," Eur. J. Phys. **28** (3), 127-141 (2007).
[2] It is not the intent of this article to give a detailed review. We therefore make reference to resources on the internet. Although not complete, the following collections of remote labs may give an impression of their growth and variety: <www.prolearn-project.org/> and <telerobot.mech.uwa.edu.au/links.html>.
[3] Our website is at <rcl.physik.uni-kl.de>.
[4] Sebastian Gröber, Martin Vetter, Bodo Eckert, Hans-Jörg Jodl, "Millikan's oil drop experiment as a remotely controlled laboratory", Am. J. Phys. (2008), to be published.
[5] World Geodetic System 1984 (WGS84), Technical Report 8350.2, 3rd ed., National Imagery and Mapping Agency (NIMA), January 2000, <www.nima.mil>.