

# A Remote Access Laboratory for Electrical Circuit Experiments\*

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*Many laboratory experiments in electrical engineering courses can be performed remotely using real equipment in a laboratory. Traditional circuit theory experiments have been conducted over the Internet at Blekinge Institute of Technology (BTH) in Sweden using the same experimental set-up from different locations simultaneously. The circuits are formed using remotely controlled switch matrices. The instruments and switch matrices used are computer-based PXI (PCI extensions for instrumentation) devices which have virtual front panels that can be displayed on a remote PC. This approach is neither a simulation nor a SCADA (Supervisory Control and Data Acquisition) application. The students control the instruments in the same way as they would in a local laboratory. The only difference is that they do not form the circuits and connect the test probes manually. These laboratory experiments have been used successfully in undergraduate engineering education at BTH and at Luleå University of Technology, Sweden using a lab server at BTH. Two transducer laboratory exercises are also available for more experienced students, who mostly welcome the chance of doing the experiments from home at any convenient time. These exercises contain comparatively slow mechanical movements allowing only one user to be logged on and controlling the experiments at once. Video transmission is provided so other users can follow what is happening and which also performs part of the experiments.*

## INTRODUCTION

REAL EXPERIMENTS are indispensable in engineering education for developing skills with which to deal physical processes and instrumentation. Laboratory exercises are integrated into many courses in electrical engineering. The traditional way of conducting an experiment is to go to a university laboratory. Students work in teams and receive tutorial help from teachers. There is no doubt that nothing can replace synchronous learning through face-to-face interaction, however, it is not always feasible for students to attend conventional classes. Models for using information technology to enhance the learning experience for students who are asynchronous in time and/or space and which are also suitable for on-campus students have been presented earlier [1].

A survey of types of laboratories and remote lab scenarios can be found elsewhere [2]. Remote access laboratories are likely to change educational practices [3]. There are different types of remote access. For example, SCADA (Supervisory Control and Data Acquisition) applications have been around for many years and are used by utility and manufacturing companies to control processes. The goal of this type of remote operation is to put the user 'in the control room' with full and immediate access to all important system parameters. The test points are fixed, as are the settings of most of the sensors and instruments.

This paper presents the remote laboratory at Blekinge Institute of Technology in Sweden (BTH). It is neither a SCADA application nor a simulation.

The three main objectives of the laboratory are:

1. to offer remote laboratory experiments to on-campus students as well as to distance learning students as part of conventional courses in electrical engineering;
2. to design remote laboratory exercises that are almost identical to local ones;
3. to use the equipment and the premises more efficiently.

At present, the laboratory provides:

- A circuit theory laboratory course. This is the least demanding in terms of equipment and transfer rate. No video or sound transmission is required.
- Two laboratory exercises in sensor technology with mechanical movements and video transmission.
- An oscilloscope and function generator user's course. This course is for students and others who are not familiar with such basic instruments. An instruction manual can be downloaded from the laboratory home page.

The client/server paradigm is used. The Internet provides the communication infrastructure between a student's client PC at home or elsewhere and a lab server in the laboratory. A lab server at BTH is a PC with computer-based instruments and switch

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matrices controlling an experimental set-up. The instruments have virtual front panels, which have been included in the client software. The basic TCP/IP (Transmission Control Protocol/Internet Protocol) is a useful tool for transferring the data streams involved [4]. In the circuit theory experiments, settings and measurement data are transferred over the Internet; however, video and/or sound transmission is not needed. More advanced interfaces between a client and a lab server can also be used [5]. These interfaces are useful in experiments containing mechanical movements or audible/visible phenomena which require monitoring of video and/or sound signals [6].

The client software can be downloaded from the website of the laboratory. The software is grouped into packages which contain all the information needed for installation purposes. Internet packages are cab-based set-up programs that are designed to be downloaded from the website. MS Internet Explorer uses a process known as Internet Component Download to install the client software on the user's computer. When a user accesses the Web page hosting the package, the system downloads it to the user's computer. The package is verified for safety, unpacked, registered, installed and then activated. This process takes place in the background and is controlled by the browser.

At present use of the remote laboratory at BTH is free around the clock for students or anyone else in any part of the world. On the days when the laboratory is in use in regular courses it will be available to the participants only. There is no demo mode because the exercises are used in basic training and education, and no short cuts should be available for the students. Complete lab assignments and solutions will be published [7]. The address of the laboratory is <http://www.its.bth.se/distancelab/english/index.htm>.

#### **LOCAL CIRCUIT THEORY LABORATORY EXERCISES VERSUS REMOTE EXPERIMENTS**

In the local laboratories at BTH there are eight identical lab stations equipped with desktop instruments and power supplies, thus eight student teams can do experiments supervised simultaneously with one teacher. The teams use breadboards to form test circuits and to connect instruments and power supplies. The cost of the laboratory equipment and its maintenance can be reduced if the number of lab stations is reduced and/or the laboratories are used outside ordinary working hours. Most teachers, however, wish to work only during the day.

It is noted that much of the time that student teams spend in the laboratory is occupied with other things than taking measurements. Would it be possible to let two student teams share one lab station? For example, could one team carry out a test, while the other considers the resulting data or

makes some necessary calculations? Unfortunately, this is rarely feasible because manual handling of test probes, instrument settings, etc. for changing experiments would almost invariably take too much time and the teams should be allowed to work asynchronously.

Is it possible to skip manual handling of the components and the test probes? The answer is 'Yes,' in many cases it is possible to use switch matrices to form circuits, connect test probes and other devices. In fact, a PC connected to the instruments and the switch matrices can be used to control the experiments. The instrument settings are then made with the mouse on virtual instrument front panels on the PC screen. This PC can in turn be controlled from other PCs if all PCs are connected in the same network and the virtual front panels of the instruments are copied to the other PCs. Remote access laboratories work in this way with the Internet playing the role of the network. The PC connected to the instruments and the switch matrices is called a lab server. The other PCs are clients. A number of student teams, each equipped with a client PC, can then use one lab station at a time from anywhere in the world, and at any time of the day or night. However, it should be said that the experience of sitting in a laboratory together with other students and a teacher cannot be recreated by remote access using currently available technology.

What factors affect the server response time? First, the switch matrices must form the circuit to test and connect the sources and the test probes. When the relays in a switch matrix engage there will be transients; these must not interfere with the measurements to be taken. When the transients have died it is time to read the instruments or, if there is an oscilloscope in the configuration, it is time to arm it for a single shot and then wait until it triggers before finally reading all instruments. By selecting proper values for the components in the circuits to be formed by the students, the transients can be made short-lived (below 0.1 s) so that their contribution to the response time will not be significant. Instrument delays will be low if computer-based instruments are used. If the client does most of the processing, it is possible to reduce the response time still further. Only a small amount of data needs to be sent between the server and a client even when oscilloscope traces are included. To meet this requirement, proper coding of oscilloscope trace data is essential to minimize the length of data strings. The normal method of reading data from an oscilloscope is to read scaled data, 64 bits per sample. However, the A/D converters of an oscilloscope usually provide only eight bits per sample. To reduce the amount of data to be transferred, only one byte per sample is sent together with a few bytes of scaling information. If the lab server response time is only a fraction of a second and it has a queue manager, it is possible for a number of clients to use it simultaneously.

Most local laboratories today have desktop instruments fitted with real front panels. One anticipates that these current instruments will be gradually replaced by computer-based instruments with virtual front panels. With this new computer-based laboratory model, it makes no difference if you handle instruments locally or by remote control. Then, if you compare local laboratories with remote ones, you will find that the only difference is the handling of the components and the test probes. Nevertheless, students need to gain considerable experience of manual work with components, cables, test probes, soldering irons, etc. At BTH students gain this experience in practical projects, which also provide the right methodology to cope with real-world problems such as EMC issues and finding bad connections. Most traditional laboratory exercises last for four hours and sometimes a student team may spend a considerable part of that time troubleshooting connecting failures resulting from a breadboard misused by a previous team and then miss a significant part of the exercise. In the remote laboratory there should be no connecting failures.

In most circuit theory experiments, instruments are required to observe all phenomena. It is clearly not possible to see the electrical current with the naked eye or hear electrons moving. There are, of course, exceptions such as an incandescent lamp or lightning where you can actually feel the heat or

see the light. Most types of electrical instruments can be controlled and read remotely so that the students obtain the same results irrespective of whether they are in a laboratory close to the set-up or using the client at home. Neither video nor sound transmission from the remote lab is required, and the instruments produce only a small amount of data. Thus the total data to be transferred over the Internet is small; a 56-kbit/second modem is adequate.

## REMOTE LABORATORY CONFIGURATION

Computer-based instruments consist of a hardware board to be plugged into a host computer, a virtual front panel and a software driver. There are no control buttons or displays on their small front panels, only connectors. Virtual front panels can be displayed on the host computer screen or on the client PC screen. You must use the mouse or the keyboard to define the settings. Plugging an instrument into a host PC entails the instrument being exposed to noise. A better method is to put the latter into a special low-noise expansion box specially designed for instruments [8]. In the laboratory a PXI box is used (PCI Extensions for Instrumentation). National Instruments launched PXI in August 1997 as an open specification. It is built on the modular and scalable CompactPCI

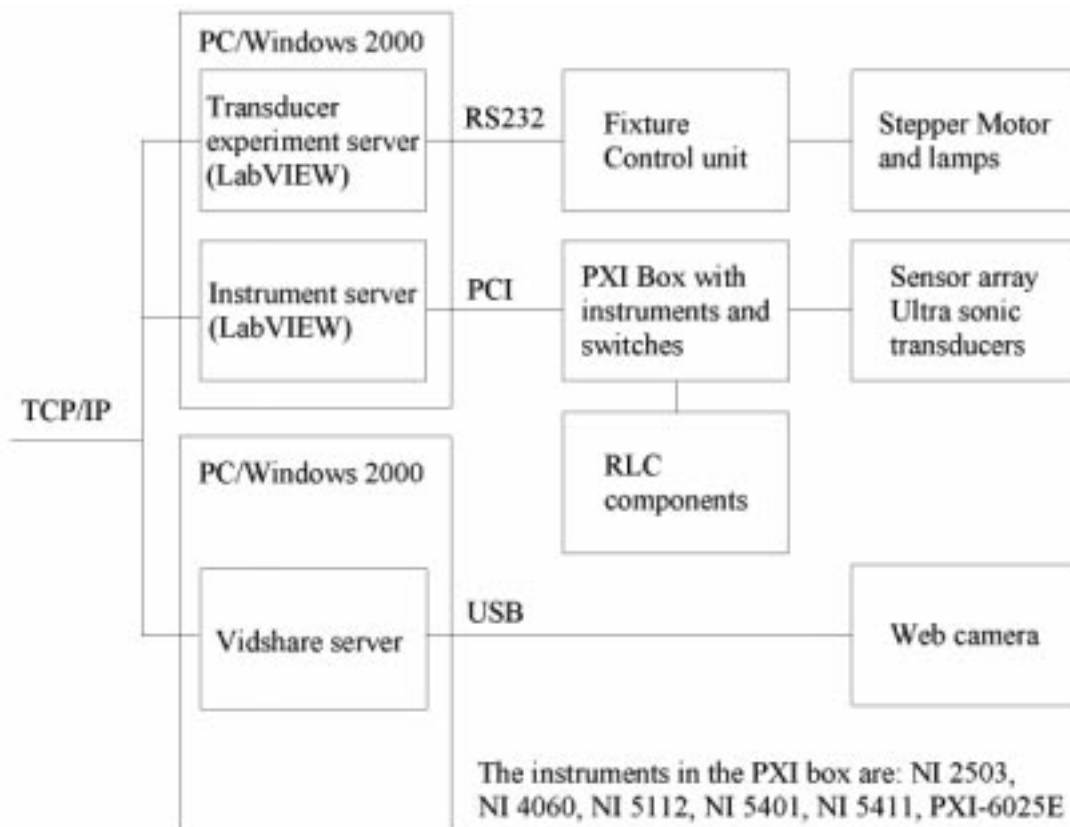


Fig. 1. The laboratory block diagram.

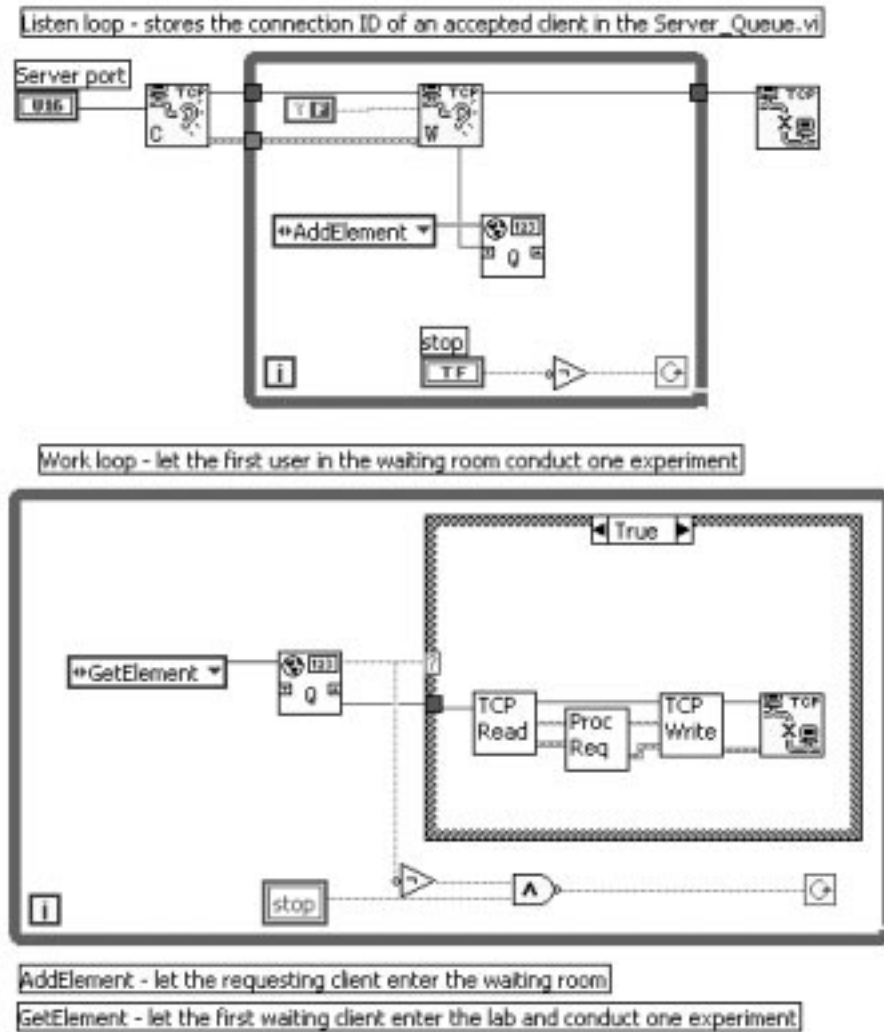


Fig. 2. A simplified diagram of the top layer of the Instrument Server program.

specification and the high-speed PCI bus architecture. A diagram of the equipment in the laboratory is shown in Fig. 1. The cost of the hardware and software is approximately US\$20,000. Three students have been employed during their summer vacation to do most of the implementation work.

The students have used LabVIEW 6i to create two of the server programs. The drivers used are NI-DMM 1.6, NI-FGEN 1.5, NI-SCOPE 2.0, DAQ 6.9.1 and NI-Switch 1.6. Hardware and software manuals can be downloaded from the National Instruments Website [9]. To cope with requests from more than one client at the same time, the server must have a short response time as well as a queue manager to take care of simultaneous calls. In the LabVIEW Full Development System there is an example 'Date Server.vi' in the file 'tcpex.llb' which includes a queue manager. Figure 2 shows a diagram of the top layer of the Instrument Server program. It is a simplified version with the error processing omitted.

The clients are Visual Basic applications packaged for Internet deployment. The largest package

is a little more than 5 MB. ActiveX technology is used to create components that can be used on an HTML page. These components include controls that run on the client. Internet component download delivers this ActiveX solution to users by means of an Internet browser. To download the packages, it is necessary to lower your security settings temporarily since the software has no digital signature.

### A CIRCUIT THEORY LABORATORY COURSE

Students who are not familiar with basic electronic instruments are invited to study the instrument user's course first. The client window of the circuit theory laboratory course as it appears at start-up is shown in Fig. 3. To the left is the lab options panel; here you can choose from five different exercises. Behind the tabs there are virtual panels for a DC power supply, a function generator, a digital multimeter and an oscilloscope. The right part of the oscilloscope panel is always displayed. The

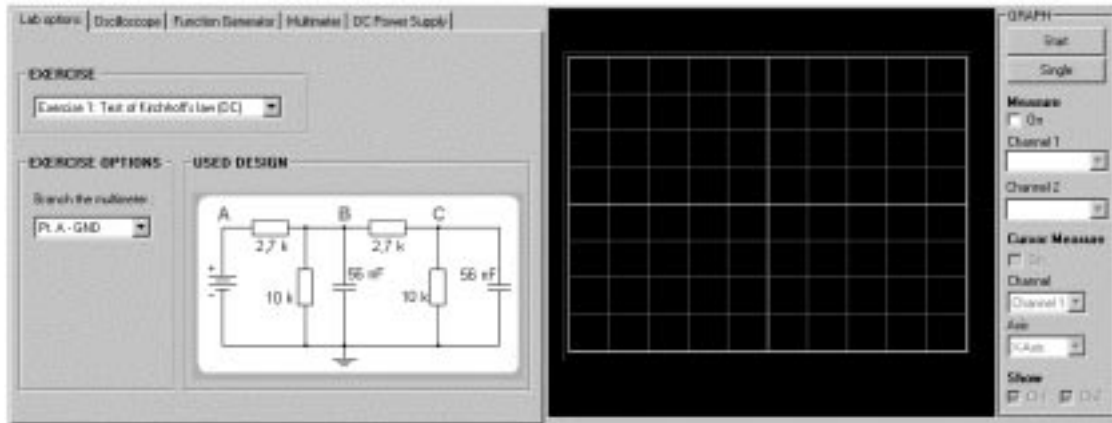


Fig. 3. The circuit theory exercises client window at start-up showing the first exercise.

instrument panels work much like the real ones. In the top right corner there are two special buttons. You can use the panels to create all settings; a string containing the settings will not, however, be sent to the server until one of the 'Start' or 'Single' buttons in the top right corner of the oscilloscope panel is pressed. If you press the 'Single' button you will receive data from a single shot only, but if you press the 'Start' button the client will—albeit for a limited time—continuously send the string containing your present settings to the server. The caption of the 'Start' button will then be changed to 'Stop', and changes in the instrument settings will almost immediately affect the oscilloscope display in about the same way as it would with desktop instruments in a local laboratory. After a short period of time, the repeated updates of the oscilloscope display ends and the caption of the button changes back to 'Start' again. You are only permitted to use this continuous mode for 30 seconds or so because the response time will increase at the same time for other connected clients.

The first exercise shown in Fig. 3 is a test of Kirchhoff's voltage law for the DC case. Physical laws must be tested with real experiments; simulations will not do. The letters A, B and C in the circuit diagram denote test points provided. You

can use the digital multimeter to make measurements referenced to ground or floating. Students are expected to calculate  $U_{B-GND} - U_{B-C} - U_{C-GND}$ . The sum will not be exactly zero since the accuracy of the multimeter is limited. In the next exercise which explores the AC case, students are expected to repeat the test. Hopefully, they will find that the sum will not be near zero this time. Students are then encouraged to use the oscilloscope and calculate the corresponding phasors. Using a standard oscilloscope fitted with normal test probes, it is only possible to measure voltages referenced to earth and no other options are provided in the client software. Thus it is only possible to make valid measurements with the oscilloscope in this remote laboratory. This is a helpful constraint because in a corresponding situation in a local laboratory a student could connect the ground lead of the test probe anywhere in the circuit. This restriction may possibly be removed in the next version of the system.

The third exercise is shown in Figs 4 and 5. If you try to break a current through a solenoid, a high voltage will be generated as in the ignition system of a car. If you want to simulate this voltage you could run into trouble because the voltage generated will, theoretically at least, be infinite. However, if you do the real experiment

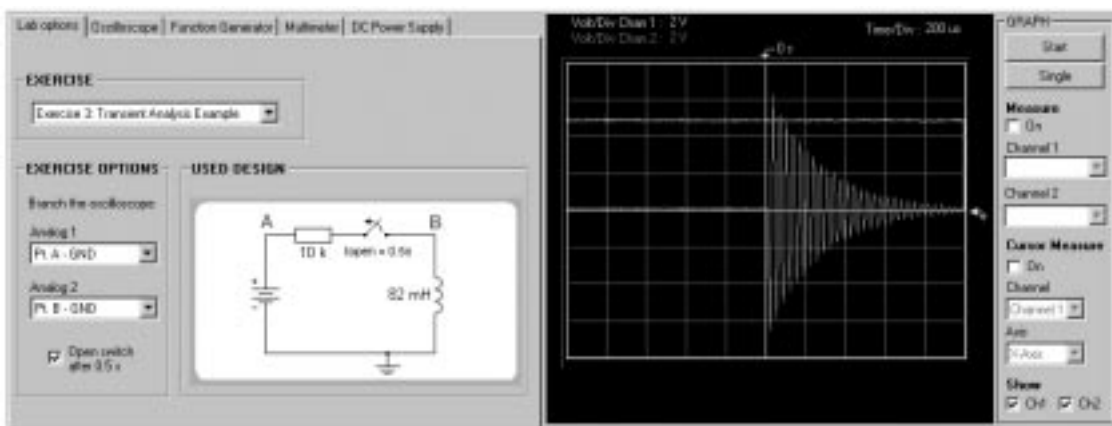


Fig. 4. The third circuit theory exercise.

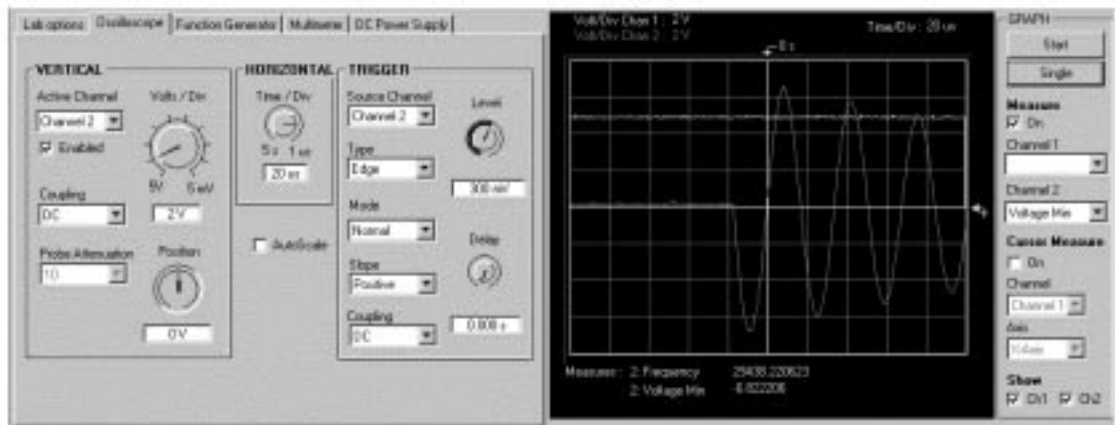


Fig. 5. Oscilloscope settings to catch the transient in the third exercise.

in Fig. 4 and open the switch when the circuit has entered steady state, the current will go through the oscilloscope. If you take the oscilloscope impedance into account in the simulation you achieve a better result. However, the cables should also be considered. This is a good example whereby simulations can be combined with real experiments to learn new things.

In the fourth exercise, students are expected to identify what is in a black box. It is a circuit with R and L or C, but what is the configuration? New measurement possibilities will be added in the next version. The fifth exercise is shown in Fig. 6. Here students are expected to draw a Bode plot and find the bandwidth.

These laboratory experiments are used in ordinary circuit theory courses and in a course in basic electricity at the Department of Mechanical Engineering. They have been evaluated earlier [10].

### LABORATORY EXERCISES WITH MECHANICAL MOVEMENTS AND VIDEO TRANSMISSION

BTH offers a project course in which teams of students are expected to design and implement

control systems for small vehicles [11]. At the end of the course there is a contest where the students' vehicles must navigate autonomously through a racetrack with five or six obstacles in the direction of a guiding light. Each vehicle is fitted with transducers, a line scan camera and two ultrasound transducers. It should find its bearing on the light source with the aid of the camera, and should detect the obstacles in its way using the ultrasound transducers. The exercise requires that the students produce certain electronic circuits and software routines. In the camera box there is only one linear sensor chip; the sensor array is mounted horizontally in the focal plane.

The students are invited to conduct remote experiments to determine how the transducers can be used to help the vehicle find its way to the light source and avoid obstacles. In the experimental set-up the transducers are attached to a stepper motor shaft as in Fig. 7. The experiments are arranged in a closed room without windows but with a network connector and a mains outlet, as shown in Fig. 8. In the room there are four light sources and one obstacle, a plank. Two of the walls can also be used as obstacles.

The transducers and the stepper motor are fed via cables from the ceiling. A web camera focusing

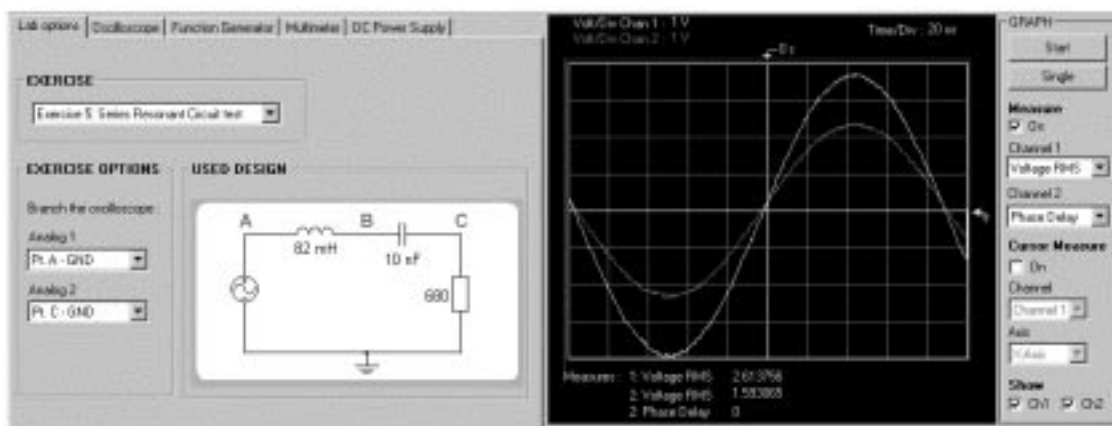


Fig. 6. The fifth circuit theory exercise.

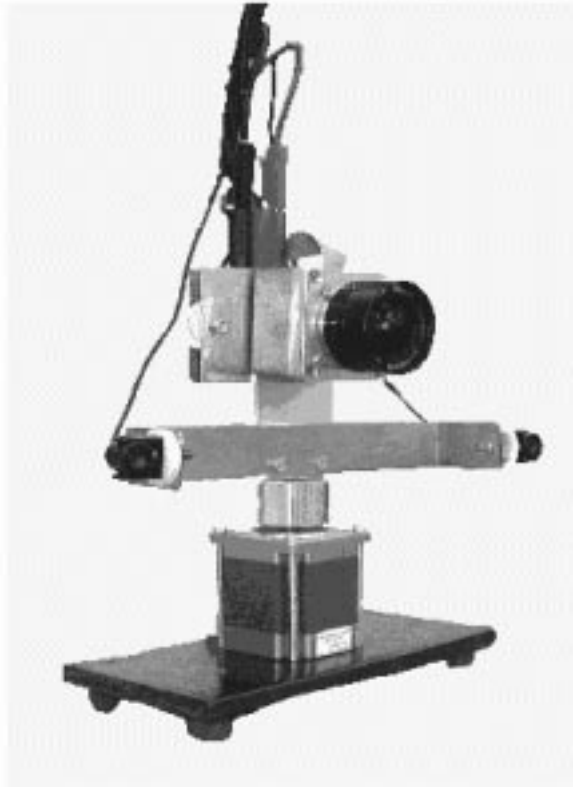


Fig. 7. The transducer fixture.

on the scene is mounted in the ceiling. In the experiments with the camera (laboratory exercise 1) the students are expected to test the camera performance, e.g., the view angle, bearing resolution and light sensitivity. With the aid of the ultrasound transducers they are expected to find out how to design a meter with which to measure the distance to the obstacles (laboratory exercise 2); is, for example, the strength of the echo correlated to the angle of incidence of the sound pulses sent towards the obstacle? The students should already have some practical experience from earlier laboratory exercises in electronics and other similar courses. They are extremely keen to perform these experiments successfully in order to win the race ultimately.

There are three servers. The Transducer Experiment server controls the fixture and the light sources. The students are only permitted to rotate the fixture  $360^\circ$ . There is a rotation limit in the server software. If this limitation fails then the author may encounter a hardware problem. The instrument server controls the two function generators, the oscilloscope and two relay switch matrices. The function generators are to generate the pulses needed to feed the transducers. Students are only permitted to switch the function generator outputs from the oscilloscope to the camera chip when the voltage level output from the generators

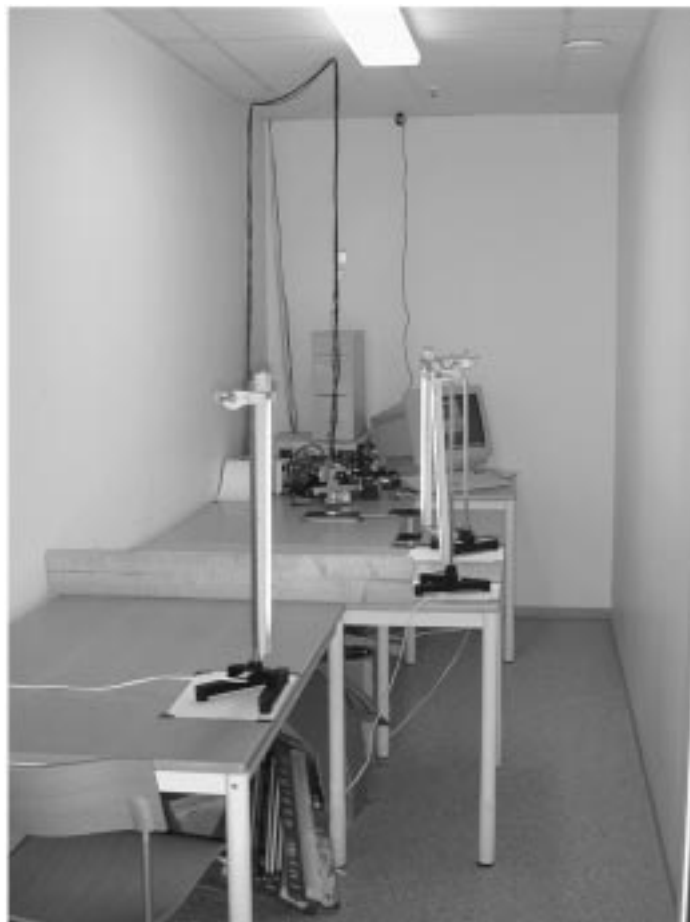


Fig. 8. Interior of the room with experimental set-up.

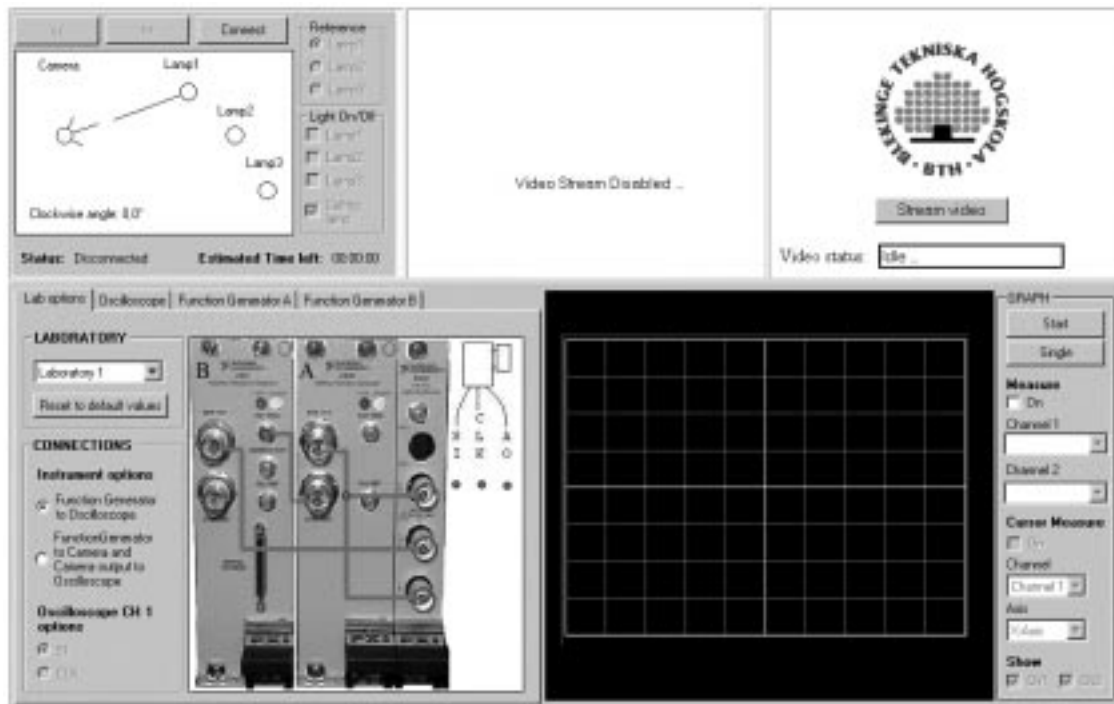


Fig. 9. The transducer exercise client window at start-up.

is acceptable to the chip. The third server controls the web camera.

The client window is shown in Fig. 9. The bottom half contains the virtual front panels of the instruments and the lab options panel controlling the switch matrices. The options panel is displayed at start-up. Students select lab options and control the instruments as in the previous section. The upper-left part of the client window is used to manage the Transducer Experiment server. Only one client can connect and log on to this server at any one time and exercise exclusive control over the fixture and lamps. A state diagram is shown in Fig. 10. At present, the

login time is limited to 30 minutes. Another client can be waiting and take over control when the login time for the first client has elapsed. When logging in, a text box will tell the second client the maximum time period to wait as well as the IP address of the client in control. Other clients can select a lab option and use the instruments and the transducers. They can also see in the web camera picture how the client in control rotates the fixture.

To obtain a video output from the line scan camera in the transducer laboratory exercise 1 as shown in Fig. 11, all instrument settings must be correct. Figure 12 shows an output from the microphone in laboratory exercise 2 when the

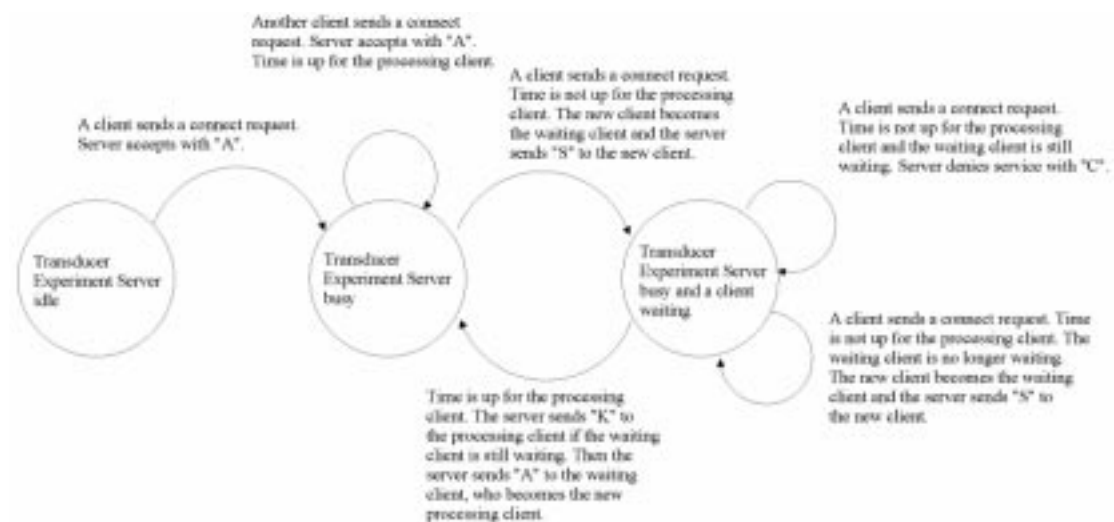


Fig. 10. A state diagram for the Transducer Experiment server.



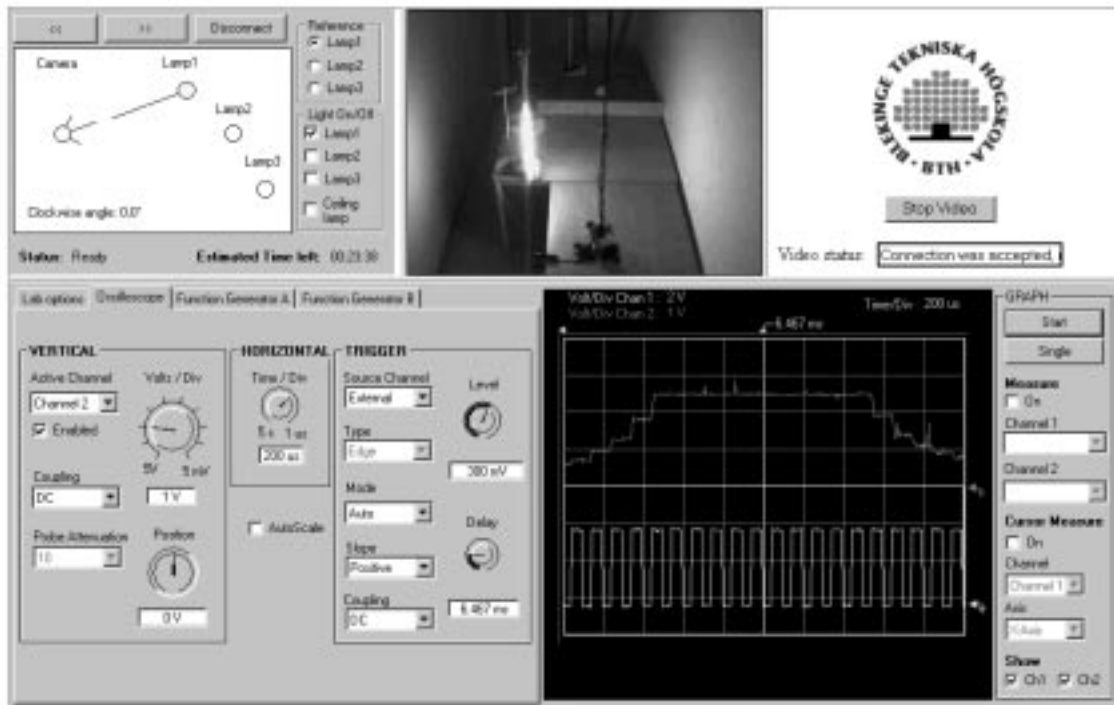


Fig. 11. The top trace is the video output from the line scan camera when it is looking at the nearest lamp. The bottom trace is the camera pixel clock.

ultrasonic transducers are directed towards the plank. The distance from the transducers to the plank is 129 cm, and the sound speed is 340 m/s in the laboratory. These are two examples of the measurements students are expected to make. Simulations can hardly replace such measurements: the richness of nature is difficult to simulate.

In the last project course in January 2002, 29 students performed the transducer experiments in the remote laboratory from home or from a computer on campus; they were without any help from an instructor. Afterwards they reported their results in written form to a teacher and discussed these with him. They also filled in a questionnaire.

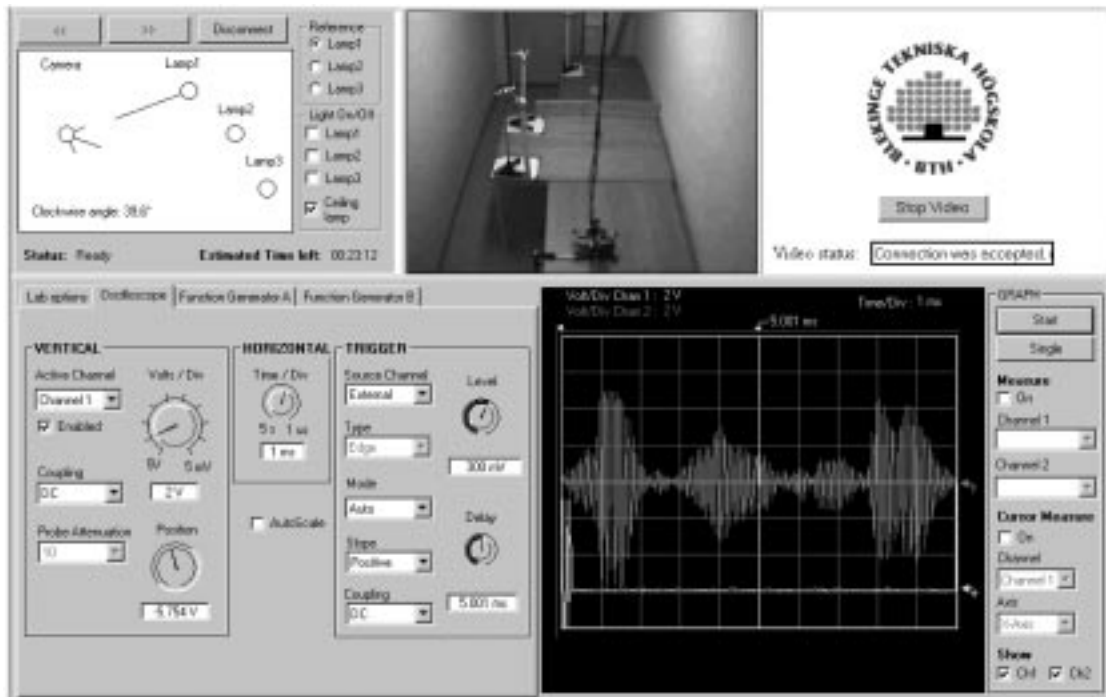


Fig. 12. The top trace is the output from the microphone illustrating crosstalk and echoes received from the plank. The bottom trace is the short burst sent to the load speaker.

Table 1

Question number	Yes	No	No answer
1	15	14	0
2	10	5	14
3	27	0	2
4	20	9	0
5	14	14	1
6	15	12	2
7	7	20	2
8	8	21	0

The main questions concerning the transducer laboratories were:

1. Have you taken the user's course?
2. If yes, is the course an adequate guide as to how to use the instruments?
3. Is the response time when you press the 'Single' button acceptable?
4. Do you prefer to perform experiments over the Internet when it suits you rather than do them in the university laboratory at a given time?
5. Do you miss the opportunity to handle the components manually?
6. In a traditional laboratory exercise it is necessary to form the circuits and connect test probes manually but here that moment is eliminated. Is this an advantage?
7. Would it be acceptable to shorten the time between 'Start' and 'Stop'?
8. Should it be more obvious that the experiments are performed on real equipment?

The answers are listed in Table 1.

The main questions concerning the user's course were:

1. Have you passed the circuit theory course?
2. Have you passed the computer theory course?
3. Have you used a function generator before?
4. Have you used an oscilloscope before?
5. If you answer 'yes' to question 4, are you more comfortable with the oscilloscope after the course?
6. If you answer 'no' to question 4, do you think you will be able to use the oscilloscope now?
7. If you answer 'no' to question 4, do you think it is necessary for you to start with a real oscilloscope?
8. Did you use the instruction manual for the course?
9. If you answered 'yes' to question 8, is it possible to do the course with the aid of the instruction manual?
10. Do you prefer to do the course over the Internet when it suits you rather than do it in the laboratory at a given time?
11. Should it be more obvious that you use real instruments in the course?
12. Is it possible to learn how to use an instrument over the Internet without any contact with the instrument hardware?

The answers are listed in Table 2.

Table 2

Question number	Yes	No	No answer
1	18	7	4
2	21	4	4
3	19	7	3
4	24	0	5
5	18	6	5
6	1	1	27
7	0	0	29
8	24	1	4
9	19	4	6
10	17	10	2
11	8	15	4
12	17	6	6

Some of the students added comments to their answers. One student missed having an instructor. Some appreciated the opportunity to decide when to do the experiments. Others had found various bugs in the software.

## CONCLUSIONS

It has been demonstrated at BTH that remote experimentation in electrical engineering courses is technologically feasible. Many experiments in electrical engineering courses exclude physical sensation and can be conducted remotely over the Internet, around the clock and without video transmission or other means requiring a high transfer bandwidth. Several students can share the same remote hardware if each measurement can be performed in a fraction of a second; this is the case for many experiments in electrical engineering courses.

It is also possible to manage experiments with a slower response and using physical sensations; only one client can then control the experiments, and video and/or sound transmission is required. At BTH, we have combined the two types of experiment in two laboratory exercises and used them in an undergraduate course—most recently in January 2002. Only one student can control the experiment, but other students from other locations can observe the physical sensations and perform parts of the experiments. The students were extremely keen to do these experiments, and the short evaluation made indicates that it is possible for experienced students to perform the experiments without an instructor; they do not miss manual handling of the components and other physical equipment.

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