

# **A Remote Electronics Laboratory for Physical Experiments using Virtual Breadboards**

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## **Abstract**

In traditional university laboratories students conduct experiments under the supervision of an instructor. A remotely-operated laboratory for undergraduate education in electrical engineering which emulates a traditional laboratory has been set up by Blekinge Institute of Technology (hereafter referred to as BTH), Ronneby, Sweden. The laboratory is a client/server application and the Internet is used as the communication infrastructure. Most remote laboratories elsewhere are used for fixed experiments but in the BTH laboratory students around the world can assemble circuits simultaneously from electronic components in much the same way as they do in a traditional laboratory. The teacher or a member of the laboratory staff mounts the components to be used in the lab sessions in a circuit assembly robot in the experiment server in Ronneby. Students use the mouse to connect some of the corresponding virtual components on a virtual breadboard displayed on the client PC. Students thus control the robot by means of the wiring on the virtual breadboard. Virtual instrument front panels are used to control and read the instruments by means of remote control. To avoid potentially serious student mistakes e.g. overloading a component the teacher can preset limits to the source voltages which are accessible to students. The teacher can also restrict student circuits by, for example, dictating minimum impedance in loops created with aid of the components provided. The number of nodes provided on the virtual breadboard is adequate for experiments in undergraduate education. The laboratory is always open and can be used by registered students and guest users alike. The time-sharing scheme used allows simultaneous access for up to 8 client PCs. A 56 kbit/s modem and MS Internet Explorer are all that are required. The client software can be downloaded from the laboratory web site at <http://distanslabserver.its.bth.se/>. This paper discusses the remotely operated laboratory at BTH; it focuses on the virtual breadboard.

## **Introduction**

During the last decades there has been a decline in the number of physical experiments in engineering education. In many countries a trend may be observed towards an increased use of

simulators which frequently replace physical experiments<sup>1</sup>. However, physical experiments are important elements in science, engineering and technical education<sup>2</sup>. They allow learners to ascertain if the laws posed by scientists like Ohm and Kirchhoff correspond with nature thereby making it possible to study the limitations of these physical laws and other mathematical models. Physical experiments also enable learners to experience common differences between the physical world and simulations based on relevant mathematical models. Hands-on experience is above all of crucial importance for engineers working in the electrical domain in particular. Unfortunately, experiments are an expensive teaching method compared to simulations and other methods of instruction. For safety and security reasons access to traditional laboratories must be restricted to ensure that instructors can be present. Simulators are based on the physical laws and cannot be used to ascertain if mathematical models correspond with nature; simulators are, however, excellent tools for analysis and design when the limits of the laws are known.

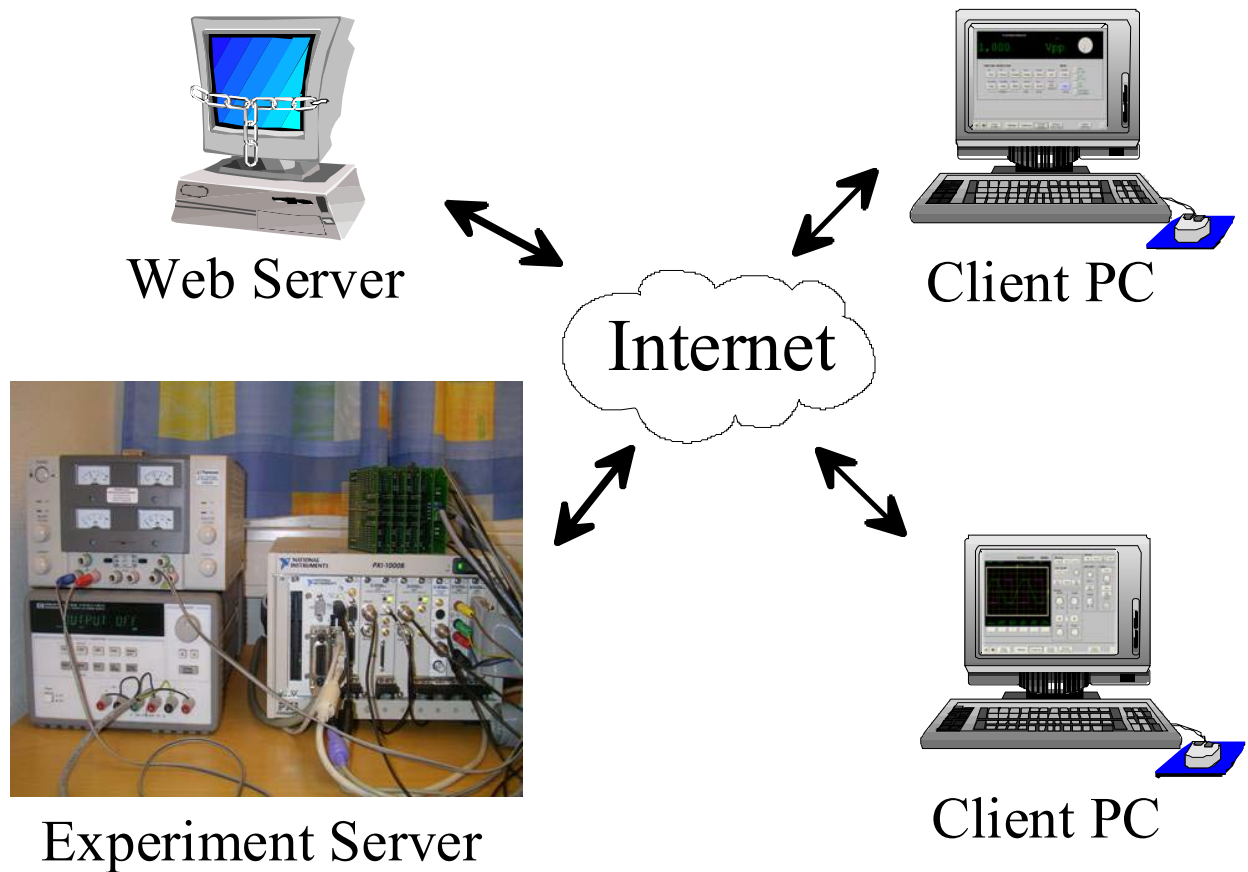
The traditional way of conducting physical experiments is to participate in lab sessions in university laboratories where students work in teams and receive tutorial help from instructors. Models for using information technology to enhance the learning experience for students who are asynchronous in time and/or space and which are also suitable for on-campus students have been presented earlier<sup>3</sup>. Many academic institutions provide web-based experimentation environments that support virtual and/or remote experiments<sup>4-10</sup>. Virtual experiments are simulations. The simulator program can either be run locally or in a server. Remote experiments, on the other hand, entail remote operation of distant experimental equipment. Home experimentation is an alternative method to be used for physical experiments which only require affordable devices such as a multi-meter and/or a soundcard-based oscilloscope<sup>11-13</sup>. However, these instruments are only adequate for elementary experiments.

A remote electronics laboratory has been set up at Blekinge Institute of Technology (hereafter referred to as BTH), Ronneby, Sweden. The laboratory emulates a typical traditional university electronics laboratory used in undergraduate education. Using a circuit assembly robot and instruments located in Ronneby students can use remote control to manipulate components and assemble circuits to perform experiments. The idea is to demonstrate how experimental activities which are already acknowledged to be an excellent didactic method can be applied outside the traditional university laboratory. Papers presenting earlier versions of the remote laboratory providing resistors, capacitors, and inductors have already been published<sup>14-16</sup>. The version presented in this paper adds active components such as transistors and operational amplifiers. The number of circuit nodes is also greater than in earlier versions.

### **The laboratory is a client/server application in which the Internet is used as the communication infrastructure**

The remote laboratory is illustrated in Figure 1. The experiment server in the photo to the left is located in a small storeroom equipped with only a mains outlet and network socket. A controller and the instruments are plugged into a PXI chassis (PCI Extensions for Instrumentation)

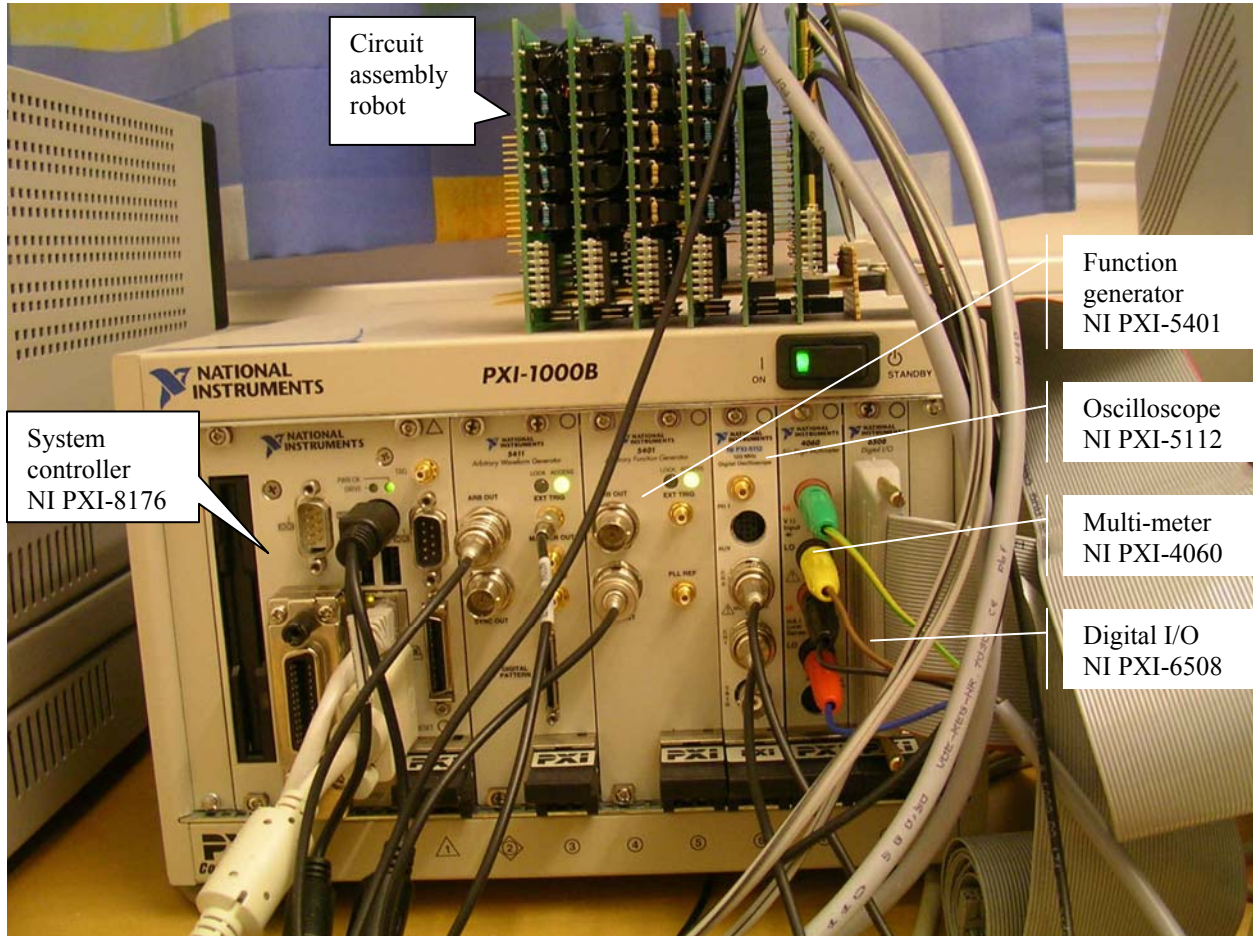
manufactured by National Instruments. The card stack on the top of the chassis is the circuit assembly robot. The two desktop units to the left in the photo in Figure 1 are power supplies. The upper unit feeds the system control electronics; the lower supply, on the other hand, is an E3631A produced by Agilent Technologies; this can be used in circuits. The client software is an ActiveX control embedded in an html page. It can be downloaded from the laboratory web server using MS Internet Explorer 5.5 or a later version. Registered students around the world can perform physical experiments around the clock or participate in regular lab sessions supervised by an instructor with the aid of MS Netmeeting or some other means of communication. Guest users are invited to test the laboratory. A 56-kbit/s modem is all that is required. A reservation system is also provided. Teachers can make reservations for regular lab sessions; they can also make a set of components available for each session.



**Figure 1. The remote laboratory at BTH. The server accommodates up to eight simultaneous users.**

The system controller shown in Figure 2 is an embedded PC; the other plug-in boards in the PXI chassis are instruments produced by National Instruments. The circuit assembly robot is the card stack on the top of the chassis. Thus, it is not a mechanical device but a switching matrix consisting of relays, sockets for components, and instrument connectors. The relays making

connections between the pins of the sockets and the connectors are controlled from the digital I/O board in the chassis. It is possible to assemble a circuit with up to 16 nodes by engaging a number of relays. The relays are selected from the DIP 14 series reed relays manufactured by Clare featuring typical  $2 \cdot 10^8$  operations. Later on a software module checking the relay performance will be added. The stack contains two types of boards, one for components and one for connecting the instruments. Capacity in terms of the number of on-line components can be increased by adding more component boards. The card stack shown in Figure 2 is large enough to accommodate components required for one or two course at undergraduate level. The teacher or a member of the lab staff mounts the components to be used in the sockets.

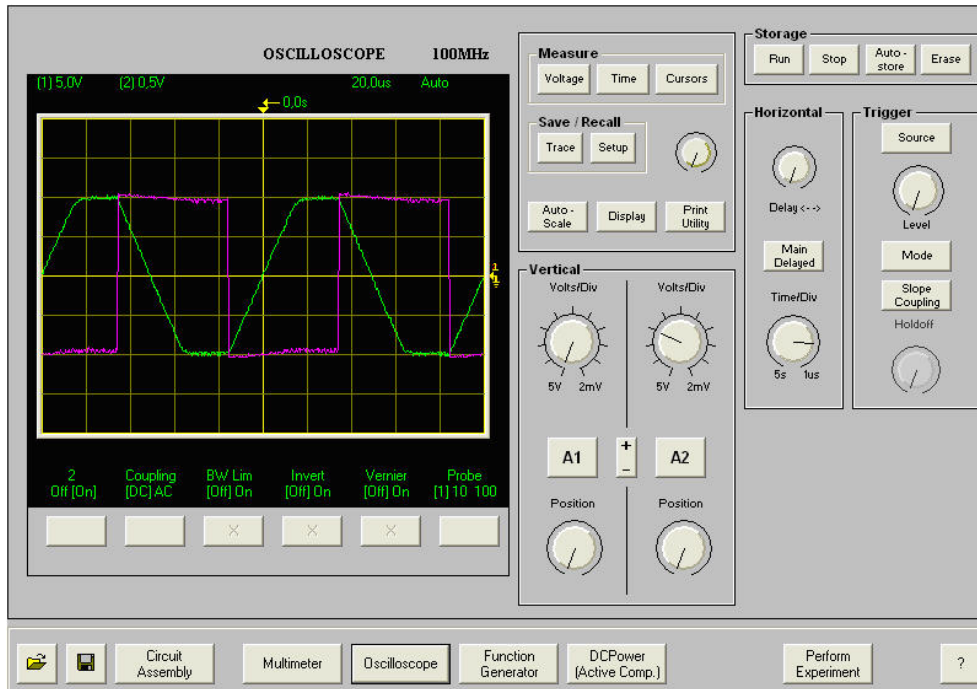


**Figure 2. System controller, computer-based instruments, and circuit assembly robot. It is to be noted that the front panels contain no control knobs only connectors. The instruments also have virtual front panels for display on the client PC screen.**

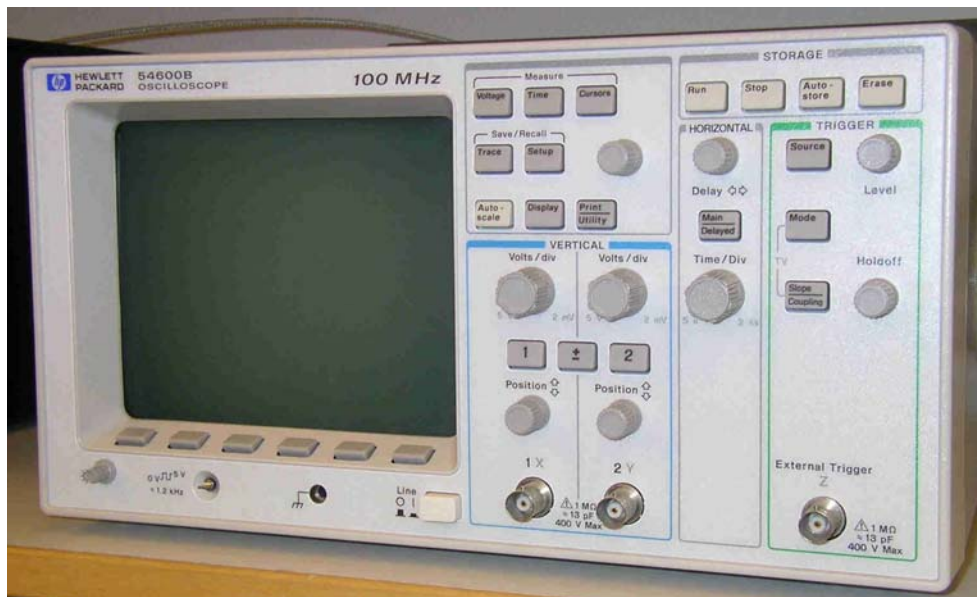
The virtual front panel of the oscilloscope is presented in Figure 3. Students use the mouse to rotate the knobs and press the buttons to set the instruments. The traditional laboratories at BTH are equipped with 54600B desktop oscilloscopes produced by Agilent Technologies (see Figure



4). The similarity between the two oscilloscope panels is an intentional design feature. Students have no problem using the real front panel with hard buttons when they are used to the virtual one. Alternative panels for other oscilloscope models will be developed in the future.

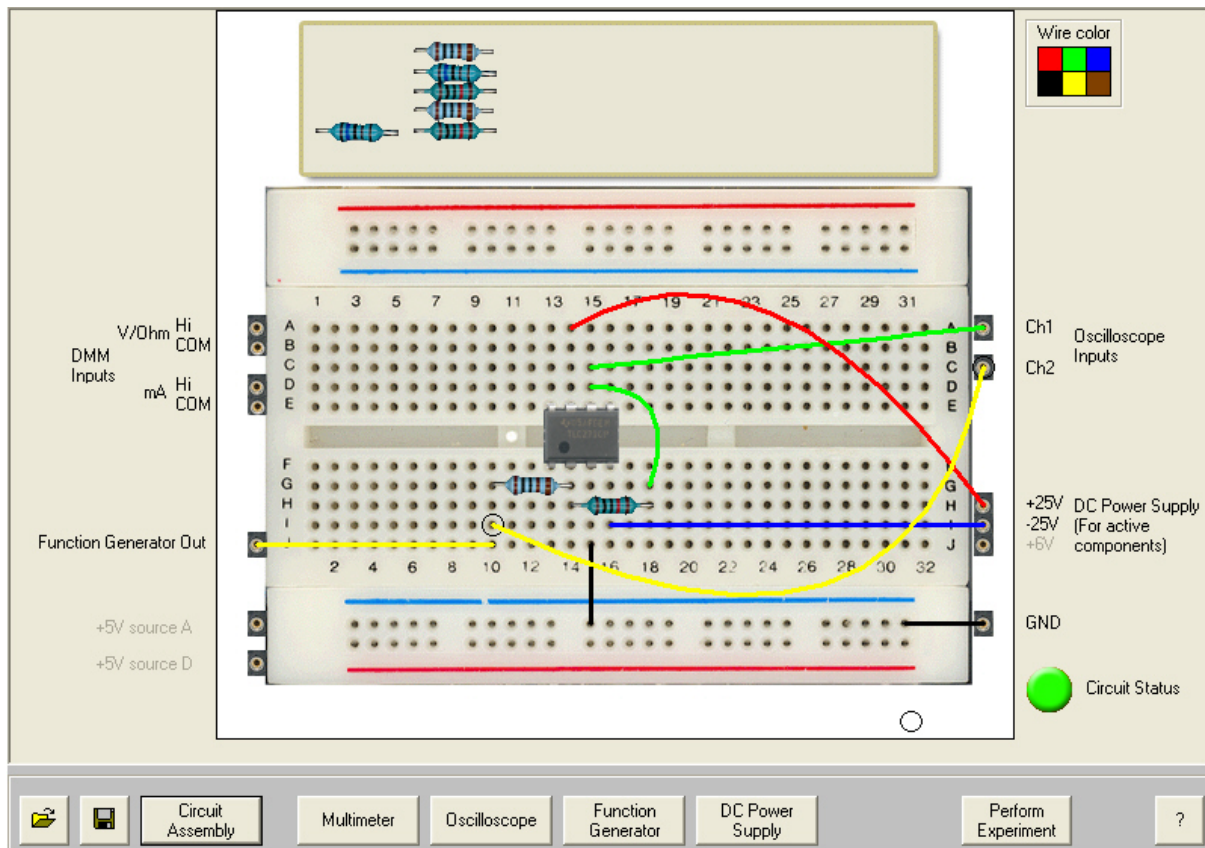


**Figure 3.** An oscilloscope virtual front panel displaying the slew rate of the uA741 operational amplifier in the circuit on the breadboard illustrated in Figure 5.



**Figure 4.** The oscilloscope used in traditional laboratories at BTH.

Figure 5 shows the virtual breadboard used by students to control the circuit assembly robot<sup>17-18</sup>. The component box at the top of the breadboard shows the components provided by the teacher for a particular lab session. These are photographs of real components mounted in the robot. Students use the mouse to position each virtual component to be used on the breadboard and to do the wiring to assemble the circuits and connect the instruments. A pattern recognition algorithm matches the wiring on the breadboard with the matrix pattern and produces a list similar to a PSpice net list describing the circuit assembled.



**Figure 5. Virtual breadboard with an operational amplifier circuit.**

In a traditional laboratory it is often possible to detach the breadboard together with the wired circuit from the supporting chassis and store it in a safe place; however, the instrument connections must first be removed. This laboratory has the same feature controlled by buttons furthest to the left in the row below the virtual breadboard in Figure 5. The instrument settings and a net list defining the desired circuit are sent to the server when the user presses the *Perform Experiment* button to the right. As soon as the user request is dequeued on the server side, a virtual instructor checks the net list in order to ascertain that the desired circuit is safe. When this is verified, the circuit is formed, the instruments are set, the test probes are connected, and the

voltage is applied. The outcome is then sent back to the client computer and displayed on the screen. In all other cases, an error message is returned.

The server software is written in LabVIEW 7 (Laboratory Virtual Instrument Engineering Workbench) and C++<sup>19</sup>. The graphics module of the client software is written in Visual Basic 6 and Component Works produced by National Instruments. The logic module is written in C++. MySQL and PHP are used for the reservation system.

### **A virtual instructor checks the desired circuits to avoid damage**

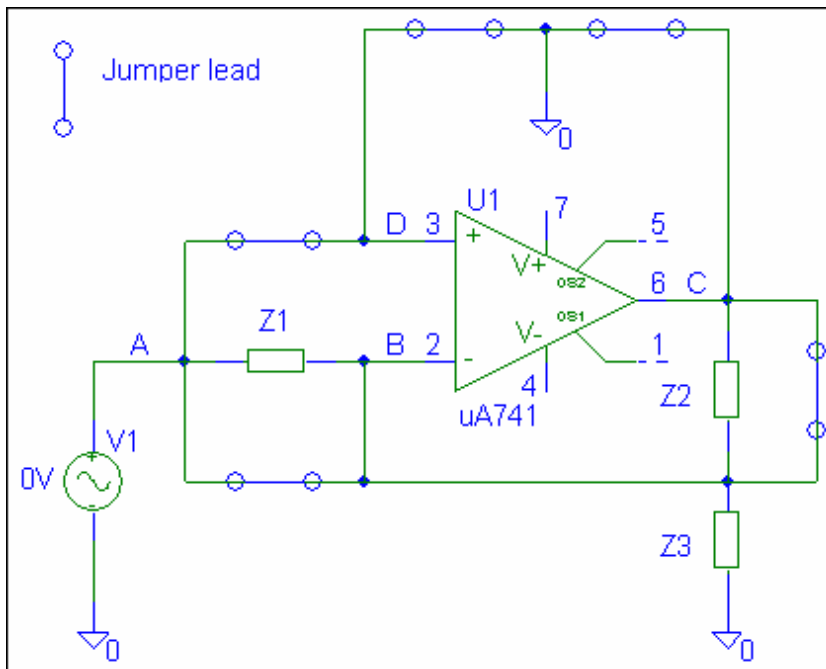
In a traditional laboratory the instructor checks each circuit formed to avoid possible damage. If the circuit is safe, students are allowed to continue by activating the source. What happens in the remote laboratory if a user forms a circuit which is potentially destructive, e.g. could overload a resistor? It would, of course, be fatal if a resistor were to burn as the experiment server is normally left unattended. Users would in all probability observe strange results in subsequent experiments involving the destroyed component. If a user damages a component or an instrument the teacher is to blame and not the student. To avoid damage to components and/or instruments, the teacher defines maximum source voltages and all circuit loops which are possible to create without overloading any component. These circuit loops are listed in net lists called checklists. Thus the checklists specify safe circuits possible to create using the components selected by the teacher and the physical wiring in the switching matrix. All subsets of a checklist must also represent safe circuits but still a number of checklists are usually required in order to maximize the freedom of the user and allow harmless mistakes. The virtual instructor routine compares each desired circuit description with all the checklists and acknowledges the circuit when it matches at least one list or a subset of a list. The maximum output voltage of the function generator is  $\pm 10$  V into a high impedance load; the power limit of the resistors provided is 0.6 W. Thus the minimum resistance in DC loops should be 170  $\Omega$ . An example of a checklist for experiments on operational amplifiers is shown in Table 1. A diagram of a corresponding circuit is shown in Figure 6. The items denoted Z1 – Z3 are sub-circuits used to show how components are to be introduced into a desired circuit. An example is illustrated in Figure 7, where Z1 represents the three resistors that can be connected between the nodes A and B in accordance with the checklist in Table 1.

Using the checklist in Table 1 and only five nodes it is possible to form both non-inverting and inverting operational amplifier circuits such as the circuit in Figure 5. The two wires, for example, connecting pin 3 of the operational amplifier (uA741) to GND in Figure 5 instruct the circuit assembly robot to insert the jumper between the nodes D and 0 (SHORTCUT\_S4) in Figure 6. The relay furthest to the left in Figure 7 will be engaged to insert the 1 k $\Omega$  resistor connected to pin 2 of the operational amplifier in Figure 5 etc. The function generator is short-circuit protected; but if by mistake the user should happen to wire it to GND, the two jumpers between nodes A and 0 will be inserted. The user is free to connect high impedance probes to any test point; the multi-meter set for current measurements is, however, low impedance and it

could be dangerous to connect. Therefore, it is only allowed to replace a jumper e.g. in Figure 6 the jumper between the output of the operational amplifier and the ground indicates that it is permitted to measure the shortcut current of the amplifier.

**Table 1. Checklist for operational amplifier experiments. The notation is similar to that used in PSpice.**

VFGENA_FGENA1	A 0	max:5
OP_OP1	NC B D -25V NC C +25V NC	UA741
VDC+25V_1	+25V	vmax: 15 imax: 0.5
VDC-25V_2	-25V	vmax: -15 imax: 0.5
R_R1	A B	1k
R_R2	A B	1.6k
R_R3	A B	10k
R_R4	B C	1k
R_R5	B C	1.6k
R_R6	B C	10k
R_R7	0 B	1k
R_R8	0 B	10k
SHORTCUT_S1	A B	
SHORTCUT_S2	A D	
SHORTCUT_S3	B C	
SHORTCUT_S4	0 D	
SHORTCUT_S5	0 C	



**Figure 6. The checklist interpreted as a circuit. Z1 is defined in the figure below.**



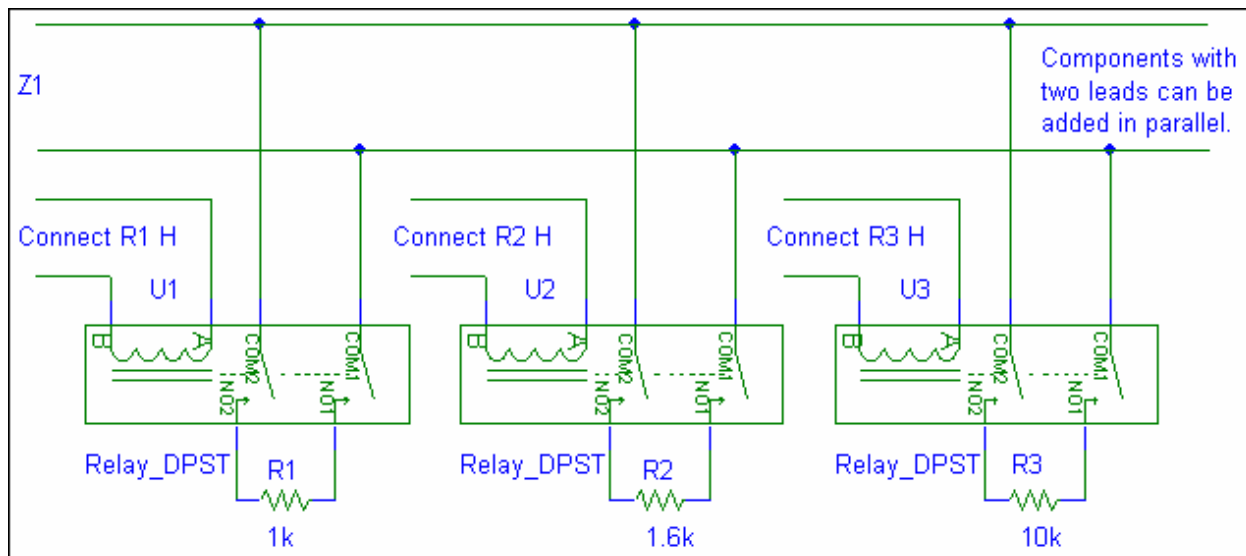


Figure 7. Z1 definition. The relays are controlled from the digital I/O board in the PXI chassis.

## Performance

The equipment provided comprises:

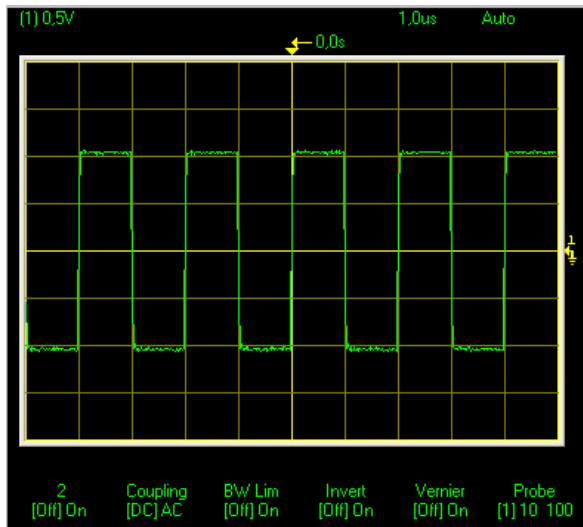
- A dual channel oscilloscope, whose virtual front panel mimics Agilent 54600B and most of its functions with the exception of ‘run mode’ are supported. The plug-in board comprises a 100 MS/s 8-Bit digitizer NI PXI-5112.
- A digital multi-meter. Only a preliminary virtual front panel of a multi-meter is currently available. Floating two-terminal measurements are supported. The plug-in board is the 5½-Digit multi-meter NI PXI-4060.
- A triple DC power supply Agilent 3136A controlled through GPIB.
- A function generator, whose virtual front panel mimics Agilent 33120A. Only standard waveforms are currently supported. The plug-in board is the 16 MHz function generator NI PXI-5401.
- A circuit assembly robot with 16 nodes. Seven of these are denoted A – F and 0 and can be used as test points for the oscilloscope and the multi-meter. A component board in the switching matrix comprises:
  - 10 sockets for jumpers or components with two leads
  - two 20-pin sockets for components with more than two leads
  - 10 double-pole single-throw reed relays.
- Components selected by the teacher.

The time-sharing scheme which is used to allow simultaneous access to one server for up to 8 client PCs and with an acceptable response time imposes restrictions on the time period allowed

for each experiment. The time period allowed for any one measurement is currently 0.1 s. However, in electronics courses the teacher can easily choose an appropriate time scale for the experiments by selecting proper values for the components to be used by the students. The time settings on the oscilloscope used in circuit analysis and low-frequency electronics experiments normally range between 1  $\mu$ s/division and 10 ms/division. Thus, a single shot is usually 10  $\mu$ s to 100 ms because the time axis is 10 divisions on most oscilloscopes.

The laboratory is designed for low frequency experiments. Circuits assembled using the switching matrix include longer wires than those found in circuits assembled by an experienced person on a conventional breadboard. The former circuits can perhaps be compared to those made by the average student. Extra wires and relays limit the bandwidth somewhat; the oscilloscope time base is currently restricted to 1  $\mu$ s/division. A square wave signal from the function generator is shown using the maximum time resolution in Figure 8.

The complexity of the switching matrix increases with the number of circuit nodes provided. If a desired circuit has N nodes and the user wish to add one resistor there are  $N \cdot (N-1)/2$  branches into which it can be introduced. There are 120 possibilities for 16 nodes; the BTH laboratory, however, is designed for undergraduate education where such flexibility is not necessary. The laboratory can only accommodate experiments used in engineering education. In such experiments only a small number of components are required, and the circuits are not very complex e.g. they usually have one input and one output and a signal flow from left to right; certain loops are not permitted for safety reasons. However, the checklists should be designed to allow maximum freedom for students to make mistakes.



**Figure 8. A square wave signal from the function generator displayed in the maximum time resolution on the oscilloscope. The fidelity of the response is good.**

The color code of the resistors is difficult to read but this is also the case in real life. If the user cannot interpret the code of a resistor it must be put on the breadboard and measured using the multi-meter. In some traditional laboratories magnifiers are provided; perhaps a virtual magnifier should be introduced?

## Conclusions

Apart from the fact that each student or team of students using a client PC works in a virtual environment with no face-to-face contact with the instructor or other students in the laboratory, the difference between a lab session in the remote laboratory described here and a session in a traditional laboratory is that it is not possible for users to manipulate the components and the wires with their fingers in a remote laboratory. However, the latter constitutes a new educational tool which is ready for use in undergraduate education and in secondary schools as well as in vocational training and life-long learning. Universities and other teaching organizations are invited to test the laboratory and conduct experiments or regular laboratory sessions using their own components and learning material in the language of their choice. Expensive laboratory equipment can be provided for students with no time or space limitations. Remote experiments will not replace traditional lab sessions but supplement them and make them more useful. It may be possible to compensate for the reduction in the number of lab sessions during the past few decades and even improve electronics courses without incurring any increase in cost. New more effective teaching methods may emerge. Experiments can, for example, easily be integrated into lectures. It is widely recognized that experiments constitute an excellent teaching method and more effective and exciting methods may contribute to increased numbers of students in electrical engineering education. The laboratory is open to guest users when it is not in use in regular courses. The address of the laboratory web site is: <http://distanslabserver.its.bth.se/>.

## Bibliography

1. Schmid, C., Eikaas, T.I., Foss, B., Gillet, D., "A REMOTE LABORATORY EXPERIMENTATION NETWORK", *Proceedings of the 1<sup>st</sup> IFAC Conference on Telematics Applications in Automation and Robotics*, Weingarten, Germany, July 24 - 26, 2001.
2. Berry, F.C., DiPiazza, P.S., Sauer, S.L., "The Future of Electrical and Computer Engineering Education", *IEEE TRANSACTIONS ON EDUCATION*, Vol. 46, No. 4, November '03, pp. 467-476.
3. Latchman, H. A., Saltzmann, Ch., Gillet, D. and Bouzekri, H., "Information Technology Enhanced Learning in Distance and Conventional Education", *IEEE TRANSACTIONS ON EDUCATION*, Vol. 42, No. 4, November '99, pp. 247-254.
4. Joler, M., Christodoulou, C.G., "Virtual laboratory instruments and simulations remotely controlled via the internet", *Antennas and Propagation Society, 2001 IEEE International Sym, Boston, USA*, vol. 1, July 8 – 13, 2001, pp. 388-391.
5. Swain, N.K., Swain, M., Anderson, J.A., "Integration of Virtual Instruments into an EET Curriculum", *Proceedings of the 2004 ASEE Annual Conference, Salt Lake City, USA*, June 20 - 23, 2004.
6. Söderlund, A., Ingvarson, F., Lundgren, P., Jeppson, Kjell, "THE REMOTE LABORATORY – A NEW

- COMPLEMENT IN ENGINEERING EDUCATION”, *Proceedings of the ICEE 2002 Conference in Manchester, U.K.*, August 18 – 21, 2002.
7. Plummer, M.C., Bittle, C., Karani, V., ”A Circuits II Laboratory Accessible by Internet”, *Proceedings of the ICEE 2002 Conference in Manchester, U.K.*, August 18 – 21, 2002.
  8. Gillet, D., Geoffroy, Zeramdini, K., Nguyen, A.V., Rekik, Y., Piquet, Y., “The Cockpit: An effective Metaphor for Web-based Experimentation in Engineering Education”, *Int. J. Engng ED.*, Vol 19, No. 3, pp.389-397, 2003.
  9. Nedic, Zorica, Machotka, J., Nafalski, A., “REMOTE LABORATORIES VERSUS VIRTUAL AND REAL LABORATORIES”, *Proceedings of the 33<sup>rd</sup> ASEE/IEEE Frontiers in Education Conference, Bolder, USA*, November 5 – 8, 2003.
  10. Auer, M., Pester, A., Ursutiu, D., Samoila, C., “Distributed Virtual and Remote Labs in Engineering”, *Proceedings of the ICIT’03 International Conference on Industrial Technology*, Maribor, Slovenia, December 10 - 12, 2003.
  11. Long, J.M., Florance, J.R., Joordens, M., “The use of Home Experimentation Kits for Distance Students in First-Year Undergraduate Electronics”, *Proceedings of the 2004 ASEE Annual Conference, Salt Lake City, USA*, June 20 - 23, 2004.
  12. Bhunia, C., Giri, S., Kar, S., Haldar, S., Purkait, P., “A Low-Cost PC-Based Virtual Oscilloscope”, *IEEE TRANSACTIONS ON EDUCATION*, Vol. 47, No. 2, May ’04, pp. 295-299.
  13. Gerdin, G., “Virtual Instruments for Distance Learning”, *Proceedings of the 2002 ASEE Annual Conference, Montreal, Canada*, June 16 - 19, 2002.
  14. Gustavsson, I., "A Remote Laboratory for Electrical Experiments", *Proceedings of the 2002 ASEE Annual Conference, Montreal, Canada*, June 16 - 19, 2002.
  15. Gustavsson, I., "User-defined Electrical Experiments in a Remote Laboratory", *Proceedings of the 2003 ASEE Annual Conference, Nashville, USA*, June 22 - 25, 2003.
  16. Gustavsson, I., Zackrisson, J., Olsson, T., “Traditional Lab Sessions in a Remote Laboratory for Circuit Analysis”, *Proceedings of the 15<sup>th</sup> EAEEIE Annual Conference on Innovation in Education for Electrical and Information Engineering, Sofia, Bulgaria*, May 27 – 29, 2004.
  17. Johnson A., “NUTS AND VOLTS: A WEB-BASED HANDS-ON ELECTRICAL AND ELECTRONICS REMOTE, WIRING AND MEASUREMENT LABORATORY” *Proceedings of the 2002 ASEE Annual Conference, Montreal, Canada*, June 16 - 19, 2002.
  18. Hodge, H., Hinton, S., Lightner, M., “Virtual Circuit Laboratory”, *Journal of Engineering Education*, October 2001.
  19. Naghedolfeizi, M., “Survey of LabVIEW Technologies for Building Web/Internet-Enabled Experimental Setups”, *Proceedings of the 2002 ASEE Annual Conference, Montreal, Canada*, June 16 - 19, 2002.

## Biography

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