Telemanipulator for Remote Wiring of Electrical Circuits

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Abstract—**Nowadays, students want extended access to learning resources and increased freedom to organize their learning activities. Remote access to laboratories enables students to perform physical experiments on their own 24/7. It is easy to control most electronic instruments remotely but some kind of telemanipulator is often required. The Signal Processing Department (ASB) at Blekinge Institute of Technology (BTH) has created an online lab workbench for electrical experiments, mimicking and supplementing workbenches in local laboratories. Students being at home can, for example, use the online workbench in order to prepare themselves for supervised lab sessions and/or participate in such sessions taking place in a local laboratory. A virtual breadboard is used to control a telemanipulator (switching matrix) performing the circuit wiring. Together with virtual front panels depicting the front panels of the desktop instruments, it gives distant students the impression that they are working in a real laboratory. This paper describes the virtual breadboard and switching matrix combination, which can be used in many switching applications.**

Index Terms—**Electronics, Remote labs, Switching matrix, Workbench**

Figure 1.   Workbench in a local electronics laboratory at BTH

I.   INTRODUCTION

At The Department of Signal Processing (ASB), Blekinge Institute of Technology (BTH) an online lab workbench for electrical experiments has been created. It mimics and supplements workbenches in traditional laboratories [1]. For several years now, the workbench has been used concurrently with on-site ones in regular, supervised lab sessions. The students are encouraged to use it on their own on a 24/7 basis, for example, in preparation for supervised sessions. Many students can use the workbench simultaneously and together with the traditional workbenches it is forming an Open Laboratory. The aim of a project known as VISIR (Virtual Systems in Reality) founded by ASB at the end of 2006, is to disseminate the online lab workbench using open source technologies [2]. Two universities abroad have implemented such workbenches and are now using them in their own courses and other universities are interested in joining. One important goal is to create a template for a grid laboratory where the nodes are workbenches, located at different universities [3].

Fig. 1 shows a workbench in a traditional electronics laboratory at BTH. The cables from the instruments connect to sockets on the box carrying the detachable solderless breadboard. These sockets connect to wire
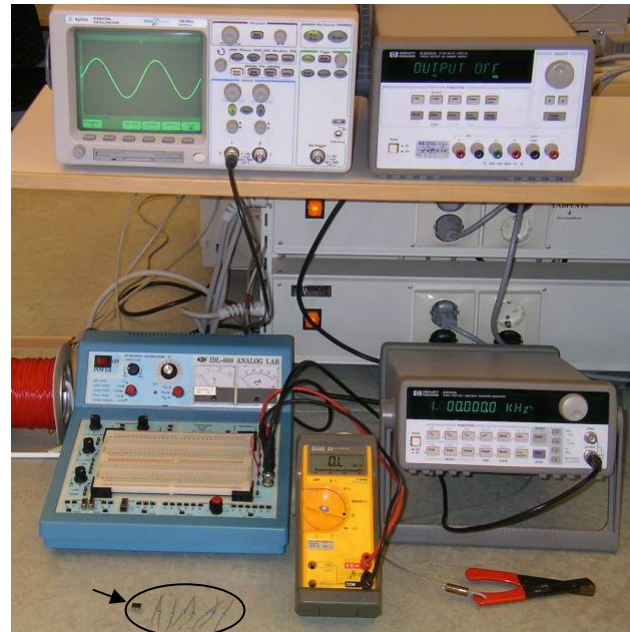
holes at the sides of the breadboard making it easy to use wires to probe a test circuit wired on the breadboard. The small components (an operational amplifier and 8 resistors) in the lower left corner of Fig. 1 at the arrow are the component set provided by the instructor to be used in a certain lab session. Most instruments in an electronics laboratory have a remote control option but the breadboard has not. To open a workbench for remote access a wiring manipulator possible to control remotely is required. A switching matrix equipped with electro-
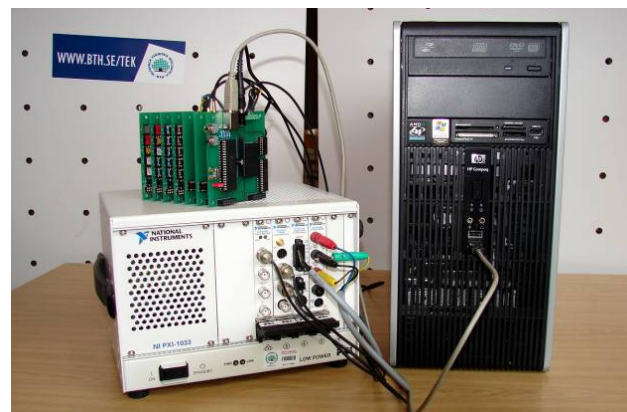

Figure 2.   Online workbench at BTH

mechanical relays can serve as such a device [4, 5]. Fig. 2 shows an online workbench at BTH. The switching matrix for remote wiring of electrical circuits is shown in the upper left side of the photograph in Fig. 2. It is the card stack on the top of the PXI chassis that contains the instruments. PXI (PCI eXtensions for Instrumentation) is an international standard [6]. The chassis and the instruments in Fig. 2 are manufactured by National Instruments. In the switching matrix the relays are arranged in a three dimensional pattern together with instrument connectors and component sockets. The component set, which is provided by the instructor in a lab session in a local laboratory, is installed in the component sockets at the edge of some of the boards of the switching matrix. Virtual front panels depicting the front panels of the desktop instruments and a virtual breadboard displayed on the computer screen give distant students the impression that they are working in the real laboratory. A workbench opened in this way can be, for example, a node in a grid laboratory where the virtual breadboard and relay switching matrix combination can be a wiring service, Fig. 3. This paper focuses on the switching matrix designed at ASB. The new version 4.1 described here has recently been tested and will soon be online. All former versions have been used in regular education at BTH and elsewhere. An early version designed in 2001 has been discussed in a comparative overview [4].

A set of components provided for a certain lab session is displayed in a component box at the top of the virtual breadboard. In Fig. 4, the components have already been moved to the breadboard and a circuit wired. The wire holes at the sides of the virtual breadboard connects to the instruments mimicking the box carrying the detachable breadboard in Fig. 1 but the BNC sockets and the instrument cables are omitted. A lab client routine transforms the virtual circuits that an experimenter wires on the breadboard, using the mouse, into a net list similar to PSPICE net lists. In the workbench, a virtual instructor compares each net list with a number of so called checklists, which define the circuits permitted and define the maximum output voltages allowed from the sources. The teachers create these rules for the virtual instructor. If an instrument or some component in the switching matrix happens to be damaged a teacher is to blame not the student who caused the damage. If the net list passes the check, a *CreateCircuit* command is sent to the switching matrix software driver Circuit Builder in the workstation PC. This driver is written in LabVIEW.
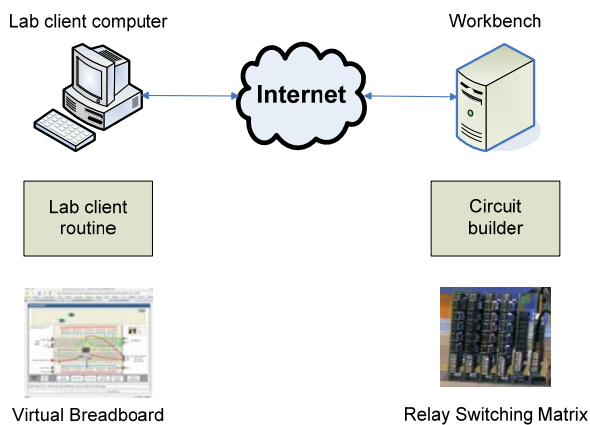

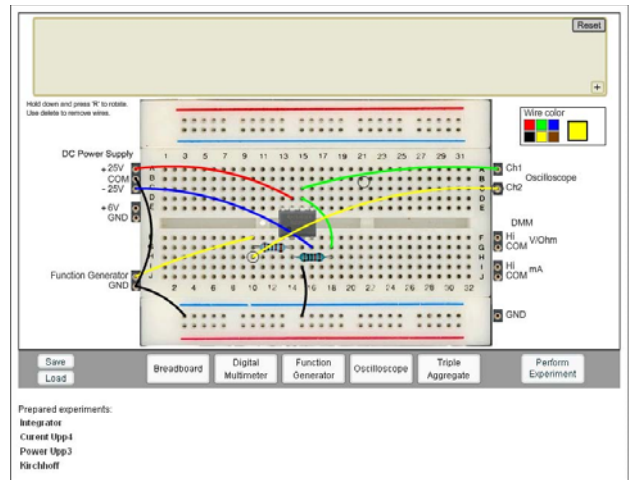Figure 3. Circuit wiring service

Figure 4. Virtual breadboard

Please note that the virtual components displayed correspond to real components installed in the matrix. Thus, it is not possible to change, for example, the resistance of a virtual resistor from 1 kΩ to 10 kΩ as it is in a simulator. If these two values are required, two resistors must be provided both virtually in the component box and physically in the switching matrix. If you have good eyes, it should be possible to read the color code of the resistors displayed. In fact, good eyes are required to read the color code of the physical resistors as well because the 0.6 W resistors used are small.

A real breadboard is, of course, more flexible but cannot be controlled remotely as the switching matrix can. In the next section, the switching matrix is compared with a solderless breadboard. The third section describes the switching matrix hardware in such detail that it should be possible to assess its circuit wiring capacity. Other characteristics are presented in the fourth section. The lab staff installs components and configures the switching matrix as is required by the teachers. In the fifth section the switching matrix configuration is discussed and an example is presented. The switching matrix operation is described in section six. The final section is conclusions and future work.

II. BREADBOARD VERSUS RELAY SWITCHING MATRIX

An electrical circuit consists of a number of connected components and at least one source. A graph can be used to illustrate its structure. Fig. 5 shows a graph with 5 nodes and 10 branches. Each branch represents a component with two leads. The complexity of an electrical circuit increases with the number of nodes. A small virtual
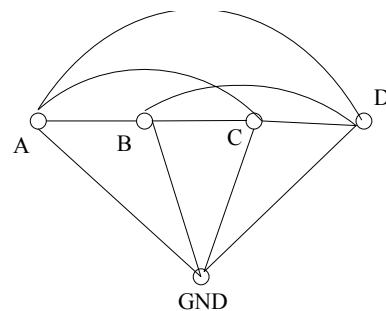

Figure 5. A graph with 5 nodes and 10 branches

breadboard and relay switching matrix combination with four nodes has been presented [5]. If a desired circuit has N nodes and if the experimenter wishes to add, for example, one resistor, there are N·(N-1)/2 branches into which it can be installed. This means 120 possibilities for 16 nodes. The number of circuits possible to wire on the breadboard shown in Fig. 1 is limited primarily by the number of components the instructor provides and is usually too high for a switching matrix of practical size [7]. However, in undergraduate lab exercises the students are expected to wire only simple circuits that are described in lab instruction manuals. Some other circuits possible to wire may be hazardous and should not be created. Trying to perform destructive experiments should cause an error message from the virtual instructor. Thus, the flexibility of the breadboard in Fig. 1 is not required. Is it sufficient if a switching matrix allows creation of the circuits in a number of instruction manuals? No, inexperienced students should be permitted to make, for example, wiring mistakes and get an opportunity to learn how to correct them. Apart from the circuits in the instruction manuals, a switching matrix should allow the student to create similar circuits that are safe as well.

In more advanced courses the students experiment with larger circuits. These students want the circuits to be prefabricated and ready to test. The virtual breadboard and switching matrix combination is still useful. The ready-made circuit to be tested can be, for example, a circuit board or a circuit wired on a conventional breadboard. The ready-made circuit should be positioned adjacent to the switching matrix, as shown in Fig. 6. In both cases the test points are wired to the switching matrix by the teacher. This circuit under test can, for example, be represented in the virtual component box as a 16 pin IC-chip where the pins are the test points or maybe source connections. These pin numbers should be found in the circuit drawing of the ready-made circuit. If the sources of the workbench are used to feed the ready-made circuit, the virtual instructor can supervise their voltages. Of course, combinations of the cases are also possible.

III. SWITCHING MATRIX HARDWARE

The switching matrix is a stack of PC/104 sized boards shown in Fig. 2. PC/104 is a common international standard for embedded systems [8]. The relays are arranged in a 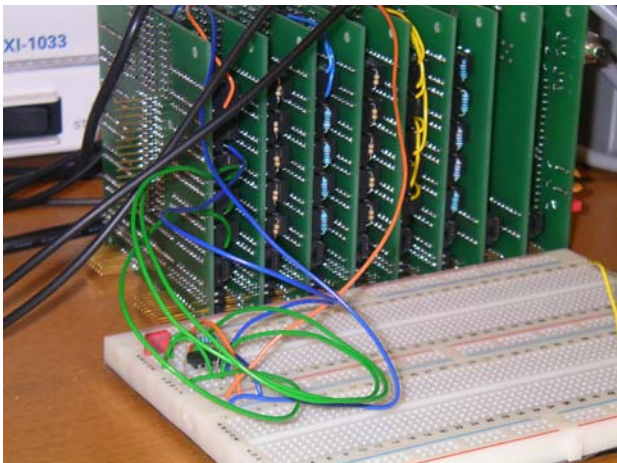three dimensional matrix pattern together with instrument connectors and component sockets. In this way, the relay switches are embedded into the circuit created limiting the length of the wires in order to gain bandwidth. The nodes of the switching matrix are propagated from board to board creating a node bus. The notation "node" refers to the fact that every conductor created by these stacked connectors can be a node in a desired circuit. The nodes are divided into two groups. One contains the nodes denoted A – I and 0. The other contains nodes denoted X1 – X6 and COM. The nodes of the first group can be connected to the multi-meter or the oscilloscope using one switch only.

The switching matrix should be positioned onto the instrument chassis as is shown in Fig. 2 to keep the instrument cables short. Putting the switching matrix into a closed case is not recommended because it should be easy to swap components and rewire branches. However, it is of vital importance to protect the switching matrix from non-qualified persons. The microprocessors and other digital circuits are sensitive to, for example, ESD (electro static discharge) and must not be touched. The foot-print of the workbench is small and a dark box room fitted with a mains outlet, an internet connection, and some air circulation is sufficient for it.

Three types of boards are defined so far; one for connecting sources, one for connecting other instruments and one for carrying components. A switching matrix usually contains one source board, two instrument boards, and a number of component boards. A matrix with one component board on the top is depicted in Fig. 7. The bottom board is the source board. It has inputs for a triple power supply e.g. NI PXI-4110 and a function generator e.g. NI PXI-5402. The instrument boards can be configured for connecting a low frequency instrument such as a multi-meter e.g. NI PXI-4070 or for connecting a high frequency one such as a dual channel oscilloscope e.g. NI PXI-5112. The component boards carry sockets where components can be installed. One component board can hold 10 components with two leads or as many components with more than two leads as can be installed in the onboard 20 pin IC socket. By adding more component boards to a switching matrix, the more components can be online.

The circuit diagrams of the boards are divided into two

Figure 6.   Fixed circuit connected to the matrix

Node connector

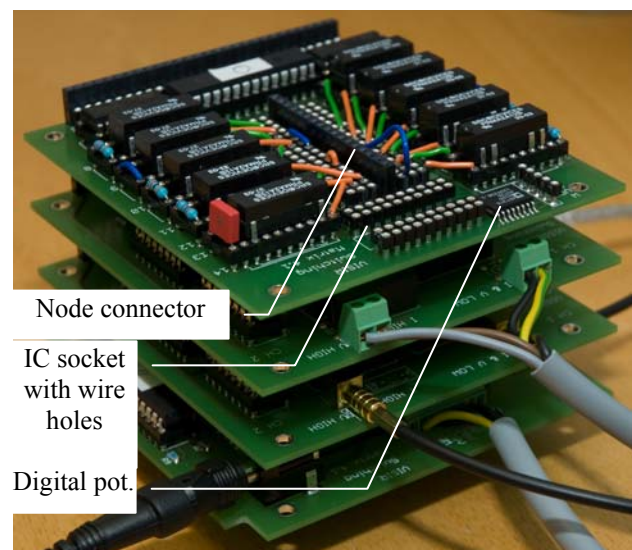IC socket with wire holes

Digital pot.

Figure 7.   A matrix with a component board on the top

sections. The diagrams below show the experimenter's section. The relay control section is omitted.

- Fig. 8 illustrates how the sources can be connected to the nodes. The FGENA input is expected to be connected to a function generator that is connected to protective ground. The DC source connector is expected to be connected to a triple power supply where the terminal "0" of the six volts supply is expected to be connected to protective ground. The COM terminal of the ± 20 V supply is expected to be floating.

- Fig. 9 shows how the instruments can be connected to the nodes. The layout of the printed circuit board is made in such a way that it can be configured either with MCX connectors for connecting, for example, an oscilloscope or with screw terminals for a multi-meter.

- Fig. 10 shows wire holes for connecting the relay switches to the nodes and to components with two leads on the component board. A 20 pin IC-socket for installing components with more than two leads and a digital potentiometer, AD7376, are omitted in the Figure. The potentiometer can be used in applications where its wiper resistance is not troublesome. The laboratory staff or the teacher installs components and wires much in the same way as on a physical breadboard to create the branches desired. Fig. 10 indicates how, for example, a resistor can be installed to be connected using relay number 3. The other ends of the relay switches can then be wired to any of the nodes.

Two types of microprocessors control the switching matrix; one matrix controller and one board controller on each board. The switching matrix controller hosted on the source board connects to the board controllers via an I²C bus.

IV. PERFORMANCE

The switching matrix has additional characteristics. Apart from being remote controllable it is possible to perform the circuit creation much faster than a human being does on a physical breadboard. In the workbench at BTH, the switching matrix is time-shared. Each time slice is set to 0.1 s. First, the desired circuit is created and then a delay of 25 ms is allowed for the switching transients to disappear before any measurements are made. The operate/release time for the relay switches is less than 2 ms. Thus approximately 70 ms can be used for measurements. The short time slice is a trade-off making it possible for BTH to support many experimenters simultaneously. However, in electronics, it is possible to perform the same experiment in different time scales by selecting the values of the components controlling the time constants properly.

The relays have reed switches. According to the data sheet the maximum carry current for them are 2 A and the minimum life expectancy is $3 \cdot 10^8$ operations meaning approximately two operations per second continuously for five years.

The switching matrix is designed for low frequency experiments. The layout of the board strips, the wiring on the component boards, and the number of boards in the stack limits the bandwidth of the switching matrix. The
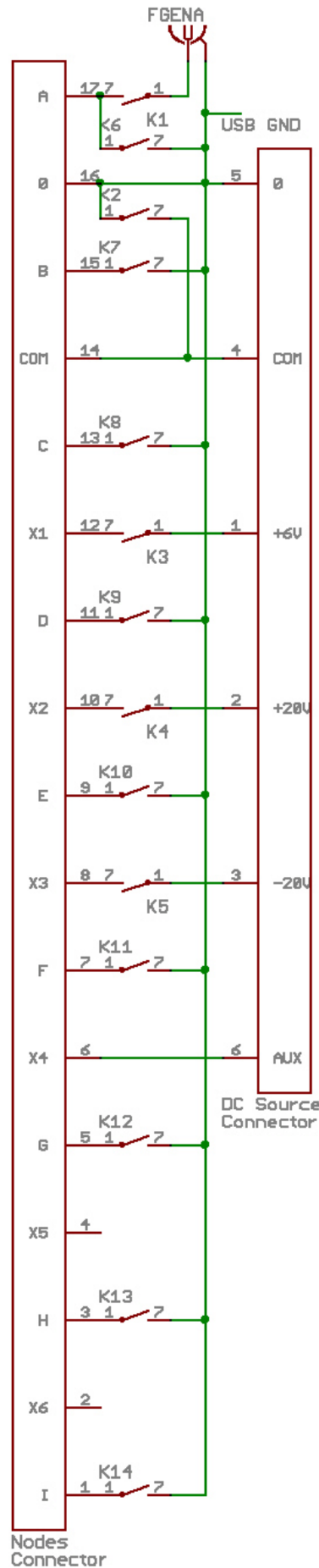

Figure 8. Experimenter section of the source board

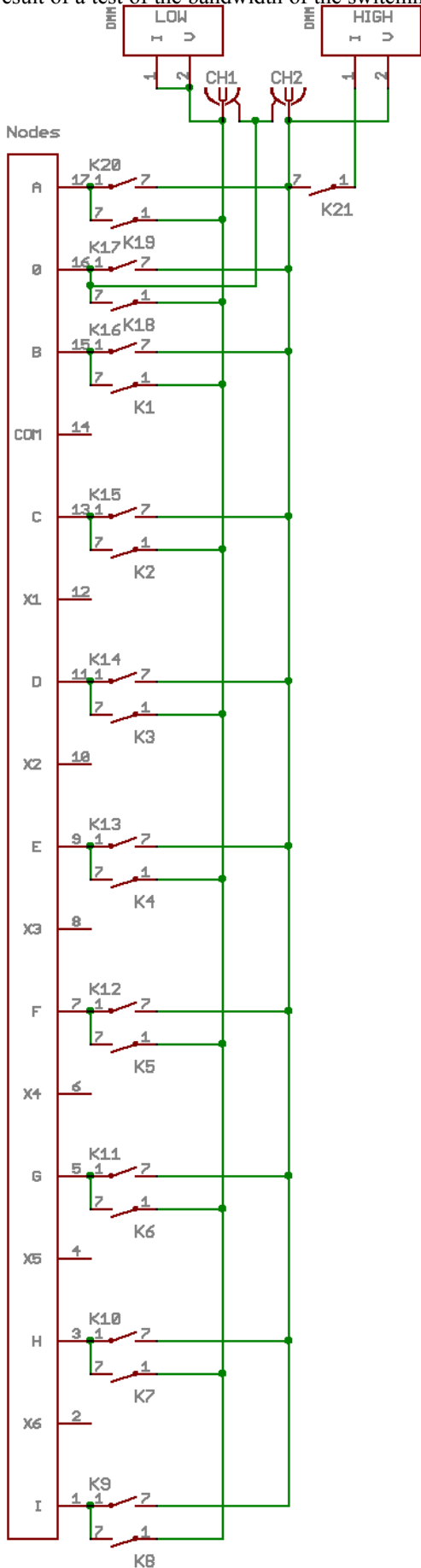result of a test of the bandwidth of the switching matrix in

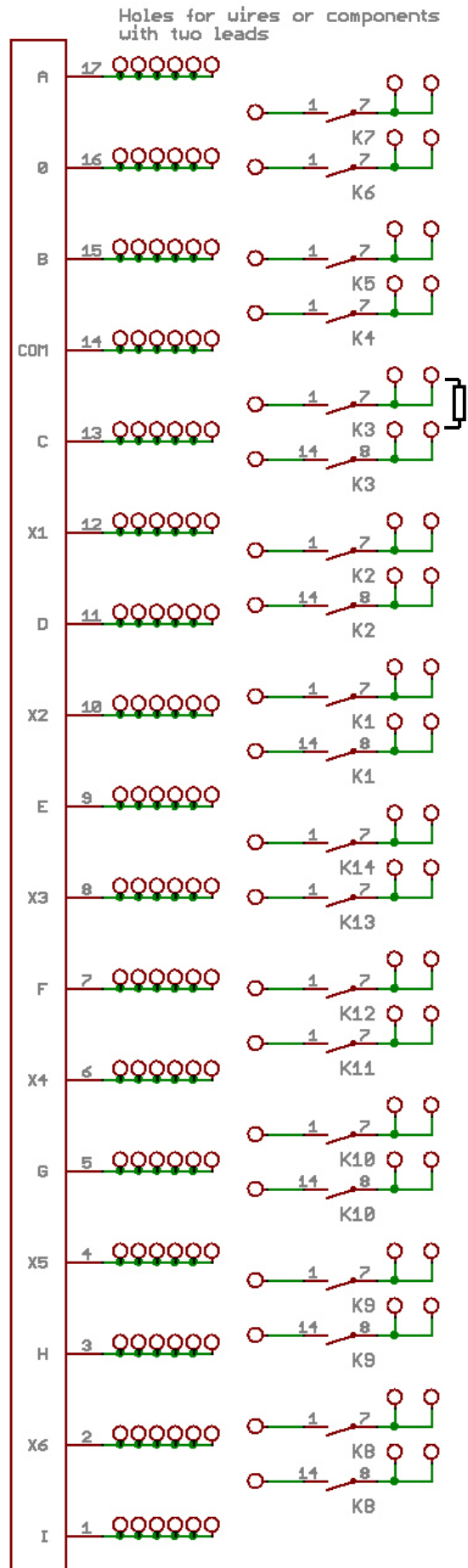Figure 9.   Experimenter section of the instrument board

Figure 10. Experimenter section of the component board

the workbench at BTH equipped with eight boards is shown in Fig. 11. The function generator, NI PXI-5402, is connected to the oscilloscope, NI PXI-5112, using this matrix. A 1 MHz square wave signal is displayed on the oscilloscope. Fig. 11 is a screen dump from a client PC.

V. CONFIGURATION

The maximum number of nodes of circuits possible to create using the current switching matrix is 17. The number of branches possible to install depends on the number of component boards in the matrix. Branches containing components with two leads include two relay switches as is shown in Fig. 12. The resistor in the figure could be replaced by two components or more in series if required. Branches containing instrument connectors includes only one relay switch. Components with more than two leads connect to the nodes using more relay switches than two. In this way the laboratory staff can form a pattern of branches and nodes from which the circuits of all online lab sessions can be created by engaging certain relays. At the same time the staff also lists the configuration data in a configuration file to be read by matrix driver.

The circuit diagram in Fig. 13 would be created if relays connecting all sources and all components installed in the current switching matrix configuration at BTH were engaged. The jumpers (JUMPER_LEAD) are zero ohm resistors used to connect nodes to each other and also used in relation to current measurements. In principle the measurement procedure is the same as when you measure a current in a circuit wired on a physical breadboard. The multi-meter set to current mode is low impedance and should only be allowed to replace jumpers. Thus, extra zero ohm branches together with extra nodes may be required to make it possible to measure currents in a circuit. The configuration in Fig. 13 supports four lab sessions in circuit analysis at BTH and experiments on a transistor and on an operational amplifier. However, there are still some spare nodes.

Would it be possible to create destructive circuits using the configuration in Fig. 13 by closing certain relay switches? Yes, it would. For example, the DC voltage drop over the inductor L3 ($R = 360\ \Omega$, $Imax = 5$ mA) must not exceed $360 \cdot 0.005$ V $= 1.8$ V DC. If you connect the +6V source set to 6 V to node A and insert the jumper
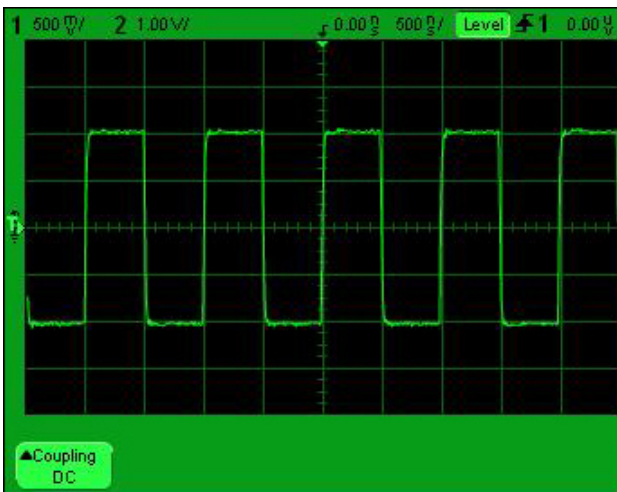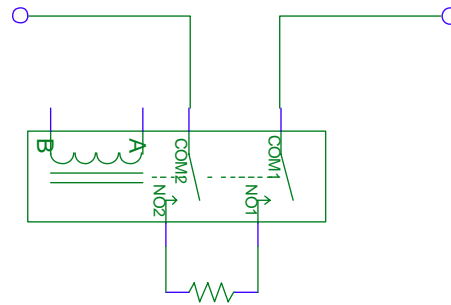

Figure 12. A matrix branch containing one component with two leads

between the nodes A and D then the voltage drop over L3 will be 6 V and the inductor will most likely be destroyed. An obvious way to avoid damage would be using a simulator to calculate expected voltages and currents in each desired circuit but in the workbench at BTH, another method is preferred. The virtual instructor compares the net list of the desired circuit with the checklists manually defined by the teachers delivering the courses that use the laboratory. An example of a checklist for simple experiments on operational amplifiers is shown in Table I. The corresponding circuit is shown in Fig. 14. All possible subsets of the circuit in Fig. 14 should be safe. If there is no checklist no circuit can be created. Thus, it is up to the teacher's imagination to create checklists, which will allow maximal freedom for the students.

The following procedure should be used to create a checklist. First, create drawings similar to the one shown in Fig. 14 of all the circuits that the student is to be permitted to create. Then list the components and check that they are installed in the switching matrix in such a way that the desired circuits can be created. Do not include the oscilloscope or the multi-meter. They are not listed in the checklists. The maximum ratings of any component in a circuit must not be exceeded. Two quantities are possible to adjust, either the output of the sources or the impedances in each current loop. In Table I the maximum source voltage has been set to 5 V and then the impedances have been selected accordingly.

VI. OPERATION

The Circuit Builder accepts four commands from the workbench PC:

- *RequestConfiguration* reads the configuration of the switching matrix written in the configuration file. It returns a list of
    - o the instruments connected to the matrix
    - o the installed components
    - o the installed jumpers

    Each item contains, type, characteristics and the nodes, to which it will be connected when the relay switches are closed, for example, resistor, 1000 ohm, A, B. Each item also has a unique id number.

- *CreateCircuit* sends a list of item id numbers defining the desired circuit. All relay switches are first opened removing all earlier connections. Then the relay switches connecting the items in the list are closed.
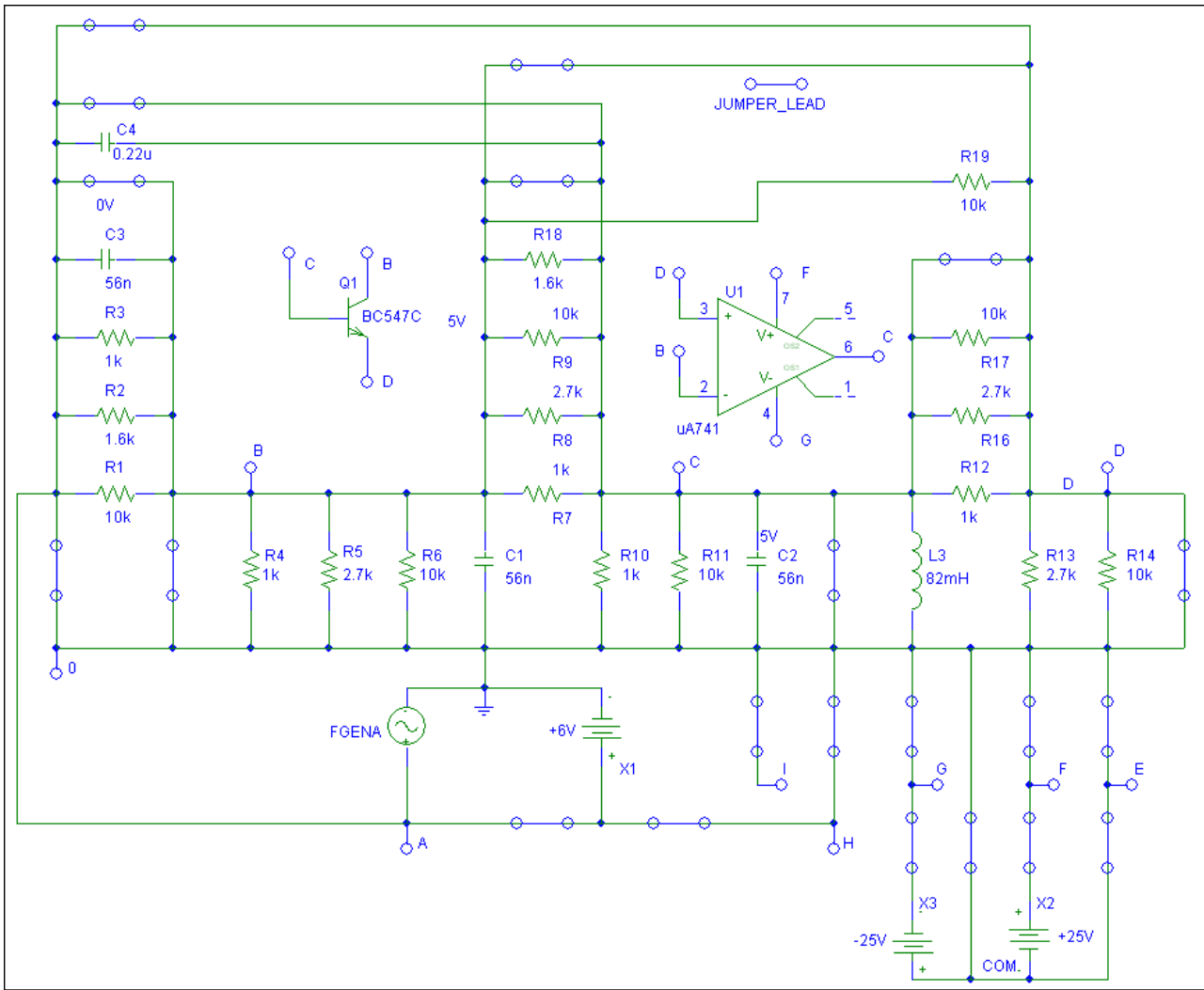

Figure 11. Bandwidth test

Figure 13. The current switching matrix configuration at BTH

- *ModifyCircuit* sends a list of item id numbers. If an item number listed is installed it will be removed from the circuit and vice versa.

Table I.   Checklist for operational amplifier experiments

VFGENA_FGENA1	A 0	max:5
OP_OP1	NC B D G NC C F NC	uA741
VDC+25V_1	X3 COM	vmax: 15 imax: 0.5
VDC-25V_2	X2 COM	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
JUMPER_S1	A B	
JUMPER_S2	A D	
JUMPER_S3	B C	
JUMPER_S4	0 D	
JUMPER_S5	0 C	
JUMPER_S6	F X2	
JUMPER_S7	G X3	
JUMPER_S8	0 COM	

- *ClearCircuit* opens all relay switches in the matrix.

When the workbench starts up, a *RequestConfiguration* command is sent to the matrix driver requesting the data in the configuration file.

When a desired circuit is to be created the workbench PC sends a *CreateCircuit* message describing the circuit to the switching matrix controller via USB. The matrix controller decodes the message and generates messages, one for each board controller affected. The matrix controller returns an acknowledgement when the messages are distributed to the board controllers.

VII.   CONCLUSIONS AND FUTURE WORK

In order to open a workbench in a local electronics laboratory for access over the Internet a telemanipulator for remote circuit wiring is required. A switching matrix is sufficient as long as the desired circuits are not too complex. This is true for experiments in, for example, courses in basic circuit analysis or analog electronics. Such experiments are described in lab instruction manuals and the switching matrix can support wiring of the corresponding circuits. It is also possible to allow the students to make harmless wiring mistakes. However, the
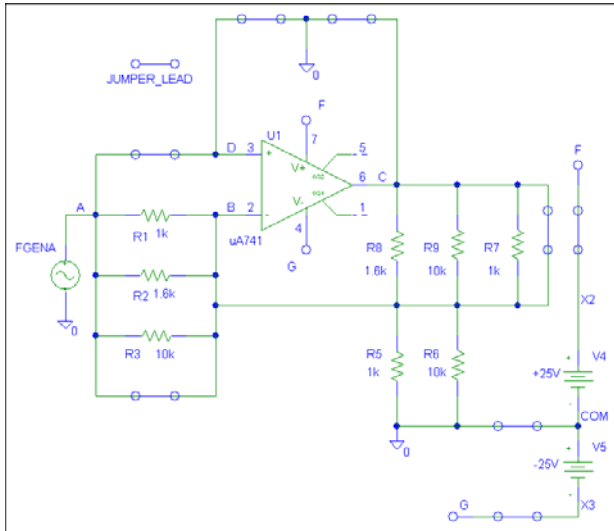
Figure14. The circuit corresponding to the checklist

virtual breadboard and switching combination is useful in experiments on complicated ready-made circuits in advanced courses too, where the switching matrix can be used for connecting and moving test probes to different nodes of the circuits.

The new switching matrix will be online and integrated in a workbench at BTH after the summer of 2008. A new version of the workbench software will also be published. The next step is to design an independent circuit wiring service, using middleware. Another option is using the switching matrix standalone together with the driver, Circuit Builder.

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