

Teaching Instrumentation and Measurement in Local and Remote Laboratories

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Abstract—This paper discusses opportunities for teaching students instrumentation and measurement in an effective way. Nowadays, remote laboratories allow students to carry out experiments outside laboratory facilities. Likewise, these types of laboratories can support life-long and continuous learning activities. In this paper, we focus on two different approaches. Firstly, we concentrate on physical instruments and circuits which students can access remotely to carry out practical exercises. Secondly, we present virtual instruments in which students do not depend on external hardware. Finally, we reveal how physical and remote laboratories can be combined to overcome challenges in teaching complex measurement instruments.

Index Terms—experiment, learning environment, online laboratory, practical activity, teaching environment, virtual laboratory.

I. INTRODUCTION

Laboratory exercises are a vital part in teaching instrumentation and measurement [1]–[3]. Due to the complexity of the field, hands-on experience is essential so that students can familiarise themselves with state-of-the-art measurement instruments [1], [4]. As available instruments and methods of measurements become more and more complex, the education of students requires more and more time as well. These circumstances have dramatically changed the nature and methods of teaching instrumentation and measurement to new students over the past decades [1], [2].

Depending on the topic and focus of the course, courses are usually a mixture between theoretical lectures and practical exercises [5]. In the field of instrumentation and measurement as well as in other technical disciplines, laboratory exercises are needed to train the day-to-day operation of measurement equipment. Commonly, laboratories are known for resulting in high costs associated with instruments and electronic devices, rental costs for spaces, and salaries for teaching and maintenance personnel [4]. As a consequence, new forms of laboratories are proposed with the aim to reduce costs in education [5].

Generally speaking, there are four possible environments for practical exercises within instrumentation and measurement courses [6]–[9]:

- 1) Local laboratories with real resources: In this traditional setup, students are carrying out exercises with physical instruments at the site of the university campus while being supervised by teaching personnel.
- 2) Local laboratories with simulated resources: In this combination, students are still working in the laboratory at the

site of the university campus. However, they are working with virtual instruments (VIs) in their exercises.

- 3) Remote laboratories with real resources: Students carry out measurements with physical instruments which are located at the university through remote connectivity for example from their home.
- 4) Remote laboratories with simulated resources: In this relatively new setup, students are working remotely with VIs. Often, there is no teaching personnel present when students are carrying out measurements.

Depending on the size of the laboratory, number of instruments, and number of supervisors, only a certain number of students can carry out exercises at a given time. Fig. 1 shows the laboratory setup of the Electrical Measurement Principles course at the University of Oulu, Finland, used in this research as field test case. As seen in Fig. 1, 16 students per shift, supervised by two assistants, can be accommodated in the laboratory. Each student works individually on the measurement tasks in the different exercises. Due to limitations in the number of instruments and equipment, at most six students can do the same exercise at the same time.



Fig. 1: Laboratory setup of the field test course

Local laboratories with simulated resources can help to reduce the costs of teaching [4]–[7]. However, they also can result in a reduction of the important hands-on experience with measurement instruments. For example, it can be challenging to include every functionality of an instrument in a simulator or web-based interface [10]. Moreover, normal behaviour such as fluctuating measurement results due to interference, environmental conditions or tolerance specifications from the device's manufacturer can be missing within simulated resources.

However, remote laboratories with VIs can also be used to assist teaching in local laboratories with real resources. In other words, it does not mean that a teacher has to necessarily transition completely from local laboratories to remote laboratories. For the potential best learning outcome, students should receive real hands-on experience with physical devices and the possibility to train with VIs in a simulated and, therefore, safe environment. In this paper, we analyse different approaches for teaching instrumentation and measurement based on the experiences and observations of a field test case study.

II. PHYSICAL LABORATORIES WITH REAL RESOURCES

A. Field Test Case Study

Instrumentation and measurement courses can be commonly found in the Bachelor degree of engineering students. Electrical Measurement Principles (*in Finnish Sähkömittaustekniikan perusteet - SMTP*, course number 521109A) at the University of Oulu, Finland, is a mandatory course in the first year for all students of the Faculty of Information Technology and Electrical Engineering (ITEE). In this paper, the course is used as a field test case for evaluating possibilities with VIs to improve the learning outcomes of students in teaching instrumentation and measurement.

While most of the 200 students participating the course have either electrical engineering or computer science as their major, also students from other faculties studying physics, mechanical engineering, process engineering, and wellbeing technology are attending the course. In addition, international exchange students include the course for their studies at the University of Oulu. Hence, given the large difference in terms of the potential engineering background, it is challenging to find a suitable level of instruction that considers the different previous knowledge of students.

B. Field Test Course Content

The Electrical Measurement Principles course is composed of an intensive series of ten lectures, each of which lasts two hours over the first four weeks of the duration of the course. Then, laboratory exercises are held for the following nine weeks. Each laboratory exercise lasts for 120 minutes. The course is equal to 5 ECTS (European Credit Transfer and Accumulation System) credits, thus, resulting in about 125-130 hours of equivalent workload for students.

In this research, we concentrate on the laboratory part of the course. Altogether, students have to carry out six different exercises, laboratory works 1 to 6, respectively. Each work has a different focus in terms of related measurement topics and also utilises different types of instruments and other equipment. As seen in Table I, the function generator and oscilloscope are a common pair in almost every exercise. Furthermore, a printed circuit board (PCB) and/or an additional electronic device are required for carrying out the measurement tasks in the exercises.

The type of electronic device differs from exercise to exercise: A remote control is used in work 4, a resistance

TABLE I: Instrument and equipment used in exercises

	W1	W2	W3	W4	W5	W6
DC power supply	x				x	
Circuit board	x	x			x	
Electronic device	x	x		x	x	x
Multimeter	x	x				x
Function generator		x	x	x	x	x
Oscilloscope		x	x	x	x	x

decade box in works 1 and 6, AC and DC power adapters as well as a portable computer in work 5. In work 2, an LCR meter is used. The desired learning outcomes of each exercise are as follows:

(a) Work 1 (W1)

- To get familiar with the basic use of digital multimeters (DMMs).
- To choose the correct measurement type, to evaluate measurement results and the accuracy of them.
- To study the DMM's test current and test voltage behaviour within resistance measurements.

(b) Work 2 (W2)

- To learn the usage of LCR-meters and an oscilloscope measuring AC-quantities.
- To demonstrate the frequency dependence of AC-components' reactance.
- To understand the theory of AC-circuits.

(c) Work 3 (W3)

- To get familiar how the signal is connected to a digital oscilloscope and how the signal is processed (i.e. attenuating probe and actual coupling).
- To change trigger settings for displaying the signal.
- To create test signals with a function generator.

(d) Work 4 (W4)

- To utilise an oscilloscope for time domain measurements.
- To carry out measurements with automatic and cursor-based techniques.
- To analyse modulated and unmodulated signals of a function generator.

(e) Work 5 (W5)

- To identify possible errors in the voltage measurement of an oscilloscope.
- To utilise the attenuation of a probe correctly.
- To assess the size of the error in voltage measurements from different sources.

(f) Work 6 (W6)

- To obtain average and root-mean-square values of different alternating voltage modes.
- To use different types of instruments for with low and high frequency measurements.
- To realise capabilities and limitations of different instruments.

III. REMOTE LABORATORIES WITH REAL RESOURCES

A. Required Modifications to Real Resources

In a first step, physical laboratories with real resources can be converted into remote laboratories. In this way, students would have the opportunity to do the same exercises either at the university campus or at their home. The outbreak of SARS-COV2 virus and the related COVID-19 pandemic has restricted the access of universities and, therefore, laboratory spaces [12]. As a result, remote laboratories are emerging to allow students carrying out measurements from their home.

Fig. 2 shows the PCB which is used in W1. As seen in Fig. 2, two $10\text{ k}\Omega$ resistors, R_1 and R_2 , respectively, are connected in series. The first task for students is to connect a DC power supply when the two resistors are connected in series and measure the voltage drop on R_2 with different multimeters (*i.e.* Fluke 111, Extech EX430A, Keysight EDU34450A). Then, in the following task, the students connect the two resistors in parallel and measure the current in the circuit with the same multimeters.

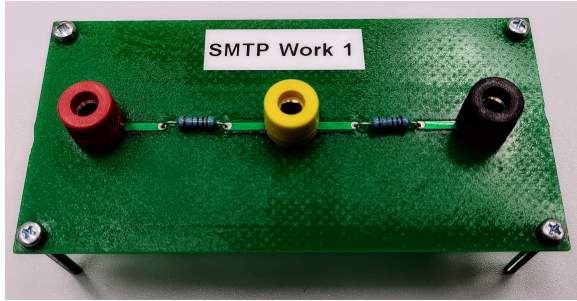


Fig. 2: PCB used in W1

On the example of these two tasks, we can study the difference between carrying out the measurements in the physical and remote laboratory. In the physical laboratory, students can change cables to modify the type connection of the two resistors (*i.e.* series and parallel) and the connection of the multimeter. However, in a remote laboratory, students require additional software and hardware to do so. Fig. 3 shows the required switches (*e.g.* optocoupler 4N35) in order to make changes to the circuit and measurement setup.

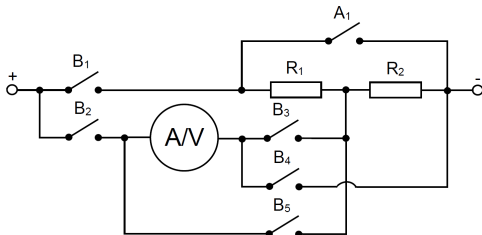


Fig. 3: Control switches for the PCB in W1

For a series connection of the two resistors and measuring the voltage on R_2 : A_1 open, B_1 closed, B_2 open, B_3 open, B_4 closed, and B_5 closed. For a parallel connection of the two

resistors and measuring the current in the circuit: A_1 closed, B_1 open, B_2 closed, B_3 closed, B_4 open, and B_5 open. It can be seen that the settings of the switches for the first measurement is the opposite for the second measurements.

In order for students to control the switches remotely, a data acquisition (DAQ) module with two outputs can be used. Likewise, one output pin and an inverter is sufficient so that the students can make changes to the circuit. In this research, we used LabVIEW and the National Instruments (NI) USB-6009. Fig. 4 shows the LabVIEW program. If students select the first circuit in which the voltage is measured on R_2 , then the switches are set accordingly. In other words, the students do not need to change the setting of switches individually.

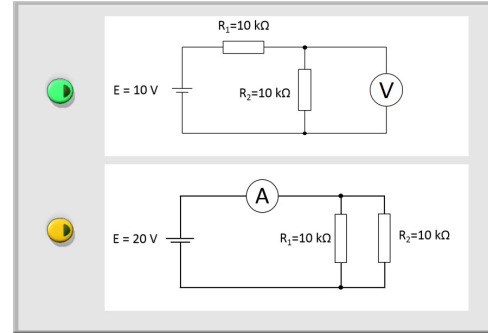


Fig. 4: LabVIEW program for W1

Fig. 5 shows the PCB which is used in W5. As seen in Fig. 5, three $10\text{ k}\Omega$ resistors, R_1 , R_2 and R_3 , respectively, are connected in series. On this PCB, students carry out altogether 11 measurements changing the measurement point (MP) as well as the reference point (RP) of the oscilloscope's probe and ground lead. In the first five measurements, pin 6 is the RP and students measure the voltage at pins 1-5. Then, the RP is set to pin 2 and the other pins are the MPs (*i.e.* pins 1, 3-6). In one additional measurement, when the MP is pin 4 and the RP is pin 6, the resolution of the oscilloscope is changed from 5 V/div to 500 mV/div to make the same measurement twice, but one time with utilising the full resolution of the oscilloscope. The goal is that students study the uncertainty of the oscilloscope within voltage measurements.

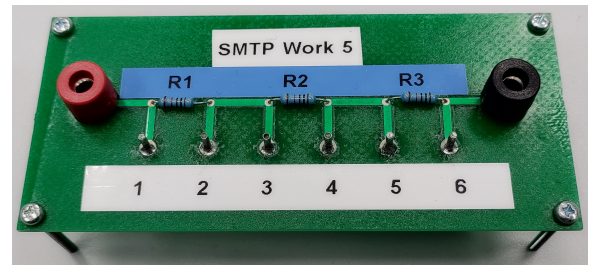


Fig. 5: PCB used in W5

Fig. 6 shows the required control switches for the PCB so that students can carry out the measurements remotely. As seen in Fig. 6, switches A_1 - A_6 change the MP, while switches

B_1 and B_2 change the location of the RP. For example, measuring the voltage between pin 4 to 6 requires A_1 – A_3 open, A_4 closed, A_5 open, A_6 open, B_1 closed and B_2 open. Again, as seen in Fig. 7, a LabVIEW program and the NI USB-6009 were used so that students can change the connection of the oscilloscope to the desired MP and RP.

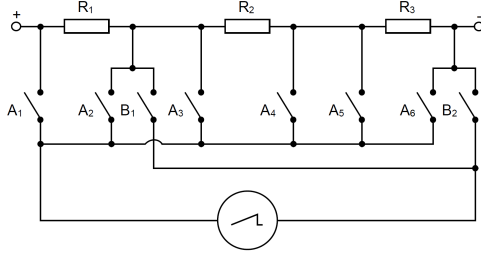


Fig. 6: Control switches for the PCB in W5

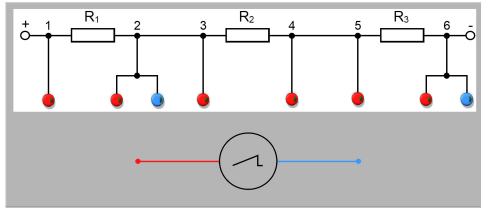


Fig. 7: LabVIEW program for W5

B. Limitations of Remote Laboratories with Real Resources

In this work, it was found out that the delay in the connection significantly affects the experience of students to carry out measurements in a remote laboratory utilising real resources. Some manufacturers (*e.g.* Keysight, GW Instek) allow controlling instruments in a web browser through LAN- and/or USB-connection between the measurement instrument and a PC. Here, the user interface in the web browser sometimes looks similar or identical to the real physical instrument. Some manufacturers (*e.g.* Siglent, Rigol) provide a separate program for controlling instruments through LAN- and/or USB-connection with a PC.

However, one major issue of controlling a real instrument remotely is the slow reaction. It takes one to three seconds for the measurement instrument to receive the user command and another one to three seconds for the web browser to refresh, in other words update the information on the settings of the instrument. As such, if the student has to configure a lot of parameters on a function generator (*e.g.* setting the waveform type, frequency, amplitude, offset voltage, duty cycle ratio, etc.), it takes the student a significant amount of time to do so. Hence, it can be said that the student's motivation is affected in a negative way when using this distant learning tool [11].

It takes more effort both, in terms of hardware and software development, to create configurable circuits for laboratory exercises. For example, the first task in work 1 is to measure the voltage drop on one resistor within a series connection of

two resistors, while the second task is to measure the current in a parallel connection of two resistors. In a remote setup, it must be possible for the student to reconfigure the circuit in order to switch between the two tasks. In other words, there need to be common connection points for measurement instruments on the outside, while changes to the connection of the components inside within the circuit.

IV. COMBINING REMOTE AND PHYSICAL LABORATORIES

A. Resource Requirements

In remote laboratories with real resources, on one setup, only one student can carry out measurements at a given time. In this way, the resource requirements are the same as for local laboratories. Hence, students would need to reserve shifts and complete all tasks within a given timeframe. However, depending on the background knowledge of the student, this restricted time can be challenging. Moreover, if the student faces technical difficulties to connect to the remote setup, the available time for measurements can be reduced further.

B. Creating Virtual Instruments (VIs)

When comparing different approaches for establishing remote laboratories in the available literature, it can be seen that hands-on experience is one of the most important factors [3]–[5], [7]. Generally speaking, laboratories are crucial for students to apply the theoretical knowledge obtained during lectures on practical problems which they also face later on in their working life. Giving the restricted time of students in laboratories, rather additional exercises are needed than to substitute exercises in local laboratories with exercises in remote laboratories.

In the past years, in the Electrical Measurement Principles course, students had problems to carry out all the measurements of one exercise within the given amount of time. One reason for that was that students were not familiar operating an oscilloscope and function generator. Hence, for example instead of measuring the current or voltage in a circuit, students spend a significant time to find different settings in menus (*e.g.* changing the probe attenuation, changing the trigger slope and mode, selecting a measurement suitable for either DC or AC voltage measurement).

As a result, the main goal of this work was to create digital teaching tools and methods that allow students to familiarise themselves with different types of measurement instruments outside local laboratories. Hence, we decided to use LabVIEW to create measurement instruments as VIs which look and work as their physical counterparts. For the first time in the 50-year history of the course, students could use an oscilloscope or function generator before the exercises in the local laboratory. One major aim was to provide guidance of the student with new measurement instruments. It is worth noting that measurement instruments can appeal to be very complex and challenging to operate for new users [1].

Commonly, there is not any kind of tutorial or guidance available. Hence, instead of confronting students immediately with all the functionalities, students should learn about one



Fig. 8: VI of a function generator (Keysight EDU33211A)

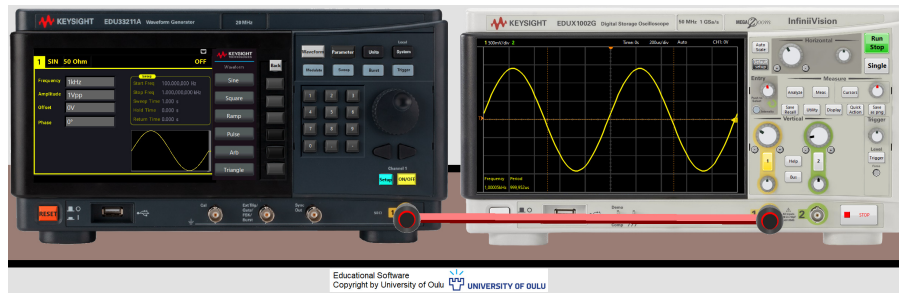


Fig. 9: VI of a function generator (Keysight EDU33211A) and an oscilloscope (Keysight EDU1002G)

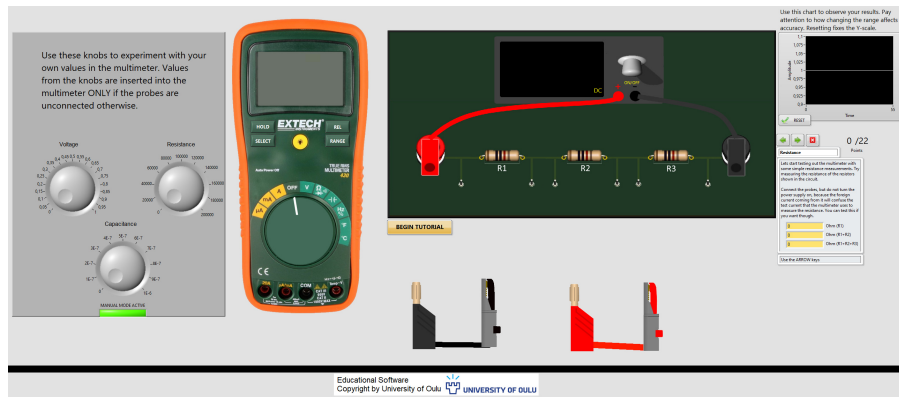


Fig. 10: VI of a multimeter (Extech EX430A), a DC power supply and a PCB

feature at a time. Unfortunately, software to control measurement instruments remotely does not allow to disable certain features nor provides an introductory guide to new users. As a consequence, we decided to create our own VIs in LabVIEW for the laboratory exercises. Fig. 8 shows the VI of a function generator (Keysight EDU33211A). The VI was used as a pre-task for the laboratory exercises.

As seen in Fig. 8, students can start a tutorial for the function generator. As a first step, students learn about the different waveforms which can be generated. On the left-hand side of the VI, students receive instructions and information, while on the right-hand side objectives are displayed. As such, the tutorial becomes interactive as students have to complete small tasks during the tutorial themselves. If needed, students can press the help button. Then, for example, the correct buttons lid up which the student needs to press.

Like the tutorial for a function generator, we created tutorials for a multimeter and an oscilloscope. However, the

goal was not only to provide VIs for individual measurement instruments, but also VIs in which on the one hand instruments could be used together and measurements could be carried out with circuits on the other. Fig. 9 shows a VI in which a function generator (Keysight EDU33211A) can be connected to an oscilloscope.

Not only can students get familiar with the basic usage of measurement instruments, but also carry out different measurements themselves remotely. As seen in Fig. 9, students can select different types of measurements (e.g. period and frequency of a signal) or can carry out measurements with cursors (e.g. automatic and manual). Likewise, as seen in Fig. 10, students can first try out a multimeter with different configurations for voltage and resistance, for example. Then, cables can be connected to a circuit to measure different voltages within the circuit.

Although the circuit is the same as in W5, in the VI, students carry out measurements which they would not usually

do in W1 or W5 in the real laboratory. Hence, it can be said that the VI supports rather than replaces the exercises in the real laboratory. As in other VIs, students have to complete tasks in which students get familiar with different types of measurements on a step-by-step basis. Once all tasks have been completed, students can freely explore the VI and try out different additional measurements by themselves.

V. DISCUSSION

Distant learning, in other words the implementation of remote laboratories, was a useful tool before the COVID-19 pandemic [13]. Likewise the concept of remote laboratories with simulated resources (*i.e.* VIs) is helpful to reduce the costs of education in local laboratories with real resources [4]–[7]. However, with the increase in complexity of the field of instrumentation and measurement [1], [2], attention needs to be paid on the quality of education as well. In particular hands-on experience with state-of-the-art instruments is essential for deepen the theoretical knowledge from lectures [3]–[5], [7].

Hence, in order to maximise the learning outcomes of students, remote laboratory exercises with simulated resources can support laboratory exercises in local laboratories with real resources. In tutorials, students can familiarise themselves with different measurement instruments on a step-by-step basis. Then, students can carry out measurements in a safe environment, experimenting with the instruments and related measurements. Instead of substituting exercises, additional exercises online can support exercises in physical laboratories.

Fig. 11 shows the students' feedback after taking the course. In Fig. 11, the students' satisfaction level from the year 2020 (*i.e.*, no VIs) is compared with the one from 2021 (*i.e.*, with VIs). In terms of teaching and guidance, due to the use of VIs including tutorials, a significant improvement could be achieved. As a result, it can be said that tools which allow students to train with complex measurement instruments before and after real laboratory exercises help to improve their motivation, learning outcomes and satisfaction with teaching.

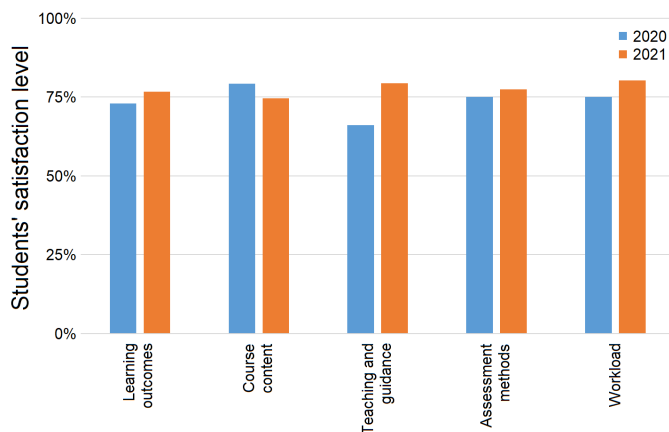


Fig. 11: Comparison of the students' feedback

VI. CONCLUSION

In this paper, we investigated different ways to implement remote exercises for students in the field of instrumentation and measurement. Remote laboratories with real resources can result in significant delays when controlling instruments through the internet. As a result, the user experience and, therefore, the student's motivation can be negatively affected. Moreover, it can be difficult to control measurement setups remotely. VIs in LabVIEW as stand-alone applications do not result in any additional software license costs. We showed that VIs can be versatile and can emulate important hands-on experience.

ACKNOWLEDGMENT

This research was supported by the ITEE faculty of the University of Oulu. Prof. Tapio Fabritius is partially supported by Academy of Finland's FIRI funding (grant no. 320017).

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