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Remote Laboratories for Teaching and Training in Engineering

Jesús García-Guzmán, Farah H. Villa-López,
Jorge A. Vélez-Enríquez, Luz A. García-Mathey and
Alfredo Ramírez-Ramírez

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Abstract

Typical mechatronic systems are a combination of advanced technologies involving several disciplines. This multidisciplinary approach to the development of industrial applications provides great opportunities for the implementation of e-learning environments and collaborative schemes. Engineering education, in particular, benefits from many of these advances, among which, virtual instrumentation is a useful tool for the development of virtual environments, e-learning spaces and, particularly, remote laboratories. This chapter describes the implementation of web-based laboratories that allow the remote operation of experiments used as training exercises in undergraduate engineering courses. The remote laboratories were developed using LabVIEW® software, and they enable remote control and monitoring of laboratory equipment, allowing engineering students to perform experiments in real time, at their own pace, from anywhere, and whenever is suitable for them. Besides the experimental training that the web-based laboratories provide to students, the system is also a powerful teaching tool since real-time demonstrations of the experiments can be performed, and they also can be simultaneously monitored by a group of students. This approach is highly beneficial for engineering schools in developing countries, as resources can be shared through the Internet. A description of the system and three proposed experiments is presented, together with the experimental results.

Keywords: remote laboratory, e-learning environment, mechatronic system, virtual instrument, web-based system

1. Introduction

In engineering education, laboratories represent an important academic resource as they provide practical training in addition to the fundamental theories taught in lectures. At laboratories, engineering students have the opportunity to learn how to properly use the equipment and tools with which they will be interacting later in a professional environment, and therefore, they gain practical experience and familiarize with that equipment. For this reason, engineering schools seek to provide properly equipped laboratories. However, the maintenance of the equipment and the acquisition of new machinery imply a large investment that only a limited number of public universities can afford.

The limited budgets and the large amount of students at engineering schools make insufficient the available resources at the laboratories and consequently, it is very difficult for universities to provide quality experimental training to all engineering students. Taking advantage of new communication technologies such as the Internet and computing tools such as virtual instrumentation, the available resources can be shared, developing and implementing collaborative schemes and e-learning environments that allow the access to practical training to a larger amount of students, regardless their location.

Several collaborative schemes, aimed at engineering education, have been developed in recent years for the remote execution of experiments in distance laboratories and on different engineering fields. For example, the remote laboratory system described in Ref. [1], where experiments conducted at control engineering laboratories can be remotely operated through the Internet. On the same trend, a more recent work [2] reports on the remote control of a nonlinear system as a tool for teaching several engineering subjects. Likewise, experiments with analog electronic circuits have been studied [3] with the aid of remote laboratories based on an existent and previously validated platform. This system aims the use of nonproprietary solutions in order to promote sharing among institutions; it also performs remote measurements over real instruments in an effort to make it as reliable as a hands-on laboratory.

Remote laboratories for experimental training on mechatronics have also been implemented, as the one reported in Ref. [4], where experiments using a two-degree of freedom robot and a servomotor can be carried out remotely. Other works have also reported the development of remote experiments implemented as web-based systems in other engineering fields such as fluid mechanics [5] and electrical engineering [6].

In general, remote laboratories deal with manipulation of real equipment and experiments, and although they make use of tools such as virtual instruments (VI) and e-learning environments, they should not be confused with either simulations or virtual laboratories. There are systems, such as the one reported in Ref. [7], using different approaches, more on the style of virtual laboratories, that involve the use of expensive equipment and topologies for the emulation of sophisticated laboratories, which are rarely available in public institutions.

Several computing tools have been employed to develop remote laboratories for engineering education. As an example, Matlab and Easy Java Simulations were used for the implementation of control system experiments in the work reported in Ref. [8]. However, since

early works on distance laboratories [9, 10], LabVIEW® virtual instrumentation has been the primary used tool, and this software has become a powerful resource for the development of e-learning environments, particularly at the development stage.

Although much work has been done for several years in the field of remote laboratories, there are still many challenges before they can be considered a quotidian resource for teaching and training in engineering. Some of these challenges and proposed solutions have already been considered [11, 12], but there is still much work left to do.

The remote mechatronic systems presented in this chapter follow the outcomes of a previous work [13] and aim to provide practical training to a larger amount of students in a public university with engineering schools in five campuses, looking to overcome current limitations such as the lack of economic resources, the consequent insufficiency of laboratory equipment, and the limited flexibility of laboratory scheduling. Three experiments for training on different engineering fields have been implemented in a web-based learning environment so that they can be remotely operated over the Internet. The web-based system was developed using LabVIEW® virtual instrumentation, and its configuration allows multiple students to access the experiments simultaneously, making the proposed system suitable for teaching and practical training.

2. Description of the web-based system

Traditionally, students who are physically at the laboratories are able to carry out experiments by making all the required connections of the laboratory equipment, and then they manually operate tools and machinery in order to execute experimental exercises. Frequently, they also measure and calculate some parameters so as to better understand the theoretical knowledge. In contrast, remote laboratories are implemented as web-based system, replacing manual operation of the experiments and enabling remote access by means of software, such as LabVIEW® virtual instrumentation, and additional hardware.

A particular web-based system has been developed for the implementation of several experiments in three different remote laboratories. The general characteristics of the system, namely overall structure, virtual instrumentation, and data acquisition (DAQ) system, are described in this section.

2.1. Overall structure

The overall outline of the developed system is shown in **Figure 1**. The required laboratory equipment to perform the experiment is already connected at the laboratory and thanks to the use of virtual instrumentation and additional hardware the experiment can be controlled through a computer interface and over the Internet.

A laptop computer equipped with LabVIEW® software is located at the actual laboratory where the experiment is performed. This is the *server computer* where the virtual instruments are developed for the control of the experiment execute. As stated before, additional

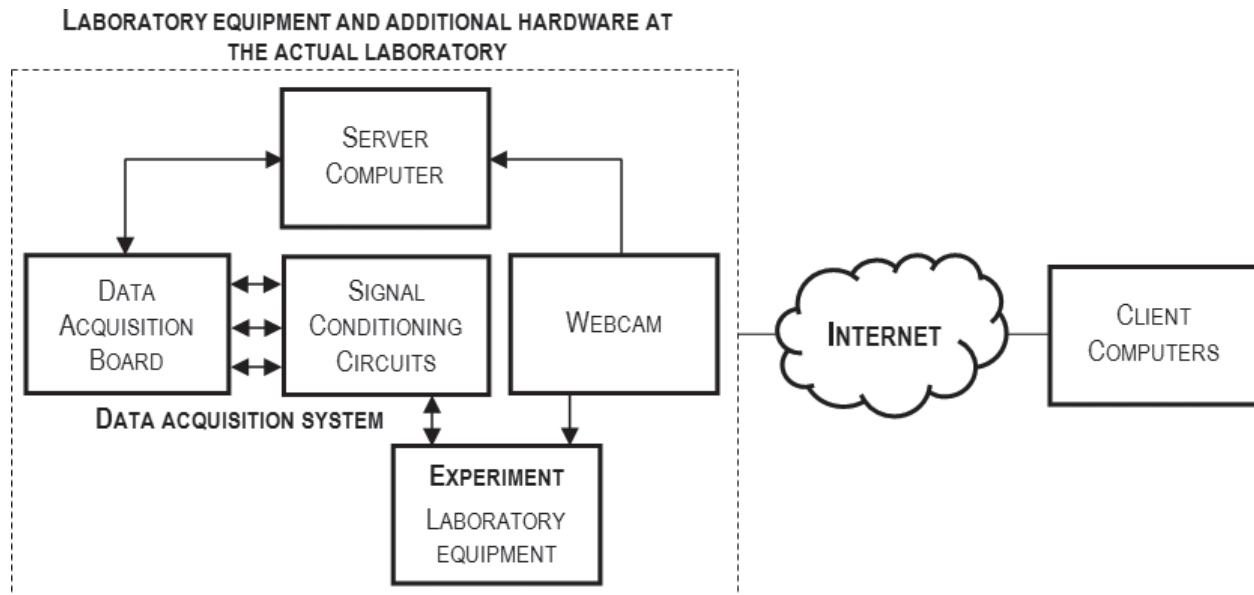


Figure 1. Overall structure of the developed web-based system.

hardware was employed for the implementation of the system, namely a *data acquisition* (DAQ) board and a *webcam*, both connected to USB ports of the server computer, as well as *signal conditioning circuits* for the conversion of software instructions into the required power actions on the laboratory equipment. The webcam allows video communication with the laboratory, displaying images through the computer interface in order to monitor the experiment. Using the LabVIEW® web server, the experiment is available on the Internet, and it can be accessed from anywhere providing that the user has a computer (*client computer*) with an Internet connection.

2.2. Virtual instrumentation

In order to accomplish every required task of the experiment through the computer interface, LabVIEW® software was employed to develop a set of virtual instruments. This software uses a graphical programming language in which each node is a virtual instrument, or VI, and the lines or wires connecting the nodes determine the flow of data. A virtual instrument consists of a *front panel* and a *block diagram*. The front panel represents the virtual interface for the user, and it accommodates *indicators*, or output nodes displaying data, and *controls*, or input nodes, in which data can be read from. The block diagram contains the source programming code, linking nodes with wires according to the desired flow of data. Programming structures are also represented graphically in the form of blocks with iterations or cases. The software is able to read external data in many ways, particularly through data acquisition boards and, hence, providing an excellent platform for the monitoring of real-time signals, a feature that makes LabVIEW® a very useful tool for engineering applications.

Three different main virtual instruments were developed, each of them for the implementation of one of the proposed experiments. In general, the front panels of these virtual instruments show graphical indicators, allow the control of certain parameters, and display images

in real time of the actual laboratory equipment controlled. Through these VI, each experiment can be controlled from the laptop computer, allowing the same practical procedures that are conventionally made by hand, e.g., pushing start/stop buttons, measuring voltages, noticing alert signals, and registering output data. Additionally, virtual instrumentation allows operations that are not easy to perform by hand, such as obtaining graphical information in real time, registering data directly into datasheet files, or recording videos of the actual experiments. It is also possible to develop tutorials using virtual instrumentation, in order to train the users in the procedures of the experiments, before they can work with the real equipment.

2.3. Data acquisition system

The data acquisition system comprising the DAQ board and the signal conditioning circuits is necessary to acquire signals sent by the laboratory equipment to the computer and to drive the actual control of the equipment after interpreting software instructions.

In order to carry out the data acquisition process, a 16-bit National Instruments multifunction DAQ board was employed for the implementation of each of the experiments, and owing to the fact that this board does not support the electric current values sent by the laboratory equipment nor it sources the required current for driving the control of the experiments, different signal conditioning circuits connected to the inputs and outputs of the DAQ board were used for each of the experiments, according to the needs. In general, these circuits were used to amplify the electrical signals sent by the digital outputs of the DAQ board and to protect this board from high voltages when receiving the electrical signals sent by the laboratory equipment. The DAQ Assistant Express VI was used in LabVIEW® software to configure the digital and/or analog ports of the DAQ board, as it was required by each experiment. Further explanation of required circuitry and DAQ board set-up is given below.

3. Remote access operation

Programming virtual instruments only to control the experiments, using a computer near to the equipment in the laboratory, may have some advantages, as the ones mentioned in Section 2.2. Nevertheless, the relevant feature of the developed systems reported in this work is their ability to be accessed from anywhere through the Internet.

The LabVIEW® web server was employed in order to remotely access, over the Internet, the developed virtual environments. Using this server, the front panel of the virtual instrument can be accessed in real time and simultaneously from different locations. However, even though multiple students can access the front panel at the same time, only one of them can control the front panel and perform the experiment at a time. This is one of the most important features of the system since this allows teachers or instructors to carry out demonstrations of the experiments in real time, while the students can monitor the experiment from their own computer. This characteristic makes the system suitable as a teaching aid, in addition to its training purposes.

How remote engineering laboratories have become a powerful tool for teaching and learning has been noticed since reviewing the perception of students about the remote operation of experiments reported in Ref. [14], and it has also been shown in Ref. [15] that remote laboratories do provide educational benefits, when comparing the remote approach with the traditional hands-on laboratories.

The procedure for the configuration of the Web server and the creation of a Web site where the virtual instruments with the laboratory experiments can be accessed remotely is explained in the following paragraphs.

3.1. Configuration of the LabVIEW® Web server and creation of the HTML file

Before students can access the front panel and remotely control the experiment, a proper configuration of the LabVIEW® server is required. In this configuration, the Web server needs to be enabled; then, it is necessary to determine which HTTP port will be used to access the virtual instrument and who will have access to it. Once this configuration has been done, the next step is the publication of the virtual instrument in a web page by creating a HTML file. For this aim, the web publishing tool, available within LabVIEW® software, was used. Using this tool, the URL of the web page is provided with the IP address of the server computer. This URL is the one used to access the front panel from a web browser.

For the developed system, the port HTTP 80 was used since the server computer runs Windows operating system. The browser access was configured in order to enable access to the front panel to all users, i.e., from any IP address, allowing them to view and control the experiments. An important part of this configuration is the control time limit; with this option in can be specified how long a student can remotely control the front panel until that control is granted to another student who is requesting or has previously booked the control of the virtual instrument.

For the creation of the HTML file, the virtual instrument to be published was selected and the option *Embedded* was chosen. Here, the option *Enable IMAQ Support* must be selected as this allows the acquisition of images required by the virtual instruments. Besides, the option *Request control when connection is established* was also enabled so that when a student access the front panel through a web browser, the control of the virtual instrument will be automatically requested. Then, the name of the HTML file is given, and it is saved. Finally, the URL is provided with the name of the file and the IP address of the computer.

3.2. Access to the front panel

As stated before, several students can view remotely the front panel of the virtual instrument, but only one of them at a time can have the control of the experiment. LabVIEW® software does not need to be installed at the client computer in order to have access to the front panel through a web browser. Instead, the applications LabVIEW Run-Time Engine and Vision Run-Time Engine, from the same version of the LabVIEW® software running the virtual instruments, are necessary.

When a student accesses the front panel via the Internet, the control of the panel is requested. However, if another student is controlling the experiment at that time, the server will queue the request and the control of the experiment will be granted to the next student on the queue list, only when the student currently having the control decides to release that control or when the time limit established is reached. To release the control, students must right-click anywhere on the front panel and select the option *Release Control of VI*. If a student who already released the control wants to have it again, the control must be requested by right-clicking and selecting *Request Control of VI*. Only the user at the server computer, who could be the teacher or instructor, is able to regain the control of the front panel at any time and he or she can also check the queue list of users.

4. Remote experiments

Three different experiments were implemented in the web-based system developed. The experiments proposed are the control of an electropneumatic system, the control of AC motors, and the manipulation of residential electrical circuits. The first one is performed at the industrial automation laboratory of the main campus, whereas the other two are conducted at the electric machines laboratory. A laptop computer, a DAQ board, and a webcam were used for each of the experiments. The laboratory equipment and additional hardware required for each experiment are permanently installed at the laboratories of the main campus, but they can be accessed by students from campuses in other cities, sharing the available resources.

4.1. Control of an electropneumatic system

The first of the experiments operated from the web-based environment is the control of an electropneumatic system. The experiment represents the automatic operation of an industrial process for stamping of parts, and it is aimed at students taking an undergraduate course on industrial automation.

Pneumatic equipment is employed to perform this experiment, and for the control of the process, an electropneumatic circuit was designed and connected using double-acting cylinders, electrically actuated valves, and proximity sensors. The motion sequence followed by the cylinders executes the stamping process. Proximity sensors are used to detect the position (retracted or extended) of the cylinders, and valves provide compressed air to the cylinders according to the programming code.

The front panel of the virtual instrument developed for the programmed control of this experiment is shown in **Figure 2**, as seen from the web browser. This virtual interface consists of different buttons that allow students to control several parameters such as the number of parts to be stamped, the drying time for each part, and the activation of the air supply. Other buttons are used to start or stop the stamping process. Indicative LEDs are also placed in this panel to show which proximity sensors are activated, and graphical indicators show an animation of the stamping process. Real-time views of the actual laboratory equipment controlled are displayed at the top right corner.

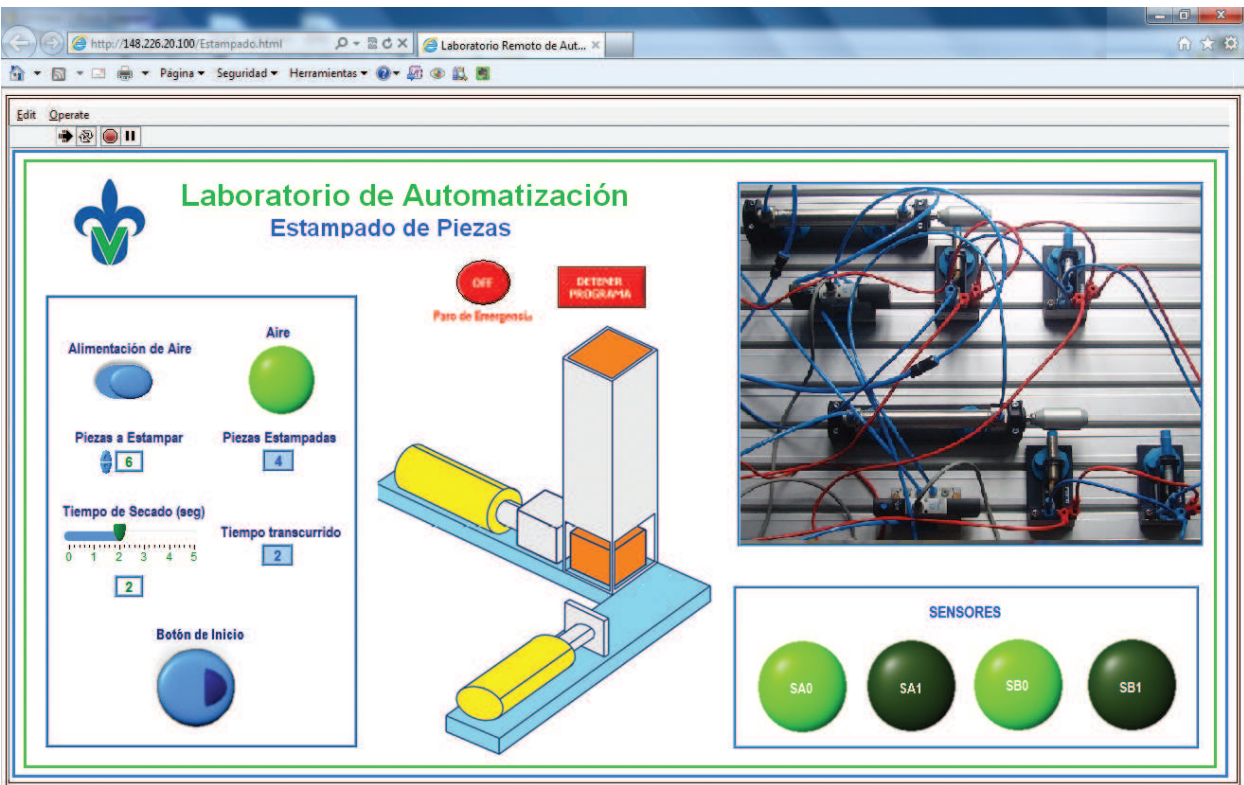


Figure 2. Front panel of the main virtual instrument for the control of the electropneumatic system [16].

The block diagram, shown in **Figure 3**, contains the programming code, in the LabVIEW® graphical programming language, called “G,” of the main virtual instrument. It consists of graphical icons that are wired to determine the flow of data, and for this application, it is composed of global variables and three subroutines (known as subVIs) whose functions are the control of the system, the image acquisition, and the virtual connections of the system. Global variables pass data among the subVIs and the main virtual instrument when they are running at the same time.

For this experiment, only digital input and output ports of the DAQ board were used. The digital inputs acquire signals sent by the proximity sensors in the electropneumatic system, whereas the digital output ports generate the signals sent to the electrically actuated valves. Communication of input and output signals, however, is not direct because the DAQ board handles only low-voltage digital signals, while the components in the electropneumatic system work with higher voltage levels. For that reason, signal conditioning circuits, mounted on a breadboard, were placed between the control section and the laboratory equipment in order to amplify the electrical signals sent by the digital outputs of the DAQ board and then drive the current needed by the valves to be activated. Likewise, another circuit was used to protect the equipment when acquiring the current values from the sensors. Further details of the remote operation of this experiment are described in Ref. [16].

4.2. Control of AC motors

The second experiment implemented in a web-based laboratory is the control of two AC motors. In this experiment, two three-phase squirrel-cage induction motors can be controlled

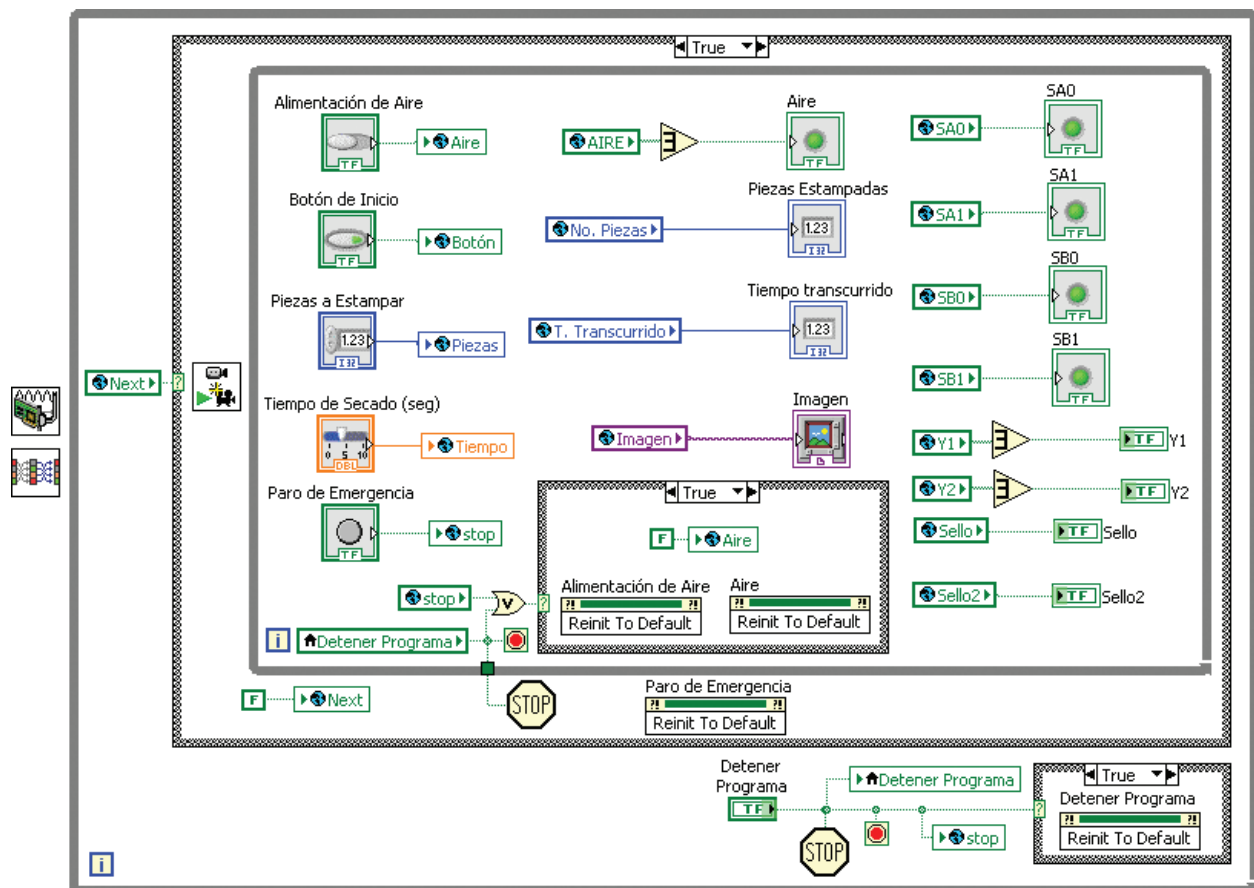


Figure 3. Block diagram of the main virtual instrument for the control of the electropneumatic system [16].

in three different ways, i.e., manually (using a virtual button), automatically, and sequentially. Students attending an undergraduate course on AC motors are the more likely to perform this experiment.

Figure 4 shows the front panel of the virtual instrument developed in LabVIEW® for the control of this experiment. Two graphical displays for voltage and current waveforms and several numeric indicators are placed in the front panel. These indicators provide useful information for students who traditionally need to measure and/or calculate parameters such as the voltage, current and real, apparent and reactive power for each phase of the tested motors. They can also visualize waveforms and phase sequence without connecting additional equipment such as oscilloscopes. For the starting of the induction motors, different buttons were placed in the pages of a tab control, according to the type of control that the students wish to perform. A camera shows the operation of the controlled motors through a real-time video image. There is also a stop button available, and all the actual equipment can be monitored in real time through the virtual interface.

Three different signal conditioning circuits were required for this experiment: one for the conditioning of the current signals acquired, a second one for the conditioning of the voltage signals acquired, and a third one for the amplification of the signals sent in order to start and stop the motors. In the case of the voltage and current signals, these must be reduced to the proper



Figure 4. Front panel of the main virtual instrument developed for the control of two AC induction motors [17].

values supported by the DAQ board. The electrical signals required to start/stop the motors were sent by two different digital ports of the DAQ board, while six analog ports of the board were employed for the acquisition of the current and voltage signals. Detailed description of the implementation of this experiment can be found in the work reported in Ref. [17].

4.3. Manipulation of residential electrical circuits

The third experiment is directed to students of an electrical engineering program for training on residential electrical wiring and circuits. This experiment represents the electrical circuits installed around a house to deliver electricity for the lights and other appliances, and it allows turning on/off and monitoring the electrical circuits.

The proposed electrical wiring for a home consists of two separate circuits, both of them connected to the mains. The laboratory equipment employed for this experiment, namely cables, fluorescent and incandescent lamps, switches and other loads such as a domestic and an industrial ventilator were connected to a board already available for training on wiring at the laboratory.

The front panel of the developed virtual instrument for the control of this experiment is shown in Figure 5. This interface contains the controls and indicators used for turning on/off the circuits and for monitoring the electrical parameters. The manual (using a virtual button) or automatic control of the circuits can be chosen. If the automatic form is selected, time and date for turning on and off the circuits must be specified. Voltage and current values of each circuit are displayed graphically and numerically. The values of active power and reactive power, together with the power factor, are also shown, and LEDs are used to indicate whether the circuits are turned on or not. Last but not least, images of the real equipment are displayed in real time through this virtual interface.

The graphical programming code for this virtual instrument consists of five while loop structures. These structures execute the following functions: two of them perform the turning on/off of the



Figure 5. Front panel of the virtual instrument for the control and monitoring of residential electrical circuits [18].

circuits, a third one is for the image acquisition, another one for the acquisition of the electrical signals, namely current and voltage of the circuits, and the last one is for changing the background color of the front panel.

Four analog input ports of the NI-USB 6211 DAQ board were used to acquire voltage and current signals of the two circuits, while only two digital output ports of the same DAQ board were employed to generate the signals sent in order to turn on (or off) those circuits. As in the previous ones, signal conditioning circuits were also necessary for the implementation of this experiment. Further description of the experiment and the virtual environment is described in Ref. [18].

5. Experimental results

For the implementation of the proposed experiments in the web-based system developed, the equipment and components required for each experiment were connected at the corresponding laboratory. For each experiment, a NI-USB 6211 multifunctional DAQ board and a web-cam were connected to a laptop computer equipped with LabVIEW® software and placed at the laboratories, as well as the required signal conditioning circuits. **Figure 6** shows the whole experimental setup in the laboratory for the remote control of AC motors. **Figure 7** shows the components, equipment, laptop computer, and power interfaces for the remote experiment on residential electrical circuits. Finally, the experimental setup for the practical exercises in the electropneumatic laboratory is shown in **Figure 8**.

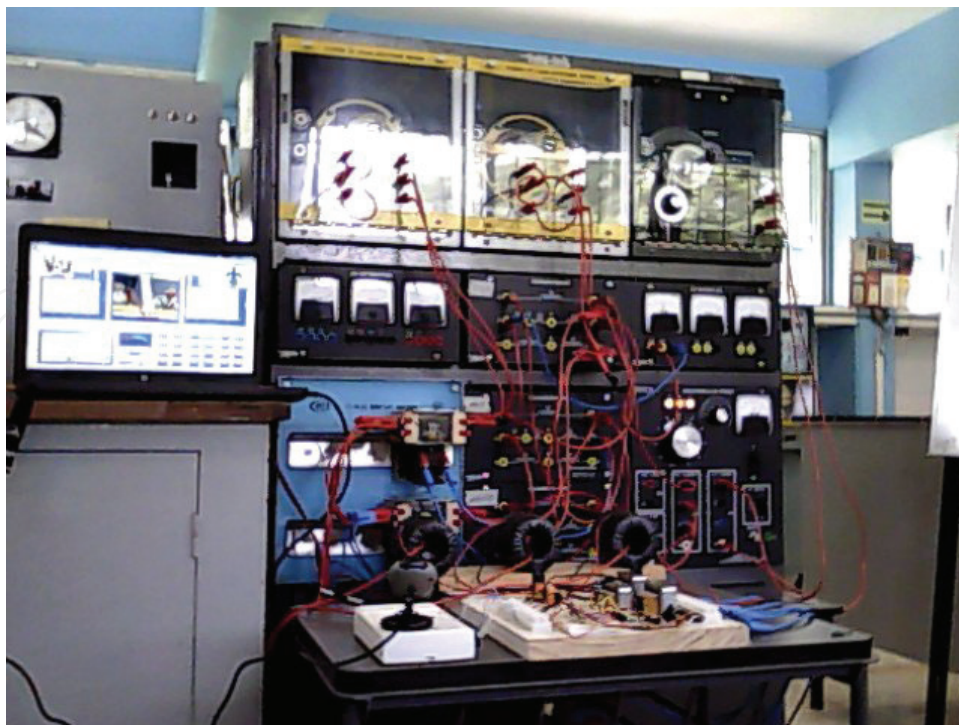


Figure 6. Experimental setup for the control of AC motors [17].

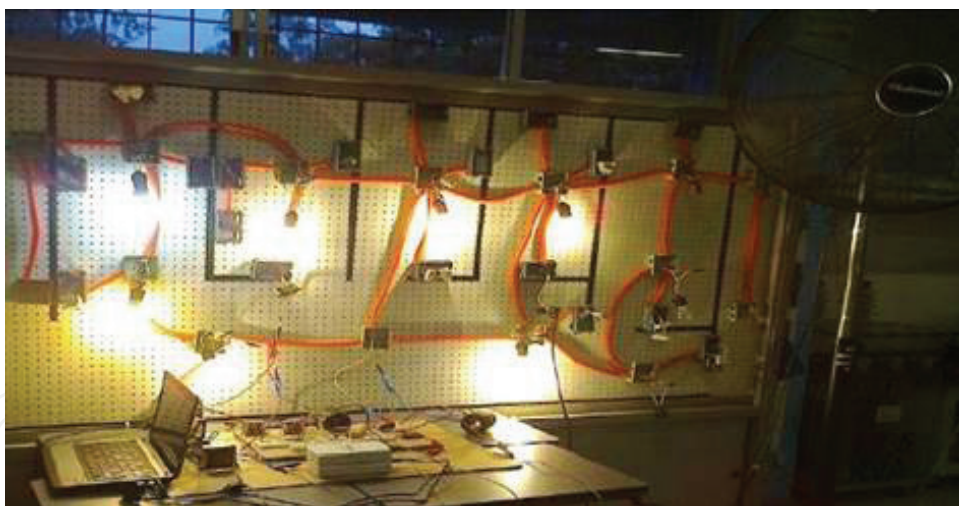


Figure 7. Experimental setup for the manipulation of residential electrical circuits [18].

Perhaps, the most important part of the project was the evaluation of these mechatronic systems when they were tested by engineering students. However, a complete evaluation of remote laboratories should cover many different aspects, from engineering and technical issues to the educational and pedagogical concerns. To this aim, standards have been defined and some studies have been reported, such as the one in Ref. [19], which have tried to cover at least part of the quality properties of remote laboratories for teaching and training in engineering.

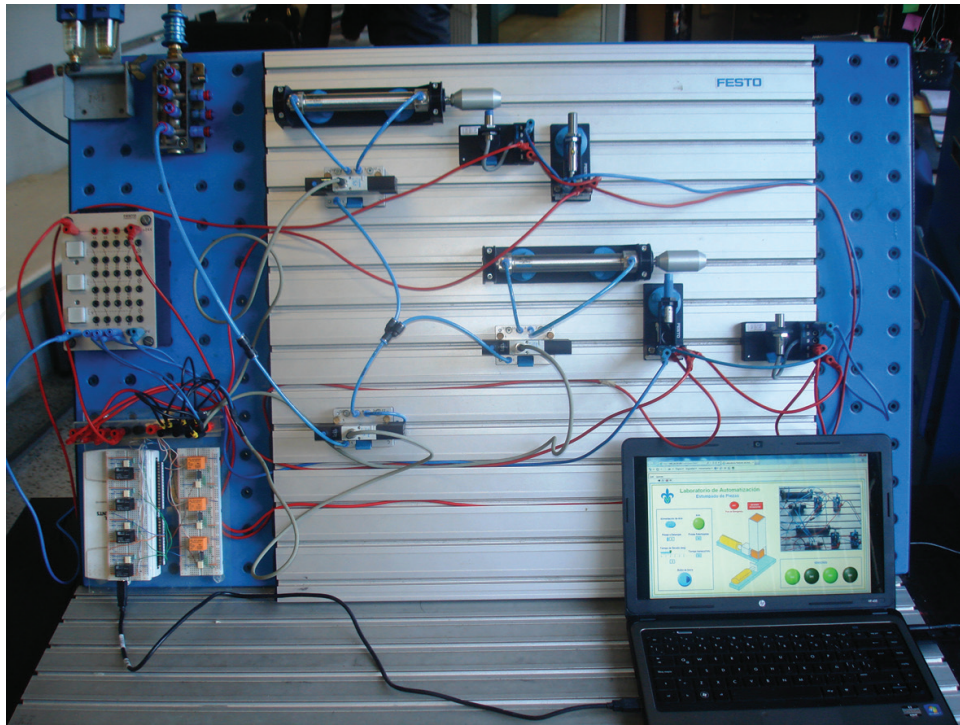


Figure 8. Experimental setup for the control of an electropneumatic system [16].

In the case of the remote laboratories described in this chapter, the virtual instruments developed for the implementation of the experiments in the web-based system were evaluated locally, at a first stage, and they worked as expected performing every required task. After this validation stage of the virtual environments, the experiments were performed over the Internet by a sample of students of the main campus in order to evaluate the remote operation of the systems. This evaluation stage was conducted in two different ways: first, by one student at a time and then simultaneously from different sites.

Students expressed their experiences when using this remote approach for experimental training and positive feedback was obtained, showing how the remote operation of the proposed experiments is a useful learning tool not only for practical experimentation but also for teaching in the engineering fields. The students were particularly satisfied with the virtual interfaces since, as they suggested, they are easy to use and they also liked the simultaneous operation of the system as a teaching aid because, as they expressed, it is possible to remotely follow the experiments while the professor performs the demonstrations.

6. Conclusion and further work

A web-based system for the remote operation of laboratory experiments has been presented. Three mechatronics experiments for practical training on different engineering fields were implemented in the web-based system developed, and they can be remotely performed from anywhere and at any time. The experiments are as follows: the control of two three-phase

squirrel-cage induction motors, the manipulation of residential electrical circuits, and the control of an electropneumatic system. For the implementation of these remote laboratories, a virtual environment for each of the experiments was developed using LabVIEW® virtual instrumentation, and the required laboratory equipment for the execution of the experiments was connected at the laboratories, together with additional hardware for the interfacing between the virtual instruments in the computers and the components and equipment in the laboratories. The experiments can be monitored in real time over the Internet and through the computer interface.

Remote laboratories are highly beneficial for engineering education. Making the experiments available over the web, students have access to practical training without time or location restrictions. Remote operation of the laboratories makes sharing the available resources within different campuses of one university possible, and it also allows the establishment of collaborative schemes between institutions. In particular, engineering schools in developing countries find this approach highly advantageous because it permits the use of local resources, which are often very limited, making them accessible through the Internet to a much higher number of students located in other campuses. Furthermore, under the establishment of proper arrangements, engineering students in developing countries can obtain access to laboratories in first world institutions, improving so the global levels of education, in accordance with the Sustainable Development Goals of the United Nations [20]. In any case, remote sharing of engineering laboratories for training and teaching among different institutions will impact by increasing the practical activities of their students, and therefore improving their learning goals, even if there are many differences between systems and protocols in universities and restrictions from one country to another, as remarked in Ref. [21].

Another important strength of the system lies in its characteristic of being accessible by several students at the same time, allowing it to be used as a teaching aid for the demonstration in real time of the experiments. In this way, the knowledge and experience of an instructor can benefit not only the local students as it occurs in conventional laboratory schemes.

A management system for the registration and authentication of students to remotely access the experiments has been previously proposed [22], and it is expected to be implemented soon with each of the remote laboratories presented. This web access system will allow students to register and schedule the usage of the experiments in order to perform the experiments by their own.

As commented before, the evaluation of the web-based laboratories extends to several different areas, and it is still in progress. At a first stage, the system was evaluated by a sample of students of the main campus in order to obtain preliminary results, but the remote laboratories are expected to be implemented as complementary exercises for different undergraduate courses offered by the schools of engineering in different campuses. At the end of each term, a poll is conducted in order to obtain feedback to determine educational achievements and usefulness of the system so as to improve its performance.

Further work is focused on the implementation in the web-based system developed of new mechatronic experiments for engineering education aimed at different fields such as fluid

mechanics, electronics, and civil engineering, improving the proposed system by adding new characteristics such as audio communication and other features currently typical of the Internet of things.

Author details

Jesús García-Guzmán^{1*}, Farah H. Villa-López², Jorge A. Vélez-Enríquez¹, Luz A. García-Mathey¹ and Alfredo Ramírez-Ramírez¹

*Address all correspondence to: jesusgarcia@ieee.org

¹ Universidad Veracruzana, Xalapa, México

² University of Warwick, Coventry, United Kingdom

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