Virtual Laboratory for the Study of Technological Process Automation*

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This paper deals with the implementation of virtual reality technology as a higher level of e-learning education comes into the teaching process. It presents the design and development of a Web-based virtual laboratory architecture that supports laboratory training in the study of technological process automation. The proposed architecture provides several advantages to institutions offering e-learning and distance education courses in Industrial Automation. It facilitates the process of learning over the Internet by providing a Web-based user interface that allows remote users to access and control several physical models of technological processes and also verify to control programs, which are also developed on the basis of intelligent control methods, via a virtual model without damaging the system equipment. The architecture presented in the paper is not dependent on a specific SLC hardware or software configuration and offers the possibility of increasing the efficiency of the pedagogical process and developing the students' creativity, practical skills and proficiency, with an accent on the possibility of developing optional solutions in the field of automatic control of technological systems.

Keywords: virtual laboratory; remote access; industrial automation; virtual model; physical model of technological process

1. Introduction

A virtual laboratory is a heterogeneous, distributed environment that allows scientists all over the world to work on a common group of projects [1]. This environment should allow experiments to be conducted using physical devices, performing simulations using computational applications, and communication between users who are working on the same topic. This new method of project-oriented learning using e-learning methods combined with real experiments presents a new trend in learning [2]. A typical online offer includes study materials and other standard means of collaboration, which often are not sufficient to support the complete learning experience required by disciplines where the students must also develop hands-on practical experience [3]. Today, rapid changes in society and technology have generated a demand for more flexible engineers who possess many more qualifications than just a high level of technical or scientific specialization. It is therefore important to provide students with real-world experience. Today this problem is getting more and more attention because a real experiment gives students the feel of practical testing as well as seeing the impact of real-time effects.

A basic requirement in engineering education is the provision of a significant number of practical activities where students can verify and practice methods learned in theoretical courses, through laboratory experiments [4]. Many engineering programs have considered virtual laboratories as an essential element of education [5, 6]. Building a virtual laboratory is a way of combining information and communication technologies with real practical experience in the educational process. These laboratories that are usually accessible through the Internet are very attractive as they reduce the costs of acquiring equipment and also allow students to perform experiments at their own place without the risk of hurting themselves or damaging the equipment and with no limitations imposed by official working hours in the laboratory. Such Web-based technology can also be applied to general remote control systems in many areas of research and engineering.

The development of virtual laboratories is not a novel idea. Many remote experience systems exist and they actually run in various areas of engineering. Chevalier *et al.* [7], Colwell *et al.* [8] and Scanlon *et al.* [9] constructed Web-based interactive virtual education systems in the mechanics area. Montero-Hermandez *et al.* [10], Crow *et al.* [11] and Ko *et al.* [12] developed an Internet laboratory in the area of power electronics. In the area of control, You *et al.* [13] described the design and implementation of a robotic system that utilizes the Internet as an experimental platform. Malki and Matarrita [14] created a virtual laboratory for process control based on the LabVIEW environment. They used virtual model software with PID control of second order plants. Another interesting project is a virtual laboratory created by developers from the Department of Chemical Engineering at John Hopkins University, Baltimore, USA [15]. The virtual laboratory is based on Java technology (Java applets) and includes models such as a robotic

arm, spatial distribution of sound, heat conduction in materials, the diffusion process and some computing and statistical programs. Casini *et al.* [16] presented a remote laboratory for automatic control where students interact with physical systems through the Internet. They describe processes for a DC motor, magnetic levitation system, and two-degrees-of-freedom helicopter simulator. Saygin and Kahraman [17] presented a Web-based programmable logic controller (PLC) laboratory for manufacturing engineering. The virtual laboratory described by Cirka *et al.* [18] was created using software the programming platform Adobe Flash and it provides virtual simulations of technological plants such as a liquid storage tank system, tube heat exchanger, and continuously stirred tank reactor.

A virtual laboratory is not just some Web-based simulation. It is a real electro–technical experiment conducted in the laboratory but it is remotely accessed, controlled and monitored by Web-based tools [19]. From this point of view a virtual laboratory including only simulations of system dynamics is insufficient for actual education needs, so we have decided to improve it with features of technological process control via small logic controllers (SLC).

However, building an experiment is expensive and it is impossible for an educational institution to have a complete range of experiments. For this reason, the Department of Electrical Engineering and Mechatronics of the Technical University Kosice (TU Kosice), in cooperation with the Department of Automation and Control of the Slovak University of Technology in Bratislava (STU Bratislava) prepared a project for building a joint virtual laboratory dedicated to technological process control via small logic controllers.

The Web-based system control architecture presented in this paper allows remote access to an SLC-controlled physical model of the technological process over the Internet. The virtual laboratories for automatic process control built so far enabled only the use of already implemented control structures [20–23], which enabled the modification of controller parameters within a controllable range due to the possible damage to the controlled physical model. The concept of the proposed virtual laboratory for control of processes on basis of SLC enables the application of various, intelligent control methods (fuzzy logic, genetic algorithms, neural networks), which are very often used in practice in the control of complex nonlinear systems. This is very important for the students for gaining practical experience. In the process of verifying the proposed control algorithms for a concrete virtual laboratory workplace, virtual models are used. These protect it from damage in the case of a wrongly designed

control algorithm. Another important aspect is to create a feeling of real experimentation in the remote user. A video and audio broadcast provides the remote user with the feeling of being present at the experiment location. With the aid of visual feedback, the user can supervise the experiment and check whether everything is running as expected. The architecture provides both on-site and distance students with the same learning environment, and minimizes the difference between the qualities of learning of both student bodies. Controlling the "real" technological process via the Internet presents a fundamental difference between this approach and other similar approaches, which rely only on computer simulation [24–26].

From the pedagogical point of view the main aim was to assess the effectiveness of this virtual laboratory compared with traditional hands-on laboratory learning scenarios. An important question is whether Web-based learning or traditional teaching is more effective at improving student achievement. Many studies suggest that there is no difference in test scores between Web-based and conventional courses [27, 28]. Other studies find that students enrolled in a Web-based course perform worse in a final exam than students educated by conventional instruction [29]. The evaluation approach of this virtual laboratory was focused on the effectiveness of different learning programs by using special evaluation questionnaires. The goal was to improve the functionality of the virtual laboratory and distinguish different designs for learning in the field of technological process automation.

2. Significance of building a virtual laboratory

Small logic controllers are nowadays the main tools used at the basic level of automation of mechatronic systems and technological processes. Almost every operational and service engineer needs to master them regardless of whether he or she is in a user or a designer of systems with small logic controllers.

In the existing laboratories, the teaching of subjects related to automation and control in practice is conducted within 42 hours altogether. This is to learn about the automation tool (SLC) proper, its programming, details of the specific technology and verification of the design. Students have to meet high demands—each piece of information is new to them. This means that they can manage to grasp the elaboration of a formal solution of an automation problem during the semester, but due to the lack of time available its correctness cannot be verified. In order to increase the quality of learning and to acquire a real ability to design control systems in

practice, it is necessary to enable the students to make the most of practical experiences in the field of control of systems with SLCs. With the structure of the given timetable and the number of students, this can be realized by more effective use of the laboratory and its physical tools. The main aim of building a virtual laboratory is to include the design aspect in the educational process of mechatronic systems, because a virtual laboratory presents a new e-learning tool in which the experiments should not be only analysis-oriented (to measure and see the results), but also synthesis-oriented [30].

The fundamental objective of this study is to develop a Web-based system control environment which uses physical models of technological processes to teach SLC programming and control over the Internet.

The main assets will be that the laboratory will serve for teaching subjects related to automation, control and visualization of technological processes and that it will enable the implementation of new forms of study (distance e-learning forms), which will promote the innovation of the educational process at the Department of Electrical Engineering and Mechatronic of the TU Kosice and the Department of Automation and Control of the STU in Bratislava. In the future, the open concept of the virtual laboratory will enable its simple enhancement by connecting more workplaces with different physical models of technological processes from universities in Slovakia and abroad. A wider range of laboratory resources will be made accessible to the students and they will have the choice between more experiments. A virtual laboratory facilitates the sharing of expensive instruments and equipment. The financial benefits will also be very significant, because there will be no need for duplication of equipment.

The benefits for students at bachelor, master and Ph.D. study level will be in the higher quality and efficiency of engineering education, greater attractiveness of the studies, the possibility of unlimited access to the solution of automation tasks in terms of time and in increasing of practical knowledge and experience in the design and implementation of technological process control systems based on logic controllers.

Furthermore, interactive experimentation on real-world plants improves the motivation of the students and also develops an engineering approach to solving real problems. Simulation is a proper way to complement control education, but in general it cannot replace experimenting on real plants. Since simulation is only as good as the model, experimentation has the advantage of making the user aware of phenomena that are hard or impossible to simulate [31].

3. Concept of the virtual laboratory

The concept of the virtual laboratory that was established at the Department of Electrical engineering and Mechatronics, Faculty of Electrical Engineering and Informatics, Technical University of Kosice is based on the requirements of remote experimentation and the available information technology.

We transformed the traditional automatic control laboratory into a virtual laboratory by taking advantage of the convenience of the Internet. The system is designed to allow students to log into the main server located in the laboratory from remote locations. Students can design and execute automatic control experiments and verify the correctness of the proposed control algorithms by means of virtual models and observe the results in real time. We designed a Windows-based application similar to a Windows operating system remote control application. This virtual laboratory runs 24/7 so that students can practice and gain hands-on experience of automatic control systems anytime and anywhere.

From the users' point of view, there are further important features that have to be fulfilled. The users may not have the choice of which computer to use on their site. They usually do not want to install specific software before they can start the experiments. For the correct design of a control program for SLC-based control of a technological process, the students need to have relevant knowledge in the field of combinational circuits, sequential circuits, logic control, programming in STEP 7 language, ladder diagram programming and SLC structure and SLC components. The control tasks assigned to each student can be solved in various different ways by using the fundamental SLC programming techniques. In the case of the design of a control structure based on intelligent control methods students use the Matlab/Simulink program that, with the help of a special block library from B&R, enables automatic generation of the code of the simulation scheme into the relevant SLC. This flexibility facilitates independent thinking and creativity. The control tasks can be assigned to individuals as well as to teams. Group members can be at different locations and communicate via e-mail while monitoring the live video stream on his or her computer.

The main features of our virtual laboratory are as follows:

1. *Online reservation and management system.* This makes it possible for the students to create a user account by filling in a registration form where they choose their own login and

password, enabling them to log into the virtual laboratory via the Internet. Here they can book time at the chosen workplace seven days in advance. The maximum time that can be booked in a single workplace is 3 hours, which is sufficient for the fulfillment of the given tasks without the student blocking the workplace for the whole day. During the reservation process a unique password will be generated for the student, valid for entry into the workplace within the booked time. In this way the workplace cannot be occupied during that time by another student. The session will be cancelled if the student fails to log in within 10 minutes from the start of the booked session.

2. *Remote desktop system design.* We developed a software application for the service of the workplaces and laboratory as a whole. This application enables the users to see the screen of the control experiment remotely, as if they were actually sitting in front of the computer in the laboratory; it further controls the switching on of the computer at the workplace prior to the time of the booking (if it is not already switched on) and it also logs the student out from the laboratory just before the time of the upcoming reservation by another student. In addition to these functions the application enables the running of the virtual model at the particular workplace for verification of the correctness of the proposed solution.

3. *Remote video monitoring system.* When a student finishes the design of the control algorithm for the particular physical model and starts executing the experiment, he or she has the option of opening a pop-up video window. A video image of the equipment screen will be transmitted to the user's computer over the Internet. Users can actually see the execution results by monitoring the status of the real-time operation in the laboratory via the screen.

4. System design and development

The design constraints and requirements can be listed as follows:

1. Elaboration of a concrete concept of the virtual laboratory, up to its HW design solution.
2. Design and implementation of concrete physical models of technological process subsystems.
3. Interconnection and activation of the individual workplaces for operation in both ON LINE and OFF LINE modes.
4. Implementation and activation of the local computer network.
5. Implementation and activation of the server for

virtual remote access to the individual laboratory workplaces via the Internet.

The general structural layout of the virtual laboratory is shown in Fig. 1.

The virtual laboratory includes nine workplaces with PCs, five of which are interconnected with inputs and outputs of small logic controllers. They can serve for work in the ON LINE mode as well as for formal preparation of tasks in the OFF LINE mode. Because in the teaching process the formal preparation of tasks takes up significantly more time than the proper functional adjustment of the (relatively simple, school) algorithms, in the laboratory there are four workplaces used only in the OFF LINE mode, or for simulation/modeling purposes. In the virtual laboratory all workplaces are connected via the local network to the laboratory server through which "remote desktop" access to each workplace or the use of the common laboratory services the by all workplaces is possible. The laboratory server enables the control of the particular workplaces through remote computers connected to the Internet and administration of their use by the students.

The laboratory as a whole has been built from the lower (technological) level towards the upper virtual user level. As mentioned above, five physical models of technological processes were built in the laboratory. Their analog and binary inputs/outputs are interconnected with the SLC. The programming and visualization software has been installed on independent PCs which are connected with the SLC through MPI (Multi Point Interface) and which are used for the work with the concrete model of a technological process in the ON LINE mode. Four PCs are for preparation of control and visualization programs in the OFF LINE mode and can be used as backup PCs.

The workplaces for ON LINE work comprise the following physical models of technological processes:

- air ball model,
- water tanks model,
- conveyors model,
- intelligent gate model,
- wheel pendulum model.

Physical models of technological processes serve only for work in the laboratory. The students are able to verify the correctness of control algorithms through the virtual model of the technological process, which is connected to the real inputs and outputs of the SLC. After verifying the control program, the students are ready to work with the real physical model of the technological process in the laboratory.
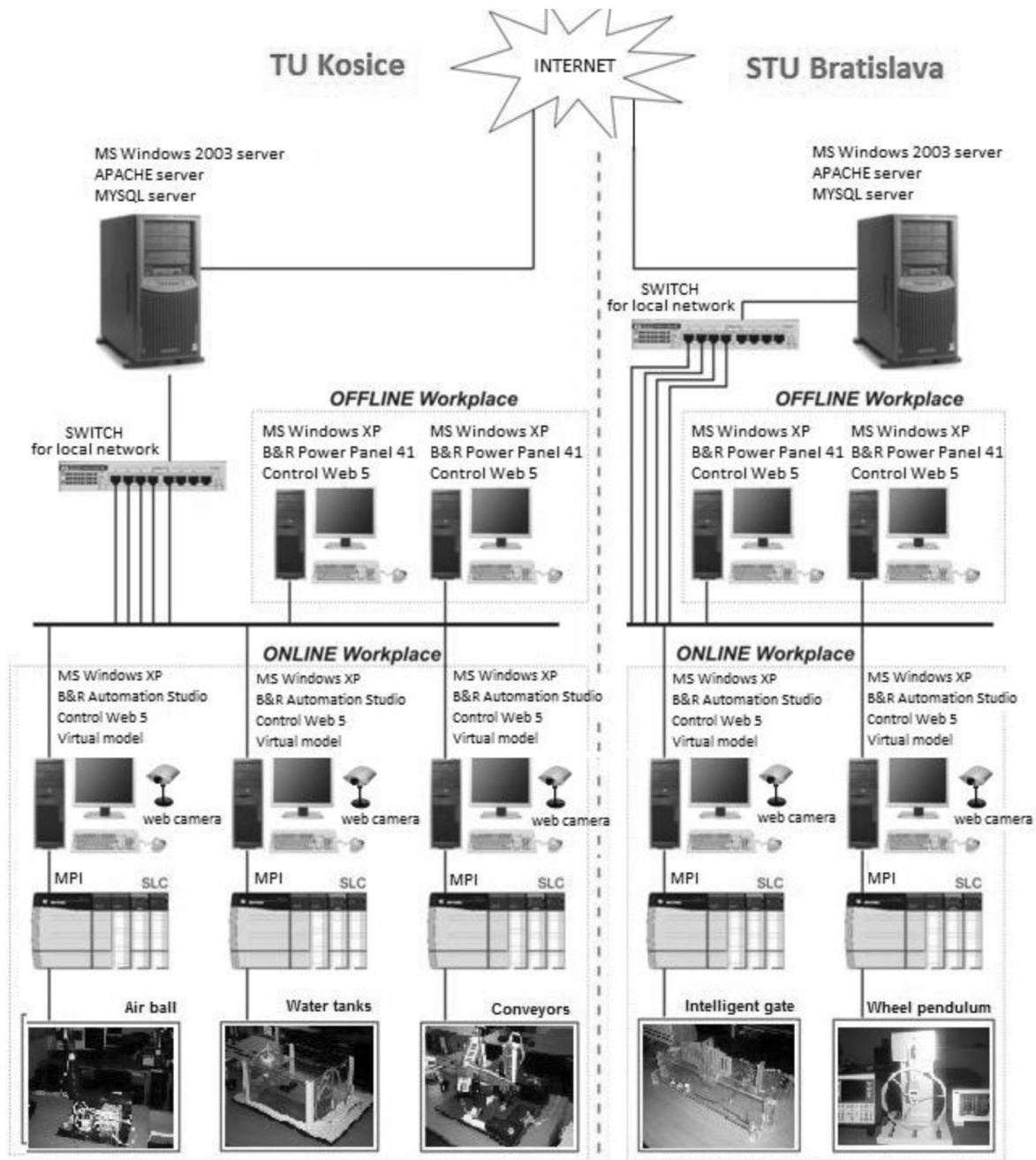
Fig. 1. The virtual laboratory structure.

A virtual model is a very powerful tool for verifying a control program. Executing programs on actual equipment without testing them via a virtual model may lead to collisions and damage to the system [32]. A virtual model helps verify a program, thus preventing damage to the equipment. A laboratory model of tanks with liquids and their virtual models are shown in Fig. 2.

The user activates and controls the virtual laboratory by means of the Web server page. The virtual laboratory home page provides students with a complete learning environment that, besides basic information such as the definition of the main goal of the SLC virtual laboratory, of what is required from the students, of the educational objectives, and the specification of the virtual laboratory architecture, also provides them with a list of the physical models of the technological processes along with a short description, as well as a detailed description, of how to develop the particular control program to control the technological process. After the student has logged into a concrete workplace, the first page of the corresponding virtual model is displayed. On this page there is the description of the physical
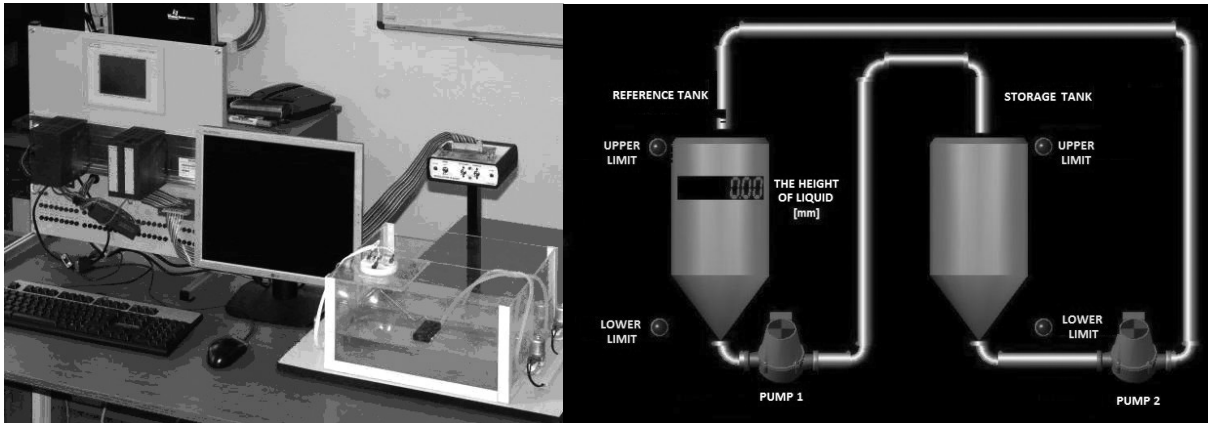
Fig. 2. The laboratory workplace and the virtual model of liquid tanks.

model, its operational modes, the goals of the physical model control, the I/O table with given analog and digital inputs and outputs of the concrete physical model, and a structural scheme of how they are connected to the SLC. It is shown which concrete I/O modules are required for the realization of the given control task.

The virtual laboratory requires communication tools to be used effectively by users who may be working on the same laboratory application as a team. The Web-based environment of the virtual laboratory is equipped with network cameras, a chat feature and e-mail to reduce the impact of the natural barriers that exist for Web-based applications.

5. Hardware/Software configuration and communication structure

The communication structure is based on a client/server architecture written in Java. Users may work on client computers equipped with Web browsers and Java runtime environment. The browser loads the client modules as Java applets from the server and starts them. The reservation system for reserving time on the physical model for doing laboratory exercises is available to the users via the Web page of the virtual laboratory, which is located on the laboratory server. The laboratory server runs on a PC with Windows 2003 operating system. It includes an APACHE server together with a MYSQL database server on which tasks for the service of the individual workplaces and the laboratory as a whole are run periodically. The laboratory server provides a virtual laboratory Web page and Java applets. Five video cameras are connected to this server, one for each physical model.

A B&R Power Panel 41 PLC is used to control the physical model. The PLC is programmed using the Automation Studio software package via Windows XP Terminal Services on the process control

PC. For the implementation of control algorithms from the area of intelligent control methods (fuzzy systems, genetic algorithms, neural networks) the Matlab/Simulink program is installed on the individual PCs, which through a special library of blocks from B&R enables automatic generation of the code of the developed control program in the Matlab/Simulink program into the PLC. For communication with the physical model, an I/O card with analog inputs and analog outputs is installed in each process control PC. Then the program is compiled and downloaded to the PLC through MPI (Multi Point Interface) interface. A virtual model of the real physical model, developed in the visualization application generator Control Web 5, provides animation for PLC program verification.

The communication structure is general; therefore it can be used in different experiments. Java applets on the client side allow continuous improvement of the software, since the applets are loaded when they are needed. The applets are always up to date, so no software upgrade is required when the software changes.

Live video is provided through network cameras so that the user can monitor the execution of control applications. The network camera is a Web-based real-time video-streaming camera with built-in video server capability. The network camera has its own IP address and includes the computing functions to handle network communication protocols, such as TCP/IP. The network camera does not need to be connected to a PC. Five network cameras are used in this application, one for each physical model. The cameras support both ActiveX and Java applets, from which follows platform independence on their functionality.

6. Virtual laboratory implementation

For the purpose of verifying its functionality, the virtual laboratory was implemented into the teach-

ing of the course Industrial Automation in the winter semester of the first year of engineering studies, as part of the study program Automation of mechatronic Systems at the Faculty of Electrical Engineering and Informatics, Technical University of Kosice. The study group of 30 students was divided into two halves. Students in the first half of the group carried out laboratory training, which included control algorithm development in the form of a ladder diagram according to the given task, its verification by means of a virtual model and a final run of the control program in SLC for the concrete physical model workplace carried out during the time determined for the teaching of the given course in the department's laboratory.

The second group of students had access to the individual experiments through the Web page of the virtual laboratory and its reservation system. After all the experiments were finished, each student was asked to provide feedback by filling in a questionnaire that was mainly aimed at the effectiveness of exploitation of the virtual laboratory. The questionnaire consisted of six questions and a choice of seven responses was given for each question: no, poor, fair, good, very good and excellent. The results of the assessment are shown in Table 1.

On the whole, more than 90% of students using the virtual laboratory assessed the services it provided as excellent. The important fact, however, is that while the students who were working only in the facility of the department laboratory during the time determined for teaching were able to work on assignments for two workplaces with process physical models during the semester, over 90% of students exploiting the virtual laboratory and experimenting in the control of all five physical models. This resulted in these students obtaining more experience in design, implementation and tuning of control algorithms based also on intelligent control methods via SLC, which was manifested in their success rate in the exam for the subject Industrial Automation. Each of them passed the exam at first try, while in the other group of students only 60% were successful. The questionnaire as well as the discussions with the students showed that the exploitation of the virtual laboratory also contributed significantly to the growth of student motiva-

tion for obtaining good results in the subject and in general for their interest in the study of automation in industry. Gaining feedback through questionnaires will be further exploited for improving the user-friendly user interface of the virtual laboratory and its functionality.

7. Discussion

In this paper, the architecture of an e-based virtual laboratory for the study of technological process automation is presented. The system architecture provides an online environment that students can access any time and anywhere to control or observe SLC-based physical models of technological processes in the laboratory via the Internet without damaging the system to be controlled. The concept uses an SLC-controlled water tanks system, an intelligent gate system, a conveyors system, an air ball system and a wheel pendulum system. As each of the universities (TU Kosice and STU Bratislava) is provided with physical models of different technological processes, the joining of both universities in the virtual laboratory project makes it possible for students to use all the tools from both workplaces and thus gain practice in a wide variety of automation tasks. Without the involvement of both universities they would be limited to the physical possibilities of a single local laboratory. The architecture of the virtual laboratory enables the implementation of various control structures, including ones based on intelligent control methods. The online learning activities of our system provide effective e-learning material and a learning environment that meets the goal of education of continuously improving the learning methods to suit the needs of the students. The platform also allows students to participate in group discussions, which helps students to establish good interaction skills and share learning experiences. In the presented system architecture only one "active" user at a time can interact with the physical model and execute his or her SLC program, which runs the physical model and also runs the virtual model. Thus, there is no difference between the "real" and the "simulated" conditions from the standpoint of SLC programming. The architecture presented in

Table 1. Questionnaire: Assessment results

Question	Assessment result
Q1. The quality of the lab materials is high, and easy to understand.	89%—excellent, 7%—very good, 4%—good
Q2. Laboratory assignments (i.e., control tasks) were well defined.	84%—excellent, 9%—very good, 5%—good, 2%—fair
Q3. Reserved time was sufficient to complete laboratory application successfully.	91%—excellent, 7%—very good, 2%—good
Q4. Virtual laboratory environment functioned satisfactorily.	98%—excellent, 2%—very good
Q5. Control program file was easily downloaded to the SLC.	96%—excellent, 3%—very good, 1%—good
Q6. The experience was challenging and interesting.	92%—excellent, 6%—very good, 2%—good
Q7. Virtual laboratory met our expectations.	93%—excellent, 6%—very good, 1%—good

this paper is not dependent on specific SLC hardware or software. It represents a general Web-based system architecture for the study of industrial automation.

In order to assess the effectiveness of our virtual laboratory, we conducted an experimental study and analysed the outcomes. We also looked into the impact of exploitation of the virtual laboratory by the students on their academic achievements in the automatic control course. As a result of the questionnaire and discussions it has been determined that the students appreciated the virtual laboratory and were highly motivated to make use of it. Most students were willing to use such Web application not only for technological process control but also for other courses. The questionnaire has also given positive results as to whether virtual laboratory and remote control can improve the quality and the effectiveness of education. The above proves that the virtual laboratory has a practical value in education and can be extended to other subjects of study or to laboratory courses for professionals from practice. Reliability of the results could also be strengthened by applying this study to more extensive student groups.

8. Conclusions

The virtual laboratory platform is an effective alternative to setting up a conventional laboratory to support courses in engineering education. This platform can be run in real time through the Web from anywhere in the world, and the actual system can be monitored using a Web camera. This remote virtual laboratory platform for automatic control is flexible and can easily be adapted to different engineering education courses for students and also for possible representatives from industrial practice who are interested in online laboratory courses. This study discusses the implementation of such a Web application and the evaluation of its effectiveness in teaching. The results have shown that using the virtual laboratory in the teaching process positively influences its effectiveness, because with it the students gained more practical experience, a fact that was demonstrated in their better study results and exam scores (it is important to emphasize that both groups were equal in all respects).

Use of this Web technology has the following benefits: (1) it allows students to gain different experiences based on the implementation of control structures, including ones based on intelligent control methods, to obtain course goals; (2) it reduces costs by sharing laboratory equipment; (3) it allows students to perform experiments repeatedly, independent of time and space limitations, without

damaging the controlled system; (4) it helps students better understand the experimental environment monitoring a real-time laboratory environment using a camera, and (5) it allows students to improve their self-learning capabilities.

As the virtual laboratory is accessible via the Internet, it can also be exploited in the training of people who are most disadvantaged in the labor market, including disabled people. The project contributes to improvement of the skills and competencies of students through education and training in the field of technological process automation and thus can facilitate their integration into the labor market.

It is our hope that our findings will help improve the effectiveness of teaching and learning in automatic control courses and will increase the interest and motivation of students for studies in the area of technological process automation.

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