Power Engineering and Motion Control Web Laboratory: Design, Implementation, and Evaluation of Mechatronics Course

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***Abstract*—During the E-learning Distance Interactive Practical Education project, 13 partners from 11 European countries joined together to build a power engineering and motion control remote laboratory, which would offer 18 complete online courses with remote experiments and high-quality documentation, to students from the universities of all participating partners. The major benefit of this project is the possibility of sharing expensive equipment and lessening the burdens of technical and organizational problems. This paper outlines the project's goals, organization, and, as an example, realization of one of the project's modules. The described module is a mechatronics motion control course, which explains the most important aspects of motion control design, from modeling, simulations, control design, experimental validation, and comparison between various controllers. The technical solutions, educational strategy, and realization details are given for the module. The pilot testing of the module was performed to assess the module and find out what the students' personal attitude concerning e-learning and remote experiments. The results of testing are presented and discussed.**

***Index Terms*—Distance education, engineering education, mechatronics, motion control, power engineering, remote laboratories.**

I. Introduction

MECHATRONICS and automatic control engineers should be able to identify components of the control system, to model and analyze individual elements, to design the control system, and to tune the controllers' parameters in such a way that the system operates in accordance with given specifications. However all topics become much more apparent when considered as a theory and coupled with an analysis of the real-time operation on target system. Therefore, it is beneficial that students test their designed control algorithms not only by using the simulations but also on a real system. In such a way, the students also become acquainted with real-world features and gain experience and knowledge, which cannot be obtained by only performing simulations. Although classical hands-on laboratories are very useful and educational, they have many limitations regarding space, time, and staff costs. They are usually fully occupied, and yet, the students still have to conclude their research within the time allotted for experimental work. The problems with traditional laboratory work could be avoided by using remote experiments and remote laboratories. During remote experimentation, students operate within the real system, although not physically present in the lab. Furthermore, they can conduct their experiments by accessing the lab when they most need it and from a remote location which is more convenient for them. Remote laboratories are mainly used within the academic field to enhance classroom lectures, to share research equipment, and to supplement the learning process. In addition, a remote lab efficiently solves those problems occurring during the course schedule planning, particularly when educating part-time students, participants in the programs of life-long learning, and students from abroad or when working with large groups of learners.

A variety of different remote experiments and remote laboratories have been developed in the field of mechatronics and automatic control [1]–[24] by using many different technologies [25]. These remote experiments include different objects under control, such as direct-current (dc) motor [1]–[11], inverted pendulum [1], [2], [14]–[17], [20], [21], magnetic levitation [1], [2], coupled tanks [1], [2], [13] [17], [18], helicopter [1], [2], [12], [13], [18], ball and beam [2], and others. In the majority of existing solutions, remote users can execute experiments, change predefined controller parameters, observe results as text or graphical views, and download the experimental results. Some remote labs also include additional functionalities, such as testing a custom-designed controller [1], [2].

Although remote experiments seem to be very useful and educational, a lot of hard work is needed when setting them up. Design of a course that is supplemented by remote experiments presents both educational and technical challenges. The educational challenges deal with the problem of how to design a course that presents the subject matter in a clear and interesting manner and in the form of e-materials supported by suitable remote experiments. The second even greater educational challenge is how to encourage the students' active engagement in the learning process and enhance their interest as the whole course is online and there are only occasional contacts between lecturer and learner. Most technical challenges arise from the problem of preparing reliable and good-quality remote experiments. The experiments are expected to be available all the time and cover most of the course's topics. When experimental

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setups include mechanical parts, additional requirements for the design of remote experiments have to be taken into account. The mechanical parts must be robust, constructed in such a way that the errors in the control algorithm and consequent controller's instability do not cause any mechanical damage. In addition, wear and the tear of the mechanical parts should not be too excessive so that replacement of the mechanism's components is rarely required.

This paper presents the "Mechatronics and Hardware-in-the-loop Simulations" course, developed within the Leonardo da Vinci E-learning Distance Interactive Practical Education (EDIPE) project [26], covering the theory, simulation, and remote operation of a mechatronic device. The presented control course has been developed primarily for the students of electrical engineering (EE), mechanical engineering, and mechatronics, although it can also be taken by students of physics/mathematics and students of other engineering and natural science study fields who have sufficient preliminary knowledge about mechanics, control theory, modeling and simulations, mathematics, and physics.

This paper is organized as follows. Section II describes the EDIPE project and the organization of the central Web site, which is shared by all the project's partners. Sections III and IV describe a remote laboratory built at the University of Maribor. Certain technical solutions are presented in Section III, while Section IV describes this module from an educational point of view. First, the adopted e-learning educational strategy is discussed. Then, the experimental mechatronic system is presented. This is followed by a description of the system's modeling, simulations, control design, and validation of the control design by remote experiments. Then, the results of pilot testing are presented and commented. The summary and conclusion are provided in Section V.

II. About the EDIPE Project

The EDIPE project [26] is funded within the Leonardo da Vinci 2006 EU Program and involves 13 partners from 11 European countries. The main goal of this project is to build an international collaborative remote laboratory that would include courses supported by remote and virtual experiments from different technical areas, including the fundamentals of EE, power electronics, and motion control. Within the framework of this project, 18 different courses or modules are developed (Table I). In contrast to the majority of existing remote labs, where only experimentation and short descriptions of experiments are offered to users, these courses contain high-quality documentation with theoretical background, simulations, various exercises, and remote accessible experiments. Therefore, each course can replace a big part or even the complete regular courses at the universities. Until now, several courses have been fully operational, and some preliminary results from them are available in [27]–[34].

TABLE I
List of EDIPE Courses

1. Fundamentals of Electrical Engineering
1.1 Single Phase and Three Phase Rectifier Circuits
1.2 DC Circuit Measurements and Resonant AC Circuits
2. Power Electronics
2.1 Power Converters
2.2 Power Factor Correction
2.3 PWM Modulation
2.4 DC-DC Converter for Renewable Energy Sources and Microgrid
2.5 Power Quality and Active Filters
2.6 Power Quality and/or Electromagnetic Compatibility
3. Electrical Machines
3.1 Basic Electrical Machinery – Synchronous generator
3.2 DC Machines
3.3 Basic Electrical Machinery – DC Motor
3.4 Basic Electrical Machinery – Asynchronous Motor
3.5 Induction machine motor drive system
4. Electro-Mechanical and Motion Control Systems
4.1 Basic Elements of Internet-based Telerobotics
4.2 Mechatronics & Hardware-in-the-loop Simulations
4.3 High Dynamic Drives - Motion Control
4.4 Automotive Electrical drive
4.5 System of Water Tanks Controlled by a Small Logic Controller
4.6 System of Conveyors Controlled by SLC

A. PEMCWebLab Course Management System

Remote experiments developed within the EDIPE project have been distributed all over Europe. Although these experiments are physically located in different locations (inside project partners' laboratories), they are accessible only via the PEMCWebLab Course Management System (CMS) [35]. This CMS contains the contents of all courses (learning objectives, theoretical backgrounds, documentation, links to remote experiments, etc.), while the content of an individual course can be modified only by a responsible partner. An access to the CMS is limited only to authorized users. Authorization is e-mail based and is currently limited to the project partners' e-mail addresses. At the end of the project, the developed courses will be available to the following project target groups [26]:

1) those who need to obtain the latest knowledge in EE: master and bachelor university students, and teachers;
2) unemployed EE graduates, who have not worked for long periods in their professions;
3) disabled people having difficulties to attend courses regularly;
4) private enterprises wishing to train employees;
5) young engineers still refining their specialties.

When a user logs into the PEMCWebLab CMS, she/he gains access to all courses. Within a specific course, the following common course menu options can be found (Fig. 1):

1) course overview;
2) course objectives;
3) documentation;
4) experiments;
5) questionnaire.

The "Course Overview" section states the description of the course, the assumed entrance competences, the optional structures of the courses, and the evaluated time requirement. The description of the course includes a short summary and a description of the main chapters. The assumed entrance

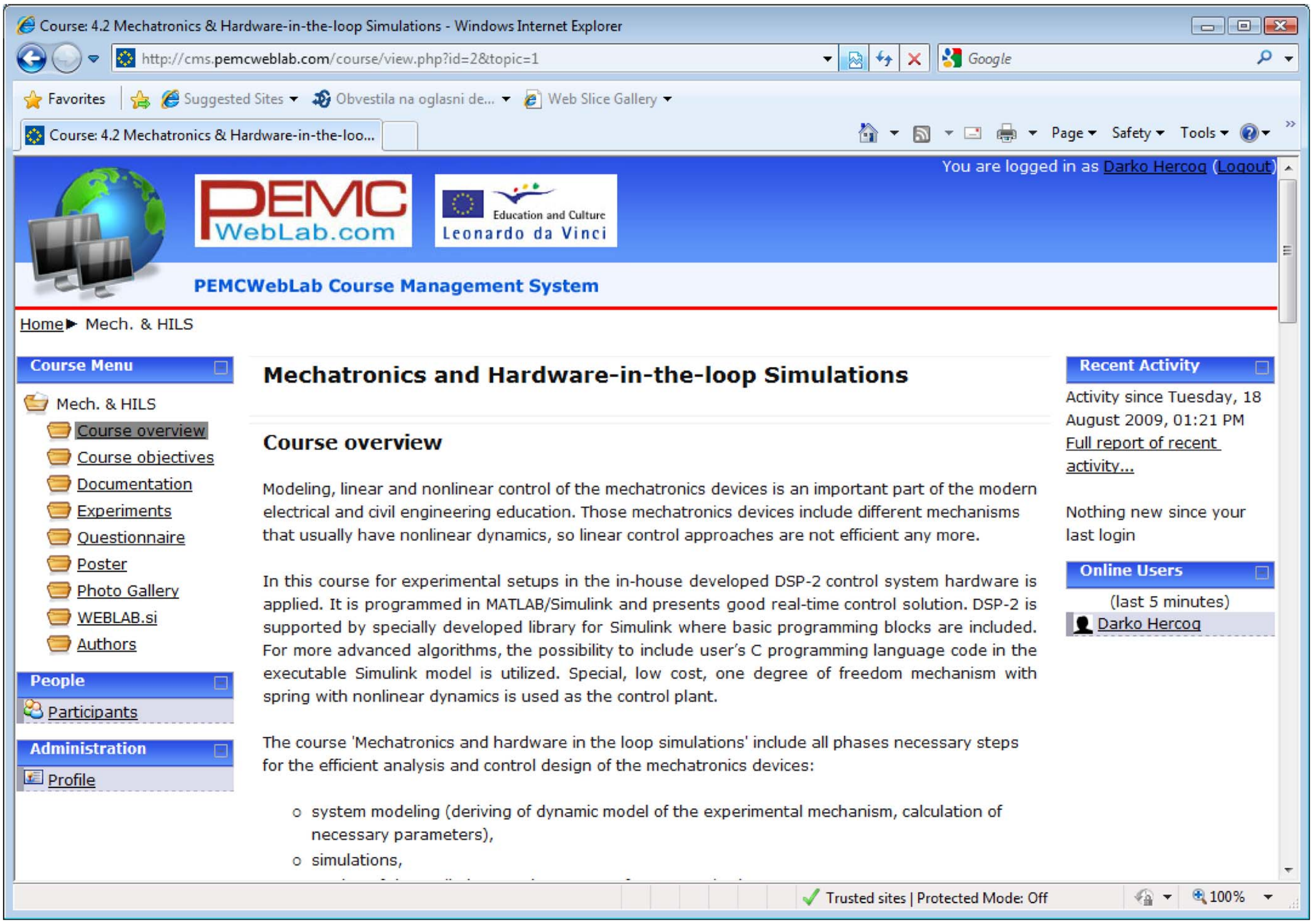

Fig. 1. Content of "Mechatronics and Hardware-in-the-loop Simulations" module.

competences include a description of the necessary knowledge needed as a basis for the comprehension and implementation of the course. The conditions are stated as concrete conditions. Thus, knowledge of, e.g., physics at the high-school level may be required, including knowledge of linear algebra basics, knowledge of programming, etc. The course structure shows the logical units or chapters which the module is composed of. A time requirement defines the total time needed for the entire module execution.

In the "Course Objectives" section, course objectives, expected learning outcomes, and a suggested method of achieving the desired learning outcomes are concisely stated. The expected learning outcomes relate to gained knowledge or skills, while the suggested method of achieving the learning outcomes describes the related procedures.

All theory is stated in the "Documentation" section, together with the literature for additional studying. The theory is combined with theoretical and computational exercises, simulation exercises (this may vary slightly from module to module), and remote experiments.

Furthermore, there is also documentation for the teacher. The course would be used by teachers from other participating faculties; therefore, such documentation is a necessity. Aside from being a key to the exercises, it also offers advice on how to include the course into a study program. A description of the most common problems that appear during practical implementation of the course is also given, e.g., problems about understanding certain details or problems when executing remote experiments. This documentation is provided on a specific demand from the author of the course and is not posted on the Web site. The final part of the documentation is for the technical staff and describes the maintenance of the experimental setup.

In the "Experiment" section, all the necessary data needed for practical implementations of remote experiments are collated. These are short descriptions of experiments and instructions on how to carry out remote experiments, and downloading of necessary software is available for certain modules. This section varies according to different courses, since different solutions for the realization of remote experiments are used by each of the project's partners.

In the "Questionnaire" section, the users can fill out an electronic questionnaire, which would help course developers to improve the qualities of the developed courses.

In addition to the stated common course menu options, some courses also include online interactive animations or simulation files, general information about course authors, a photo gallery of remote experiments, etc. The web page for the course "Mechatronics and Hardware-in-the-loop Simulations" is shown in Fig. 1.

B. Booking System

An important part of PEMCWebLab CMS is the booking system, which allows remote users to carry out a booking procedure for remote experiments by themselves and, at the same time, prevent simultaneous access to the same remote experiment by different users. The developed booking system is integrated into the PEMCWebLab CMS and enables course developers easy and rapid creation of a booking system for their remote experiments. In addition, the booking system allows any adaptation to the needs of specific experiments by means of time-slot duration and dates and hours during which the experiment would be available to remote users.

Each developed module has an "Experiment" menu on the left side of the module, where the "Book and run experiment" link can be found. After selecting this link, a new web page with a seven-day calendar (timetable) appears. This calendar page shows the local time (in the user's time zone), which may be different from the server time (GMT+1). The time conversion takes place automatically so that users in any time zone can see the free/booked time slots, according to their local time zones. Each column of the calendar is divided into time slots (cells). By clicking on the book icon inside an individual calendar cell, the remote user is able to book the selected time slot. When the reserved time slot becomes a current time slot, a red arrow icon appears inside the cell, which represents a valid link to the remote experiment. When this link is selected by the remote user, the booking system creates an access key and, along with certain other experiment parameters, sends it to the lab PC, which is located inside the responsible partner's laboratory. Based on the received key, additional program running on that lab PC creates unique experiments' web page, which is only valid until the end of the reserved time slot. After a successful response from the lab PC, the booking system redirects the remote user to the newly created experiment web page.

III. Remote Laboratory of "Mechatronics and Hardware-in-the-Loop Simulations" Course

Different technical solutions for establishing a remote laboratory are used by each project partner. As one of the solutions, a remote control laboratory developed at the University of Maribor and implemented in the module "Mechatronics and Hardware-in-the-loop Simulations" will now be described in more details.

The laboratory is based on in-house developed control hardware and two commercially available software packages. MATLAB/Simulink is used for control algorithm development, while LabVIEW is used for the user front end and remote control. The DSP-2 control system [36] is implemented as basic hardware (Fig. 2). It is based on a DSP-2 controller [37], which includes a TI TMS320C32 floating-point processor, Xilinx FPGA, A/D and D/A converters, a three-phase pulsewidth modulator, an optically isolated digital I/O, interface for the incremental encoder, RAM, FLASH ROM, and CAN controller. The DSP-2 control systems can be used in different control applications and can be easily programmed using the block-oriented programming language MATLAB/Simulink [36], [38].

Fig. 2. DSP-2 control system.

The structure of the remote laboratory is shown in Fig. 3. This remote laboratory, accessible at web page [39], is composed of DSP-2 control systems and a laboratory server. DSP-2 control systems are connected to the lab server which is, in turn, connected to the Internet. The control systems implement a control algorithm and, through the analog and digital I/O signals, drive the real process. At the same time, the LabVIEW virtual instrument (VI) for individual experiments and the LabVIEW server are run on the lab server for the purpose of enabling remote control. Individual VI performs data exchange between the DSP-2 control system and the lab PC, while the LabVIEW server enables remote operation of this VI. VIs for individual experiments are published on the Web using a LabVIEW built-in Web Publishing Tool [40]. When a remote viewer enters an appropriate URL address, the LabVIEW front panel appears within the Web browser. Once the user has been granted control, the GUI controls become active, and running the LabVIEW application is like running the application from a local environment.

In the remote laboratory at the University of Maribor, there are also other remote experiments and courses at one's disposal. These are the courses "Servomotor in mechatronics," "SCARA robot," and "Electrical circuits" with various remote experiments performed on electrical and electromechanical devices. All courses are organized in the same way as described in the continuation and also given with complete documentation available in English.

IV. Module "Mechatronics and Hardware-in-the-Loop Simulations"

The module "Mechatronics and Hardware-in-the-loop Simulations" belongs to the category electromechanical and motion control systems. Topics from the areas of dynamic systems and motion control are addressed in this module. The following aspects are discussed:

1) identification and modeling of mechatronic systems' components;
2) analysis of system dynamics by using numerical simulations;

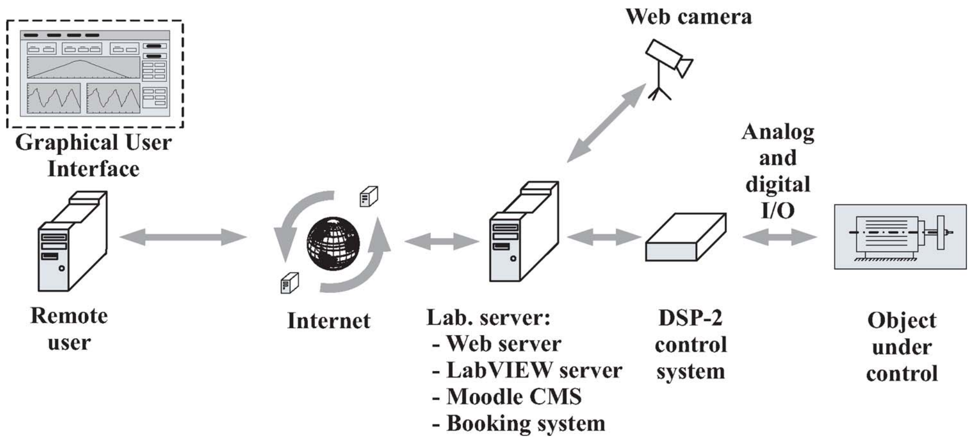

Fig. 3. Structure of remote laboratory.

3) control system design;
4) tuning of a controller's parameters;
5) experimental validation of control system design;
6) comparison between various linear and nonlinear control methods, in terms of performance and complexity.

Continuation of this section describes how all these aspects are exactly presented to the student by using the e-learning-based teaching approach. The results from pilot testing the module are also presented. The testing was executed in order to improve the module. Therefore, the students who participated in the pilot testing were asked to provide a feedback by means of completing an anonymous questionnaire concerning their experiences.

A. E-Learning Strategy

Aside from the learning contents, a number of other relevant factors must also be considered when developing an e-learning strategy. These include the learners' characteristics such as learners' motivational states, learning preferences and interests, background knowledge, prior knowledge, and experience.

For the module "Mechatronics and Hardware-in-the-loop Simulations," prior knowledge regarding physics with classical mechanics, mathematical analysis, linear control theory, system modeling and MATLAB/Simulink simulations was requested. In addition, it was assumed that the learners are motivated enough for autonomous work. As a stimulus for promoting the learning process, tasks are used with practically oriented goals that require profound analysis based on acquired theoretical knowledge. These tasks are given after each theoretical unit. They are designed in such a way that the motivated learners can mostly self-assess their own results and, therefore, do not require constant supervision by the tutor. As a guideline for self-assessment, some additional hints are provided for each exercise.

The adopted learning strategy is shown in Fig. 4. The theory and prelaboratory tasks are given in the form of two basic units. The first unit topic is identification, modeling, and analysis of the control system. The second unit gives a theoretical background for motion control. This also includes the derivation of a few linear and nonlinear motion controllers.

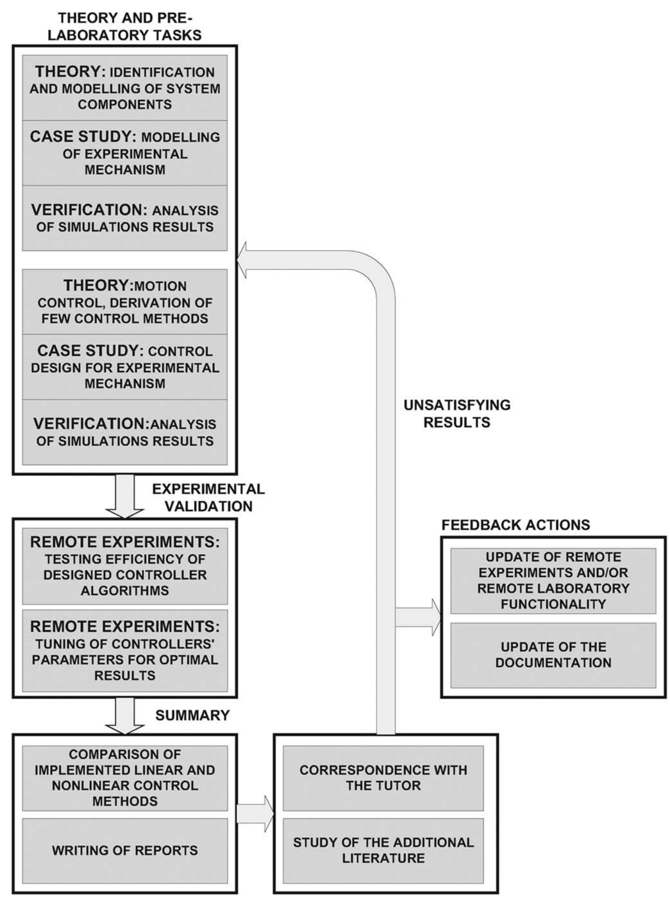

Fig. 4. Learning strategy.

Remote experiments are used for the experimental validations of derived controllers. By observing the system's performance, the learner can draw the conclusions about the controller's efficiency. The learner can also remotely change the structures of the controllers and tune the controllers' parameters in order to achieve optimal performance.

Finally, all implemented control methods are compared regarding the efficiency and implementation costs that include the computational complexity of the controller, design effort, and time cost. Feedback from the learners is considered before any further update of the module.

Fig. 5. Mechanism with spring.

B. Experimental System

The experimental mechatronic device applied in the module is a one-degree-of-freedom mechanism with a spring, as shown in Fig. 5. This mechanism has nonlinear dynamics; therefore, it is also suitable for the testing of nonlinear motion control algorithms. It is driven by a dc motor and equipped with an incremental encoder. The motor shaft drives an acrylic glass disc, which is part of the mechanism. The friction between the motor's shaft and disc can be set manually by adjusting the distance between the disc and the shaft. The disc is fastened to a bearing, while a spring is attached on the other side of the bearing. The spring can be attached in a few different positions. The mechanism is fastened on an acrylic glass housing. It is table size, easily portable, and quite robust, and it requires no special maintenance. Since the motion of mechanism is not restricted by limit switches, it is particularly suitable for remote experiments.

C. Identification, Modeling, and Analysis of the System

The design of the mechatronic control system should start with a clear idea of the physical system to be controlled. This could be obtained by developing a dynamic model and executing some numerical simulation. For a mechanism with a spring, a dynamic model can be derived by applying basic knowledge of physics. The derivation procedure is briefly described in the continuation.

The torque T that must be compensated by the motor depends on the sum of the mechanism's inertia J and the spring torque T_s. The influence of gravitation is negligible. An inverse dynamic model of a mechanism with a spring can be written as

$$T = J\ddot{\theta} + T_s\,(\theta). \tag{1}$$

Inertia J can be easily calculated, while the spring torque must be described as a function of mechanism's geometry and the measured angle θ. The spring torque scheme shown in Fig. 6 can be used for derivation. The only basic definitions of torque, Hook's law, and some calculus using the law of cosines and the law of sines are required to obtain a dynamic model

$$T_a = J\ddot{\theta} + rk\Delta x(\theta)\frac{(l+r)}{d}\sin(\theta). \tag{2}$$

Here, the spring extension Δx is

$$\Delta x = \sqrt{r^2 + (r+l)^2 - 2r(r+l)\cos(\theta)} - l. \tag{3}$$

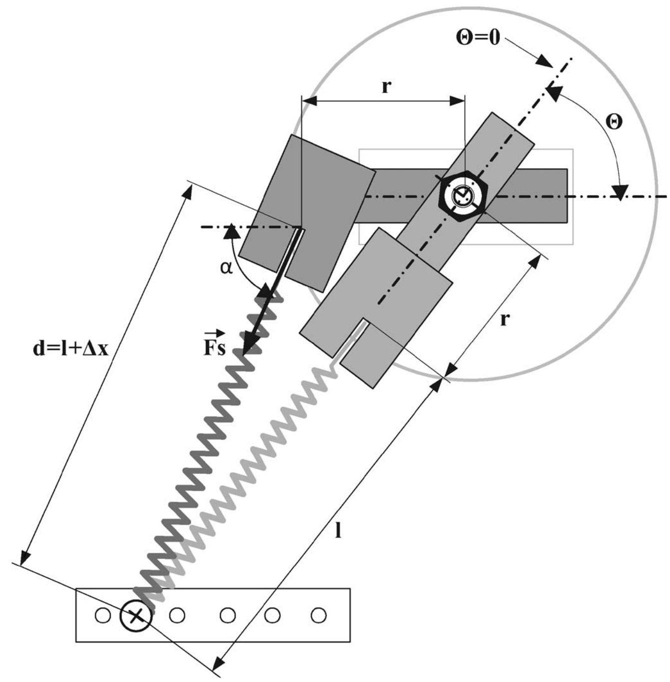

Fig. 6. Scheme of mechanism with spring.

k is the coefficient of elasticity, while r and l are known dimensions, as shown in Fig. 6.

The friction torque could also be included for a more realistic model. In the mechanism with a spring, the friction is mostly a rolling friction at the contact between the Acrylic glass disc and the motor shaft, which is covered with a flexible silicon material. Measurement of the parameters would be necessary in order to build a friction model. However, this is a time-consuming procedure that cannot be performed by using remote access. Therefore, friction is not included in a dynamic model.

A MATLAB/Simulink simulation model based on a derived dynamic model (2) is shown in Fig. 7. Students have to build the model, verify it by the simulations, and self-assess the results.

Verification of the model can be, to some extent, done by performing simulation tests. For example, in the first test, the initial position of the mechanism is a stable equilibrium point (zero initial position, zero initial velocity, and zero control torque). The mechanism should stay at a standstill, or the model is incorrect.

In the second test, the mechanism's response is considered for the case where the initial position is an unstable equilibrium point. In this initial condition, the spring is fully extended, but the sum of the torques that influence the mechanism is zero. The expected result is that the mechanism stays at a standstill for a short time, but later on, it starts to move due to the simulations' numerical errors. Namely, the numerical errors cause the position to start to differ from the unstable equilibrium point, which initiates movement.

In the third test, the motion trajectory of the mechanism for nonzero initial position is observed. Because the friction is not included in the model, a trajectory with periodic movement is to be expected. A nonperiodic movement would indicate that the model is incorrect.

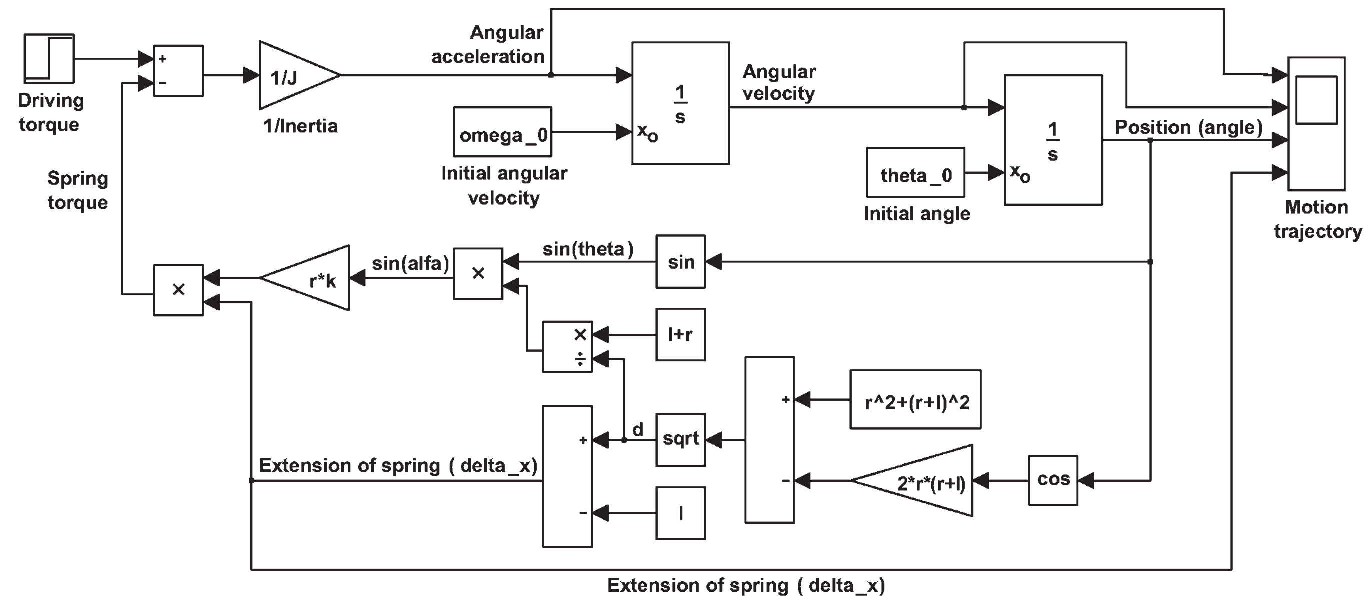

Fig. 7. Simulation model for mechanism with spring.

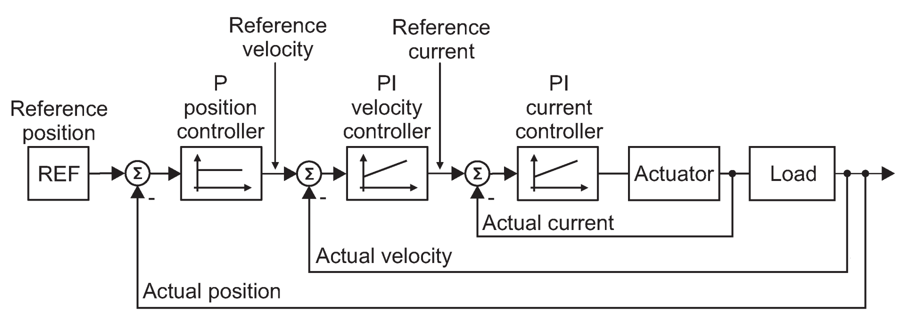

Fig. 8. Cascade controller.

D. Control System Design

The theoretical part of the control system design topic is based on the presumption that the students are already familiar with linear control concepts. However, it is assumed that they have no experience in the control of mechanisms with nonlinear dynamics. Therefore, initially, two linear control motion controllers (cascade controller and potential difference (PD) controller) are discussed and designed for the mechanism with a spring. Only then that the nonlinear robotic motion control algorithm, i.e., the computed torque control, is discussed and designed.

The first controller, i.e., the cascade controller, is composed of three controllers connected in a series, as shown in Fig. 8. A PI controller was chosen as a current controller. For a velocity controller, both PI and PID controllers were discussed, while P, PI, and PID controllers were considered for the position controller. For the motion control of the mechanism with a spring, a suitable cascade controller's parameters can be calculated by using the linear control theory and a linearized mechanism model. Simulations in MATLAB/Simulink are performed for testing the controller.

A PD controller, as shown in Fig. 9, was discussed as a second controller. This is also a linear controller, but it has a better performance than the cascade controller. The reason for this is that the reference velocity signal is used when calculating the controller's output, which is not the case with the cascade controller. The controller is suitable for motion control of the mechanisms with linear dynamics. When this controller is applied for the control of mechanisms with nonlinear dynamics, as it is a mechanism with a spring, higher following and steady-state errors are to be expected. The controller's gains must be set at high values for achieving lower position and velocity errors; therefore, the problem of motor saturation frequently arises. The controller's parameters for the mechanism with a spring can be calculated according to the control theory for a linearized model or determined by simulations through a trial and error procedure.

The third discussed controller is the computed torque controller, as shown in Fig. 10. This is a nonlinear controller known from robotics, which is efficient for the motion control of mechanisms with nonlinear dynamics. It is model based; therefore, a very accurate inverse dynamic model of the mechanism needs to be available. In the case where the model is accurate, the computed torque control linearizes and decouples the system (if it has more degrees of freedom) and provides accurate tracking of the desired path. The drawbacks of this method are high computational requirements, because the whole dynamic model must be calculated at each sampling time. In addition, when

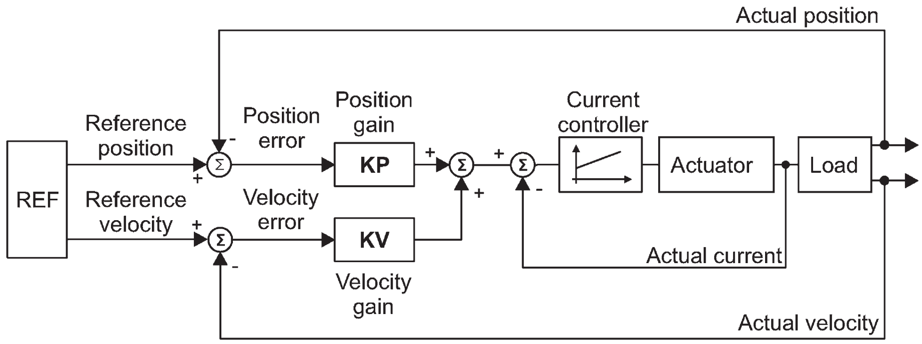

Fig. 9. PD controller.

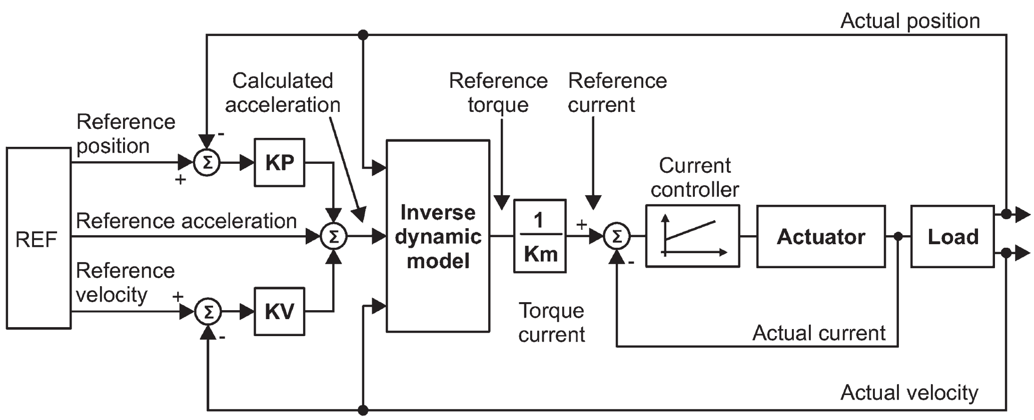

Fig. 10. Computed torque controller.

the dynamics' parameters vary and the variations cannot be modeled, as in the case of a varying payload, this method cannot be applied. However, for motion control of the mechanism with a spring, the computed torque controller yields better results than those achieved with the other two linear controllers.

The computed torque control law is

$$T = \tilde{J}\ddot{\theta}^c + \tilde{H}(\dot{\theta}, \theta). \tag{4}$$

Here, $\tilde{J}$ is the estimated inertia, $\tilde{H}(\dot{\theta}, \theta)$ are the other dynamic influences, usually without friction estimation, and $\ddot{\theta}^c$ is the calculated acceleration given by

$$\ddot{\theta}^c = \ddot{\theta}_{\mathrm{ref}} + KV \cdot \dot{e} + KP \cdot e \tag{5}$$

where KP is the position gain and KV is the velocity gain. If the parameters and the structure of an estimated dynamic model applied in the control law (4) are close to the real values, then this control linearizes and decouples the system. The error dynamics equation is linear

$$\ddot{e} + KV \cdot \dot{e} + KP \cdot e = w = J^{-1}T_d. \tag{6}$$

Here, T_d is the disturbance torque. The characteristic equation for (6) is

$$\det(\lambda I - A) = \ddot{e} + KV \cdot \dot{e} + KP \cdot e. \tag{7}$$

It can be seen that the control is stable for positive gains KP and KV. The error equation can be compared to the general equation of the second-order system after Laplace transformation

$$\Delta_c(s) = s^2 + KV \cdot s + KP = s^2 + 2D\omega_n s + \omega_n^2. \tag{8}$$

It can be seen that the position gain KP depends on the natural frequency ω_n, i.e.,

$$KP = \omega_n^2 \tag{9}$$

and the velocity gain KV depends on natural frequency and damping, i.e.,

$$KV = 2D\omega_n. \tag{10}$$

Overshoots must be avoided in most mechanical systems; therefore, critical damping $D = 1$ is a common choice. The natural frequency ω_n determines the speed of response. Higher values are chosen for faster responses. However, the upper limit of natural frequency is limited by many factors. Since the mechanical systems are never totally stiff, a low enough natural frequency must be chosen which does not induce resonance. Furthermore, by choosing a high natural frequency, the calculated controller torques can be higher than those provided by motors (motor saturation problem).

Derived dynamic model of mechanism (2) should be used for the implementation of computed torque control in the motion control of a mechanism with a spring. It is impossible to simulate the method, since the same dynamic model is implemented in the controller, and for the controlled plant.

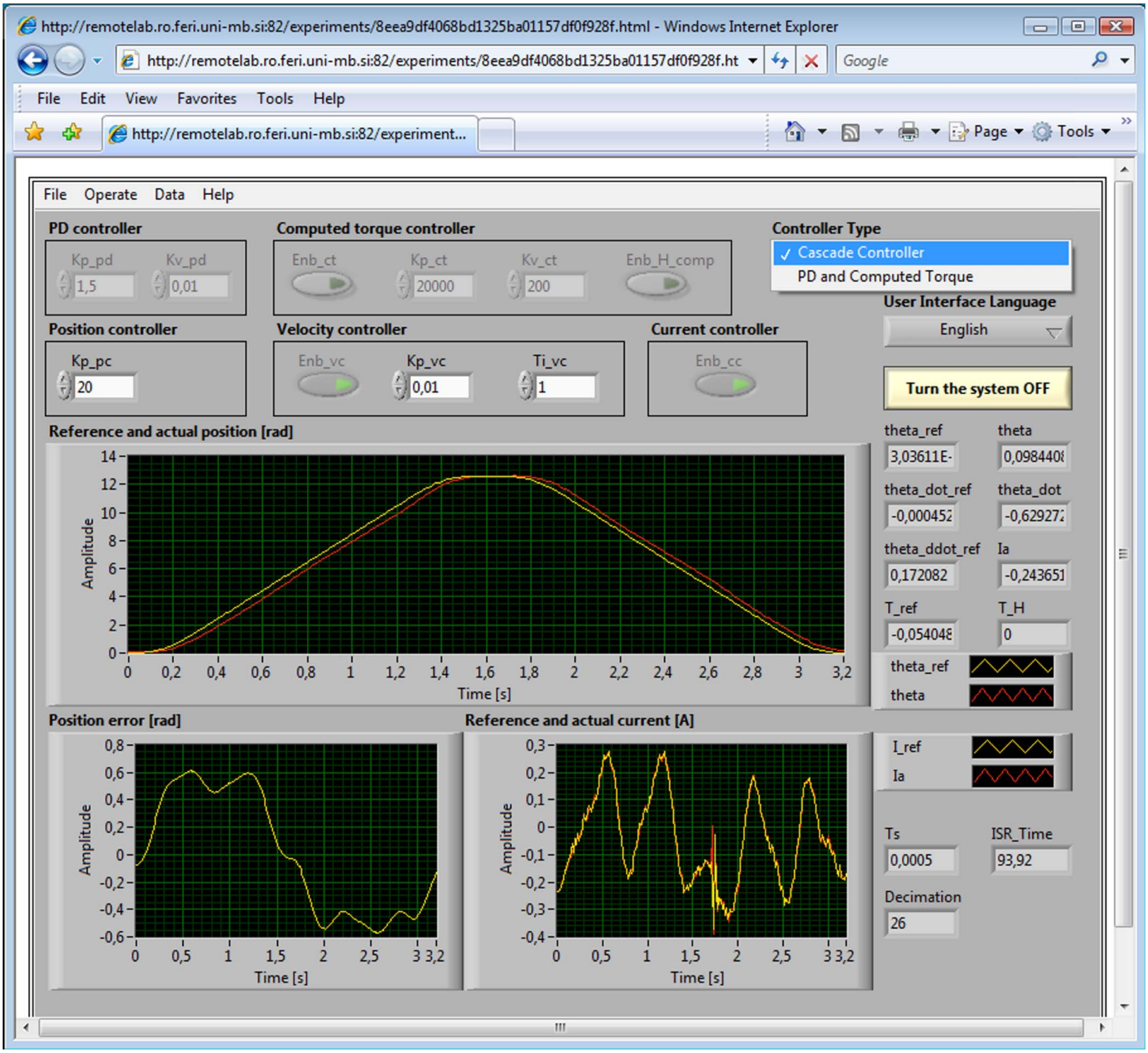

Fig. 11. User front end for remote control of mechanism with spring.

E. Experimental Validation With the Remote Experiments

The design of mechatronics control systems is one of the areas where computer simulations without experimental verification are highly questionable, maybe even useless. Therefore, experimental validation of the system's control design is necessary. By performing remote experiments, the students can test all three described control methods: the cascade controller, the PD controller, and the computed torque controller.

When performing remote experiments, the students do not see the executable files but only a specially created user front end, as shown in Fig. 11. The user front end enables switching between the controllers, tuning of the parameters, and observation of the measured and calculated data. In order to keep the front end clear and easy to use, only those signals that have to be constantly monitored during the experiment are shown in graphical form. This comprehends the actual and reference positions of the mechanism, position error, and the actual and reference currents.

Only the signals/values that cannot be manipulated by the students are shown numerically. Their current values (updated at each sampling time) are given on the right side of the user interface. These are mostly calculated or predetermined signals/values that cannot be influenced by the user and are unaffected by the controllers' parameter tuning or any change of the parameter structure (reference velocity, reference acceleration, and sampling time). Those signals/values are also fully explained in the documentation.

It is also possible to observe live photographs of experiment through a Web camera (Fig. 12).

The students start design validation using the cascade controller. Fine-tuning of the PI velocity controller and P position controllers' parameters had to be done. It is also similar in

Fig. 12. Webcam live photograph of experiment.

the case of the PD controller, where optimal values for the position and velocity gain should be found. The initial values of the controllers' parameters are the ones that are calculated or determined by simulations.

The computed torque control method allows online tuning of the position and velocity gain and also some changes in the controller's structure. For example, the compensation of spring torque and friction is optional. In this way, the student can see what effect that the compensation of those two dynamic effects has on the efficiency of the controller.

The reference trajectory is the same for all controllers so that the comparison of the controllers' performances is easier. The reference trajectory is a cyclic trajectory, calculated by using $\sin^2$ velocity profile. The end reference position is 4π rad, the maximum angular velocity is 10 rad/s, and the maximum angular acceleration is 50 $\mathrm{rad/s^2}$.

After finishing the experiments, the students compare all implemented linear and nonlinear control methods in terms of performance, complexity, and comment, if the results meet their expectations. In addition, the discrepancy between the simulation and measurement results should be noted and commented.

F. Results of the Pilot Testing

The pilot testing of the course "Mechatronics and Hardware-in-the-loop Simulations" was performed with 18 regular students of EE at the University of Maribor. For all students, this was their first experience with e-learning and remote experiments. In order to be able to compare the experiences between remote and conventional experiments, the students had also executed experiments locally in the laboratory.

After completing the course, the students were asked to fill an anonymous questionnaire. The objectives of the pilot testing were the following:

1) to find out to which extent the remote laboratory can be implemented in practice, in order to complement and optionally replace the conventional laboratory exercises;
2) to test the functionality and stability of the remote laboratory;
3) to make sure that the materials and exercises provided for the course "Mechatronics and Hardware-in-the-loop Simulations" are clear and concise;
4) to find out what is the students' personal attitude toward the e-learning and remote experiments (level of obtained knowledge and preferences).

Three possible answers were available for each question: agree, undecided, and disagree. Aside from answering the formulated questions, the students were also asked to write down additional remarks and suggestions for improving the course. All 18 students filled in the questionnaire and answered all the questions. The results are shown in Table II.

First, it was discovered that all students have, at home, the necessary equipment for the execution of remote experiments, including fast Web connection and a personal computer.

Answers to the second question show that 72% of students agree that remote laboratories are suitable for acquiring new knowledge. Next, 95% of the students agreed that the remote experiments are a useful addition to the conventional laboratory experiments. However, only 22% are of the opinion that remote experiments could entirely replace conventional laboratory exercises, while 77% think that remote experiments cannot replace laboratory exercises.

Similarly, 61% of the students prefer performing experiments in the laboratory more than remote experiments, 27% could not decide on which option, and 12% (i.e., two students) prefer the remote experiments. As many as 78% of students are of the opinion that they learn more in laboratory sessions than when executing remote experiments. The other 22% could not decide on one option.

Questions concerning the Web page, booking system, and documentation showed that the majority of students agreed that the Web page and booking system are easy to use and that the documentation is clear and concise.

Probably, the most important finding is that most of the students stated that they prefer conventional laboratory exercises and learn more there than when executing remote experiments. This can be reasoned by the fact that no amount of documentation or remote assistance can provide exactly the same level of support that is obtained from assistants and colleagues when sitting in the laboratory. In the additional comments, the students also stated that they prefer to be physically in contact with the equipment.

However, the main advantage of Web Lab, which is the possibility of using modules with remote experiments from other universities, was not specially emphasized during the pilot testing. The students' attitude concerning this point requires further investigation. This investigation will be conducted after the Web Lab will be actively used by all universities and more students are actively engaged. This is being the case in the study year 2009/2010. Any investigation will be conducted based on the results of an online questionnaire equivalent for all 18 modules, which is already included in the home page of the Web lab. It could be expected that the choice of a wide range of modules with remote experiments will outweigh the deficiency of remote experiments when compared to conventional experiments and

TABLE II
RESULTS OF THE STUDENTS' QUESTIONNAIRE

Questions concerning students' opinion about the remote experiments	Agree	Undecided	Disagree
1. I have at home all necessary equipment for the execution of the remote experiments.	100%	-	-
2. Remote experiments are suitable for the acquiring of the new knowledge.	72%	17%	11%
3. Remote experiments are useful as the addition to the local lab exercises.	95%	5%	-
4. Remote experiments could totally replace local laboratory exercises.	22%	11%	77%
5. I rather execute remote experiments then the experiments in laboratory.	11%	27%	61%
6. When working with the remote experiments I learn much more as when performing the lab experiments.	5%	17%	78%
7. I would like to have more remote experiments in the program.	78%	22%	-

Questions concerning specific module	Agree	Undecided	Disagree
8. Web page is clear and easy to use.	83%	17%	-
9. Creation of user account was easy.	89%	5%	6%
10. Booking system is easy to use.	89%	11%	-
11. Installation of the software required for execution of the remote experiments was hard.	17%	17%	61%
12. Provided documentation is clear and concise.	61%	-	39%

that there will be lesser mixed feelings than that after pilot testing.

Nevertheless, the remote experiments were very well accepted as completion of the laboratory exercises, and most of the students would like to have more such experiments in their programs.

V. Conclusion

This paper has described the EDIPE project, particularly one of its modules, i.e., "Mechatronics and Hardware-in-the-loop Simulations." In the project, 13 partners from 11 European countries joined together to build a remote laboratory which would offer a wide range of remote experiments and high-quality documentation to students from the universities of all participating partners. Such solutions would significantly lessen the burden of providing equipment and solving technical problems. Consequently, there is also more possibility to enrich engineering study and enable students to gain knowledge and practical skills by executing courses that are unavailable at their home university.

As an example, realization of module and remote experiments built at the University of Maribor has presented. The module topic is motion control of a mechatronic system. It discusses all important aspects of the control design from component identification, analysis, control system design, and tuning of the parameters. The module was tested by the students in order to find the students' opinions about remote experiments, as well as to appraise the quality of documentation and remote experiments for this specific module. The outcome of the pilot testing and teachers' observations showed that the conventional laboratory work is highly valued among the students but that the same results cannot be achieved using only remote experiments. Students appreciated remote experiments as a completion of conventional laboratory exercises but do not think that the remote experiments can be used as a replacement of laboratory work. The major reason for this is that the students need personal contact with the teacher and classmates, as well as physical contact with the experimental devices. Surprisingly, there were only a few comments showing that students appraised the possibility to learn and execute remote experiments at their own time at home. Summarizing the pilot testing, it was found that online courses with remote experiments are a welcome supplement to the traditional study curricula and that the students would like to have access to more remote experiments but are, to some degree, skeptical when it comes to the idea of replacing conventional laboratory exercises with remote experiments. However, it is expected that, after the students are offered all modules from the Web Lab, the advantages of having such rich enlistment for courses with remote experiments from many other universities will be welcomed and very much appreciated by the students.

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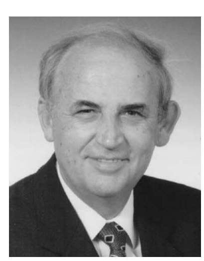

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