Development and student evaluation of an Internet-based Control Engineering Laboratory

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Abstract: This paper presents the structure, functionality and application of an improved Remote Laboratory for engineering students hosted at Ghent University. The Remote Laboratory consists of two setups: Ball and Plate system and Quadruple Water Tank system. These setups introduce basic control aspects such as PID control design and non-minimum phase systems. Also more challenging aspects such as multiple-input-multiple-output control, decoupled and decentralized systems and advanced control strategies such as Internal Model Control or Model Predictive Control can be investigated on the setups. Based on a feedback study that targeted the bachelor degree students, the level of effectiveness of this concept has been shown but also possible functional enhancements that can be applied to the systems have been pointed out. The feedback survey data concluded that the Remote Laboratory has attracted the attention of students and had a positive impact in their training.

Keywords: Remote Laboratory, Control engineering, Feedback study, Ball and Plate, Quadruple Water Tank.

1. INTRODUCTION

The Remote Laboratory (RemoteLab) has gained increased popularity as an alternative to on-site laboratory experiments since it was first introduced more than 15 years ago (Overstreet (1999)). This concept was developed by universities as an educational tool providing an option for advanced research and learning for students. Nowadays, due to the facilitated access to the World Wide Web (WWW), it is possible to implement remote laboratories in academic environments. This tool has proven useful in the curriculum of undergraduates who required hands-on experiments on test beds provided by the universities.

In the last decade, more and more attention was focused on implementing and developing platforms that allow students to perform remote experiments with the help of the Internet. The idea behind the RemoteLab implies that the user connects remotely to a real-life plant via the Internet without the constraint of having the same location as the setup. Major universities have brought their contribution to this still-in-development sector of teaching, amongst them we can mention the iLab and European Schoolnet (Gomes and Bogosyan (2009)). This additional teaching resource can be applied to various fields such as mechatronics (Chaos et al. (2013)), control engineering (Jara et al. (2009)) and electronics (Hsu et al. (2000)).

The development of the RemoteLab came as a complement to the theoretical aspect of teaching in order to satisfy the necessity of applying acquired knowledge to real-life applications. It is considered that besides theoretical background one must also acquire a practical experience for a better enhancement in knowledge. This principle has been applied to undergraduate students who study in the field of science and engineering and require practical experiments to provide better insight into the theoretical aspects.

Academic environments have resorted to implementation of Remote Laboratories due to multiple factors:

- The lack of necessary space or available hardware equipment required to conduct the laboratory experiments for a large group of students
- The reduced number of academic staff required for on-site surveillance of the remotely controlled equipment
- Possibility of sharing remote laboratories between multiple universities in close collaboration
- Increased number of enrolled students on an yearly basis

Due to the expansion and variety of the remotely controlled experiments, a classification can be developed based on the nature of the equipment. On one hand, we can talk about the Remote Simulation which implies that the user controls a virtual system hosted on the server side. On the other hand, the Remote Experiment deals with controlling actual hardware equipment available on a different location than the user. This paper concentrates only on the concept of Remote Experiment where students connect remotely via the Internet to actual real-life plants.

On a yearly basis, the number of students which enroll in the bachelor and master programs at Ghent University, is in continuous expansion, reaching approximately 1000 students in the academic year 2014-2015 (Ghent University (2014)). A major percentage of these students specialize in the field of mechanical, electrical, chemical or physics engineering. All these disciplines take the course Modeling and Control of Dynamical Systems included in their bachelor curricula to learn about basic control engineering concepts. Advanced control techniques are also taught in the master degree for the control engineering students.

The RemoteLab has proven useful in academic teaching because it offers the possibility for students to conduct multiple experiments, control the input of the systems and analyze the generated output. The idea behind the current version of our RemoteLab is to provide short experiments on a bachelor level and more advanced experiments on a master level. Provided the fact that the bachelor students by far outnumber the master students, short exercises make an introduction to the practical aspects possible for a larger number of students. Master students have the possibility for more extended experiments to test more difficult theoretical concepts.

The two applications that are part of the Remote Lab are the Ball and Plate system and the Quadruple Water Tank system. The Ball and Plate system has proven to be an educational tool for fields like mechanical and electrical engineering while the Quadruple Water Tank is a representative example in the chemical engineering field.

The purpose of this paper is to conduct a feedback study on the bachelor degree students which required conducting experiments on the RemoteLab setups and afterwards having the students fill in a survey.

The structure of this paper is as follows: section two covers the concept which lies behind the RemoteLab. The third section contains a detailed presentation of the two applications: the Ball and Plate system and the Quadruple Water Tank system. In section three, the educational context of the RemoteLab is discussed based on the feedback provided by the students. The final section formulates a conclusion based on the outcome of the study and discusses possible future work.

2. REMOTELAB

The purpose of the RemoteLab is to ensure facilitated access to real-life experiments provided by the university via an Internet connection (Farias et al. (2010)). The current implementation of the RemoteLab hosted by the Electrical energy, Systems and Automation department from Ghent University is the result of significant structure and content improvements. Starting from the old implementation which used Java Applets and Virtual Private Network connection (Hegedus (2013)), new features have been included with the help of open source and up-to-date technologies. A step forward is made using the web hosting framework Django which enables access to the RemoteLab even from portable devices such as mobile phones or tablets. Besides this accessibility feature, also a wider range of control applications, e.g. Internal Model Control or Model Predictive Control, have been made available to the student.

2.1 Conceptual presentation

The architecture of the RemoteLab cannot be summarized to a standard implementation due to the different requirements and real-life plants. Nonetheless, a general structure can be defined comprising of: the plant itself, a local server (experiment server) which acts as a gateway between the plant and the remote computers controlling the plant and last, a middleware responsible for the exchange of information between the local and remote computer, which is located on the core server. The architecture for the RemoteLab presented in this paper is illustrated in Figure 1. The four components used in the structure of the RemoteLab can be easily differentiated: the clients, the core server, the experiment server and the plant setup.

The **client** is represented by the students that access the remote experiment via an Internet connection. This implies that the client has no constraints regarding his location; the only requirements imply a browser and an Internet connection.

In order for the client to control the plant, a web application is developed. To make this application live and available on the Internet a website hosting server, i.e. the **core server**, is used which acts as a middleware between the client and the experiment server. The core server is used to host the Django website alongside the HTML files and JavaScript files used in the development and is in fact an Ubuntu based virtual server. Due to the fact that the core server is Linux based, Apache is chosen for the software configuration. This server software uses an SSL protocol complemented with the Secure HTTP connection to manage the request received by the user and to ensure proper security. Also for the video stream provided by the cameras, a reverse proxy that protects the output stream of the camera from external malware is configured. The communication between the client and the core server is done using a TCP/ IP protocol. The client application, which is hosted on the core server, is a modular project based on sub-applications which have a specific functionality and are loosely linked in order to avoid influences that may occur in the development of the application's structure. The sub-applications are the accounts module which is responsible for the management of the user accounts, the reservation module which provides an efficient time management system to control the setups, the laboratories module which is responsible for the user interface to control the experiments and the remote_lab module which ensures the integration of all these modules in the Django project.

The **experiment server** establishes the link between the remote personal computer and the plant, the physical setup to control the system and an Internet Protocol camera for visual feedback. This experiment server is configured differently in the two RemoteLab applications. For the Ball and Plate system, an Apache server is used which redirects the user's request to the C# application which controls the actual plant. For the Water Tank system, the experiment server handles the incoming requests with the

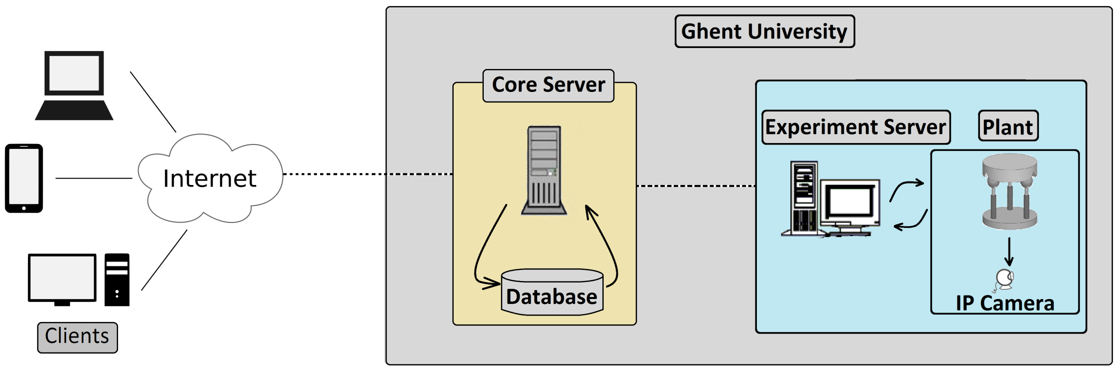

Fig. 1. General Structure of the RemoteLab

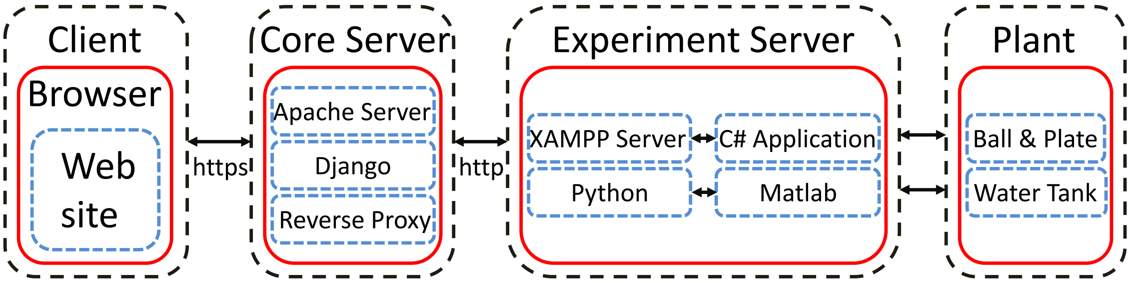

Fig. 2. Schematic representation of the software architecture

help of a Python application which redirects the control commands to the MATLAB environment.

The **plant setup** consists of the actual hardware which is controlled by the user and the IP camera used for monitoring the experiment. In Figure 2 the software applications and the communication protocols used in the RemoteLab are presented.

2.2 RemoteLab Applications

1) *Ball and Plate Setup:* The setup consists of a six Degree of Freedom (DoF) parallel manipulator known as a Stewart platform and a ball which describes a trajectory on the platform due to the tilt of the platform (Stewart (1965)) and can be seen in Figure 3. Movement of the platform is done by a servo system consisting of six actuators which are connected to the platform via spherical joints. The servo motors are steered using voltages provided by a microcontroller. The control signals determine the motion of the actuators and thus the position of the ball on the plate.

The standard platform describes three linear movements x, y, z (lateral, longitudinal and vertical) and three rotational movements (pitch, roll and yaw). Even though the system is a six DoF motion platform only two movements are used: the pitch and the roll (De Paepe (2010-2011)). Feedback on the position of the ball on the plate is determined using only the aforementioned platform. A visual feedback device was integrated in the Ball and Plate system.

The visual feedback regarding the position of the ball is provided by a webcam positioned above the motion platform. Before running an experiment, a calibrating MATLAB program, Camera Calibration Toolkit MATLAB (Bouguet (1999)), determines the position of the camera with respect to the platform. Using the help of three markers placed on the surface of the platform the position of the camera is being identified. This calibration

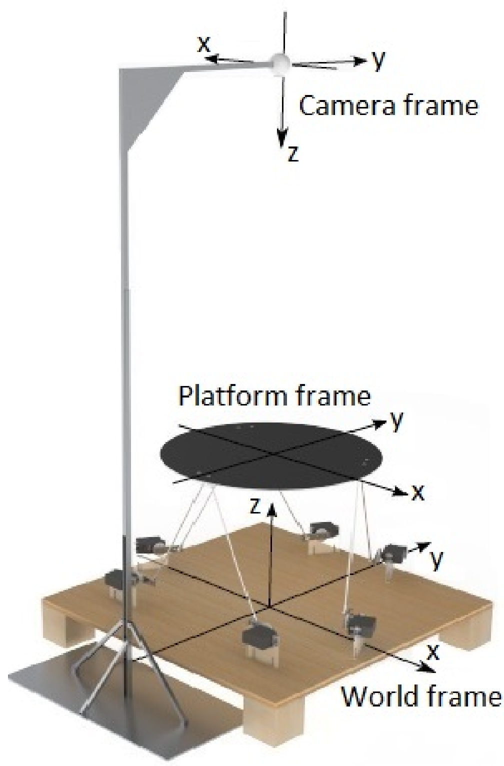

Fig. 3. Ball and Plate setup

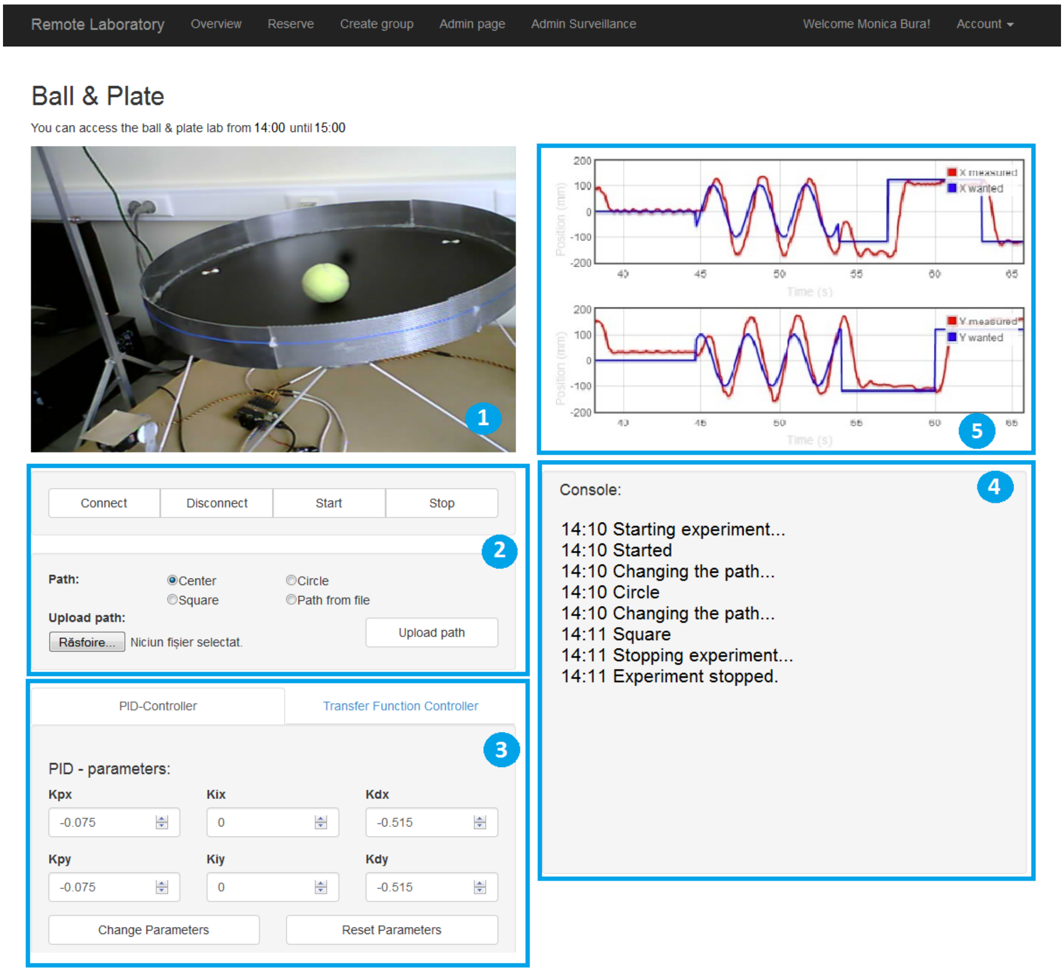

Fig. 4. Ball and Plate graphical user interface with: 1) video stream, 2) control of the setup, 3) controller options and 4) console 5) resulting graph at the end of the experiment.

ensures a better computation of the ball's position on the platform. Using the images provided by the camera, the position is computed using the Kalman filter after the image was passed through an edge detection filter.

The Ball and Plate setup uses a Proportional-Integral-Differential (PID) controller which is one of the targeted subjects for the bachelor curriculum. The students are required to design a suitable PID controller, commonly used in control of physical systems and implement the tuned controller on the setup. The student can analyze the behavior of the plant choosing different trajectories such as circle, square, fixed point but also has the opportunity to upload a text file with a predefined path.

Besides this, the graphical user interface shown in Figure 4 allows the user to perform experiments on the Ball and Plate setup using advanced control strategies such as IMC, fractional PID or MPC which are the focus of more advanced master courses.

2) *Quadruple Water Tank Setup:* The quadruple Water Tank system was designed with the purpose of illustrating different model-based control strategies. It is a Multiple-Inputs-Multiple-Outputs (MIMO) system composed of four coupled tanks and two input pumps manufactured by Quanser (see Figure 5). With the help of this setup the students can study the control of minimum and non-minimum phase systems and the effects of coupling and decoupling in a system.

The purpose of this laboratory experiment is to regulate the water level in the lower water tanks by

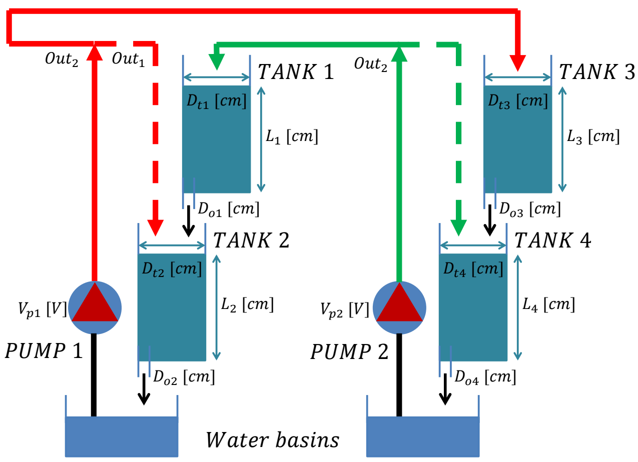

Fig. 5. Schematic overview of the Quadruple Water Tank Setup

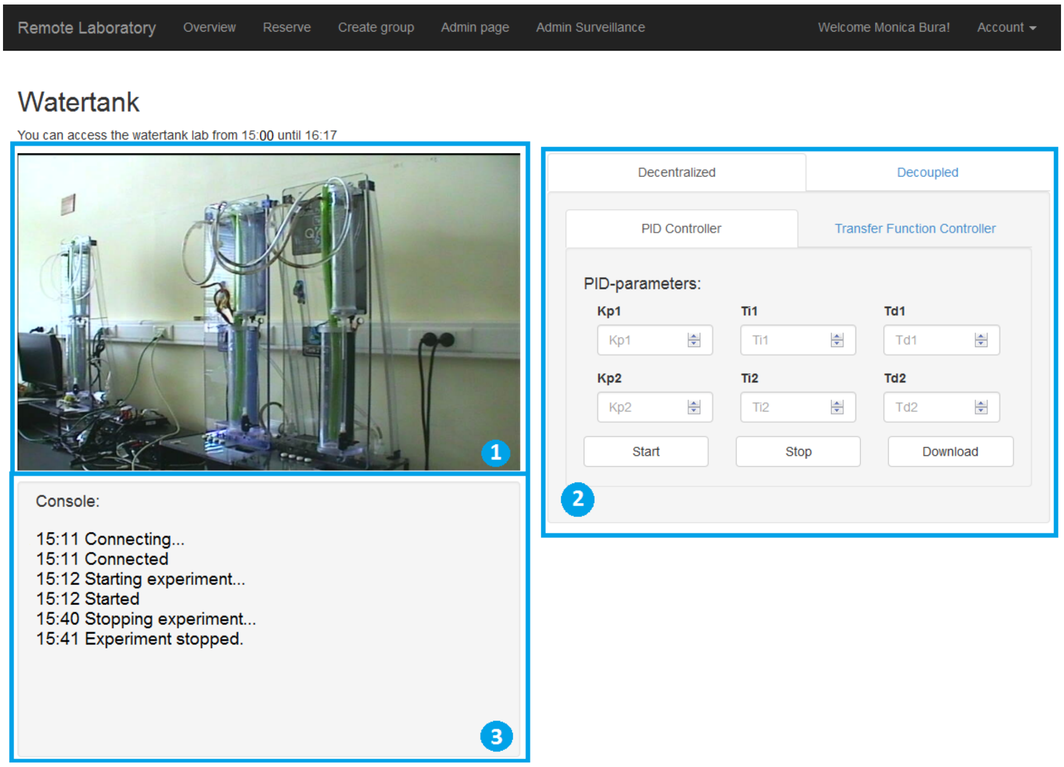

Fig. 6. Quadruple Water Tank user interface with: 1) video stream, 2) control of the setup and controller options and 3) console

controlling the inputs of the two pumps. The principle upon which the Water Tank setup is based, is presented as follows: pump 1 delivers water into tank 2 and tank 3 while pump 2 delivers water into tank 1 and tank 4. The upper water tanks (Tank 1 and Tank 3) communicate with the lower water tanks (Tank 2 and Tank 4) with the help of a small opening. Also, the lower tanks (Tank 2 and Tank 4) have an opening through which the water flows into a water collecting reservoir. The D01 and D03 openings in Figure 5 are much smaller in size than the D02 and D04. The level of the water in the tanks is measured by a pressure sensor placed on the bottom of each tank. Depending on the distribution of the water in the split after each pump (Out1 vs Out2), the system can result in a minimum or non-minimum phase system.

The MIMO setup presents to the students a challenging problem where coupling between inputs and outputs is significant. The coupling effects can be observed as each output is affected by the two inputs: the level in Tank 2 is affected by the water flow from pump 1 and pump 2, same for the level in Tank 4. The students can apply the theoretical concepts of relative gain array (RGA) and decoupling control to this challenging system.

On the graphical interface control page, illustrated in Figure 6, the user has the possibility to choose between multiple control loops with which they can run experiments. The user interface supports four types of controllers that can be implemented on the setup: the decoupled PID controller, the decentralized PID controller, the decentralized and decoupled advanced control strategies where more complex controllers can be implemented. The control of the pumps is done with the help of MATLAB Real Time Workshop (RTW) tool.

3. EDUCATIONAL EVALUATION

To discuss the importance of the developed RemoteLab in the context of education, a feedback study has been conducted among bachelor degree students. The study is based on two parts: the first part aimed for the practical application of the control theory knowledge acquired by the students and the second focused on filling out a survey based on the e-learning experience with the help of the RemoteLab. The survey covered a wide range of aspects starting with the impact of the RemoteLab on the teaching quality, the interest towards the idea of multimedia learning or the level of student's satisfaction regarding the interaction with the RemoteLab application. This study was evaluated using a bench of 135 bachelor level students.

Before starting the study, a prior tutorial was given to the students and also a User Manual was handed out to make the learning experience as straightforward as possible. The exercise had to be prepared in advance in order to reduce the actual experiment time. The preparation consisted of tuning of the control parameters based on given specifications for overshoot and settling time. Every student could reserve a time slot of 15 minutes in which he or she could log into the system from a remote location and perform experiments.

The exercise proposed for the bachelor degree student consisted of the design of two PD controllers for the Ball and Plate system: one to control the x-position of the ball and the other to control the y-position. A model of the system was provided to the student together with the design specifications of the controller that included maximum overshoot and maximum settling time.

Using the designed controller the students had to implement it on the system and use the different trajectories for the ball available on the RemoteLab as reference signals. They had to analyze the evolution of the error between the reference position and the measured position of the ball.

As an evaluation method, a survey which uses a 5 point Likert-type scale (1 = very dissatisfied, 2 = dissatisfied, 3 = neutral, 4 = satisfied and 5 = very satisfied) is used. The 25 questions are divided into six main sections: Interest for the RemoteLab, Requirements, Technical Documentation, Technical quality of the platform, GUI interactivity, Quality of education. A sample of five questions extracted from the survey are presented in Table 1.

Table 1. Example questions

How satisfied are you with ...	
the accuracy and usability of the User Manual	5 4 3 2 1
the time-response of the application	5 4 3 2 1
the live streaming performances during the experiments	5 4 3 2 1
using a RemoteLab for a practical experience	5 4 3 2 1
the degree of freedom in the remote control of the camera	5 4 3 2 1

Based on the statistical results, i.e. mean value and standard deviation, presented in the Table 2, we can observe the increased interest manifested by the students regarding remote learning. This appealed to the student because of the constraint-free character of RemoteLab with respect to location, the flexibility in the schedule and the portability of the RemoteLab application which covers devices ranging from personal computer or laptops to mobile phones and tablets. The users proved to be satisfied with the real time response and performance of the Ball and Plate setup. The quality of education has a lower mean value as the students find the accessibility to the teacher limited during the RemoteLab exercise. With the help of this survey, future improvements can be implemented in order to provide the student with an efficient teaching environment that would complement the theory aspects of the course. With the help of the acquired statistical data, it can be stated that the RemoteLab concept can provide an efficient educational tool in teaching new control concepts to students.

Table 2. Evaluation Results

Main sections	Mean	SD
Interest for the Remote Control of the Experiments	4.31	0.7
Prerequirements	4.18	0.7
Technical documentation	4.16	0.8
Technical quality of the platform	4.19	0.9
GUI interactivity	4.07	0.7
Quality of education	3.91	0.8

4. CONCLUSIONS

Nowadays, due to fast Internet development and evolved technology, the RemoteLab can be considered a useful method to replace the traditional on-site experiments. This concept appealed to both students and academic staff. For the students this concept represented flexibility in both time and place because they are not bound to a tight schedule or specific location. For the university environment, the RemoteLab is a possible solution to reduce the time and financial resources that are required for a hands-on practical application. In this study, a survey was conducted based on 135 bachelor students to investigate the interest in the RemoteLab as an educational tool. The results show that the RemoteLab is efficient in teaching control engineering and providing theoretical insight for bachelor students. This encouraging result can be seen as a motivation for further development in the RemoteLab application, providing more alternatives for teaching control strategies to both bachelor and master degree students. Even though these positive results give a good sense of how the RemoteLab is viewed from the educational point of view, further effort must be put into the research of the long term learning efficiency. Thus, a study of comparison has to be made that targets both the traditional on-site experiments and the remote controlled experiments, in order to get a better insight of the impact on the student's grades and the interest manifested by the student towards control engineering.

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