A Remote Laboratory Platform for Electrical Drive Control Using Programmable Logic Controllers

Coia Ferrater-Simón, Lluís Molas-Balada, Oriol Gomis-Bellmunt, Member, IEEE, Noelia Lorenzo-Martínez, Oriol Bayó-Puxan, and Roberto Villafafila-Robles, Student Member, IEEE

Abstract—Many teaching institutions worldwide are working on distance learning applications. In this field, remote laboratories are enabling intensive use of university facilities, while aiding the work of professors and students. The present paper introduces a platform designed to be used in industrial automation practical work. The platform is communicable through the Internet, includes programmable logic controllers that can be programmed with the open software CoDeSys, and has various sensors and actuators used in industrial installations. The various experimental stations of the platform, and the proposed laboratory exercises are described. The results of having used the platform with students are discussed.

Index Terms—Manufacturing automation, PLC programming, project-based learning, remote laboratory.

I. INTRODUCTION

The increasing importance of automation is boosting the demand for qualified automation and mechatronic engineers. This fact has motivated universities and other teaching institutions to provide laboratories to train electric and mechatronic engineers capable of meeting the challenges they will encounter in their professional careers. Among other topics, these have to be introduced to the different programmable controllers and automation devices common in the industry, among which programmable logic controllers (PLC) [1] and programmable automation controllers (PAC) [2] are crucial.

Traditional on site laboratories are of course a good solution, but these can be complemented by or in some cases even substituted with, remote [3], [4] or virtual [5], [6] laboratories. Remote or virtual laboratories have practical advantages; they can be used at any time, from anywhere, thus, overcoming geographic and time barriers. International networks of teaching centers can thereby share and make available their various resources, thereby maximizing their use of the laboratories and reducing costs [7]. Developing countries are also able to take advantage of such remote laboratories. Some important advances have been introduced in the last decades [3], [4], [8]–[10], presenting remote laboratories ranging in fields from optics to the control of robots. In the field of industrial automation, for example, [11] presented a PLC course for the remote programming of a cell of flexible manufacture with PLCs.

This paper introduces a platform that has been designed to be used to teach PLC programming to electrical engineering students. The various experimental stations of the platform are described, along with the course structure. Although [11] also presents a remote laboratory that deals with PLC programming, this work focused on a manufacturing cell, without focusing in the control of the electrical drives and without introducing any exercises related to regulation. The main contribution of the present paper is the introduction of an extremely low-cost PLC-based electrical drive platform. Electrical drive control is clearly an increasingly important issue in the training of future engineers. The platform can be accessed through the Internet without the need for a server and therefore, allows the student to operate in the same environment as if s/he were dealing with a real industrial process. Furthermore, part of the hardware (PLCs and inverter) and software (CoDeSys software) components used are typical to in real industrial applications, to ensure that students will use the same tools they would encounter in a real industrial platform.

The platform was developed in the Center of Technological Innovation in Static Converters and Drives, Technical University of Catalonia (CITCEA-UPC), Barcelona.

The paper has been structured as follows. In Section II the laboratory platform is described. The remote access and supervision is discussed in Section III. In Section IV, some proposed laboratory exercises are described, while the results obtained are presented in Section V. Conclusions are summarized in Section VI.

II. EXPERIMENTAL PLATFORM

The platform was designed as an ensemble of different electrical actuators, to be used remotely. The goal is not to create a powerful application, but to provide a compact, simple and visual model, that allows students to program the PLCs and to practice with the different experimental stations available in the remote laboratory. The platform is shown in Fig. 1(a) and (b).

The various stations of the platform are described in Sections II-A–C, divided in those connected to the so-called PLC1 and the others connected to PLC2.

A. PLC1

1) Conveyor Belt Driven by a Stepper Motor (SM1): This station of the platform comprises a stepper motor that drives a conveyor belt which has a metallic element [Fig. 2(b)]. The
motor windings are fed directly from four digital outputs of the PLC, through four current limiting resistors [Fig. 2(a)] and four free-wheeling diodes that limit the overvoltages produced by the switching.

Three inductive sensors detect the position of the metallic element in the belt. The aim of this station is for the student to determine the phase sequence of the stepper motor windings, to drive the belt in both directions and apply position control.

2) DC Motor Driven by a DC/DC Converter (DCM): This station comprises a dc motor that has a mechanical reducer coupled to a disk with metallic elements, similar to a low resolution encoder. An inductive sensor detects a total of six pulses per turn. To control the motor from the PLC a dc/dc buck converter was designed. The MOSFET duty cycle that drives the motor is determined by a reference value given by a PLC analog output. The main control element of the converter is the SG3524 component, which is used as the duty cycle generator to excite the BUZ71 MOSFET transistor gate. The signal is previously amplified by a stage of HC4049 inverters. The SG3524 compares a ramp signal with an adjustable continuous signal that controls the PLC analogue output, as shown in Fig. 3.

3) Illumination ILU: The implementation of remote laboratories requires that the equipment be fully operational at any time of day. Therefore, to allow night time operation, the platform can be illuminated activating a digital output. The connection of the lamp is made by a static switch, which is activated directly from a digital output of either of the two PLCs. This experiment is the first that the students perform.

B. PLC2

1) Stepper Motor (SM2): This station comprises a stepper motor that has an eccentric metallic axis. The motor windings are
fed as the stepper motor of the first station. An inductive sensor detects the axis eccentricity, providing a single pulse by turn.

2) Induction Motor With a Variable Speed Drive (IM): The station shown in Fig. 4 is constituted by a three-phase induction motor with a commercial variable speed drive. The PLC analogical output gives the reference speed value to the converter. This station is intended to show the possibility of interconnection between the PLC and commercial drives, as well as showing students a typical industrial application of speed control.

3) Temperature Regulation (TR): This station (see Fig. 5) comprises a Pt-100 temperature sensor, a power resistor and a fan. The Pt-100 sensor measures the temperature of the power resistor. The signal is converted to a 4–20 mA current signal, using a XTR105 converter.
Fig. 4. Block diagram of the induction motor drive.

Fig. 5. Temperature regulation (TR).

(a) Detailed view of the station TR

(b) DC/DC Converter

(c) Block diagram
The system works by applying a variable voltage across the terminals of the resistor, thus generating a current; the dissipated heat in the resistor can be determined by the Joule effect. To control the voltage, a buck converter is used. This dc/dc converter uses a PLC analogical output to determine the duty cycle of the MOSFET transistor.

The purpose of this station is to teach the students to control a slowly-evolving system, in this case temperature control, so that the changes can be readily appreciated by the students over the Internet. This station also introduces PID regulators.

To control the plant, different strategies may be used. First, the buck converter can regulate the temperature, directly changing the applied average voltage through the variation of the duty cycle. An alternative strategy is to use the action of the fan to evacuate the heat of the resistance.

C. Learning Management System Employed

Theoretical background for the practical work, and the scheduling and management of the practical session themselves, was done using a Moodle [12] management system. Inside the Moodle application (see Fig. 6) there are the various useful features: chats, forums and resources, which are all the part of administration (A), as well as the theoretical and practical documentation support for the course, and any additional material that students may need their training (B). In spaces C and D, the teacher can post news of interest for the students.

III. Remote Programming and Supervision

All that is necessary for a student to be able to work with the platform are the open and free programming software CoDeSys, and a connection to the Internet in order to download the program to the PLC and to check the functioning through an IP camera. As shown in Fig. 1(c), the platform can be accessed either from the Internet or from the local university network. Students directly access the PLC they are going to control, without the need for any computer access control.

Distance learning using remote laboratories requires a visualization device, to allow checking and supervising of the correct
Fig. 7. IP camera screen shot.

functioning of the applications when downloading the programs to the PLC. This visualization enforces "real-world" perception for the students and really demonstrates to them that they are not performing a simulation, but carrying out real laboratory work.

In the platform an IP camera is installed that has its own internet server (Fig. 7), without needing any PC. Its field of vision is limited to the different elements of the stations, with the functions of monitoring and supervising the educational system.

A fast Internet connection is recommended, so that the refresh rate of the screen allows the observation of the functioning of the drivers at an acceptable speed. Nevertheless, the platform has been used with low-speed Internet connections, with acceptable results.

It is important to remark that the students receive feedback from the system not only from the IP camera, but also through the CoDeSys software, which has HMI (Human-Machine Interface) capabilities. Moreover, students are encouraged to develop their own supervision screens where they can monitor and supervise the process they are controlling.

Program examples implemented with CoDeSys, along with the supervision screens, can be seen in Fig. 8.

IV. SUGGESTED PRACTICAL WORK

The described platform has been employed in the course "Electric Automation Workshop," which was taught to Electrical Engineering students. The theoretical background is introduced through a Moodle learning management system (described in Section II-C). In this e-learning platform, all the relevant concepts concerning automation, PLCs programming and drives are given. The students perform on site and remote practical work. The remote practical work is done using the platform described in this paper. The instructors propose a list of exercises and the students have to solve a number of theses using the various IEC61131–3 languages [13]. Among such
languages, the most frequently used are sequential function chart SFC (GRAFCET) [14] and ladder logic. Comprehensive information, with some worked examples and all the necessary instructions, is provided to the students [15].

Fig. 8. Programming and supervision examples.
TABLE I
SURVEY RESULTS

<table>
<thead>
<tr>
<th>Question</th>
<th>Response</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General questions</strong></td>
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</tr>
<tr>
<td>Q1 - Was the course challenging and interesting?</td>
<td>0 1 2 12 2 3.88</td>
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<tr>
<td>Q2 - Have you learned with this course?</td>
<td>0 0 1 12 4 4.18</td>
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<tr>
<td>Q3 - Do you think that you will apply the learned concepts in the future?</td>
<td>0 1 3 11 2 3.82</td>
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<tr>
<td>Q4 - Are the course materials of high quality and easy to understand?</td>
<td>0 2 7 8 0 3.35</td>
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<tr>
<td>Q5 - Was the course website appropriate?</td>
<td>0 2 9 5 1 3.29</td>
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<tr>
<td>Q6 - Would you recommend this course to other students?</td>
<td>0 0 10 6 1 3.47</td>
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<tr>
<td>Q7 - Has the practises division been appropriate? (local/remote)</td>
<td>0 1 3 12 1 3.76</td>
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<tr>
<td>Q8 - How would you rate this course?</td>
<td>0 1 3 11 2 3.82</td>
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<tr>
<td><strong>Local Laboratory</strong></td>
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<tr>
<td>Q9 - There were enough exercises.</td>
<td>0 6 1 9 1 3.29</td>
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<tr>
<td>Q10 - I have acquired basic automation concepts.</td>
<td>0 1 3 13 0 3.71</td>
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<tr>
<td>Q11 - How would you rate this part of the practical work?</td>
<td>0 1 4 10 2 3.76</td>
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<tr>
<td><strong>Remote Laboratory</strong></td>
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<tr>
<td>Q12 - It has been easy to work from home.</td>
<td>1 1 4 7 4 3.71</td>
<td></td>
<td></td>
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<tr>
<td>Q13 - The remote lab resembles a real industrial process.</td>
<td>0 0 3 13 1 3.88</td>
<td></td>
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<tr>
<td>Q14 - The remote lab has worked appropriately.</td>
<td>0 0 2 10 5 4.18</td>
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<tr>
<td>Q15 - The comparison with other students’ work has been useful.</td>
<td>0 1 0 9 7 4.29</td>
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</tr>
<tr>
<td>Q16 - How would you rate this part of the practical work?</td>
<td>0 0 3 8 6 4.18</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Some of the exercises are listed here.

**Becoming familiar with the platform**
- **Software introduction**: The students learn how to use the CoDeSys software. Manuals and comprehensive information are given.
- **Simulation**: Students simulate their initial simple programs.
- **Downloading**: Students download a sample program to the real PLC and learn how to connect through the Internet and how to visualize the system with the IP camera.

**ILU Illumination of the platform**
- **Light control with buttons**: Introduction of the HMI supervision screens, buttons and basic ladder language.
- **Temporized light**: Introduction of the timers TON, TOF and TP.
- **Blinking light**: Practising with timers.

**MP1 or MP2 Stepper Motors**
- **Unidirectional motion**: Speed and Position Control. Programming with their chosen language (SFC is suggested), the students have to make the motor move at the desired speed.
- **Bidirectional control**: Different sequences have to be chosen depending on the direction of motion.
- **Full-step and half-step control**: The different strategies are programmed and the students note the different behavior of the motor.
- **Counter**: Count the number of steps, set the time between different sensors and make the motor follow it. The students use the various programming languages.
- **Automating motion sequences**: A controller has to decide the direction and speed of the motor in order to achieve certain control objectives.

**MCC DC Motor**
- **Speed control of the DC Motor**: Analog outputs are introduced to the students
- **Speed control**: Setting different speeds for the motor depending on the position.
- **Speed calculation**: Using the sensors and timers.

**MI Induction Motor**
- **Speed control**: Control of the speed of an induction motor.
- **Speed ramps**: Generation of speed ramps

**RT Temperature Regulation**
- **Calibration of the pt100 electronics**: Check that the measurement is correct.
- **Hysteresis control**: Control the temperature between two thresholds.
- **PID**: Using a PID regulator to control the temperature.
- **PID**: Using the Ziegler-Nichols methodology to tune the PID controller.

**Final practices**
- Generation of certain complex automation sequences mixing different machines (the stepper motor, the DC motor and the induction motor).
- Introduction to Ethernet communications; mixing sequences of different PLCs.
- Testing different controllers to regulate the temperature of the resistance.

At the end of the course, the students have to prepare an oral presentation, where they talk about the programs they used, the problems they found and the way they have dealt with these. Debate between students, discussing different strategies to solve problems, is encouraged.

V. DISCUSSION OF RESULTS

A. Students Response

Seventeen students, divided in two groups, took the course. The students were requested to answer (on the scale of 1–5) an anonymous questionnaire. The survey questions and results are shown in Table I and Fig. 9.
The survey results show that students agree that the course was interesting and that the material they learnt may be useful for them in the near future. The quality of the website and documentation is considered to be fair, but the results indicate that some efforts to improve these should be made. In particular, students feel that more examples should be given instructing them, step by step, on how to get started. The general rating of the course is rather good, but it has to be noted that the best score was given to the remote laboratory, where students agree that the lab worked without problems, and to the way the classes were devised (with oral presentations and the encouragement of participation), which proved useful for them.

The analysis of the results shows that the introduced platform significantly improved the quality of the course. At the same time, the course methodology has proved to be satisfactory, and students have valued it accordingly.

In the oral presentation, students explained their programs, along with the problems and solutions. The debates after presentations were centered on the following:

- **Supervision of the controlled processes:** The different operation modes, and the buttons and programming needed for these.
- **Synchronization of different tasks:** The various techniques to do this.
- **Emergency stops:** When and how such an emergency procedure to be activated.
- **Tuning of the PID regulators:** The differences in tuning found in the different groups raised the issue of the appropriate methodology to find the suitable constants for the controller.

The debate was useful, and students acquired ideas from other students during this process.

### B. Platform and Course Assessment

In order to assess the results obtained with the introduction of the new platform, the initial objectives of both the platform and course have to be evaluated. Such objectives, along with the assessment criteria to evaluate whether each objective was accomplished or not, and the assessment results, are presented in Table II.

The objectives are separated between platform objectives and course objectives. All the relevant objectives are listed in Table II, specifying the criteria to assess each objective.

The assessment criteria for the platform evaluation are as follows:

- Survey results illustrated in Table I.
- Connection failures: Number of communication failures. These data can be obtained from the PLC Ethernet module.
- Incidences: Number of student and users complaints about problems when working with the platform.
- Modifications needed: Changes made in the platform since the beginning of the platform operation.
- Down time: Time with the platform stopped and disconnected.

The assessment criteria for the course evaluation are as follows:

- Table I.
- Report prepared by the students and submitted to the instructor.
- Oral presentation and debate about the different solutions proposed by students.
- Final exam.

Each objective was assessed according to each criterion and the average value calculated shown in the third column of Table II. It can be noted that the results are satisfactory. Nonetheless, further work will be done to try to improve both the platform and the course, focusing in the issues which obtained the worst results in the assessment. In particular, special attention will be given in the next offering of the course to languages other than Ladder and GRAFCET, and to regulatory issues.
TABLE II
PLATFORM AND COURSE ASSESSMENT

<table>
<thead>
<tr>
<th>Objective</th>
<th>Assessment criteria</th>
<th>Result %</th>
</tr>
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<tbody>
<tr>
<td><strong>Platform evaluation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote operation of the laboratory</td>
<td>Survey, report, presentation and exam</td>
<td>92 %</td>
</tr>
<tr>
<td>Robustness of the remote laboratory</td>
<td>Description, report and exam</td>
<td>81 %</td>
</tr>
<tr>
<td>Maintenance needed</td>
<td>Survey, report, presentation and exam</td>
<td>71 %</td>
</tr>
<tr>
<td>Real system similarity</td>
<td>Survey, report, presentation and exam</td>
<td>81 %</td>
</tr>
<tr>
<td><strong>Course evaluation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Introduction to real industrial automation components</td>
<td>Description, report and exam</td>
<td>84 %</td>
</tr>
<tr>
<td>Programming skills in Ladder language</td>
<td>Description, report and exam</td>
<td>85 %</td>
</tr>
<tr>
<td>Programming skills in GRAFCET language</td>
<td>Description, report and exam</td>
<td>63 %</td>
</tr>
<tr>
<td>Programming skills in other IEC61131-3 languages</td>
<td>Description, report and exam</td>
<td>84 %</td>
</tr>
<tr>
<td>Grasping motor control concepts</td>
<td>Description, report and exam</td>
<td>84 %</td>
</tr>
<tr>
<td>Grasping PID regulation concepts</td>
<td>Description, report and exam</td>
<td>71 %</td>
</tr>
<tr>
<td>Grasping automation sequences concepts</td>
<td>Description, report and exam</td>
<td>81 %</td>
</tr>
<tr>
<td>Developing Supervision systems</td>
<td>Description, report and exam</td>
<td>87 %</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This paper describes a novel low-cost platform to develop practical work in the field of drive control with programmable logic controllers. The platform is accessible through the Internet, and students directly access the PLCs as though they were dealing with a real industrial application. The CoDeSys open free programming software is used.

The authors would like to underline the increasing potential of distance learning, and the great possibilities this offers for both theoretical and practical approaches. This potential is especially important because it allows the implementation of remote laboratories networks, where resources can be employed without geographic or time constraints. Thus, students of any of the centers belonging to such a network will be able to access the laboratories of any of the other centers, allowing them to be trained in any field offered by the network at large, and introducing them to new technologies and methodologies of study. The cost reduction is remarkable, since each center provides only a single platform, and students can access a number of these. Of course, a key issue when dealing with such networks is the scheduling of the laboratories. Another crucial issue is the importance of the Internet connection speed (important for the rate of downloading and refreshing the program, the supervision screens and the IP camera). Although students having a good Internet bandwidth will be able to supervise the evolution of their programs better than those with slower connections, the platform has been devised so that even students with slow connections will be able to follow most of the exercises without problems.

It is important to note that remote laboratories are not devised to substitute for local laboratories, but to complement them, allowing students to perform more experiments from home, while still experiencing actual laboratory work. Moreover, the advantages of both local and remote laboratory approaches can be exploited by students, resulting in an improvement in their training.

REFERENCES


Coia Ferrater-Simón received the M.Sc. degree in electrical engineering from the School of Industrial Engineering of Barcelona (ETSEIB), Technical University of Catalonia (UPC), Barcelona, Spain, in January 2006. She is currently working toward the Ph.D. degree with the UPC focusing on brushless ac control, digital signal processing, and high-resolution velocity measurement. Since July 2005, she has been with the Center of Technological Innovation in Power Electronics and Drives (CITCEA-UPC), UPC. Her work focuses on hardware and software development of converters and remote platforms designed for e-learning studies. In 2007, she was an Assistant Professor in the Electrical Engineering Department of the UPC.
Llúis Molas-Balada received the technical degree in electrical engineering in June 2003 from the Engineering School of Vilanova i la Geltrú (EPSEVG), Technical University of Catalonia (UPC), Vilanova i la Geltrú, Spain, and the M.Sc. degree in electrical engineering from the School of Industrial Engineering of Barcelona (ETSEIB), UPC, in January 2006.

From May 2005 to January 2008, he was with the Center of Technological Innovation in Power Electronics and Drives (CITCEA-UPC), UPC, where he began his Ph.D. degree studies. His work with the CITCEA-UPC focused on e-learning remote platforms design, substation monitoring for predictive maintenance, dynamic behavior of wind power generators, electrical power quality, and superconductor power cables. Since February 2008, he has been with MAESSA, working in substation control and design.

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Since 2007, she has been with Emte Sistemas where she develops software applications for industrial automation.

Oriol Bayó-Puxan received the degree in industrial engineering from the School of Industrial Engineering of Barcelona (ETSEIB), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 2005.

Between October 2005 and April 2006, he worked on permanent magnet synchronous motor control in Nagaoka University of Technology, Nagaoka, Japan. Since 2006, he has been with the Center of Technological Innovation in Power Electronics and Drives (CITCEA-UPC) research group focusing on mechatronic systems and industrial automation projects.

Roberto Villafañia-Robles (S’05) was born in Barcelona, Spain, and received the degree in industrial engineering from the School of Industrial Engineering of Barcelona (ETSEIB), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 2005. He is currently pursuing the Ph.D. degree regarding distribution networks and renewable-sources-based distributed generation.

Since 2003, he has participated in the Center of Technological Innovation in Static Converters and Drives (CITCEA-UPC), where he is involved in technology transfer with the local industry due to research and innovation projects in the field of power quality, renewable energies, and power systems. Since 2007, he has been an Assistant Professor in the Electrical Engineering Department of UPC at the Escola Universitària d’Enginyeria Tècnica Industrial de Barcelona (EUETIB). His research interests include power systems, distributed generation, engineering education, and power quality.