A student-friendly approach to undergraduate teaching of experimental industrial control systems

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Abstract This paper describes a computer-based approach applied to a laboratory course in industrial control systems, providing interactive tools for understanding complex concepts. Based on modern hardware and software we at the University of Patras have developed experimental set-ups where the most recent industrial control themes have been included. The experimental equipment and computational tools used are all industrial products that students will meet later in industry. Students can thus acquire experience in the real behaviour of the various industrial-type subsystems.

Keywords automation; industrial control; robotics; SCADA; WWW environment

The science of electrical engineering is under continuous evolution due to the numerous and interesting fields in which it can be applied. The sector of industrial automation is one of those that have undergone great development in recent years, so that industries tend to seek engineers with specialisation in industrial control systems. There has been an increasing emphasis on manufacturing automation in order to cut the cost of production and increase product quality. Consequently, the majority of new control engineering positions are now in manufacturing and involve PLC-based automation, robotics, industrial communication networks and SCADA systems. Many universities have devoted a portion of a course or laboratory to PLCs and industrial networks. A representative one can be found in Ref. [1].

The Electrical and Computer Engineering Department of the University of Patras has a division dedicated to systems and control. This paper describes a portion of the laboratory for experimental training in industrial control systems. The following three integrated experimental setups are presented:

1 A robotic arm accompanied by an interactive real-virtual computer-aided operation environment;
2 A PLC and PC-based control system for the production, measurement and acquisition of industrial-type variables accompanied by a SCADA application and demonstration;
3 An expert fuzzy controller of a wastewater treatment plant implemented in a PLC station.

Each of the above experimental setups covers various topics, is equipped with several different devices, instruments and components and uses more than one software program. Hence, each setup constitutes something more complicated than a simple laboratory exercise and requires previous knowledge of the corresponding theory. In order to familiarise students with the required theory and also to introduce them to the experimental procedure the Web-Windows^{TM} environment was selected for working space, as in many laboratories.[2,3] The training program, apart from being profitable, must also be attractive, given that students are usually prejudiced against their laboratory duties and tend to avoid them, especially the study of the corresponding theory. That is, the training should be organized and presented in such a way that it motivates students to do a new laboratory activity. Today, almost all students use the Internet and Web-based environment for various reasons. Therefore, it can be considered that they are *a priori* familiarised with the very attractive environment of the Internet. That is why the specific course program is accompanied by a Web-based electronic presentation available through the Internet or on a CD that aims to facilitate students to prepare for the laboratory experiment and to encourage them to carry out specific tasks without the need for their supervisor to be present. Some hardware components and software packages of the above experimental setups have been developed by the authors and talented students who participated in the project through their diploma theses.

The remainder of the paper is organised in the following fashion: the next section investigates some pedagogical issues and briefly introduces the course program. Three subsequent sections describe the experimental setups of the fuzzy logic controller, robotic arm and industrial variables respectively, including their hardware and software structure. A further section presents the developed Web-environment software training tool. Finally, conclusions are presented.

The approach philosophy

Experimental study is a very important component in engineering education. It acts not only as a bridge between theory and practice but also solidifies the theoretical concepts presented in the classroom.[4,5] The era when a professor could teach for hours and hours the theory of a scientific field belongs to the past. Today, students are pushed towards the application stage and encouraged to leave a deeper knowledge of the theory for later when they will have to face a real problem in their job. On the other hand, the classical approach to laboratory work consists of students' theoretical presentation in a classroom and some handouts, which are available for reading prior to a laboratory session. According to such a classical way of experimenting, students either observe a pre-designed experiment throughout its course of action or modify at most some system parameters to observe their effects.

In order to overcome the above restraining factors, the realisation of an entire and complete training should not be limited to a simple presentation of the setup function in the laboratory. Recent technological trends in engineering education have evolved around the use of computers, software tools and multimedia presentations.[6] The impact of technology-enabled instruction on students' comprehension has been analysed in Ref. [7]. In this sense, a Web-environment tutorial software tool was developed which presents to the user the theoretical and experimental topics of the setups through user-guided links. These links may concern the various web pages or the executable files related to the real or virtual operation of the apparatus. An interactive approach inherent in the developed software supports human-computer collaboration to satisfy user goals by effectively allowing the user to access the underlying knowledge base dependent on the user's level of understanding of the subject matter. Students should prepare themselves at home, aided by the tutorial software tool, in order to understand thoroughly the cognitive field of each of the setups and also to observe virtually the experimental procedure. The overall structure of the experimental setups, the software tools and the covered cognitive objectives serve the following pedagogical features:

- The laboratory setups are small versions of real systems or processes and involve real equipment and not only simulations;
- Creating a motivating environment for the practice of industrial control systems, allowing experimental verification of fundamental methods, laws and concepts;
- Providing opportunities for immediate correlation between theory and experiment;
- Stimulating team work, cooperation and interaction throughout the laboratory session from preparation of the experiments to elaboration of technical reports.

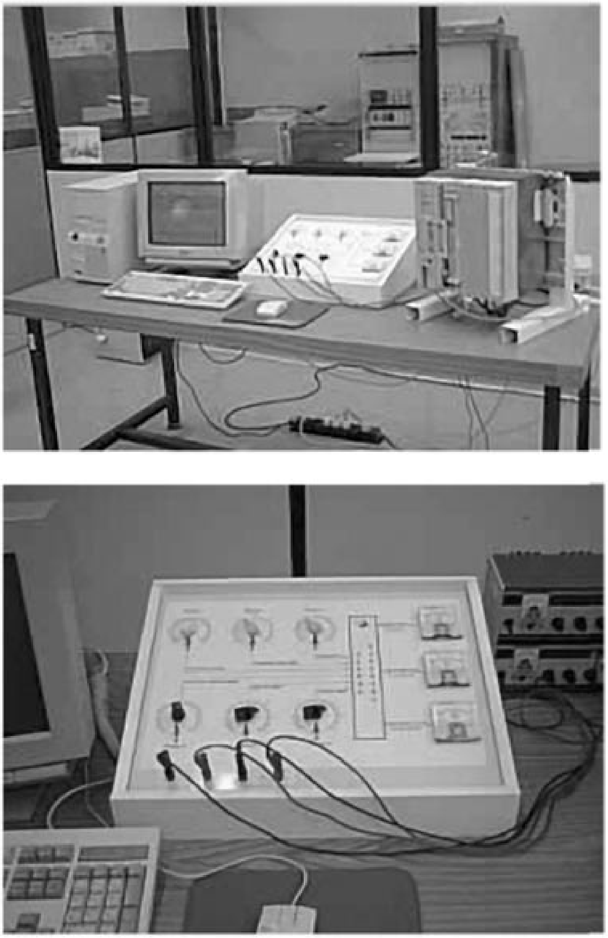
Since a typical manufacturing plant may contain discrete, continuous and batch processes, a basic aim was to cover as many such applications as possible. This specific laboratory course covers basics on robotics, human-computer-machine interaction, virtual reality, PLC usage, PLC programming, analog sensors/inputs, industrial-type physical variables, PID control, fuzzy logic and expert fuzzy control, supervisory control, PC-PLC communication and SCADA stations. All three experiments take place within a segmented training philosophy and operate with a PC and/or PLC unit.

This course, covering the above topics, has two hours of introductory lecture and five hours of lab each week per experiment. For the course, it is important to get the student into the laboratory as soon as possible and integrate the various laboratory exercises per experiment in one session. The student teams (three-student groups per experiment) rotate among the three laboratory experiments spending at least three weeks on this portion of industrial control systems laboratory. One more week is available to students who want to use the experimental setups further in order to acquire more experience.

The expert fuzzy controller

This experimental set-up consists of a wastewater treatment plant's input/output simulator, a PLC, some analog input and output indicators and a PC, as shown in Fig. 1. The I/O simulator was necessary because it is impossible to bring a real wastewater treatment plant into the laboratory, even with scaling. The PC is a 486/100 MHz and is supplied with 'PROFUZZY' software, developed by Siemens and accompanied by 'Compact Fuzzy Control', a software package necessary for the support of PROFUZZY in the PLC. The PLC is a SIMATIC S5-115U unit with 941b CPU.

The PROFUZZY program is a software tool in a PC environment and it is used



(a)

(b)

Fig. 1 *The expert fuzzy controller. (a) An overall view of the set-up; (b) the simulator panel.*

to design the fuzzy controller. The introduction of the rules, the definition of the membership functions, the specification of the input/output signals and the definition of an interchange element between PC and PLC are the basic steps used to compose the controller inside the PC. After downloading the fuzzy controller into the PLC, the operation and hence the presence of the PC is not necessary. If however the PC operates, someone can inspect the variation of the inputs and the corresponding actions of the controller.

The wastewater treatment plant's I/O simulator is a manipulation panel that provides electrical signals to the PLC through potentiometers and DPDT switches, representing the six inputs of a real wastewater treatment system. The PLC through the action of the expert fuzzy controller produces the control output signals, which can be viewed in three indicators calibrated in corresponding physical units of the real outputs.

The course program recommended consists of the following segments:

1st segment (e-learning)
The aims of the first segment are:

- Provision of the basic knowledge on fuzzy logic. Concepts such as 'fuzzy logic' and 'fuzzy sets' are fully explored here as they compose the foundations upon which the whole system is formed and functions.
- General description of classic control systems. Their design takes place in a specific procedure and can give solutions to a certain range of problems.
- Elevation of the need for using fuzzy control in some applications. The weakness of classic control methods presented above revealed the fact that fuzzy logic may be the only solution to satisfy some specific demands.

2nd segment (e-learning)
This segment aims to:

- Describe the elements that make part of an ordinary urban waste process system. The characteristic variables involved in the entire process are analysed with their physical meaning.
- Realise the transition from the existing physical problem to a control problem. The way that the control system is shaped is explained and the magnitudes presented above become inputs and outputs of this system.

3rd segment (e-learning)
Data fuzzification takes place here. With the basics on fuzzy logic as well as the variables already known, students can see how these are depicted in the control system with the use of fuzzy logic principles.

4th segment (practical)
Students familiarise themselves with the PROFUZZY software tool in this section. More specifically, they first come to know the software environment with its menus and the options it offers, as shown in Fig. 2.

5th segment (practical)
Having familiarised themselves with the software used, students now operate the controller of the wastewater treatment plant. They give specific values to the input variables, making various tests to identify cases in which they get the best results, and checking the results both from the outputs' indicators on the panel and from the output participation function in the computer screen.

The robotic arm

This experimental set-up treats a robotic arm shown in Fig. 3 and a software package which has been developed[8] for its programming, motion planning and motion exe-

(a)

(b)

Fig. 2 *The PROFUZZY environment. (a) Basic menu for introducing expert rules; (b) on-line monitoring of the PLC's outputs.*

Fig. 3 *The training type robotic arm.*

cution through the support of a PC. The robotic arm is the ‘Atlas’ training robot, manufactured by L&J Electronics Inc. After reconstruction of the robot’s electronics it is now controlled by a PC. The software tool that accompanies it is called CERS (Cad Enhanced Robotic System) and has been written in Borland C++. The goal of its innovative development in the laboratory was to provide a more attractive environment for students. Its object-oriented environment makes it easy to use and friendly to access. It has two separate versions, a 16-bit one for Windows 3.1™ or higher platforms and a 32-bit one for the Windows NT™ environment. The graphical user interface is shown in Fig. 4.

The course program consists of:

1st segment (e-learning)

The aims of the first segment are:

- Introduction to the world of robotics. For this purpose, basic meanings such as links, joints, transformations and degrees of freedom are quoted.
- The presentation of Atlas manufacturing characteristics. On the one hand motions of joints are explained (rotary or linear) and on the other hand the external characteristics of the robotic arm are cited (that is height, weight, and rise ability).

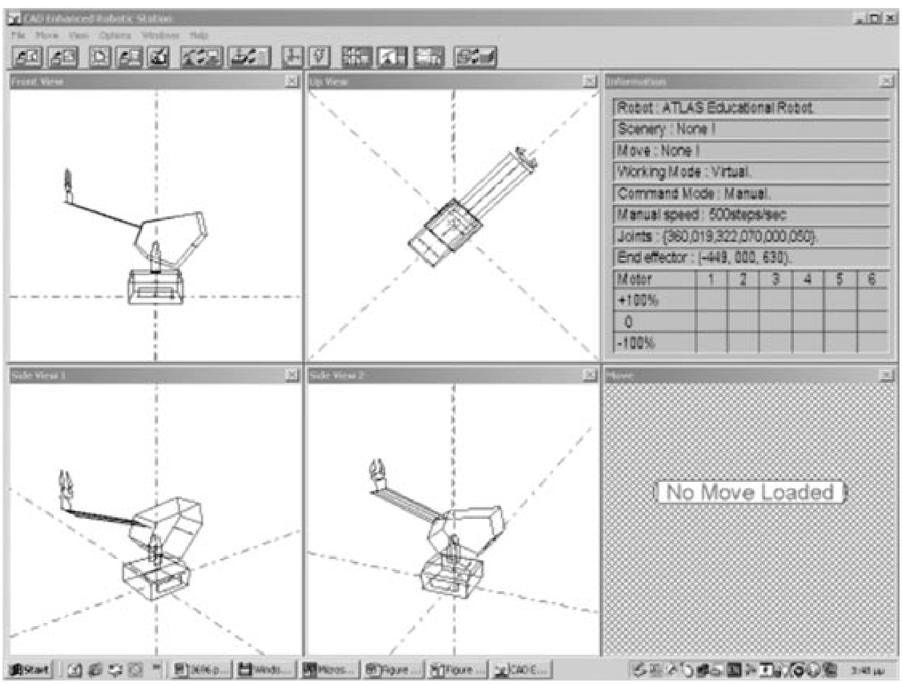


Fig. 4 *The overall menu view of the developed CERS software.*

- Explanation of the way motions are executed. Step motors, basic elements of their operation and the way they drive joints' motions are analysed.

2nd segment (e-learning)
This segment aims to clarify the way the interaction between the robotic arm and the PC takes place. The AD/DA Lab-Tender card constructed by Scientific Solutions Inc. is mentioned and how it realises this interaction is described.

3rd segment (practical)
This segment is signalled by familiarisation with the software tool used and its explanation. More specifically:

- It presents the graphical user interface (GUI). Menus, options and everything needed for software usage are explained.
- Usage of the software tool is explained. Students learn how to load a robotic arm or a motion of it and collect all information of interest during each motion's execution.

4th segment (e-learning)
This part focuses on an understanding that one can work with two different modes of the robotic arm. The first is when someone is in the laboratory working with the robotic arm and is the real one. The other mode is the virtual one, which is achieved everywhere, without the arm, just with the software usage that assimilates its motions.

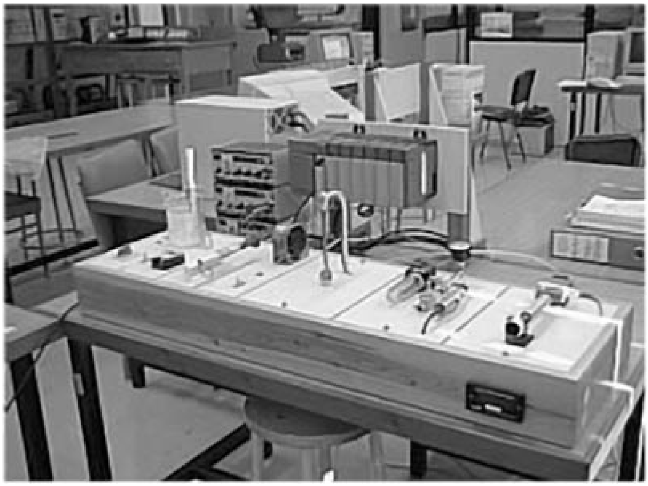
5th segment (e-learning and practical)
Here, students understand and apply the ways in which they can drive the arm. The first way, which is the simplest to learn, is the manually operated one with the use of certain keys of the keyboard, while the second way, in general more useful, is via the writing of program code, the teaching of which comprises a separate part.

6th segment (e-learning and practical)
As mentioned above, the exclusive explanation of motions that have already been determined and programmed takes place here. There is a quotation and extensive analysis of the commands used by the software tool in order to execute various programmable motions.

7th segment (practical)
After the presentation of all demanded knowledge, each student undertakes a project for the execution of one or more programmable motions.

The industrial variables control system

This control system is a set-up for the production, measurement and visualisation of pressure, force-weight, air velocity, inclination, acceleration and temperature variables. As shown in Fig. 5, it consists of:


(a)


(b)

Fig. 5 *The industrial variables experimental set-up. (a) The panel of variables and the PLC; (b) the SCADA station at the left-hand side of the panel.*

- A panel where these magnitudes are produced.
- An Allen-Bradley PLC with an SLC 5/03 processor where some analogue and digital (A/D) input-output cards have been installed.
- Sensors that accept the physical magnitudes and apply the corresponding analogue signals in the PLC's inputs for further processing.
- A PC loaded with SCADA software that allows visualisation, monitoring and control of the physical variables.

It is notable that the PLC used in this application realises a PID controller for adjustment and control of the temperature in a small vessel of water and hence students have the opportunity to gain experience with this. Also, the SCADA software package is the InTouch 5.1 platform, created by Wonderware, which provides the flexibility both to create one's own application windows and to view and control the set-up operation.

The course program articulates as follows:

1st segment (e-learning)

This part is dedicated to the understanding of PLCs. More specifically:

- The basic PLC structure is analysed with all its necessary components such as CPU, input-output cards, power supply, communication card etc.
- Students subsequently learn how a PLC operates; that is, the way it receives discrete signals or analogue magnitudes from the external world, transforms them in digital form, processes and sends them back in corresponding outputs.
- With the operation of the PLC should also be a brief reference to the operating system of PLCs, the way they start and subsequent steps to complete a sweep cycle.

2nd segment (practical)

Students see, in the laboratory, how each of the industrial variables has been represented in the construction. The voltage supply of sensors, the scales of the measured variables and the limits in voltage outputs are also explained.

3rd segment (e-learning)

Having already completed the comprehension of meanings that concern the 'material' world, that is the PLC's structure, sensors and everything mentioned so far, students can now learn the basics of PLC programming methods. The best-known programming languages are explained here.

4th segment (e-learning and practical)

This segment deals with the variables' visualisation and control through the computer. It aims to:

- Present the principles of SCADA systems. Informatics has nowadays intruded into industrial applications, strengthening control systems and optimising production (which is the ulterior goal).
- Explain the software tool used in the specific experiment. The InTouch environment is simple enough that students can rapidly understand the way the variables are shown on the screen. Apart from monitoring, they can also control the entire system via the computer. That is, they can give a control command in the virtual environment, inspect the result in the real system and confirm it in the monitor, realising a kind of feedback. For example, these activities can be applied in the case of temperature variables with the corresponding window shown in Fig. 6.

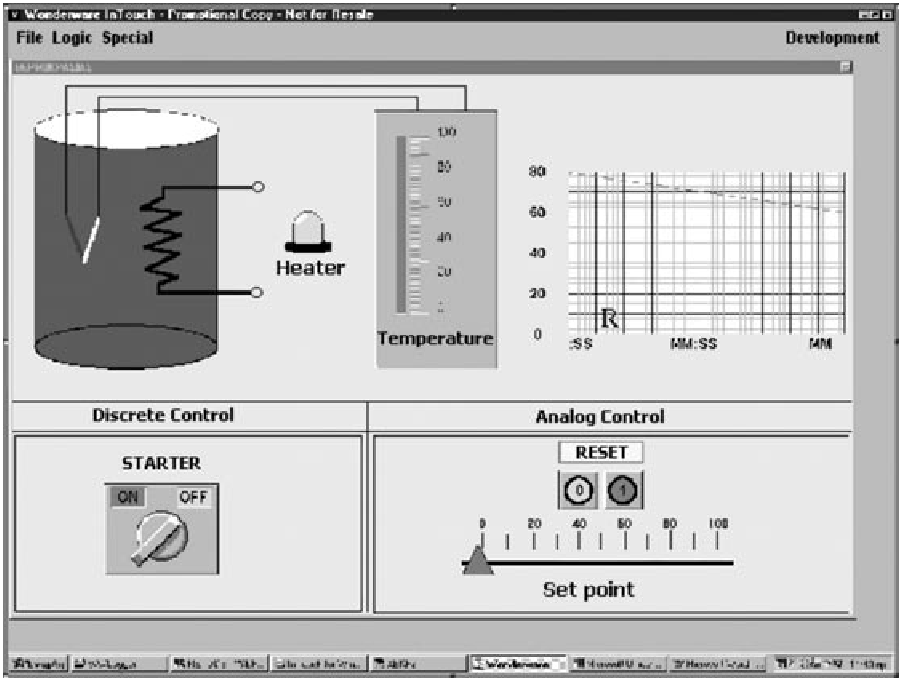


Fig. 6 *The InTouch window for temperature monitoring and control.*

5th segment (practical)
This part of the course is optional and aims to explain how students can shape their own software environment to make it more flexible and user-friendly, according to their preferences.

The computer-aided training environment

The computer-based teaching approach is accompanied by a software tool that allows the student to browse the topics he/she is interested in. It has been developed with FrontPage 2000 and can be browsed via Microsoft Internet Explorer or Netscape Navigator. That is, it has been designed based upon the principles of Web pages, to appeal to modern young people. As mentioned above, the principle of attractiveness upon which the software tool has been designed can motivate students for a creative occupation, avoiding a simple and simultaneously unproductive presentation of theoretical knowledge, characteristics and figures. It is also intriguing that they can execute the software packages (PROFUZZY and CERS) used in the various set-ups through this Web-based environment. The backbone structure of the developed software tool is shown in Fig. 7.

As has already been mentioned, the part of the software tool that refers to each of the setups is divided into segments, some theoretical for e-learning and some prac-

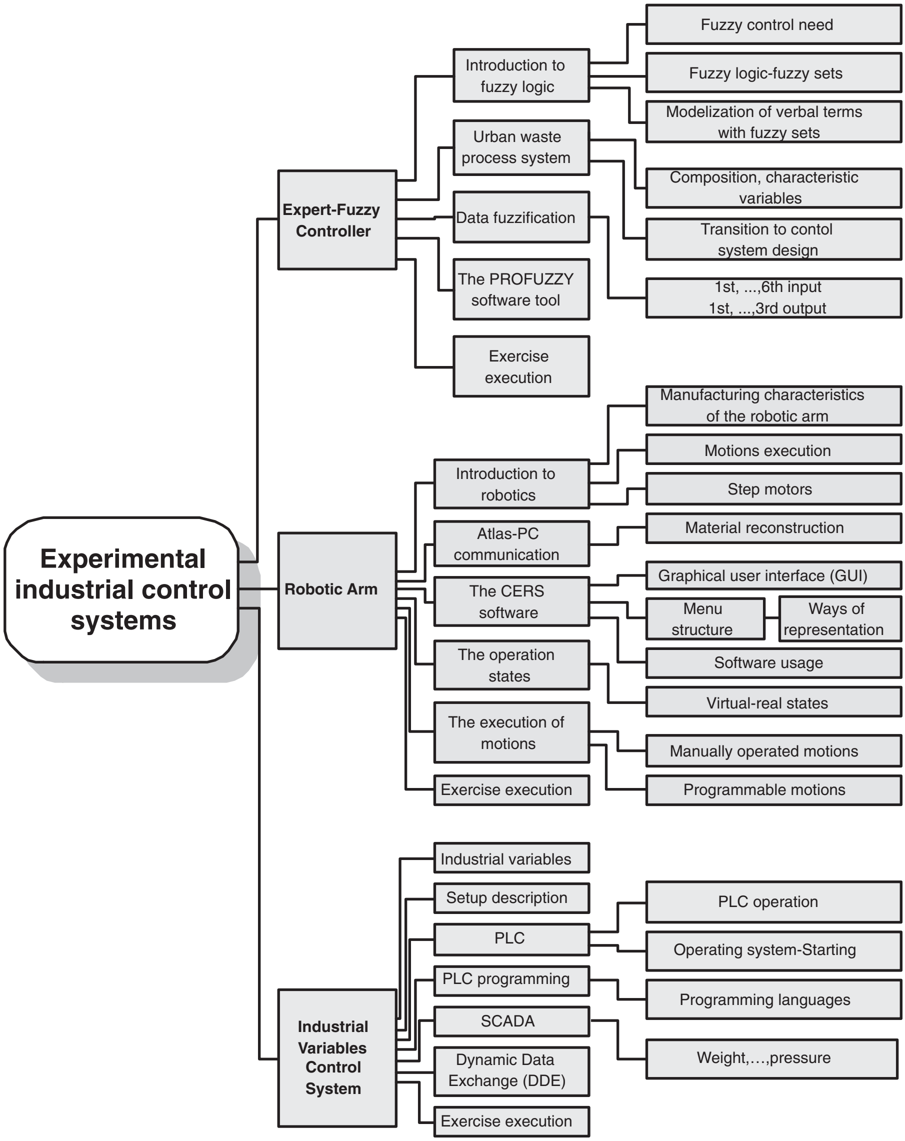


Fig. 7 *Block diagram of the developed Web-based software structure.*

tical for virtual or true realization in the laboratory. The first provide the basic theoretical knowledge for an understanding of the setup, while the latter give the description and technical characteristics of each setup. Every part ends with a page that presents the exercise that must be executed, giving specific directions, step by step. We shall refer to each setup separately:

The expert fuzzy controller

The initial part consists of three pages: the first one tries to explain why modern industries' needs have necessitated the use of fuzzy control in some specific applications. The second clarifies the basic principles of fuzzy logic. The last page explains the way that linguistic terms can be modelled, using fuzzy sets and participation functions.

The second part describes a typical urban wastewater process system. There is a page that refers to the composition and the characteristic variables of such a system and one more that explains the way that this system can be converted to a control system. As a continuation of the previous page, the next part clarifies the fuzzification of the physical variables involved in the process, containing links that present the participation functions of each input and output of the system.

The fourth part presents the software tool PROFUZZY. Initially it gives the number of inputs, outputs, participation functions and rules that can be accepted and later it presents analytical directions about the way that a fuzzy controller is developed with PROFUZZY.

The last page aims to guide the students through the procedure for the execution of the exercise. It gives the input variables that must be selected and the changes that must be made in order to check the behaviour of the controller. It also requires the development of an independent simple fuzzy controller using PROFUZZY.

The robotic arm

The first page mentions the general features of the Atlas robot, such as the number and type of motions executed and the external manufacturing characteristics. It also contains a link that leads to a page with an explanation about step motors.

The second page clarifies the realisation of the communication between the robotic arm and the computer, giving a picture presenting the AD/DA card Lab-Tender that is interposed between these devices.

The third page refers to the software tool CERS and contains three more pages. One presents the interface with which the user comes into contact. The other explains the structure of the menu and contains a link leading to a page about the two different ways that the robotic arm can be represented. The last page gives directions about the operations that must be made to use CERS.

The next part mentions the operation states of the robotic arm, that is the virtual state and the real state.

The fifth part concerns the execution of motions and consists of two more pages: one that refers to the manually operated motion and another that clarifies the way that the programs are written when using CERS.

The last page refers to the execution of the exercise in the laboratory, also containing a warning about the movements of the robotic arm.

The industrial variables control system

The first page refers to the industrial variables that the setup produces and measures, as well as the sensors used to realise these measurements.

The second page describes each part of the setup and the way that the variables are produced.

The third part explains the principles upon which the operation of a PLC is based and includes one more page; this page explains the reading of the inputs, the conversion of the circuit to a program, the execution of the commands and the notifying of the outputs.

The next part indicates the main languages used for PLC programming, which are the ladder diagram, the function block diagram and the statement list programming.

The fifth part refers to the software package InTouch and the way it represents each physical variable. The next page explains the way that the communication between the PC and the PLC is realised, which is the DDE server. The last page gives accurate directions about how students must execute the exercise.

Conclusions

Innovative teaching methods have been implemented in the Systems and Control Laboratory, at the Electrical and Computer Engineering Department of the University of Patras, Greece. The corresponding experimental course is based partly on three integrated setups developed in the Laboratory, which cover a wide range of industrial automation topics. The development of setups included both hardware (new PC-Atlas interface, I/O simulator for fuzzy controller, industrial variables panel etc.) and software (CERS package, Expert Fuzzy controller code etc.). Furthermore, a Web-based software tool was developed for electronic presentation of the theoretical and experimental issues, helping students to understand the complex concepts and perform the experiments.

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