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Teaching Control of Irrigation Canals to Non System Engineers*

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This paper presents an experience of teaching automatic control within the master course Real-time Control of Irrigation Canals. It is part of Semester 3, focusing on Decision Support Systems, offered by the Technical University of Catalonia (UPC) in the framework of the Erasmus Mundus Master Program Hydro-Informatics and Water Management (EUROAQUAE). After some insights into signals, systems and control theory, the students are introduced to the operational management of irrigation canals and to the mathematical models needed for simulation and control purposes. PI and predictive control are taught and used to design irrigation canal control systems. MATLAB-Simulink and Real Time Workshop environments are extensively used to provide explanatory exercises along with lectures, student homework tasks and a final design project on a laboratory canal. A visit to a real canal installation is organized during the course.

Keywords: automatic control; irrigation canals; water management; control education; course design; course evaluation; teaching strategies

1. INTRODUCTION

AUTOMATIC CONTROL has grown to real maturity in the last decades, mainly due to a strong mathematically based background and a high potential of offering tools to give systems and processes enhanced performances. This potential has been confirmed through the introduction of control methods and control loops in an increasing number of areas. Beyond the "traditional" areas including electrical, mechanical and aeronautics engineering, controls have been introduced to other areas, such as computer science and engineering, economics, biology, medicine, physics, environmental science and engineering, nanotechnology and civil engineering.

The introduction of control to a new area and, in general, the acceptance of a technology that is in principle seen as "foreign" to the established scientific and professional community, is usually slow: it requires a sufficiently mature theoretical basis, a suitably reliable technology that is available for a practical implementation and the perception that it will yield benefits. In addition, human and intellectual interactions play a significant role, since control designs and applications naturally involve interdisciplinary activities. In this direction, new educational activities have recently been addressed to "non-traditional" control areas. For instance, in [1], a university undergraduate/graduate course is described, which aims to make control concepts and tools accessible to a variety of students with backgrounds in non-engineering areas, such as physics, biology, economics and environmental sciences. A virtual laboratory is presented in [2], designed for a biomedical engineering program, which involves non-linear models and control blocks. A course on modeling and control of irrigation canals that is taught within a graduate program on hydraulic engineering is described in [3].

This paper presents the experience of teaching the master course Real Time Control of Irrigation Canals. This course is part of a specialty block called Decision Support Systems that is offered by the Technical University of Catalonia (UPC) within the Erasmus Mundus Master Program Hydro-Informatics and Water Management (EUROAQUAE).

The audience is very mixed, with students holding degrees as different as: civil, hydraulic, environmental and agricultural engineering; geology; geography; water resources management, and computer science. Moreover, the students come

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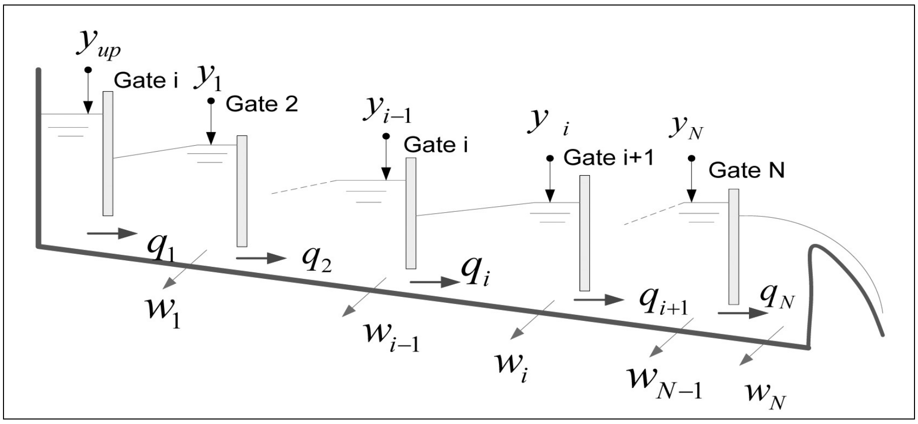

Fig. 1. A prototype multi-pool canal.

from different countries around the world with their own educational systems and degree schemes. Only a few of the students have a previous background in control systems. Consequently, the course primarily follows a conceptual approach rather than focusing on a deeper mathematical treatment of control theory.

Open channel hydraulics and automatic control are usually considered as belonging to separate disciplines (civil engineering and control engineering), and hence are taught in separate degree programs.

The essential educational objective of this course is that graduate students, interested in building a professional career in water management, are trained to acquire skills that are essential for developing automation projects for real irrigation canals.

The structure of the paper is as follows. Section 2 briefly introduces the problem of controlling an irrigation canal system. Section 3 describes the Master Course. The educational resources are presented in Section 4, while the teaching methodology is described in Section 5.

2. AUTOMATIC CONTROL OF IRRIGATION CANALS

Modernization of irrigation canals to improve the efficiency and the operational flexibility in the delivery of the water has become a strategic issue in many areas of the world. One of the measures that have been considered in the last years is the introduction of some level of automation in the canal operation. Essentially, automation means the presence of control systems that are able to automatically operate canal cross structures based on feedback information on the state of the canal.

As an example, let us consider a canal with a series of N pools, gates and offtakes as illustrated in Fig. 1. The upstream and downstream bounds of the canals are such that there is a reservoir upstream of gate 1 and a weir at the downstream end of the pool N. A lateral offtake is placed immediately upstream of each gate. A typical control objective is to maintain the prescribed downstream levels at each pool, even in the presence of disturbances in the form of lateral offtakes, by manipulating upstream gate openings.

In addition to the installation of single automated gates to regulate nearby water levels, the potential of more sophisticated control systems has been exploited in practice only in a small number of projects. This reflects the difficulties of introducing new technologies in any well established area. In this sense, we believe that interdisciplinary education and background can substantially help in this direction.

The design of an irrigation canal control system is a complex task with challenging problems. Canals are distributed over long distances, with significant time delays and dynamics that change with the operating conditions. Check structures, like gates and offtakes are located along the canal and strongly interact with the canal dynamics. Thus, the whole canal has to be regarded as a complex dynamic system with a large number of variables related to states, inputs and outputs.

Great efforts in modeling and control techniques for irrigation canals have been made in recent years. Only a few references, which are particularly relevant for the course, are mentioned below. A recent state of the art review and a complete project on modeling, identification and real time implementation of control algorithms in a laboratory canal can be found in [4].

Several models have been used as the basis for control design, such as the integrator plus delay model [5], the Muskingum model [6] and Saint-Venant equations based models [7]. Since 1998, work based on Proportional plus Integral (PI) controllers for irrigation canal systems have been developed, focusing on improving the tuning of this type of controller [8]. Applications of Linear Quadratic (LQ) optimal controllers can be found in [9], while robust control methods application can be found in [10].

Predictive control [11] has achieved good performance in irrigation canal control. First steps in this application can be found in [12]. More recent studies have been presented in the literature,

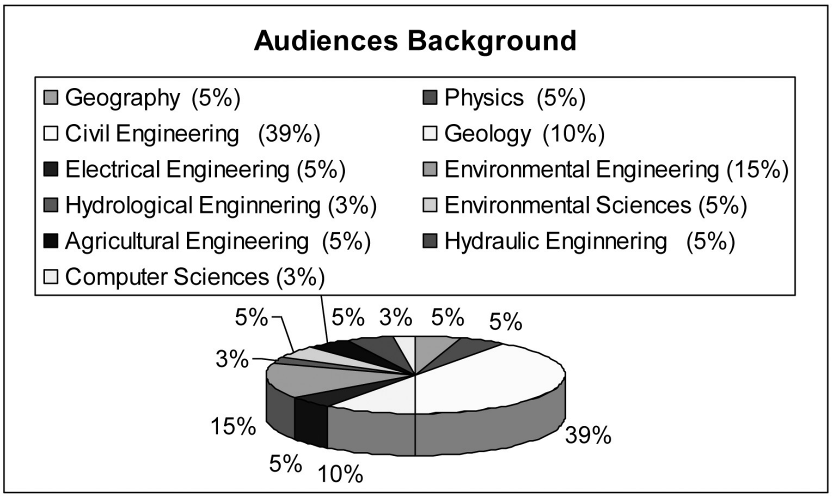

Fig. 2. Audience background.

taking into account the actuator dynamics [13], constrained predictive control [14], real-time application of predictive control to a laboratory canal [4] and a real canal implementation [15].

3. COURSE DESCRIPTION

3.1 Course Workload

The first round of the course Real-time Control of Irrigation Canals was held on September 2005–February 2006 as a part of the block on Decision Support Systems in the Erasmus Mundus Master Program Hydro-Informatics and Water Management (EUROAQUAE). The whole two year program gives 120 ECTS (European Credit Transfer System) divided into four six-month modules. The course itself has 6 ECTS, and is aimed at students who are interested in the field of automatic control within the water management area.

3.2 Audience

The students of this master course come from virtually all countries of the world; some more represented countries are: France, Argentina, Colombia, Spain, Canada, Russia, Israel and Pakistan among others. Preferred first degree subjects are Engineering (any branch), Environmental Sciences, Physics, Computer Sciences, Geography, Mathematics, Chemistry, Geology or a similar subject. Advanced level Mathematics is required; see [27] for details. The background distribution of the last four rounds (42 students in total) can be seen in Fig. 2

From this percentage distribution, it can be seen out that almost 85% of the students have no previous background in signals, systems and control.

3.3 Teaching challenges

The diversity of the origins of the students, both in nationality and graduate studies, the variety of the topics to be taught (hydraulics, system theory and automatic control) and the short time allocated for the course, bring the following difficulties:

- to teach hydraulics and control engineering together within a unified approach;
- to find a trade-off between the amount of contents and the depth of the explanations, imposed by the time constraints;
- to take into account the different backgrounds of the students without affecting the required standard of the teaching quality;
- to find a trade-off between theoretical concepts (academic purpose) and practical tools (professional purpose);
- to also find a trade-off between teaching basic control techniques (like PID) for acquiring basic feedback concepts and tools, and more advanced control techniques (like predictive control) for more complex real world oriented design projects;
- to transmit the inherent difficulties in controlling irrigation canal systems as non-linearities, pool delays and inter-pool couplings;
- to teach simplified linear models for control purposes that can reasonably approximate the complex dynamics of canal flow.

3.4 Course objectives

The final goal of the course is the implementation of a control algorithm in a laboratory canal, which is briefly described in Section 4. Figure 3 shows a typical flowchart with the necessary steps to the implementation of a control system. This flowchart is presented to the students at the beginning of any new topic to help them to keep track of the whole design process. Through these steps the students are faced with the real elements of the automation: models of the system, control algorithms, simulation runs and instrumentation

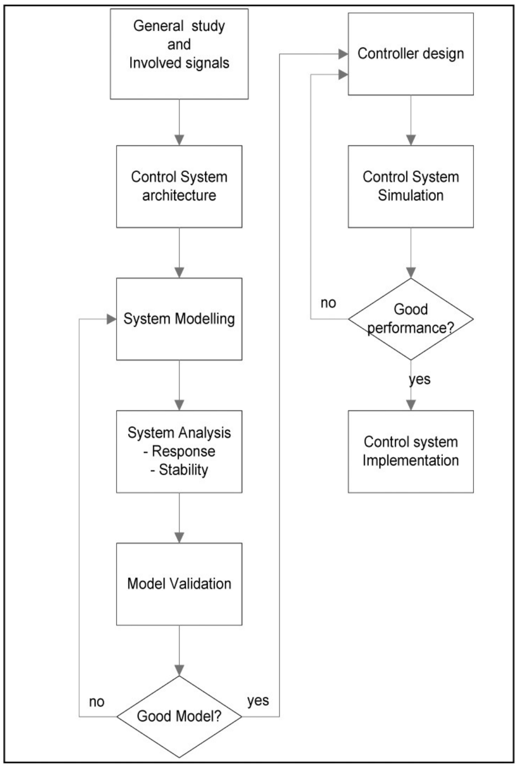

Fig. 3. Control system design steps.

issues such as sensors, actuators, acquisition cards, and others.

The need to teach the basis of control theory and, some weeks later, develop a professionally oriented design project lead us to teach classical PID control at a first level due to the simplicity of the technique, and later on to teach a more advanced control technique as the control method to develop the design project. Predictive control, Optimal control and Robust control have been considered but, dictated by the time constraints, Predictive control has been chosen for the following reasons.

1. There is a high degree of adaptability to the problem of irrigation canal system based on the anticipatory behavior of predictive controllers, which compensates the delays always present in a canal pool.
2. There is a good performance of predictive controllers in the field of irrigation canals control systems [12–14].
3. There is an intuitive and, at the same time, rigorous formulation of predictive control [11] that makes it specially suited for both academic and professional purposes.

Prior to testing their algorithms on the laboratory canal, the students must check them at simulation level. To do this, they are provided with an in-house simulator developed in Simulink [16], where they are able to test the algorithms they have designed. The students have already been provided with a reasonable background of canal models, control methodologies and foundation on signals, systems and control theory.

3.5 Syllabus overview

With the course objectives in mind, the chronological structure of the syllabus is as follows:

1. A general introduction on the irrigation canals automation field [4, 17,18] (1.5 h)
2. An introduction to the software tools that will be used along the course, specially the MATLAB, Simulink and Real-time Workshop environments [16] (1.5 h)
3. Some essential concepts of signals and systems: enough to introduce system modeling and analysis [19] (3 h)
4. A classical introduction to system analysis both in continuous time and in discrete time [19] (15 h)
5. Some insights into system modeling with examples on systems dynamics [20]. System identification is briefly introduced [21] (4 h)
6. An introduction to classical feedback control [22–24] (6 h)
7. An insight into the development of some control-oriented mathematical models of irrigation canal systems [6, 25] (6 h)
8. An insight into predictive control concepts and algorithms with examples in canal control [11-15] (6 h)
9. An introduction to the canal simulation software and presentation of the final design project [15, 26] (3 h)
10. A description of the installation of the laboratory canal and the necessary guidelines to test the students projects of a laboratory canal [4] (3 h)
11. A description of the real canal installation that the students will visit [15] (2 h)

4. EDUCATIONAL RESOURCES

This section briefly describes some of the resources that we have used in structuring the master course content, namely the introduction of classical concepts of signals systems and control, the use of specialized software to deal with the practical exercises posed at the end of any lecture, the use of in-house developed simulation software to carry out a complete canal automation design project, the use of a laboratory canal where students can test the project that they have designed at a simulation level and, finally, a brief description of the real canal which the students are invited to visit at the end of the course in order to experience the real world of the irrigation canal automation.

As noted above, students need a minimum background in the classical concepts of signals, systems and control. Several lectures are devoted to this at the beginning of the course within the constraints

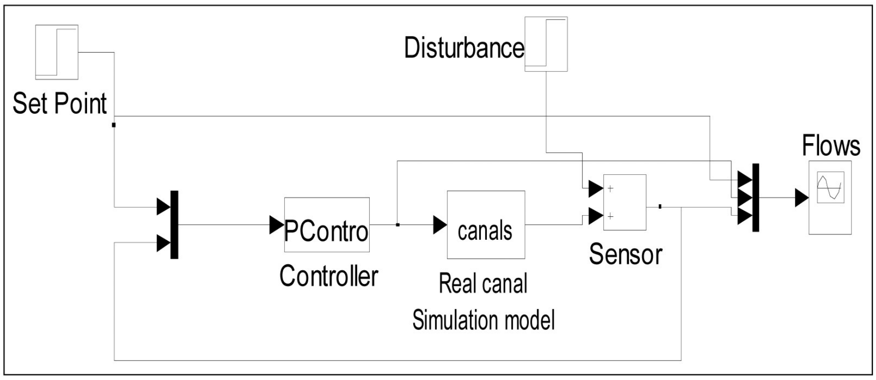

Fig. 4. Simulator main scheme.

imposed by the course time schedule. PID control is introduced as a tool to explain the foundations of control, but recently predictive control has been studied as the basic technique to develop real control designs. Apart from these theoretical approaches, some other educational resources are used in the course to improve the level of teaching. Some of them are described below.

4.1 Software Tools

During the course, the MATLAB environment is used extensively. MATLAB has been chosen for the following reasons:

1. the great popularity of this software package among the control engineering community;
2. the great facility of use offered by the command line and graphical interfaces of MATLAB;
3. the facilities offered by specialized Toolboxes like the Control System Toolbox, with a great set of programmed commands and graphical tools;
4. the high quality simulation environment offered by Simulink to support simulation projects like the course final design project;
5. the real-time facilities offered by the Real Time Workshop to implement the design project of the laboratory canal where acquisition devices are supported by this software package.

Students are provided with a set of MATLAB based software elements during the course. First, they are provided with a set of MATLAB M-files with the objective of reinforcing the concepts dealt with during the lectures. The M-files cover such subjects as: solving ordinary differential equations, model validation, continuous and discrete system analysis, and classical PID control. These M-files make extensive use of specialized MATLAB Toolboxes like the Control System Toolbox and the Signal Processing Toolbox. Second, a basic canal control system simulator is provided. It is built in Simulink and is devoted to helping the students to develop their final design project at a simulation level. The simulator implements a numerical model of the laboratory canal using the Method of Characteristics and allows the students to insert into the provided Simulink scheme its own controller developed in the MATLAB language. Technical details of this simulator can be found in [26]. The main scheme is shown in Fig. 4.

4.2 Water Tank System

A laboratory three tanks system (Fig. 5) is used to support modeling examples in early lectures. The three tanks system helps in the study of practical low order system modeling and control problems. It is made of three coupled tanks, one of them with a constant section and the other two with variable sections. It is equipped with three level sensors, three valves and a pump that lifts the water from a small reservoir. Tanks are particularly well suited for this course, since they allow the students to be in touch with a classical hydraulic system with less complexity than a real canal and they help the teacher to visualize the theoretical concepts of signals, systems, modeling and control.

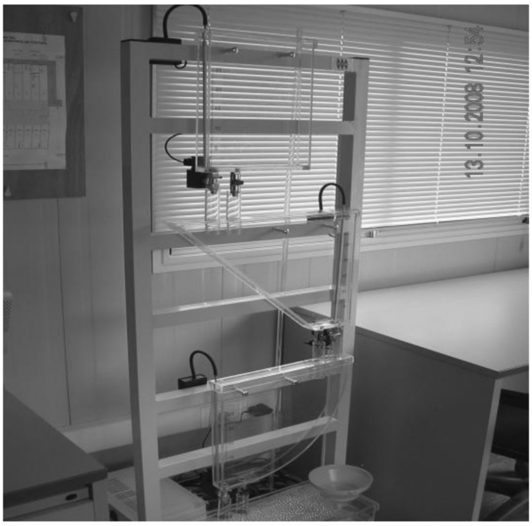

Fig. 5. The three tank system.

Fig. 6. Laboratory canal.

4.4 Laboratory Canal

The canal is located in the Laboratory of Physical Models of the Hydraulic, Marine and Environmental Engineering Department at the UPC. Currently, the canal has tree pools connected by gates. The canal is 220 m long, 44 cm wide and 1 m deep. The canal is rectangular in shape with a zero bottom slope. Variable flow lateral offtakes are located downstream of each pool to simulate disturbances. A partial view of the laboratory canal is shown in Fig. 6. A detailed description of this canal can be found in [4].

The canal is equipped with the following instrumentation:

1. level sensors upstream and downstream of the gates;
2. active gates hoisted by motors;
3. a variable location ultrasonic flow meter;
4. a central computer equipped with acquisition cards to receive sensor signals and to send orders to the actuators (servo controllers of the motors).

Students are required to run the final design project on this laboratory canal, which significantly improves their degree of understanding of the concepts learned in the course and also allows them to face real implementation issues. To carry out their task, students are provided with a basic SCADA software that has been entirely developed in the MATLAB-Simulink environment. This software deals with the acquisition cards installed into the PCI slots of the computers, receiving signals from sensors and sending setpoints to the actuators. The SCADA is designed in such a way that students can fit their control algorithms into the SCADA scheme, compile it with the Real Time Workshop and run their control algorithm in real-time.

4.5 Field Canal

The course includes a visit to a real canal. The canal visited in the past round of the Master course was the Lodosa Canal. It flows across the provinces of Navarra, Logroño and Zaragoza (Spain). It originates on the right bank of the Ebro River in the vicinity of the town of Lodosa (Navarra). The canal was first proposed in 1860 and was built between 1915 and 1935. Today the canal is 127 km long with an inflow at the origin of about 22 m^3/s. It irrigates a surface of 23.694 ha. The initial reach of the canal is about 600 m (Fig. 7). The origin of the reach is the housing of a series of gates (C_1) installed for the extraction of water from the river. The interconnection of the canal and the river is facilitated by the elevation produced in the river by a small dam that is 150 m long and 4 m high. At the end of the reach, there is a series of four transversal gates (C_2).

There are two control loops governed by gates C_1 and C_2, respectively (see [15] for details). In the first one, the gates C_1 are manipulated with the goal of controlling the level L_2, which must be maintained at prescribed values to assure the operation of gate C_2 (the actuator of the next control loop) and the supply for a lateral secondary canal. The second loop has the objective of manipulating the gates C_2 to control the flow Q_4 (downstream users' supply), measured 300 meters downstream as indicated in Fig. 7. The control systems are implemented in a PLC Siemens Simatic S7-300, which is part of a

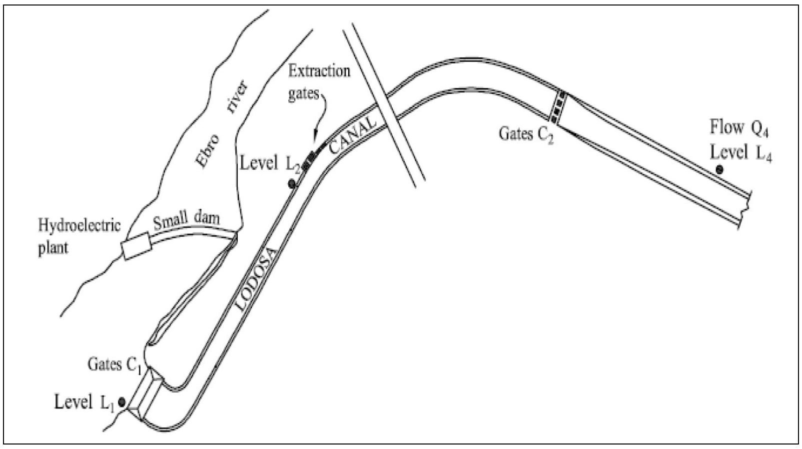

Fig. 7. Lodosa Canal main reach scheme.

system for remote, centralized supervision and control of the whole canal. The visit to the real canal is very much appreciated by the students sharing a free day with the staff of the canal facilities and the master course teachers in a relaxing and profitable way.

5. TEACHING METHODOLOGY

The main issues highlighting the teaching approach are summarized as follows.

1. Weekly lectures are given with conceptual and mathematical explanations using high quality slides made in Latex-Beamer, which are complemented with interactive use of the MATLAB-Simulink environment in order to obtain in-site practice and "feel" the explained concepts. The completion of these classroom exercises allows the teacher to track the evolution of each student and to ascertain the degree of general understanding. Selected M-files are provided for home revision of the lecture material.
2. The diversity of the audience is taken into account considering the previous degree of each student, and the level of personal understanding. A small test is made at the beginning of the course to check each personal background. Students with weak backgrounds are especially cared for during the lectures and in-site exercises. People with personal difficulties in tracking the course are specially supported with individual tutorships.
3. At the end of each lecture, homework exercises are offered to the students so that they can review the explained concepts using MATLAB and Simulink at home.
4. Case studies on modeling and control are proposed and studied exhaustively both at simulation level and at laboratory level.
5. A final design project to control a single pool canal, to be tested on the laboratory canal, is proposed at the end of the course.
6. The course is completed with the visit to a real canal where the students can see and feel, in the field, how the concepts, instrumentation and machinery that have been taught in the course are useful in a real life canal. The visit to the canal also gives the opportunity to enjoy a free day and improve the relationships between teachers and students.
7. Electronic tutorships via e-mail are established seven days a week during the course. Personal meetings are agreed when required. Regular tutorships are not held because, in our opinion, it is better to give support to the students when they really need it, and not as a regular basis.
8. A website containing all the course material (slides, MATLAB m.files, additional notes on pdf, bibliographic references and more) is available to the students to help them to work at home.

6. ASSESSMENT CRITERIA

In previous rounds of the master course, each student's mark was made up of classroom exercises (30%), final design project (60%) and personal evaluation based on the student's attitude in the classroom and on the quality of their homework (10%).

In recent rounds the concept of peer-assessment has been introduced as a tool for improving student motivation and engagement. A final exam has also been implemented. The design projects have been presented orally by the students while their companions and the teacher assessed them. The experience has been positive, but we think it can be improved in future rounds to avoid generalized over marking. In the last round the marking criteria has been homework and exercises (5%), design project presentation (50%), final exam (35%) and personal evaluation (10%).

7. COURSE EVALUATION

The fifth round of the Real-time Control of Irrigation Canals course was held on September 2009–February 2010. At the end of the course the students were required to fill in a questionnaire assessing some aspects of the course. The results of this assessment for the last two rounds are summarized in Table 1. Marks range from 0 (low) to 5 (high).

Table 1

	Question	Mean	Std
Q1	How adequate is the syllabus for the purpose of the course?	4.12	0.99
Q2	How adequate is the master course for the purpose of the DSS module?	4.20	0.88
Q3	Assess your previous background on signals systems and control.	0.75	0.70
Q4	Assess your present background on signals systems and control.	3.00	0.53
Q5	Assess the course utility for your background and curricula.	3.00	1.41
Q6	Assess the course utility for you future professional career.	3.60	0.91
Q7	Assess the course material (slides, software tools, etc.).	4.00	1.19
Q8	Assess the utility of experiments of computer aided experiments.	3.62	1.50
Q9	Assess the utility of the experiments with physical systems.	4.00	0.92
Q10	Assess the utility of the visit to the field canal at the end of the course.	4.60	0.74
Q11	How adequate do find the peer-assessment as a help for student marking?	4.12	0.35
Q12	Assess your general satisfaction with the master course.	3.75	0.46

8. RESULTS AND DISCUSSIONS

After the experience of five years teaching and evaluating the course, we can conclude that it is reasonably satisfactory as indicators Q4, Q5, Q6 and Q12 suggest. We may point out that the course gives added value to the students in their curricula, which can be summarized s follows.

1. Students receive sufficient background on signals and systems and control theory and methods and are supplied with a large number of well commented references that they may find useful not only in canal control but also in other problems in their future professional life.
2. Students acquire the basic skills in the normal steps involved in designing a control project: modeling, control algorithms, simulations, instrumentation and testing.
3. Students are best candidates to join professional teams in the field of automation and modernization of irrigation canals

9. CONCLUSIONS

The experience acquired in the last four rounds of the master course lead us to conclude that students coming from different disciplines exhibit at the end a fairly uniform knowledge of the concepts and techniques taught in the course. They have also acquired the basic skills to join a professional team in the field of automation of irrigation canals. The trade-off between theory and practice and the availability of educational resources like the three tanks system and the laboratory canal are greatly appreciate by the students who are particularly motivated after having applied the theoretical concepts learnt during the course to a real case project and having seen all these concepts running in a real life canal.

It is worth to remark that this teaching experience has not yet reached a steady state and is still subject to improvements at each round. Some of the new improvements that we have in mind are to add some lectures to the master course devoted to the management of the irrigation canals facilities, also some lectures on the instrumentation of real canals systems and more practical experiments with physical systems (i.e. tank system).

Nevertheless we must take into account the inherent difficulties and time constraints of the master course prior to considering more ambitious objectives that the ones explained in this paper.

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