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Interdisciplinary Knowledge Integration Through an Applied Mobile Robotics Course*

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In this paper the use of an open mobile robot platform as an innovative educational tool to promote and integrate different interdisciplinary curriculum knowledge is presented. In addition the program and acquired experience of a summer course named 'Applied Mobile Robotics' is outlined. The main aim of the course is to integrate different subjects such as electronics, programming, architecture, perception systems, communications, control and trajectory planning by using the educational open mobile robot platform PRIM. The summer course is offered to Electrical and Computer Engineering students at around the time of their final academic year. As a practical approach, most of the educational activities of the course are developed in our university labs. The students are greatly motivated by working on such a robotic platform, which allows them to consolidate their previously acquired knowledge and to extend their complementary curricula. To achieve this, the resolution of real-world approaches is used to increase the students' understanding of fundamental engineering concepts within an interdisciplinary methodology context. Moreover, realistic platforms that incorporate engineering standards and realistic constraints increase student skills and experience through engineering practices.

Keywords: robotics; electrical and computer engineering; interdisciplinary knowledge; control and mechatronics; educational applied programs

INTRODUCTION

THE IDEA of incorporated and applied interdisciplinary concepts is an important objective in engineering education. Future work in Electrical and Computer Engineering education points towards gaining the ability to understand the technical details of a wide variety of disciplines [1]. In this sense, mobile robot platforms can be used as educational tools to promote and integrate different curriculum subjects. Therefore, the control system world and computer science share a mutual interest in robotics. However, despite the enormous progress in robotics over the last half century, the field is still in its infancy. For instance, robot behavior is much simpler than human behavior, in which an ability to move, to understand complex sensorial inputs, or to perform higher level reasoning, is limited.

The clue for renewing the path of progress is the integration of several fields of knowledge, such as computing, communications, and control sciences, in order to perform a higher level of reasoning and to use decision tools that have a strong basis in theory [2]. Moreover, experimental environments that have been developed have helped to breathe life into the theoretical concepts found in textbooks and have thereby greatly changed the educational experience of the students [3]. Students react positively to realism, since the models used for such experiments are in general accurately described by some relatively simple differential equations. Within this framework, the challenge of using mobile robots becomes evident.

Therefore, in the educational community, the Robotics Education Lab becomes a resource for supporting courses with an academic curriculum in a broad range of subjects. Some important institutions have developed various teaching activities by introducing the mobile robots as a necessary academic tool in a broad sense in order to extend the student's previously acquired knowledge [4–5]. In addition, other related activities are developed, such as mobile robot competitions or special summer programs like RoboCamp, which permit the students to design, program and construct the autonomous robots themselves. The education benefits are not only constrained to the university framework but also involve society in a broad sense. In this way, science museums develop experiences for teaching about autonomous robots. Therefore, the aim is to produce technology, curriculum and evaluation techniques for use with after-school, out-of-school and informal learning environments mediated by robotics. Interactive robotic museum exhibitions have been proposed for involving visitors in the role of rover robots [6].

In this context, many universities take advantage of mobile robot competitions in engineering

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education. This allows real world problem projects to be tackled, and fundamental concepts to be reinforced by increasing motivation and retention. Thus, for example, the FIRST (For Inspiration and Recognition of Science and Technology) mobile robot contest attracts young people to careers in engineering, technology and science. The robotics competition encourages students to apply the knowledge gained throughout their engineering degree, it also offers all students a chance to serve as members of interdisciplinary engineering teams, and introduces both freshmen and sophomores to engineering concepts. Moreover, the university curriculum is reinforced by the knowledge gained through applied experiences that embrace a wide spectrum of subjects [7]. The educational and research objectives can also be achieved through the use of configurable, small, low-cost items such as LEGO mobile robot kits [8].

This paper presents the educational aspects of the summer course '*Applied Mobile Robotics*' that has been developed. The course started in the summer of 2005 at the Polytechnic School of the University of Girona. It was proposed by a group of faculty members in the teaching areas of Control and Computer Engineering who shared a common background involving research into mobile robots. The main aim of the course is to integrate different subjects such as electronics, programming, architecture, perception sensors, communications, control, computer vision and trajectory planning by using the educational open mobile robot platform PRIM [9]. Academic skills as a whole are attained by the students; hence experiments are used to reinforce previously gained knowledge by integrating relationships between different academic subjects. The main difference with other mobile robot courses is the use of an open mobile platform as an interdisciplinary experimental tool. Moreover different multidisciplinary fundamentals, related to previously developed research, are introduced to the students within a practical framework.

The remaining part of the paper is organized as follows: the next section indicates which community of students is suitable for this teaching activity within the context of our university framework. The robotic platform used and the summer course program are presented within the multidisciplinary context. The program related to the educational content of the summer course is given in detail. Attention is paid particularly to describing the different experiments designed to fulfill the process of gaining knowledge. The last section briefly introduces the assessment criteria. The students' feedback is also considered as a useful way of improving future directions in research.

THE EDUCATIONAL FRAMEWORK

This section outlines the basic profile of the student community to which the course is addressed. The topics and schedule as well as the mobile robot platform used in the course are also described.

The course schedule and the student curricula

The summer course is addressed mainly to Electrical and Computer Engineering student profiles. Both undergraduate and graduate students can take this course to consolidate complementary curriculum studies. However, it is of special interest to the students around the time of their final academic year. It is recommended that a student wanting to pursue the course has previously acquired the basic skills in some fundamental areas such as electronics, programming, control and perception systems. Moreover, a self-guide lab practice manual that includes a theoretical introduction concerning the related issues is provided. In this way, it is guaranteed that those students who come from different educational backgrounds with different curricula, can follow the summer course without any difficulties. The number of students is limited to 12, which accords with the lab's actual capacity and the need for a mutual relationship and individual contact between the students and teachers. Furthermore, the presence of two lab teachers allows the students to acquire different levels of skills with adequate assistance, according to their educational background, through a continuous assessment process. The summer course ran for two weeks in July, with 4.5 hours of classes/practices every day. The students who pass the course are awarded 3 credits on their degree which corresponds to 45 hours of teaching activities. It consists of theoretical (T) and laboratory (L) sessions, related to the following topics:

- PSE: Power System Electronics
- DPED: Design & Programming of Electronic Devices
- MCS: Modeling and Control Systems
- TPC: Trajectory Planning and Control
- CVS: Computer Vision Systems.

The schedule for the course is shown in Table 1.

The mobile robot platform

The robot structure, shown in Fig. 1, is made from aluminum. It consists of different levels where the parts are placed. On the first level there are two differential driven wheels, controlled by two dc motors, and a third omni-directional wheel that gives a third contact point with the floor. On the second level there is an embedded PC computer, and on the third level specific hardware and the sonar sensors are placed. On the fourth level is the machine vision system. Table 2 summarizes the basic mechanical description of the robot PRIM.

The system can be powered by 12 V dc batteries or by an external power source through a 220 V ac, and a switch selects either mode of operation. The 12 V provided by the batteries or the external source

Table 1. Schedule for the teaching activities taking place over the summer course

First week					
Time	Monday	Tuesday	Wednesday	Thursday	Friday
8.30–1.00	Introduction PSE & DPED (T)	DPED (L)	DPED (L)	MCS (L)	MCS (L)
Coffee break					
11.30–3.30	DPED (L)	DPED (L)	MCS (T)	MCS (L)	MCS (L)
Second week					
Time	Monday	Tuesday	Wednesday	Thursday	Friday
8.30–11.00	MCS (T+L)	TPC (T)	TPC (L)	CVS (T)	CVS (L)
Coffee break					
11.30–13.30	MCS (L)	TPC (L)	TPC (L)	CVS (L)	Final demo

Table 2. Basic robot features

Features	
Width	580 mm
Length	400 mm
Height	1200 mm
Distance between wheels	560 mm
Diameter of the wheels	160 mm
Weight	20 kg
Maximal speed	0.48 m/s
Motor max. cont. torque	131 mN m
Gear reduction	86.1
Total robot force	141 N

of 220 V are transformed into the wide range of dc voltages needed by the system. Moreover, the use of a 220 V power supply allows an unlimited use of the platform during the teaching activities. The robot has the following sensorial system:

- two encoders connected to the rotation axis of each dc motor;
- an array of sonars composed by eight ultrasounds sensors;
- a machine vision system consisting of a monocular camera.

The meaningful hardware consists of the following electronic boards:

- the dc motor power drivers based on a MOSFET bridge that controls the energy supplied to the actuators;
- a set of PCB (printed circuits boards) based on PLD (programmable logic devices) act as an interface between the embedded PC system, the encoders, and the dc motors. The interface between the PLD boards and the PC is carried out by the parallel port;
- a μc processor board controls the sonar sensors. Communication between this board and the embedded PC is made through a serial port. This board is also in charge of a radio control module that enables the tele-operation of the robot;
- the embedded PC is the core of the basic system, and it is where the high level decisions are taken.

The PLD boards generate 23 kHz PWM (pulse width modulation) signals for each motor and the consequent timing protection during the command changes. This protection system provides a delay during power connection, and at the moment of change of the rotation motor direction. A hardware ramp is also implemented in order to facilitate a better transition between command changes. The value of the speed is encoded in a byte, it can be generated from 0 to 127 advancing or reversing speed commands that are sent to the PLD boards through the parallel port. The PLD boards also measure the pulses provided by the encoders, during an adjustable period of time, giving the PC the speed of each wheel every 25 ms. The absolute position of each encoder is also measured by two absolute counters used in order to measure the position and orientation of the robot by the odometer system. The shaft encoders provide 500 counts/rev since encoders are placed at the motor axes; it means that the encoders provide 43 000 counts for each turn of the wheel due to the gear reduction. Moreover, the μc has control of the sonar sensors, so for each sensor a distance measure is obtained. The ultrasound sensor range is between 3 cm and 5 m. The data provided by these boards are gathered through the serial port in the central computer based on a VIA C3 EGBA 733/800 MHz CPU running under LINUX Debian OS. The rate of communication with these boards is 9600 b/s. Figure 2 shows the electronic and sensorial system blocks.

The flexibility of the system allows different hardware configurations as a function of the desired application and consequently enables different programs to run on the μc or PLD boards. The open platform philosophy is reinforced by the use of the similar μc and PLD boards that are used as teaching tools at our school. Furthermore, reinforcement of the teaching activities can be achieved through the integration of different subjects. The system's flexibility is increased with the possibility of connecting it to other computer systems through a local LAN.

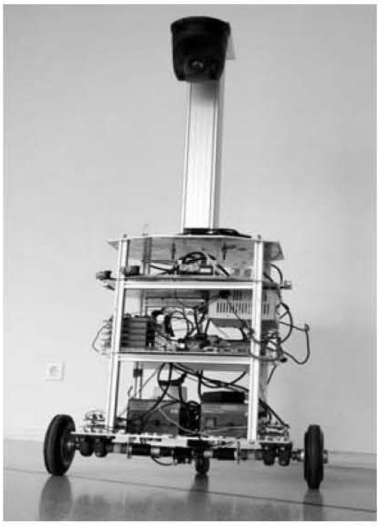


Fig. 1. Mobile robot educational platform PRIM.

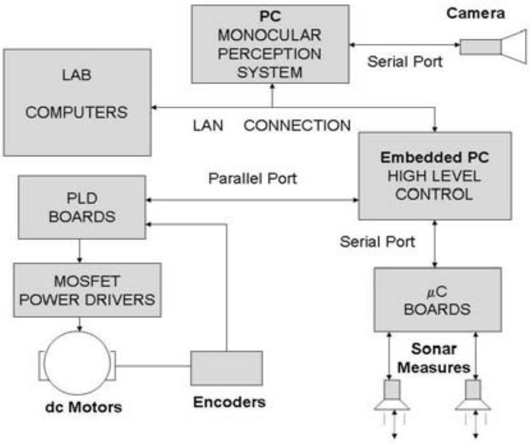


Fig. 2. Sensory and electronic system blocks.

Hence, in this research a network server has been implemented that allows the different lab groups to make their remote connection with the mobile robot during different practices. The use of a PC as a high level device is shown from two different points of view, consisting of PC high level programming and the TCP/IP protocol net knowledge that allow on-robot LINUX created functions to be run using the laboratory LAN. Thus, lab personal computers become a flexible and easy tool that allows communication with the on-robot hardware real-time devices through the use of WIFI connections.

THE INTERDISCIPLINARY EDUCATIONAL PROGRAM

In this section the course program that consists of the theoretical and laboratory sessions related to the following different topics is developed.

- *Power System Electronics*. This block briefly introduces the power system of the robot, where several basic concepts should be considered in order to design the dc motor power drivers.
- *Design and Programming of Electronic Devices*. This block presents the robot architecture and the PLD (programmable logic device) and μc use. Finally, by using high level language from the PC labs, students can learn how to use the functions created to carry out the remote inter-actuation with the robot sensors and actuators.
- *Modeling and Control Systems*. The basic control topics related to experimental modeling, classic PID controllers design and optimal observers are presented.
- *Trajectory Planning and Control*. This block presents the strategies of trajectory planning as well as trajectory tracking by using techniques of speed control or MPC (model predictive control).
- *Computer Vision System*. The last block introduces computer vision as an advanced perception system that can improve robot environment knowledge.

Power system electronics

The power system is an interesting topic that is briefly introduced from a basic point of view. An inquiry-based instructional strategy is used which allows the student to be led to conclusions about important aspects such as, for example, the influence of the amount of current or the necessary constraints when change in flow direction occurs. Once these basic concepts are completely understood, basic MOSFET features are introduced. Table 3 shows some features of the MOSFET used in our power bridge.

Moreover, basic dc power bridge designs are also introduced. Figure 3 shows the implemented dc power bridge. It consists of continuously switching from one diagonal to the other, so the level of the PWM signal decides which branch should be ON. Using this method means that the motor remains stopped when the duty cycle of the PWM signal reaches 50% of period time.

Design and programming of electronic devices

This subsection presents the DPED teaching module concerning the architecture of the mobile robot PRIM. The basic devices to be programmed are the PC, the microcontrollers and the PLD boards. The theory addressed can be covered by references such as [10, 11]. The objective is to consolidate theoretical aspects by developing introductory approaches. The set of practices are divided into PLD, microcontrollers and PC issues.

The proposed PLD practices are addressed to implementing a PWM signal and odometer system approaches. The laboratory material used consists of logical trainers with multiple inputs and outputs, such as switches, LEDs (light emission diodes) and displays, which allow the different performed practices to be tested. The logical trainer includes the ispLSI1032E programmable logic device [12].

Table 3. Electrical characteristics switching resistive loads

Electrical characteristics of the n-channel power MOS transistor IRF540						
Symbol	Parameter	Test conditions	Min.	Typ.	Max.	Unit
$t_{d(on)}$	Turn-on time	$V_{DD} = 50$ V		55	80	ns
t_r	Rise time	$I_D = 5$ A $R = 50\ \Omega$ $V_{GS} = 10$ V		110	160	ns
$t_{d(off)}$	Turn-off delay time		290	410	ns	
t_f	Fall TIME		125	180	ns	

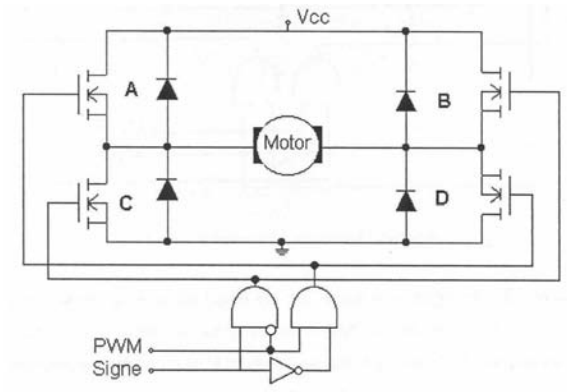


Fig. 3. Power bridge MOSFETs.

$$f(A_i = B_i) = \left(\overline{A_i \oplus B_i}\right)E_{i-1=}$$
$$f(A_i > B_i) = A_i\overline{B_i} + \left(\overline{A_i \oplus B_i}\right)E_{i-1>}$$
$$f(A_i < B_i) = \overline{A_i}B_i + \left(\overline{A_i \oplus B_i}\right)E_{i-1<}$$

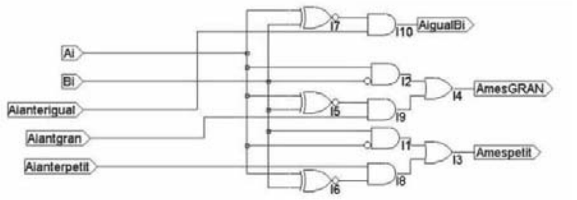


Fig. 4. Equations and electronic scheme of one bit recursive magnitude comparison.

The set of PLD practicals introduce the logic digital design by creating different basic blocks such as a one-bit magnitude recursive comparison and binary counters. Figure 4 shows the equations of one-bit recursive magnitude comparison and the corresponding electronic scheme. The tools provided to program the PLD consist of using schematic and ABEL (Advanced Boolean Equation Language) modules [13].

By using previously developed basic blocks, students can approach closer on-robot developments. So, for instance, Fig. 5 shows the 4 bit PWM implementation, where the inputs (d0, d1, d2, d3) denote the selected value for the output PWM signal.

Other PLD practices consist of designing absolute counters, to be used by the odometer system, or the speed system block. The speed system block is tackled by counting external pulses, produced by an external frequency generator, during the duty cycle of a periodic signal.

The first microcontroller practical objectives are to gain knowledge of the hardware and software environment of the 80C552 devices [14]. The microcontrollers have integrated special functions such as PWM, ADC (analog digital converter), or serial interface. Once again the knowledge of this is pursued by using educational trainers used in other teaching subjects. Knowledge of the environment is acquired by implementing short C code programs that will be used in an integrated final practical, in which the students will learn how to edit, compile, link and program the code as well as the serial communication, the analog/digital conversion, and PWM signal generation.

Finally the use of a PC as a high level device is presented from two different points of view, consisting of PC high level programming by using high level languages and the TCP/IP protocol net knowledge. The proposed practices first introduce high level language by creating short source codes that include protocol with created objects to perform TCP/IP communication with the robot. Students learn client–server protocol by programming the follow steps: server connection, receiving and transmitting commands, server disconnection and how to turn off the socket. Finally, reading the values of sonar sensors, sending speed commands, or reading the robot position, orientation and speed, are proposed as practice, in order to test the remote robot connection.

Modeling and control systems

The MCS block presents the basic control theory related to experimental modeling, classic PID controllers design and optimal observers. Students acquired a similar background concerning the basic classical control theory in continuous time [15–16]. However, this knowledge is not homogeneous and some variations arise from the difference in academic profiles. For example, Electrical Engineering students have acquired additional knowledge through some advanced material in control theory [17–18], while obviously Computer Engineering students show more experience in their programming skills. The above differences in educational background is solved by providing students with a self-guide lab practices manual that includes the theoretical fundamentals of the summer course. Students try to obtain the

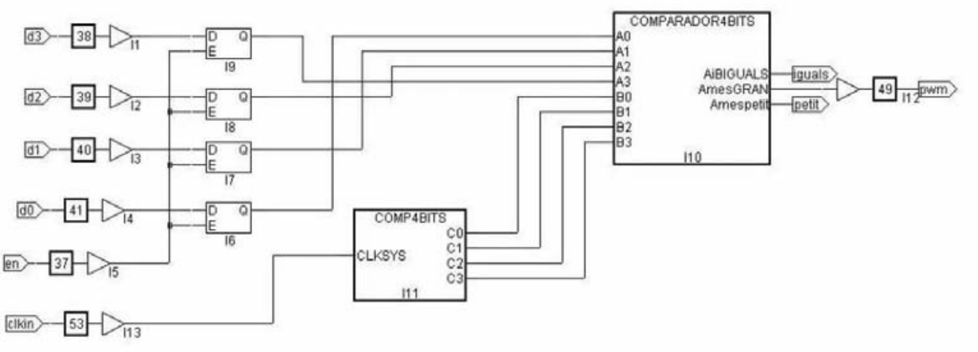
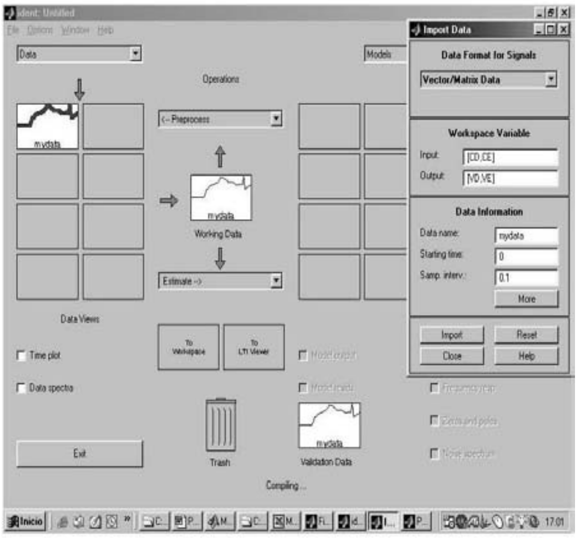


Fig. 5. The 4-bit PWM implementation.



Input: [CD,CE]
Output: [VD,VE]
Data name: mydata
Starting time: 0
Samp. interv.: 0.1

Fig. 6. MATLAB system identification toolbox.

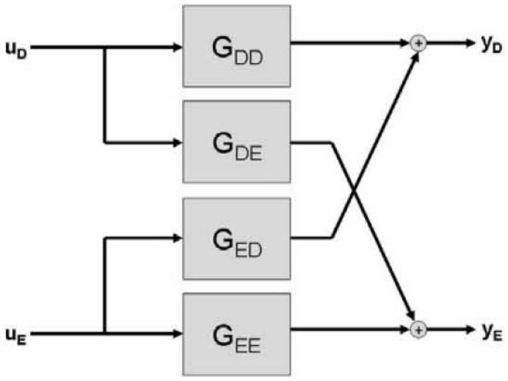


Fig. 7. Robot MIMO coupled system.

Table 4. The second order WMR model

Linear transfer function	High velocities	Medium velocities	Low velocities
G_{DD}	$\frac{0.20s^2 - 3.15s + 9.42}{s^2 + 6.55s + 9.88}$	$\frac{0.20s^2 + 3.01s + 8.44}{s^2 + 6.17s + 9.14}$	$\frac{0.16s^2 + 2.26s + 5.42}{s^2 + 5.21s + 6.57}$
G_{ED}	$\frac{-0.04s^2 - 0.60s - 0.32}{s^2 + 6.55s + 9.88}$	$\frac{-0.02s^2 - 0.31s - 0.03}{s^2 + 6.17s + 9.14}$	$\frac{-0.02s^2 - 0.20s + 0.41}{s^2 + 5.21s + 6.57}$
G_{DE}	$\frac{-0.01s^2 - 0.08s - 0.36}{s^2 + 6.55s + 9.88}$	$\frac{0.01s^2 + 0.13s + 0.20}{s^2 + 6.17s + 9.14}$	$\frac{-0.01s^2 - 0.08s - 0.17}{s^2 + 5.21s + 6.57}$
G_{EE}	$\frac{0.31s^2 + 4.47s + 8.97}{s^2 + 6.55s + 9.88}$	$\frac{0.29 + 4.11s + 8.40}{s^2 + 6.17s + 9.14}$	$\frac{0.25s^2 + 3.50s + 6.31}{s^2 + 5.21s + 6.57}$

model through experiment, making the controller design on the computer using MATLAB and then finally validating the results on the robot. The first lab control practical begins with experimental parametric model identification [19]. The model is then obtained by sending different PRBS (Pseudo Random Binary Signals) to the robot for the low, medium and high speeds. The students select an adequate speed model and load the experimental data onto the MATLAB environment. Each data group has five different arrays containing time, right motor consign, right velocity, left motor consign and left velocity, respectively. They then obtain the time response of the inputs and outputs. The system identification is carried out using the MATLAB toolbox *'ident'*, shown in Fig. 6, selecting a second-order ARX model and importing the necessary workspace data that should be identified.

Tendency suppression and data filtering are suggested. The complete MIMO (Multiple Input Multiple Output) discrete-time model obtained will be used by the students to validate the effectiveness of control. The robot MIMO system structure is shown in Fig. 7.

Table 4 shows the continuous transfer functions obtained for the three different speed linear models that were used.

The second practical involves finding a simplified robot model. The continuous-time model is introduced into the SIMULINK environment, as shown in Fig. 8.

Several studies concerning the importance of coupling terms are carried out by the students through the analysis of stationary gains, while the order reduction is achieved by searching for dominant poles. The students can learn from the results obtained that the MIMO model can be approximated by two SISO (Single Input Single Output) models. Thus, the coupled system analysis using analytical and experimental data is

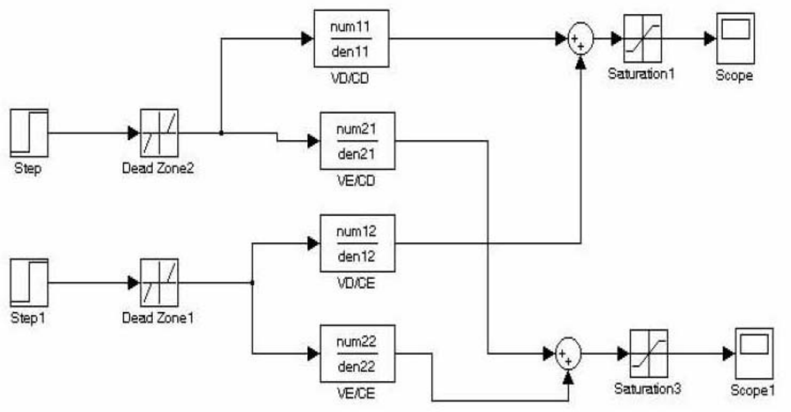


Fig. 8. MIMO robot model in the SIMULINK environment.

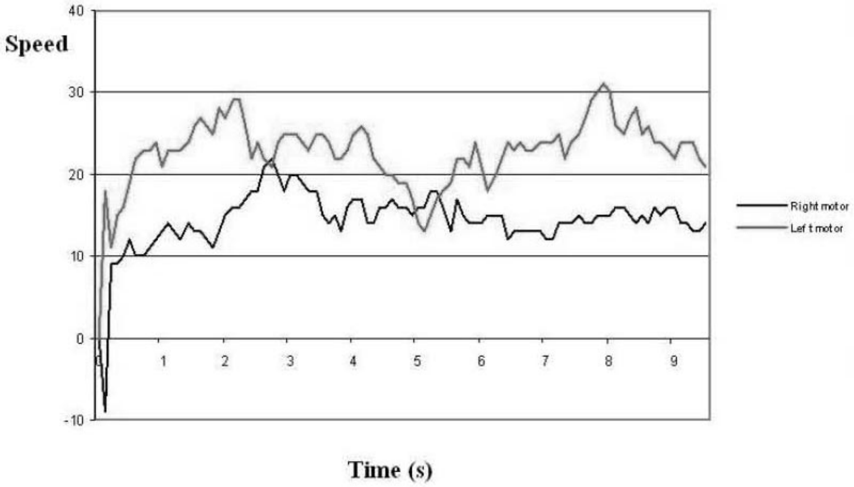


Fig. 9. Open loop output for low velocities.

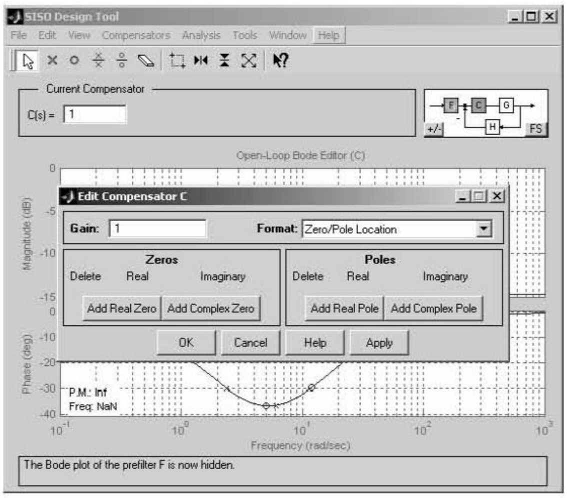
proposed. The frequency response and BODE analysis can prove the existence of a dominant pole, which can reduce the system order. Finally, the reduced SISO systems should be validated by considering the static gain and simulating reduced and complete robot models. The students can validate the results obtained by sending open loop speed commands to the robot, Figure 9 shows the results obtained when low speeds are demanded.

The third practical consists of obtaining a controller based on the simplified SISO models. The students will try to design the controller using pole placement techniques and the MATLAB design facilities. For instance, students can use the MATLAB '*sisotool*', as shown in Fig. 10, to design the controller by first importing the transfer functions corresponding to both robot wheels. They then depict the open loop frequency response without a compensator. Afterwards, students learn to add a PI controller to the system in order to achieve the desired response. The control performance is verified by using the complete MIMO model of the robot in the presence of several perturbations.

The students will analyze the uncontrolled and controlled system response. The advanced students are also encouraged to consider the case where the measurement of noise is involved. A Kalman filter is designed based on the knowledge of the model and it is implemented in the SIMULINK environment. The on-robot speed control is the subject of the last MCS practical. First the students transform the controller from continuous to discrete time. They then use the robot remote network server to send the PID controller parameters to the robot in order to test the speed control performance.

Trajectory-planning and control

TPC theory introduces the trajectory planning techniques through concepts such as C-space and robot wide-path [20]. The path planning approach consists of following a sequence of straight lines and considering the vertex of obstacles and the desired final configuration [21]. Thus, the trajectory tracking can be performed either through straight lines or turning actions [22]. The trajectory control tracking is attained by introducing discontinuous control laws and MPC (Model Predictive



C(s) = 1

Gain: 1

Format: Zero/Pole Location

P.M.: Inf
Freq: NaN

The Bode plot of the prefilter F is now hidden.

Fig. 10. SISO design tool window.

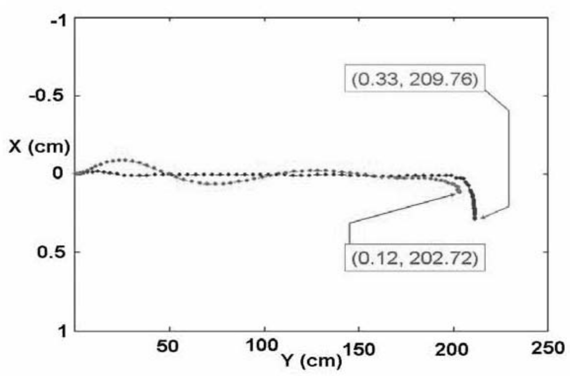


Fig. 11. Trajectory tracking simulation with two different prediction horizons.

Control) [23–24]. The discontinuous control approaches are presented to students as an in-lab robot demo, while the MPC strategies are simulated in the laboratory by using the methods and software developed by the teaching staff who are participating in the course [25]. In the MPC design, students will try to find the optimal input sequence taking the input constraints, prediction horizon, and cost function weights as design parameters.

The MPC simulation software provides students with a set of files and facilities to draw up the results, and consequently the students can represent the files containing the cost function values, for different available sets of inputs, corresponding to different moments of the simulation. The computation of optimal cost can be done by using the complete input search and gradient descent approaches. The prediction horizons between 0.5 s and 1 s were proposed and the computation time for each MPC step was set to less than 100 ms, running in the embedded PC of 700 MHz. The simulated results, for the trajectory tracking of a 2 m straight line, are shown in Fig. 11.

Two simulated results with two prediction horizons are shown. 1 s, n = 10 (in gray) and 0.5 s, n = 5 (in darker gray). The final TPC practical consists in implementing a high level program code for achieving the reactive obstacle avoidance behavior, in which the students should avoid obstacle collisions by sending the speed commands to both wheels of the robot by taking into consideration the sonar sensor measures.

Computer vision systems and final demos

The CVS teaching block briefly introduces to students some applied basic concepts such as color constancy and image energy filters. The theoretical aspects concerned can be covered by using related bibliographies [26–27]. Computer vision features are introduced from a wide area. Image formation based on basic paraxial optics is also shown. The image segmentation is depicted in such a way as to obtain the relevant areas on the image. Thus, segmentation is a first step for getting a binary image where the area of interest is obtained from the rest of the image. The image representation is considered in continuous and discrete spaces. The Fourier transform is studied as a meaningful tool for developing frequency filters. Therefore, the radiance energy measures are studied as a way for obtaining object boundaries.

The CVS practicals are addressed by using the facilities provided by the MIL Matrox libraries running under a high level source code [28]. The code is implemented by using previously acquired frames. First some basic functions, such as space memory management, image acquisition and visualization, are introduced. Once this is done, students learn how to process RGB color images by using three different buffers. The use of three different histograms allows efficient color segmentation. Other MIL facilities, for instance HSI color space conversion, are also proposed to students. Hence, the results should allow a featured color object to be segmented from the rest of the scene. Application aspects such as noise reduction are introduced by using existing functions that can filter small particles such as blob analysis. The last practical consists of object boundary detection using frequency filters. The design of filters is achieved by performing image convolutions through either the use of existing MIL filters or the creation of arbitrary filters. Students can analyze the effects of filters by comparing histogram results.

The course ends with some final demonstrations concerning the trajectory tracking and advanced perception features. The accuracy of trajectory tracking using the MPC technique is also discussed. The effectiveness of different applied machine vision systems tested during the robot's navigation are also presented. By using previously computed floor radiance energies, the one bit of depth is used for obstacle detection and obstacle avoidance navigation strategies with reactive robot behavior are tried and commented on [29]. The robot tracking abilities are also shown by using a color featured target. Therefore, the final demonstrations are used as a way of experimenting with

Fig. 12. Featured colored object tracking performed during the final demonstration.

previously introduced and tested concepts such as color segmentation and constancy. Figure 12 shows robot color tracking.

CONCLUSIONS

On the whole, student evaluation is done by considering the amount accomplished in the different proposed practicals. The level of difficulty, the correctness of the solutions and their independence and decisions are looked at within a continuous evaluation laboratory process. Moreover, exams consisting of short questions are also proposed when the practices related to the different counterparts are completed. The test assessments are focused either on interdisciplinary concepts or practical issues that complement some previously developed lab approaches. The results obtained show that nearly 94% of students pass the summer course (30 out of 32 students). The marks of these 30 students are shown in Table 5.

Table 5. Student evaluation

Assessment	Percentage (%)	Number of students
A	22	7
B	50	15
C	23	8

Mark A, in the evaluation, is given to students who have satisfactorily finished at least two advanced practicals within different blocks, with examination results of over 85% in the questions. C is given to students who have succeeded in the basic practicals, and gain at least 50% in the exam questions. Students between A and C obtain a mark of B in their assessments.

It should be mentioned that the lab practicals related to their theoretical counterparts have greatly increased the motivation of the students and have achieved the goal of the proposed objective in multidisciplinary knowledge. In this context, according to the students' feedback on the course, the average opinion of 30 students of the summer course is 4 out of 5, according to the survey questions that the university asks at the end of the course. They underline that the interesting and attractive educational and practical aspects are the relevant characteristics of the course. One of the suggestions is to increase the number of hours in order to perform the theoretical analysis, lab practices and algorithm implementation better. Furthermore, some students decide to improve the robot performance in some practical aspects for their compulsory FYP (Final Year Project). For example, currently the design of factorial experiments to enable MPC cost function tuning, indoor occupancy grid construction using sonar sensor information, and floor line tracking using computer vision techniques, are some of the FYPs in which some students are actually engaged. The teaching experience gained from the summer course has proved the usefulness of the mobile robot as an important experimental platform for education.

In the future, the teaching staff from different research areas will do their utmost to promote the development and consolidation of the course so that the quality of teaching can be further improved. The students' opinions are positive enough to encourage this work. Therefore, the path to achieving renewed progress in robotics is through the integration of several fields of knowledge, such as computing, communications, and control sciences, so as to obtain a higher level of reasoning and use decision tools with strong theoretical bases.

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REFERENCES

1. P. Antsaklis, T. Basar, R. Decarlo, N. H. McClamroch, M. Spong and S. Yurkovich, Report on NSF/CSS workshop on new directions in control engineering education, *IEEE Control Systems Magazine*, **19**(5), (1999), pp. 53–58.
2. R. M. Murray, K. J. Aström, S. P. Boyd, R. W. Brockett and G. Stein, Future directions in control in an information-rich world, *IEEE Control Systems Magazine*, **23**(2), (2003), pp. 20–33.

3. D. Hristu-Varsakelis and R. W. Brockett, Experimenting with hybrid control, *IEEE Control Systems Magazine*, **22**(1), (2002), pp. 82–95.
4. The Carnegie Mellon University. The Robotics Institute. Robotics Education in the School of Computer Science. On http.//www.ri.cmu.edu/roboed.html.
5. Z. Qu and X. H. Wu, A new curriculum on planning and cooperative control of autonomous mobile robots, *International Journal of Engineering Education*, **22**(4), (2006), pp. 804–814.
6. I. Nourbakhsh, E. Hamner, E. Ayoob, E. Porter, B. Dunlavey, D. Bernstein, K. Crowley, M. Lotter, S. Shelly, T. Hsiu and D. Clancy, The personal exploration rover. educational assessment of a robotic exhibit for informal learning venues, *International Journal of Engineering Education*, **22**(4), (2006), pp. 777–791.
7. V. Wilczynski and W. Flowers, FIRST Robotics Competition. University curriculum applications of mobile robots, *International Journal of Engineering Education*, **22**(4), (2006), pp. 792–803.
8. A. Valera, M. Weiss, M. Valles and L. J. Diez, Control of mobile robots using mobile technologies, *International Journal of Engineering Education*, **23**(3), (2007), pp. 491–498.
9. L. Pacheco, N. Luo, I. Ferrer and X. Cufí, Control education within a multidisciplinary summer course on applied mobile robotics, *Proc. 17th IFAC World Congress,* Seoul, Korea, (2008), pp. 11660–11665.
10. R. H. Barnett, *The 8051 Family of Microcontrollers*, Prentice Hall, New Jersey, (1994).
11. J. F. Wakerly, *Digital Design Principles and Practices*, Prentice Hall, New Jersey, (1992).
12. Lattice Semiconductor. Data sheet. ispLSI and pLSI 1032E. On http.//doc.chipfind.ru/lattice/isplsi1032e70lj%5B1%5D.htm.
13. Lattice Semiconductor Corporation, *Schematic and ABEL-HDL Design Tutorial*, Hillsboro, OR, (October 2005).
14. Philips Semiconductors Integrated Circuits, *80C51 Family Derivatives. 8XC552/562 Overview*, (August 1996).
15. K. Ogata, *Modern Control Engineering*, Prentice Hall, New Jersey, (1993).
16. B. C. Kuo, *Automatic Control Systems,* Prentice Hall, New Jersey, (1996).
17. K. Ogata, *Discrete-Time Control Systems,* Prentice-Hall, New Jersey, (1996).
18. K. J. Aström and B. Wittenmark, *Computed Controlled Systems. Theory and Design*, Prentice Hall, New Jersey, (1988).
19. L. Ljung, *System Identification. Theory for the User*, Prentice Hall, New Jersey, (1989).
20. R. J. Schilling, *Fundamentals of Robotics*, Prentice Hall, New Jersey, (1990).
21. L. Pacheco and N. Luo, Trajectory planning with control horizon based on narrow local occupancy grid perception, in K. Kozlowski (ed.) *Robot Motion and Control,* Springer-Verlag, London, (2007), pp. 99–106.
22. J. A. Reeds and L. A., Shepp, Optimal path for a car that goes forwards and backwards, *Pacific Journal of Mathematics*, **145**(2), (1990), pp. 367–393.
23. J. M. Maciejowski, *Predictive Control with Constraints,* Pearson Educational, Essex, (2002).
24. E. F. Camacho and C. Bordons, *Model Predictive Control,* Springer-Verlag, London, (2002).
25. L. Pacheco and N. Luo, Mobile robot local predictive control using a visual perception horizon, *Int. Journal of Factory Autom., Robotics and Soft Comp.*, (2), pp. 73–81, (2007).
26. B. K. P. Horn, *Robot Vision,* McGraw-Hill, MIT Press Edition, Massachusetts, (1998).
27. R. C. Gonzalez and R. E. Woods, *Digital Image Processing*, Prentice Hall, New Jersey, (2002).
28. Matrox Imaging Library, Command Reference, Manual No. 10368-MS-0311, (April 1996).
29. L. Pacheco, X. Cufí and J. Cobos, Constrained monocular obstacle perception with just one frame, in J. Martí *et al.* (eds) *Patter Recognition and Image Analysis,* 1, Springer-Verlag, Heidelberg, (2007), pp. 611–619.

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