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Introduction to microbots: a hands-on, contest-driven, interdisciplinary course on mobile robot design in a developing country

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Abstract Engineering outreach in a developing country like Chile is a difficult challenge. Different reasons explain a sustained decrease in the number of students enrolling in engineering education in the past years, and a special effort is necessary to reverse this trend. Focusing on teamwork, the non-conventional undergraduate-level course described in this paper represents an opportunity for motivated students in a developing country to focus their abilities in engineering design. In order to make the course more attractive for students, the final project consisted of designing an autonomous robot to compete in a contest. This article reviews experiences associated with this course and the students' design teams over a five-year period. The course methodology is explained, and the results are summarised.

Keywords developing engineering education; microcontrollers; mobile robots; multidisciplinary group project; robotics contest

Design is the essence of engineering,[1] and the ability to design a system is among the most important skills that students of an engineering programme must learn and develop.[2] 'Learning by doing'[3] is a powerful approach in engineering education, particularly effective in the field of mobile robots.[4–7] The positive effects of robotics contests on education[8–11] and research[12] have been extensively reported.

Focusing on teamwork, the course described in this paper attempts to achieve the goals of attracting talented students to technical areas, and teaching engineering design at Pontificia Universidad Católica de Chile (PUC-Chile), through the topic of mobile robots.

Chile as a developing country in the transition to a developed country has rapidly changing needs. Engineering education plays a key role in the transition, by preparing future engineers in the abilities and tools required throughout and after the process. The main challenges to be faced in Chile in the context of this paper are a limited budget, the inadequate infrastructure, and the relatively difficult access to a variety of sensors, prototyping tools and commercial robot frames. Both instructors and students must develop ingenious solutions in order to circumvent these limitations.

At the College of Engineering, PUC-Chile[13] the Career of Engineering is a 6-year (12-semester) undergraduate programme split into two parts. The first part is common for engineering students in all fields, spans three years and addresses the fundamentals of mathematics, science and engineering. During the second half, the programme focuses on a particular field, from its fundamentals (undergraduate-level courses) to advanced topics (graduate-level courses). Nearly 500 students enrol in the programme every year, which offers the following majors: Civil Engineering, Industrial Engineering, Mechanical Engineering, Electrical Engineering, Computational Engineering and Biotechnology Engineering. The most popular area is Industrial Engineering, chosen by about 75% of all engineering students. It is an attractive area, because although it focuses on management, it also includes some technical background, allowing the students to choose a technical area and a balance between management and technical abilities.

The course described in this paper was designed as an undergraduate level course, intended to attract students to technical areas, through robotics. As a non-conventional course, it represented an opportunity for motivated students to focus their abilities in an interesting project, under the guidance of the instructors. In order to make the course more appealing for students, the course final project was the design of an autonomous robot to compete in a contest. The first time the course was offered, the contest was the First IEEE Latin-American Robotics Contest for Students.[14]

This article reviews experiences associated with this course and the students' design teams over a five-year period. The practical details of the course are described in the next section. The third section summarises the results obtained by the course students in various robotics contests, and the fourth section shows an analysis of the contribution of this course to education in engineering, based on student surveys.

Course implementation

In this section, the main aspects of the course methodology, classes, assignments, material and laboratory work are presented. The grading system is also explained.

Administrative aspects

The course was offered for the first time during the spring semester of 2002 as IEE2900 'Introduction to Microbots', open for all engineering students, and nominally requiring a dedication of about 10 hours per week. There were more applicants than enrolment vacancies, thus a selection was necessary. In order to apply for the course, the 41 interested students had to fill out a short survey designed to know their interests, time availability, team preferences and previous knowledge in robotics – which was not really necessary to enrol in the course. Based on the survey results, 24 students of Electrical (14), Computer (8) and Mechanical Engineering (2) were accepted, filling all the vacancies offered. The students were grouped into 6 interdisciplinary teams of 4 students each.

As specified in the course programme, classes were scheduled for every Thursday morning, covering three lecture hours (8:30–9:50, 10:00–11:20 and 11:30–12:50). During the first half of the semester, one or two mandatory lecture hours per meeting were offered, covering some theoretical aspects of the course; the remaining portion of the morning was used as a laboratory session for assignment work. During the second half of the term, the three hours per week were fully allocated to laboratory work.

A set of basic mechanical and electronics components was provided to each team, to be returned to the course staff at the end of the semester. If more components were necessary, the students were required to provide them. All the information about the course and the communication between meetings was done through the course web page.

Teaching staff

The permanent staff consisted of two instructors and two teaching assistants (TA), in addition to guest lecturers for each one of the course topics. One of the TAs was assigned to administer the web page, and the other one to help the students during their laboratory work.

Course objectives

The course objectives, as stated in the course programme, are:

> *'To provide the students with the basic knowledge on Engineering design, electronics, mechanics and programming, necessary to design, build and program special purpose mobile robots; to help the student in developing teamwork abilities and creativity, encouraging the application of their intelligence to solve engineering problems."*

At the beginning of the semester, it was emphasised that all the teams were not simply random groups of students; they had the responsibility of organising as small companies, with a name, a web page and specific tasks for each member according to their specialism and interests. The primary objective of each team was to develop a small robot project during the semester, using electronics, computing and mechanical tools. The robot should qualify to compete in the First IEEE Latin-American Robotics Contest for Students.[14] Interdisciplinary teamwork was encouraged, but not required.

Grading aspects

The student grade was awarded as a weighted average of the components presented in Table 1.

TABLE 1 *Evaluation components*

Component	Weight	Scope
Assignments	10%	Team grade
Project log	5%	Team grade
Course project	30%	Team grade
Individual grade	40%	Individual grade
Final exam	15%	Individual grade

Assignments were programmed on a weekly basis. There were two kinds of assignments: written assignments and hands-on assignments. Written assignments were brief papers, to be presented in a standardised technical report format, oriented to test and improve the teams' written expression abilities. These assignments were given mostly during the first half of the semester, addressing particular aspects of robotics such as sensors, microcontrollers, actuators, etc., complementing the theoretical classes' topics. Some generic design and planning assignments were also included.

Hands-on assignments, mostly given during the second half of the semester, were practical design tasks involving different aspects of robot design: mechanics, electronics, sensors, programming, etc. These assignments were carefully prepared in order to address particular issues that the teams should face when building their robots for the contest. This was a very effective means of controlling the timing of their projects. After every hands-on assignment was done, students felt one step ahead in their pursuit of the best robot design. Some hands-on assignments also included an oral presentation, intended to test the teams' oral expression abilities.

The project log, included in each team web page, was another way to control the ongoing work of the students, and helped the teams to organise their tasks. Every time they tried a new design, achieved a new goal or had a failure, they had to log it on their web page. A single line of text was usually sufficient.

The course project, as the main deliverable of the course, constitutes a particular evaluation component. Features such as electronic design, mechanical design, algorithms, robustness, overall construction and performance were considered in this grade. The first evaluation of the robots was to take place during the CITEI 2002 (Congreso de Innovación y Tecnología de la Escuela de Ingeniería, Innovation and Technology Conference of the College of Engineering). This is a two-day technology fair at PUC-Chile that includes talks, contests, and departmental and industry presentations. During this event, a robot contest would serve as the means of grading. Students were aware that the course project grade considered the robot design and build process, and the robot performance during the contest. If their robot worked during the whole semester, except during the contest, the course project grade would be penalised. This was an incentive to work on the robustness of their system, preventing any failures and being prepared to solve any last-minute problem. The students were encouraged to assess each design, theirs and the other teams'. This makes the educational process highly cooperative, even in a competitive environment such as a contest.

The individual grade is *crucial* in this course, because it allows the instructors to determine the individual work of each student within a team. This grade considers attendance, interest, quality of the work performed and contribution to the team. A more radical option consists of distributing the teams' final grade among the team members according to their individual grade.

The final exam aims to evaluate the aspects that each student learned in the course. The evaluation is difficult due to the task differentiation among members of a team. One option considered is to take oral examinations; another option, which was actually implemented in this course, is to replace the exam grade for the robot performance in the IEEE contest. In this case, however, the grade does not directly address the objective it was intended for.

Finally, in a recent version of the course, the authors added a *self-grade* in order to make a distinction in grade, if applicable, between the team members. This is a grade given by the instructor to the whole team, according to the overall performance; the team has the responsibility of dividing that grade among its members according to the work of each. This is a very sensitive and important point for some teams, where work has not been split evenly.

Components for hands-on experiences

While planning the course, it was necessary to define the components to be provided to the teams. Two choices were considered: Lego Mindstorms and discrete components. The first option has the advantage of being a versatile, proven, excellent platform for rapid mobile robot prototyping;[6,15] however, it is relatively expensive for large projects, and may be somewhat disadvantageous for some particular designs. On the other hand, discrete components are similar to those that engineers use in the industry and allow more flexibility; however, rapid prototyping is more difficult. If enough funds were available, both options together would have been chosen: Lego Mindstorms at the beginning, to build prototypes and prove concepts and ideas, and discrete components at the end, to build the final robot; however, as funds were limited, only the option of discrete components was implemented. The main components provided to the teams are:

- *Basic tools*: A basic set of general purpose tools (two screwdrivers and two pliers) was provided to each team. The cost of the set was around US$4.
- *3-mm Bolts and lock nuts*: The set consisted of 20 of each, intended to be used on permanent links and 1-degree-of-freedom links. The total cost was around US$1.5 per set.
- *Mechanic kit*: This was a very useful tool for rapid mechanic prototyping. The kit consists of a few dozen of pieces including nuts, bolts, wheels, platforms, arms, etc. The cost was US$12. Although this is a convenient way to test mechanisms at the beginning of the lab work, it is not recommended for final prototypes due to its high weight, low mechanical resistance and difficulty to customise in detail.
- *Electronic components*: A basic set of electronics components, with a cost around US$7, was given to each team. The set contained wires, connectors, IR emitters and detectors, transistors, LEDs and a small 3 V d.c. motor.
- *OOPIC Microcontroller board*: Developed by Savage Innovations, the OOPIC[16] is an excellent solution for rapid integration to control small robots. Although it is slower and less versatile than most microcontrollers, it has the benefit of being very easy to adapt to most hardware configurations and programme in a high-level language. It has several features such as PWM output, servo driving, analog inputs, etc. Its learning curve is surprisingly fast, even for students without previous experience on microcontrollers. Certainly, it is an excellent choice to reduce

programmeming time in courses like this. Its cost in the USA was $40 when the course was offered for the first time. Arduino-based platforms are currently attractive, affordable options.

- *Sharp GP2D12 IR Sensor:*[17] This IR ranger, capable of detecting objects up to 0.8 m, represents a low-cost solution for detecting objects and obstacles. Its cost in the USA was around $15, and is simple to integrate with the OOPIC.
- *Polaroid 6500 Sonar*: This ultrasonic sensor complements the ranging capability of the IR sensor, detecting objects up to 10 m. Its cost was around US$45.
- *Dinsmore 1490 compass:*[18] This electronic, low-resolution compass, with a cost around US$10, was crucial in the success in the first IEEE Latin-American robotics contest for students.
- *GWS Standard R/C Servo*: Three $10 servos were provided to each team. These were the main actuators of their robots.
- *Rechargeable batteries and charger*: Four AA-size Ni-MH batteries and a fast charger (totaling US$14) were provided to each team. Although they were insufficient for the robots' needs, they helped in their first steps.

Not all the components were provided at the beginning of the semester; most were provided when required, according to the weekly assignment. The total cost of the components provided to each team was around US$190, totalling less than US$1,200 for the whole course. The students, however, had to provide the final mechanical structure, manufacturing costs, additional electronics, sensors and actuators.

Lectures and assignments

A group of five lectures comprises the basic set of classes, but extra lectures in different topics were also included every year. Each lecture was linked to one or more assignments. Below, the lectures and corresponding assignments are briefly described.

- *Engineering design*: Concepts, the design process, modelling, planning, Gantt chart. Assignments: Planning, and web page design.
- *Mechanical design*: Concepts, kinematics, transmission systems, rapid prototyping techniques. Assignment: hands-on, mechanical design and testing of a mobile platform.
- *Electronic design*: Concepts, operational amplifiers, transistors, practical aspects of circuit design. Assignment: hands-on electronic design of a sensor/actuator system.
- *Radiocontrol Servos*: Diagram, operation and modifications. Assignment: hands-on electronic design, involving driving a servo.
- *OOPIC Programmeming*: A practical lecture with live examples of microcontroller code, compilation and execution. Assignments: programmeming the mobile robot to perform simple tasks.

Extra lectures were intended to cover specific topics of the project, to introduce the very diverse group of students to related areas, and familiarise them with current research in robotics. A brief explanation of the main extra lectures is presented below.

- *Microcontrollers*: Digital electronics, microcontroller architecture and programmeming.
- Perception: Perception concepts and review of the basic sensors in robotics.
- Robot Control: Control Theory, PID controller and basic tools to implement simple control algorithms.
- *Artificial intelligence*: Basics, focused on practical aspects for mobile robot design.
- Mobile Robotics: Advanced topics in mobile robotics.
- Vision: 3D Vision and a hands-on session on setting up and programmeming the CMUCam (available since the second year) for the project.

The second half of the semester was oriented to hands-on assignments only: preliminary contest (2 weeks), outdoors contest (CITEI) and final contest (IEEE).

The course philosophy

Some elements about the course philosophy that made a success of this educational experience are explained below.

Teamwork

Teaching cooperative learning is a difficult task. Learning how to deal with peers is an important skill that it is not normally taught in college. Under a conventional grading system, the instructor tries to assess how well each student finds a solution to the problem presented. But in industry, the individuals need different skills to succeed, more related to finding real world solutions working along with other people. One wise decision on this matter was to divide the team into three to four people. With one or two people, the objective of dealing with peers is lost, and with more than four, it is very difficult to manage. With three or four per team, the student needs to define some degree of specialization within the team. The course does not require all team members to do all tasks.

Real solutions

The first day of classes, right after the introductory lecture, all the students walk to the laboratory for the first time to complete the first laboratory assignment: to build a hand-launched car using a metal construction kit (at least two axles). The team whose car reaches the longest distance in the hallway after three tries wins the improvised contest. The students use to take that as a simple game. After defining the winner, the students discuss and comment on the activity, trying to find the key elements in their design process.

Simple solutions

The first time that students try to solve a complex design problem they make some common mistakes. They fail to identify the real problems they face, to plan ahead, to design for easy maintenance and upgrade, etc. Using simple concepts, such as ‘divide and conquer’, the students can obtain amazing improvements in their own plan. Most times the solution is found after two or three iterations over the original concept, and was always simpler than their first idea. Using these simple concepts, course students won almost all the national and international robotics contest where they participated in a 5-year period.

Laboratory facilities

The laboratory consists of a 1000 square feet room with 6 work benches. Each team has access to the following equipment:

- Function generator
- D.c. power supply
- Digital multimeter
- Oscilloscope
- Old PC, sufficient for programming the OOPIC and displaying datasheets.

The course and robotics contests

The final project of the course was to compete in an external contest. To satisfy this requirement, two options were considered: the IEEE Latin American robotics contests, provided that the first edition was in done Chile; or a national contest organised by the course former students.

IEEE latin american robotics contest for students

Since 2002, the IEEE-RAS Latin American Robotics Council[19] has organised a robotics contest for students. The contest consists of two categories: *Lego* (High School level) and *Advanced* (College level). Table 2 shows the results obtained by the course students in the advanced category, and Fig. 1 shows *Bender*, the robot that won the second place in the first IEEE Latin American Robotics Contest for Students.

RoboPUC and cowbots duel

In 2003, after the successful participation in the First IEEE Latin American Robotics Contest,[14] some students of the course created RoboPUC,[24] the PUC-Chile robotics student chapter. RoboPUC designed and organised the *Cowbots Duel*, a national robotics contest in Chile. Unlike the IEEE Latin American Robotics contests, the

TABLE 2 *Results achieved by course students in the IEEE Latin American robotics contest for students*

Version	Venue/Date	Course students' result
1st (Ref.14)	Chile/2002	1st, 2nd & 3rd place
2nd (Ref. 20)	Brazil/2003	1st place
3rd (Ref. 21)	Mexico/2004	1st place (former students of the course)
4th (Ref. 22)	Brazil/2005	1st & 3rd place
5th (Ref. 23)	Chile/2006	2nd place

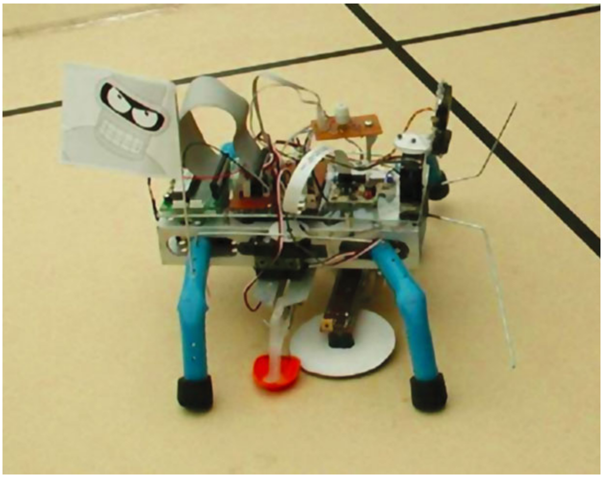

Fig. 1 *Bender, second place at the first Latin America Robotics Contest for Students. Image credit: Michael Van Sint Jan.*

Cowbots duel keeps the same rules year after year.[25] More than 50 teams from all over the country competed in the four versions of the contest between 2003 and 2006.

Course evaluation

At the end of each semester, the students were asked to answer a brief survey about the course, its methodology, its results and its impact on their careers. In this section, the results of that survey are presented and analysed.

The survey, taken by the classes between 2002 and 2005, consisted of 17 questions. In that period, 54 students answered the survey out of 72 students who enrolled on the course. Fig. 2 shows the distribution of majors among the students enrolled on the course during the 5-year period.

The survey confirmed the motivation of all students that enrolled on the course. On a scale of 1 to 10, the average motivation was 9.0. This is an important factor to succeed in this course, and also the main requirement to enrol.

The students assessed their own skills covered by the course objectives, on a scale of 1 to 10, before and after taking the course. Table 3 shows the averaged results, with improvement in all skills. On average, the greatest improvements are in those skills that are not normally covered in their study plans.

As shown in Table 4, some lectures were considered dispensable by some students. This was because those lectures were not necessarily related to the final project. As the final project was changed every year to meet the IEEE contest rules, it is difficult to have a set of lectures that fits all possible contests. Some of the lectures were designed to cover different topics related to robotics, even though they were not directly related to the final contest.

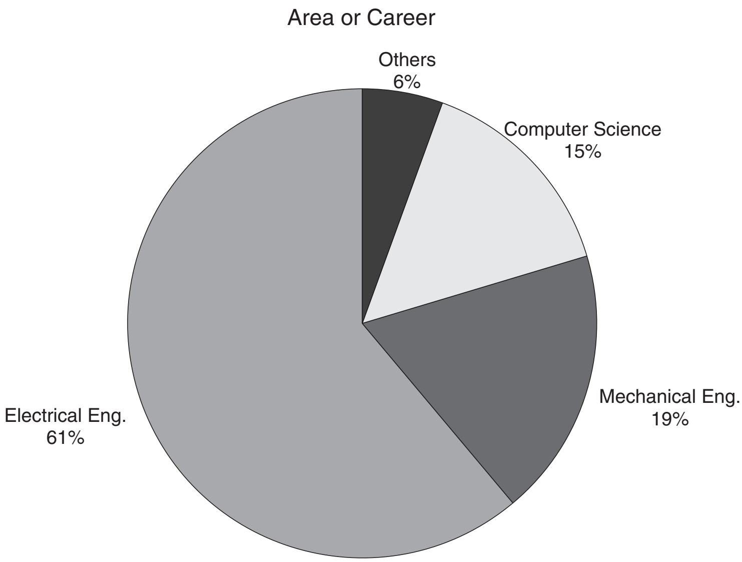

Fig. 2 *Total distribution of majors among the students enrolled in the course.*

TABLE 3 *Students' opinion on skills improvement due to the course*

Skill	Before	After the course
Management of multidisciplinary projects	4	7
Implementation of the real problems in engineering	5	7
Electronic design	5	7
Mechanical design	4	6
Programmeming applied to electromechanical systems	3	6

TABLE 4 *Students' opinion on the different course lectures*

Lecture	Lecture score (1–10)	Would you remove this lecture?	Comment
Design in Engineering	5.8	15%	Important, but students did not see the direct application.
Mechanical Design	5.8	13%	Should include more applications
Electronic Design	6.3	0%	Very important
OOPic Programmeming	6.4	7%	Necessary
Artificial Intelligence	3.6	7%	Dispensable
Computer Architecture	4.0	13%	Dispensable
Mobile Robotics	5.0	7%	Too research-oriented
Perception	6.3	2%	Good
Robots Control	6.2	2%	Good
Microcontrollers	5.5	9%	Dispensable
3D Vision	5.0	4%	Dispensable
CMU Cam	6.8	2%	Good, but too late in the semester

TABLE 5 *Students' opinion about the course*

Topic	Average (1–10)	Standard deviation
Assignment contribution to the course objectives	7	2.0
Course website contribution	5	2.1
Importance of the course to learning engineering design	8	1.5
Overall course score	8.7	1.0

In the survey students were asked about which new topics should be included in the programme. Some of the answers suggested increasing the number of practical lectures for solving specific problems towards the final project.

One of the main concerns in the design of this course is to balance the number of theoretical lectures and applied laboratory experiments. In this regard, 46% of the surveyed students considered that there should be more experiments, whereas only 17% of them thought that more theoretical lectures were necessary. This trend was exacerbated in the years when more theoretical lectures were included.

Finally, different topics regarding the course were surveyed. The results are shown in Table 5.

One of the most common comments among students was about the unusually high workload that this course requires, considerably higher than the suggested 10 hours per week. The assignments required a significant amount of student time, but it was an effective instrument to continuously control the progress of each team. Also, the assignments allowed the instructors to cover some topics not included in some of the final projects (e.g., odometry, control, etc.).

The overall course evaluation was outstanding. Despite the amount of work, all students were satisfied with the results. They consider the class as an effective training to solve engineering problems.

The success of the course in terms of enrolment, evaluations, contest results, news coverage[26] and student motivation was so intense and impressive, that shortly after the course was created, the Department of Electrical Engineering at PUC-Chile created its first position for a full-time faculty member in the area of robotics.

Conclusion

Using robotics and contests can be very effective as an outreach tool, especially towards engineering design, and to teach the students more about teamwork and some key engineering subjects.

Designing a course with project-related lectures and assignments has been an interesting challenge with effective results. The students learned how to *face* a new problem, rather than how to *solve* textbook-like problems. The formula behind this course proved to be successful in many aspects: students' opinion, contest results, and diffusion.

The implementation of this course in a developing country made the work described in this paper more challenging: research is not an activity embedded in

Chilean industry; technology is usually imported and adopted from abroad; and the budget was incredibly low. Under this prism, the course pioneered robotic contests in Chile and helped to pave the way for future generations of engineering students interested in technology.

Acknowledgements

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