A Multidisciplinary Industrial Robot Approach for Teaching Mechatronics-Related Courses

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***Abstract*—This paper presents a robot prototype for an undergraduate laboratory program designed to fulfill the criteria laid out by ABET. The main objective of the program is for students to learn some basic concepts of embedded systems and robotics, and apply them in practice. For that purpose, various practical laboratory exercises were prepared to teach different aspects of communications, control, mechatronics, and microcontrollers. The practicals are organized such that the students can systematically solve real-world problems. The most important feature of the presented program is that, it incorporates interdisciplinary knowledge, and inculcates technical and professional skills required in pursuing a successful career. Furthermore, students and instructors can modify the software and hardware units of the robot prototype as necessary, to explore more ideas and to apply the robot in other mechatronics-related courses. A digital electronics course taught at the Automation Department at Universidad Autónoma de Querétaro, Querétaro, Mexico, is presented as a case study in which the evaluation process was based on ABET criteria and the corresponding student outcomes. A student survey elicited students' observations of, and interest in, the learning process. The positive student feedback and student academic outcomes indicate that the inclusion of prototype had a significant impact on student academic outcomes.**

***Index Terms*—ABET accreditation, design practice, engineering technology, higher education, interdisciplinary, industrial robotics, project-based learning.**

I. Introduction

THE CONTINUOUS growth and use of Information and Communication Technologies (ICT) means that these technologies have become an essential element in the education system for developing the skills required to solve real-world problems. The various challenges of the digital world mean that careful development of teaching tools is required to obtain useful, interactive, relevant, up to date software and hardware that offers the creative experiences typical of increasingly collaborative applications [1], [2].

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The main purpose of a technical education is to provide students with the appropriate skills for their professional career. Learning becomes more effective when integrated with real-world experience [1], so hands-on learning is highly recommended in technical education [2]. Many kinds of educational prototypes and laboratory equipment have been developed to facilitate the teaching and learning of technical knowledge [3]–[5]. Some of these prototype developments are industry- or job- oriented, others are based on teaching and learning experiences. New technologies now make it possible to take completely new approaches in physical and virtual classrooms. Tracking and exploring new teaching technologies for teaching laboratory practicals can yield an optimal and efficient learning experience.

In teaching mechatronics, typical prototypes used to demonstrate practical knowledge and technical skills range from basic controllers to plant automation systems. Examples of innovative techniques education include teaching the control of multiple motors with one drive [5]–[8], digital systems for easy interaction with industrial actuators, and embedded systems [3], [9]–[11]. Apart from providing a topical education, the prototype must provide comprehensive learning that is rich and interesting. From this point of view, a robot prototype is a potential candidate for teaching mechatronics, being popular and of interest to students [4], [12]–[14].

Generally, undergraduate programs follow a traditional disciplinary approach, where one prototype is used to teach a particular discipline. This results in students often failing to connect, generalize and transfer knowledge to a variety of problem-solving situations in the real world. A multidisciplinary approach, however, incorporates and connects key concepts and skills from many disciplines in one activity that has students acquire and apply knowledge, skills, and strategies in multiple subject areas, and thus construct a more integrated Web of knowledge. Furthermore, the integration of multidisciplinary knowledge in the student curriculum is essential to achieving the desired graduate profile [15]. Multidisciplinary teaching should therefore be a part of technical education, with the courses and projects making explicit connections both within the technical world and between engineering and society [16]–[18].

Certain criteria are used to accredit education institutions. To that end, institutional curricula are continuously evaluated, revised and actualized to ensure that industrial needs are supported by interdisciplinary education [19], [20]. To improve technical education, ABET requires that engineering

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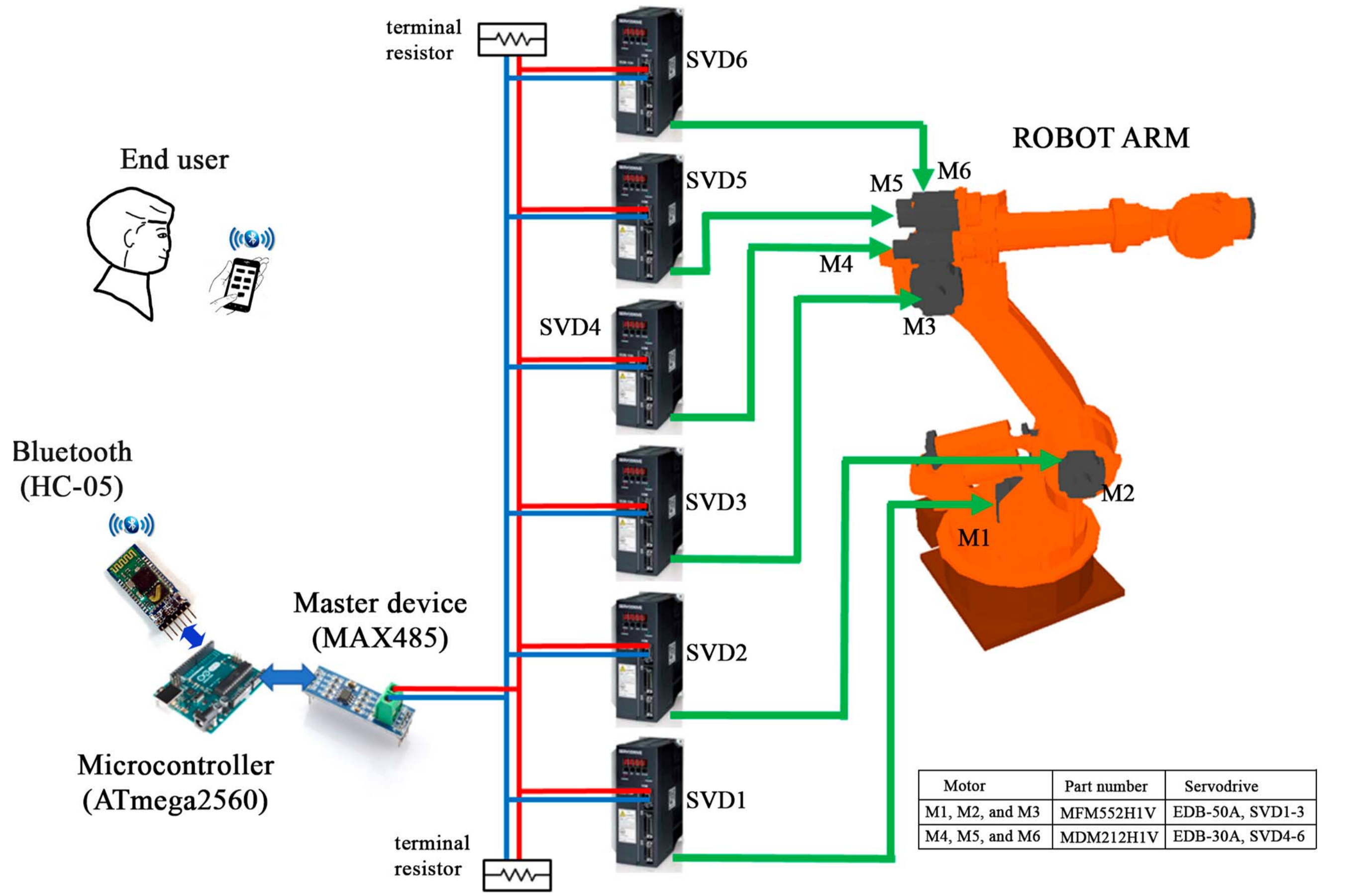

Fig. 1. Block diagram of the robot prototype.

programs fulfill certain criteria by which engineering students are introduced to the "essence" of engineering early in their undergraduate careers [19]–[21]. Although many programs offer interesting prototypes (comprising the physical hardware and the software to control it) for students to work on in the laboratory [3], [5], [7], these must support the program's accreditation by having an innovative education model and contributing to the curriculum. On the other hand, some laboratory activities [9] deal with interesting applications but do not offer real-world experience.

This paper presents a robot prototype for teaching different aspects of mechatronics in a Digital Systems II course in the undergraduate Automation program of at Autonomous University of Queretaro (UAQ), Mexico. The proposed robot prototype is intended to: 1) teach multidisciplinary aspects of mechatronics; 2) promote students' interest in learning mechatronics; 3) allow easy upgrades as the course evolves, and 4) meet the ABET accreditation criteria.

II. Robot Prototype Design

The robot prototype, a robot arm that students learn to manipulate, comprises three main systems: the mechanical parts, the electronics, and the control interface; its block diagram is shown in Fig. 1. The robot arm's mechanical body and servomotors are essentially a NACHI SA160F-01 industrial robot manipulator, so the discussion here will only treat the electronic systems and control interface.

A. Servo Drivers

The robot arm has six degrees-of-freedom, Fig. 1, each of which has a servomotor (M1-M6) controlled using EDB-30A servo drivers (SVD4,5,6 for motors M4,5,6) and EDB-50A (SVD1,2,3 for motors M1,2,3), matching the electrical specifications of each motor. The servo drivers use 220V three-phase AC power and can be configured for three modes of operation: torque, velocity or position. The reference input for each motor can be set either externally or internally, but the most practical approach is to control these parameters digitally using a personal computer or a microcontroller. Students can access the robot's control panel to make any required hardware modifications, such as to power connections, or to the servo driver-controller interface. An extensive description of the control panel can be found in [22].

B. Controller

A controller device is an essential part of any robot system; various types have been used to control educational robot prototypes, the most widely used being Personal Computer [23] and Programmable Logic Controller [24], [25]. Since the course in which the robot was used (see Section III below) focuses on microcontrollers, a microcontroller was chosen for operating the robot arm.

A suitable commercial low-cost control board that can operate all six servo drivers was the Arduino ATmega2560 board featuring the powerful ATmega2560 microcontroller. The board features four serial ports, one of which is dedicated for operating the servo drivers, and another is used to establish wireless connectivity - here, an HC-05 Bluetooth module was used to communicate with a cell phone with Bluetooth connectivity. An Arduino IDE 1.6.5 was used to program the microcontroller.

C. Servo-Controller Communication

The interaction between the microcontroller and servo drivers can be performed using an industrial bus. For this robot prototype, Modbus protocol was used; this is widely used in machine automation and industrial systems (for example, communication between PLCs, drivers, and sensors). The main advantage of this industrial protocol is that, by using a master-slave configuration, it is possible to control multiple devices by just using a single controller. In this case, the microcontroller ATmega2560 (the master) is used to send the position, velocity or torque commands to each joint motor drive (the slaves). Since the serial port of the Arduino board uses transistor–transistor logic (TTL) level signals, it is necessary to convert them to the RS485 standard using the MAX485 converter, Fig. 1.

D. Control

The software to control the robot's operation was developed by researchers at UAQ. As well as being free software, it gives the user freedom to make any desired modifications, such as programming the robot to perform different task routines, or replacing and updating the existing hardware design.

This robot prototype allows students to learn and to apply knowledge from various academic disciplines such as microcontrollers, dynamics, communications, motors, advanced programming, and robotics.

III. Course Sequence and Student Background

The undergraduate Automation Engineering program at the UAQ was started in 2002, and has had ABET accreditation since 2016, helpful in improving the quality of technical education in the region.

The robot prototype was first introduced in 2016, in the sixth-semester Digital Systems II course, which meets for five hours per week over the 17-week semester. Although the Robotics course comes after the Digital Systems II course, in previous semesters students will already have taken the courses Design of Electrical Systems, Electric Machines I and II, Digital Systems I, Dynamics and Statics. This means students were prepared to work with all the robot's motors, drivers, electrical connections, serial communications, Modbus, and so on. Students had also worked on research projects in each of the previous semesters. The knowledge and skills gained during those first five semesters equipped students for the Digital Systems II course.

At the start of their seventh semester, the Automation Engineering students must select one of three specializations: Instrumentations, Electronics, or Mechatronics. The robot and its associated practical activities combine these three disciplines, so they can influence students in making an appropriate decision as to their field of specialization.

The robot contributes to meeting several ABET criteria for student outcomes, particularly: criterion 3c) an ability to design a system, component, or process to meet desired needs within realistic constraints, such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability; and criterion 3d) an ability to function on multidisciplinary teams [26]. Both criteria were considered in the grading rubric (see below), examining students' abilities to synthesize the particular elements of a problem, evaluate solutions, document integrated solutions in engineering language, identify knowledge that builds the solution, integrate the vision of other disciplines, and play an appropriate role in the success of the work team.

IV. Practical Sequence

The objective of the practical sessions, designed by the UAQ instructors, is for students to gain practical experience of, and insight into, the underlying principles of robotics, including: programming microcontrollers, handling motors, robot dynamics, industrial protocols, etcetera. Each practical activity can take several laboratory sessions to complete. The laboratory activities were given in the following sequence:

A. Practical 1: Introductory Session

Objective: To familiarize the students with the robot prototype and practical sessions.

Before starting the actual activities, students need to become familiar with the robot prototype. The instructor first gives step-by-step instructions on how to control the robot movements, the general functions, global connections, and robot movements from the computer and cell phone (via Bluetooth). Then the sequence of practicals and their objectives is explained. The students were divided into five teams to perform the practical sessions.

The instructor then disconnects the microcontrollers and Modbus Net connections, and has the students tackle the problem of how to move the robot, how to get Modbus communication with the servo drivers, how to use the industrial protocol, how to program the microcontroller, and so on.

B. Practical 2: Using the Servo Drive

Objective: To learn how to use an industrial servo drive to move the joint motors (manual mode).

Both the servo drivers, EDB-50A and EDB-30A, can be set to manual mode using a digital operator located in the servo drive [27] that allows the students to set the parameters, send commands and display the status of the servo drivers. To carry out this practical, students are taught some basic concepts of servo alarms, electro-mechanical specifications, operating modes, auto-tuning operations, speed, torque and position controls, JOG movement, parameter ranges, robot's limits, and more.

C. Practical 3: Communication Protocol

Objective: To understand the Modbus protocol and how to configure it in AVR microcontrollers.

The servo drivers have RS-232, RS-422, and RS-485 communication capabilities. To use the Modbus protocol, the RS-485 is operated in the ASCII mode, where the microcontroller sends ASCII characters in a group separated by the characters ':' and "\r\n" (trailing newline CR/LF).

For example, the characters sent to read the data in the address location (0001) of the device (02) in the network is :020300010001F9\r\n. The characters 'F9' corresponds to the Longitudinal Redundancy Check (LRC), which can be obtained as, $LRC = (FF - (02+03+0001+0001)+1) = F9$. This example considers the single register case, but Modbus can read data from multiple registers. More details of the servo drive can be found in [27].

Similarly, it is possible to write data to an address location by using the instruction code "06". For example, in this practical, a student can use "JOG motion" by writing the address location of the corresponding servo drive. First the servo drive must be turned on by sending the command sequence, :020610230001C4\r\n. To activate the JOG forward rotation, the required command sequence is :020610240001C3\r\n. Finally, to turn off the JOG forward rotation, the command sequence required is :020610240000C4\r\n. Similarly, the students can construct sequences of commands to perform various robot motions.

D. Practical 4: Communication Network (Modbus)

Objective: To implement the Modus network.

Students must connect six servo drivers in a network using the standard RS-485 protocol (TIA-485), dealing with the physical layer of the Open System Interconnection (OSI) communication model. Making these physical connections helps students acquire the skills to work with the physical environment, and to understand the concepts of the RS-485 protocol, such as its physical characteristics, operation, noise reduction techniques and so on.

The servo drivers can be configured into various communication modes. In this practical, the serial asynchronous mode was selected, 8N2 (8-8 data bits, N-no parity bit, and 2-two stop bits) with 9600bps. From practicals 2 and 3, students have already: 1) understood the basic concepts of the Modbus protocol; and 2) established communication between the microcontroller and servo drivers using the Modbus protocol.

For this practical, the students need to build the connections as shown in Fig. 2, which require knowledge of MAX485 operation and the bus topology. Here, the microcontroller is configured in master mode and the six servo drivers are configured in slave mode. Once the physical connections between the microcontroller and the servo drivers are established, the student verifies the physical connections, and the communication with the master device and each servo drive

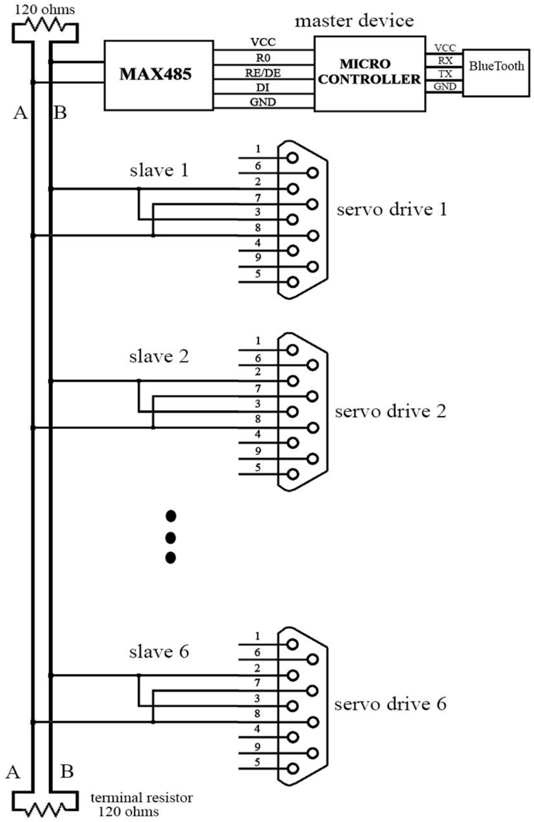

Fig. 2. Connection diagram for the network bus.

and motor; and programs various robot motions. During these activities, the students are encouraged to solve problems by themselves to achieve this practice session's goal of moving all the robot arm motors.

E. Practical 5: Wireless Operation of the Robot Arm (Bluetooth)

Objective: To move the robot arms using a cell phone via Bluetooth.

The Bluetooth devices' use of a serial 8N1 (9600 bps) makes it easy to connect with the microcontroller to program various robot joint movements. During this practical, the students use a cell phone with Bluetooth connectivity to control the movement of each robot arm joint. For this purpose, the cell phone needs to have a dedicated mobile application software or mobile app; students decide whether to use a generic app (e.g., BlueTerm) or one they develop themselves (e.g., MIT App Inventor).

F. Practical 6: Robot Arm on the IoT (Internet of Things)

Objective: To move the robot arm via an Internet connection.

The Internet of Things (IoT) is a rapidly growing network of connected objects that can collect and exchange data using smart devices. A number of IoT applications for monitoring and control purposes are being implemented in many parts of the world, and are having a great impact in areas such as appliance control, sensors and buildings. To exchange the required

TABLE I
SURVEY RESULTS FOR THE ROBOT PROTOTYPE LABORATORY EXPERIENCES

Questionnaires	Average (1-5)
Q1. The robot prototype proved to be interesting.	4.78
Q2. The prototype successfully motivated me to perform the practicals.	4.30
Q3. The prototype helps me to understand about real-life industrial problems	4.34
Q4. The sequence of the practicals was appropriate for the learning process	4.39
Q5. The prototype helped me to acquire skills required for industrial applications	4.47
Q6. The practicals helped me to acquire technical knowledge and skills.	4.17
Q7. The prototype provides opportunities to make software and hardware modifications and to gain knowledge.	4.26
Q8. The prototype can be used in teaching more robotics-related programs.	4.60
Q9. Learning through the practicals was satisfying for me	4.56

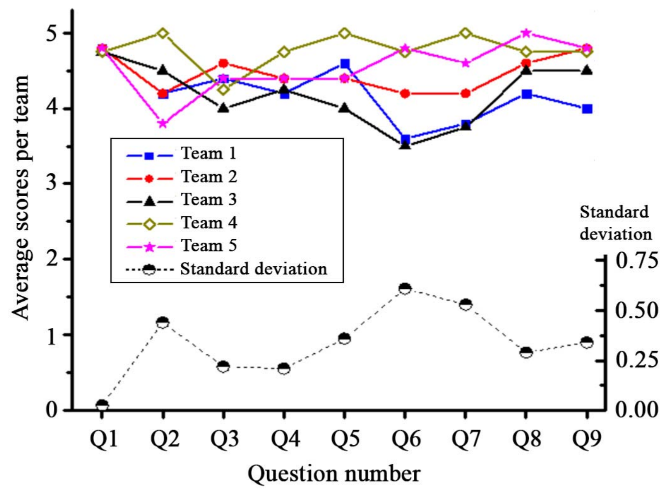

Fig. 3. Average scores for each team (5 teams) and their standard deviation values.

information, the microcontroller needs to have access to the Internet. Some modern microcontrollers come with a built in Wi-Fi module, or additional hardware can be used to provide Internet connectivity. For example, the ESP8266 module or Wi-Fi shields provide a simple and inexpensive solution.

In this practical, students control the movement of the robot via Wi-Fi. They work in the laboratory, so that they can simultaneously monitor and control the robot's operation. As mentioned above, the advantage of IoT is that the process can be controlled remotely. One future goal is to install a video camera to monitor the robot operation; by accessing this, for example via an IP address, students can interact with the robot prototype from a remote location.

V. PROGRAM EVALUATION

To evaluate the success of this program: 1) a qualitative analysis based on student feedback was made to gauge students' enthusiasm towards the prototype; and 2) a quantitative analysis based on UAQ's Specific Indicators (learning outcome metrics), to determine the impact of the prototype in the Digital Systems II course.

A. *Student Survey*

The survey was administered to 23 undergraduate engineering students enrolled in the Digital Systems II Lab program in 2016 (Semesters I & II), after all the practical sessions were completed. Responses were on a 5-point Likert-type scale (1- strongly disagree; 2- disagree; 3- neither agree nor disagree; 4- agree and 5- strongly agree). The questionnaire and corresponding average scores of the 23 respondants are given in Table I.

The average score obtained for each question is above 4 (agree), which indicates that the students responded positively to the laboratory learning experience with the robot prototype. Of all the questions, Q1 has the highest score, which indicates that the students found the laboratory activities intellectually stimulating. The second highest average value was for Q8, where the students recommend using the robot prototype in other teaching programs robotics-related. The third highest average score was for Q9, which indicates that the students did have a valuable learning experience with the robot prototype.

The average results from each team were also analyzed, Fig. 3, to determine the correlation of responses between teams. For Q1, a strong agreement between different team's responses can be seen from its low standard deviation. A similar response can be noticed in the case of questions Q3 and Q4. For Q6, which has the lowest average score, a diversity in the team responses is shown by its high standard deviation, where three teams gave a score of 4-5, and the remaining two teams gave a score of 3-4.

B. *Evaluation Based on Specific Indicators*

The UAQ has its own organized grading system for evaluating student work, based on certain criteria termed Specific Indicators, selected to satisfy ABET criteria. The Specific Indicators for the Digital Systems II course, Table II, correspond to ABET Criterion 3. This table also includes the scoring rubric for the Digital Systems II Lab program.

For the Digital Systems II course, SI-1 was evaluated using the test scores from a written exam. SI-2 and SI-4 were evaluated based on students' ability to design and conduct experiments, and SI-3 was based on the students' programming skills. Finally, SI-5 was evaluated based on the final lab report writing.

The final grade for the Digital Systems II course is based on:

- 20% Written exam (SI-1)
- 50% Conducting practicals (SI-2,3,4)
- 20% Written lab report (SI-5)
- 10% The student's participation and their ability to function in a multi-disciplinary team (qualitative)

For a qualitative analysis on the impact of the robot prototype on the Digital Systems II course, an analysis of the student outcomes for the last three years (2014 to 2016) was been conducted. Student grades during the year 2016 (after

TABLE II
RUBRIC USED FOR EVALUATING THE SPECIFIC INDICATORS

Specific Indicators *(ABET's outcomes)*	Criteria	Grade 90-100	70-89	60-69	0-59
SI-1. The student works in teams, analyzes, designs, and tests electronic circuits based on microsystems. *(3c,3d)*	a. Knows microcontroller fundamentals. b. Knows microcontroller programming. c. Designs microcontroller interfacing circuits. d. Knows measurements using sensors. e. Applies communication protocols. f. Optimizes the microcontroller program codes. g. Contributes to the team with their theoretical knowledge.	a b c d e f g	a b c d e	a b c d	a b
SI-2. The student develops diagrams using microsystems as the basis. The student contributes this kind of ability in teamwork. *(3c,3d)*	h. Implements microcontroller interfacing circuits. i. Designs signal conditioning circuits for sensors. j. Designs the optimal connections for an industrial network. k. Designs wireless interface circuits to implement communication between microcontroller and servo-drives.	h i j k	h i j	h i	h
SI-3. The student compiles codes with specialized software. The student contributes this kind of ability in teamwork. *(3c,3d)*	l. Compiles codes in development programmer software. m. Debugging and verification using a simulator. n. Optimizes the codes. o. Understands how the instructions are executed.	l m n o	l m n	l m	l
SI-4. The student designs printed circuits following the design rules of the specific software. The student contributes with this kind of ability in teamwork. *(3c,3d)*	p. Designs printed circuit boards (PCB) for use in the practicals. q. Applies appropriate methods for PCB development. r. Designs PCB according to specific standards. s. Optimizes component placement and size of PCB.	p q r s	p q r	p q	p
SI-5. The student documents the development of the firmware of projects and laboratory sessions, developed in the format of a work portfolio. *(3c)*	t. Writes lab reports in a detailed and structured manner. u. Explains results and observations in detail. v. Follows the proper format for report delivery. w. Includes necessary figures in the report with appropriate explanation. x. Cites proper bibliographic sources. y. Writes with correct spelling and grammar.	t u v w x y	t u v w x	t u v	t

TABLE III
ANALYSIS OF STUDENT PERFORMANCE IN DIGITAL SYSTEMS II: 2014–2016

Specific Indicators	ABET´s outcomes	2014		2015		2016	
		I	II	I	II	I	II
SI-1	3c, 3d	73.3	66.7	60.0	67.0	84.0	87.3
SI-2	3c, 3d	73.3	73.3	66.7	71.1	82.9	85.6
SI-3	3c, 3d	80.0	80.0	73.3	77.7	83.4	84.3
SI-4	3c, 3d	66.7	60.0	66.7	64.4	73.3	75.1
SI 5	3c	60.0	60.0	66.7	62.2	81.5	85.6
Total Average		**70.7**	**68.0**	**66.7**	**68.5**	**81.0**	**83.6**
Students evaluated		11	12	12	14	10	13

the inclusion of the robot prototype) were evaluated based on the criteria in Table II. The corresponding results are summarized in Table III, where the Specific Indicators are chosen according to the ABET outcomes 3c and 3d.

The results show that the learning outcomes for the students of batches 2016 I and II are higher that those of the previous four batches. This indicates that the inclusion of the robot prototype had a great impact on the learning of Digital Systems II, and by extension of the topic of mechatronics. Also, the ABET indicators help in improving the teaching experience, therefore the overall learning-teaching process.

C. Discussion

The evaluation results indicate that students achieved: 1) a firm understanding of robotic concepts, from both a theoretical and a practical standpoint; 2) knowledge of embedded systems; and 3) the ability to perform laboratory experiments. Furthermore, the inclusion of Modbus protocols enabled the students to acquire some basic experience with industrial standards.

The modular topology followed during the teaching program helped the students in understanding step-by-step design involved in a robotic system. In addition, by exposing students to engineering through hands-on experience and projects, the program helps students develop scientific skills required to tackle challenging and interesting real-life engineering problems. Furthermore, working as a team enables them to share and acquire knowledge of the complete system.

The student survey result shows the effectiveness of the robot prototype in the teaching program. However, some issues may alter survey results in a study program like this:

- The evaluation may contain "subjective" responses, influenced by personal perception at the time of the survey.
- The measure of the effectiveness of the robot prototype is only based on student responses; since they have no industrial working experience, the responses for Q3 and Q5 cannot provide a concrete assessment on the industrial aspects of the robot prototype.
- The effectiveness of teaching depends on many factors, such as the instructor, teaching program, teaching methods, student backgrounds, laboratory activities and their sequence. These factors may cause the impact of the robot prototype to vary for different programs.

These are therefore open to discussion.

VI. Conclusion

This paper presents a robot prototype used for teaching in multidisciplinary engineering courses. This prototype has three important goals: 1) to meet criteria for international certification; 2) to provide multidisciplinary knowledge; and 3) to convey industrial applications, always necessary in technological education.

The prototype was designed to explore new technologies and to encourage students' interest in studying mechatronics and in solving ever-changing real-life engineering problems. Students and instructors can modify the software and hardware units as necessary, to explore more ideas and to apply the robot in other mechatronics-related courses.

Planning the laboratory activities and their sequence is crucial to improving the effectiveness of the robot prototype. This should be tailored to meet both student and academic requirements, which obviously will depend on the program and the instructor. Students are provided with a lab manual, giving the practical sequence and instructions for performing the activities. Should the course be taught by a different teacher, the laboratory activities, strategy, and sequence can be modified as desired.

Finally, student performance during the course was evaluated qualitatively and quantitatively. The qualitative analysis based on survey scores indicates that the students find the prototype an interesting part of their learning process, and they recommend its inclusion in other technical and industrial training programs. The quantitative analysis of student grades indicates that the robot prototype helped to achieve the learning objectives. Considering the student outcomes in terms of ABET criteria, it can be concluded that the prototype helps students to: improve their system design skills; acquire desired skills within realistic constraints; and learn to work in multidisciplinary teams. Furthermore, student portfolios from the laboratory activities will be useful in future ABET evaluations, to emphasize the contribution of the robot prototype to improving the student learning outcomes.

In future work, laboratory activities will be further improved based on feedback from both the students and the instructor, and the work described here will be extended into more advanced courses.

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