A Methodology To Teach Students To Implement Digital Controllers Using Embedded Systems.

Ing. Juan Felipe Patarroyo, University of Puerto Rico at Mayaguez

Electrical Engineer from the University of Quindío in Armenia, Colombia with emphasis on Digital Systems. Currently pursuing Master's Degree in the University of Puerto Rico at Mayaguez in the Area of Control Systems with minors in Digital Systems.

Dr. Gerson Beauchamp, University of Puerto Rico, Mayaguez Campus

Dr. Gerson Beauchamp is a professor at the Electrical and Computer Engineering Department of the University of Puerto Rico at Mayagüez. Dr. Beauchamp received a BSEE from the University of Puerto Rico at Mayagüez (UPRM) with High Honors in 1984. Dr. Beauchamp was the recipient of the Georg Simon Ohm Prize to the Best Graduating Electrical Engineering Student of his graduating class. He also earned an MS degree in Electrical Engineering in 1985 and a Ph.D. degree in 1990 both from the Georgia Institute of Technology. As part of his GEM Fellowship assignments, Dr. Beauchamp worked as a Technical Support Engineering for the E.I. DuPont De Nemours and Company during the summers of 1984, 1985, and 1986. Since January 1990 he started teaching at the Electrical and Computer Engineering Department of the UPRM. Dr. Beauchamp research interests include process instrumentation and control, renewable energy applications of control systems, and innovative teaching strategies and methods. Dr. Beauchamp has worked on a Solar-Assisted Air Conditioning project and is the co-author of two US Patents for this project. He was the coordinator of the Electrical Engineering Team that represented the University of Puerto Rico in the 2002 Solar Decathlon competition. He also was the general coordinator of the UPR Team for the 2005 competition. During the six years period from 1992 to 1998, Dr. Beauchamp was the Coordinator of the Pre-College Engineering Program, a Summer Internship for High School raising seniors, sponsored by the National Science Foundation. He has also served as the Process Instrumentation and Control Laboratory Coordinator since 1992, as Academic Senator (1995-2001), Faculty Representative at the Administrative Board of the UPRM (2000-2001), Controls Area Committee Coordinator, Departmental Personnel Committee (1996-1997), and Liaison Officer for the Puerto Rico Louis Stoke Alliance for Minority Participation (PRLS-AMP) Project (August 1995 – December 1999).

Dr. Aidsa I. Santiago Roman, University of Puerto Rico, Mayaguez Campus

A Methodology To Teach Students To Implement Digital Controllers Using Embedded Systems.

Abstract

Most of the course projects in the Control Systems Area are implemented using high-level simulation tools and data acquisition boards. This method has yielded excellent results; but it has the disadvantage of not exposing students to implementing digital controllers directly with microprocessors. This issue is common to many universities. In this paper we propose a methodology that will improve student's understanding on how digital control systems are implemented in the real world using microcontrollers. Specifically, the proposed methodology includes a set of workshops to train students in the use of microcontrollers for digital control purposes and a microcontroller based workstation for implementing the digital controllers. The effectiveness of this approach, compared to other methods (Simulink, LabVIEW, among others) was tested with a pedagogical experiment that followed a backward design approach. Assessment techniques allowed instructors to evaluate course objectives and revealed student acceptance of the proposed methodology.

Introduction

The *Digital Control System*s (DCS) course is highly demanded in our undergraduate electrical engineering curriculum. The *Introduction to Control Systems* course, as well as basic knowledge of electronics and signals and systems, are prerequisites. The topics covered in the *Digital Control System*s course include modeling of discrete-time control systems, using the Z-Transform to analyze discrete-time systems, stability criteria, and root locus design in the z-domain. These topics appear commonly in digital control systems textbooks[1,2,3,4].

There are two main objectives of the digital control systems course. First, to teach the fundamentals of digital control theory, and second, to teach how to design a discrete-time controller and implement it in the laboratory using embedded systems and high-level tools (Simulink, LabVIEW among others). The first objective is accomplished through lectures, homework assignments, and simulations. Lectures provide the theoretical background of digital control systems, while homework assignments and simulations are used to reinforce the theoretical knowledge learned by students.

The second objective is accomplished by following a project-based learning inductive methodology[5] referred to as a Term Project. For this project, students are organized in teams of two or three students and the instructor specifies an assignment to carry out one or more tasks that lead to the development of a final product. Teams are required to design, simulate, and implement a digital controller on a Quanser's Ball and Beam (B&B)[6] system available in the Process Instrumentation and Control Laboratory (PICL)[7]. The controllers should be implemented using a microcontroller based system (MCS) as well as with Simulink through Quanser's Quarc® tool. Finally, a comparison between both implementations was made. The MCS workstation uses the Texas Instruments C2000 F28069 Microcontroller, the DRV8833 motor driver, and a custom made Analog Signal Conditioning Board. The system is enclosed in a box with all the ports needed to connect to the Controls Laboratory Experiments. Also, a set of C language libraries with solutions to the most common control problems was developed.

To document the project, students delivered a work plan, two progress reports and one final report. The work plan specified how each team completed the tasks assigned and included a time schedule with the activities needed to complete the project. Progress reports were used to assess progress and allowed the instructor to provide guidance to the teams accordingly. Teams presented a demonstration and an oral test to validate these reports. In the final report, students are expected to apply the theory acquired in lectures and assignments and demonstrate dominion of it.

Many approaches have been followed in the area of embedded control systems for educational purposes[8,9,10,11,12]. However, most of them lack of formal assessment methods. Also, they do not define a formal methodology to design and implement the pedagogy used in courses. Therefore, the objective of the proposed approach is to design and implement a teaching methodology to teach students in the DCS course to implement digital controllers using a MCS. The research question that guided this study was: **What is the effectiveness of using an MCS to teach students to implement digital controllers in the Digital Control Systems course?** A backward design approach based on Streveler's, et al, work was implemented to re-design the Digital Control Systems course, in which the content, assessment, and pedagogy used to implement the proposed system are aligned[13]. As part of this design, a set of workshops were developed and were taught alongside the course lectures. In this paper we will focus on the design and assessment of these workshops.

Research Design

This section describes the methodology that was followed to achieve the educational objectives. First, we present the participants that were the subjects of the experiments developed in this research. Second, we present the methodology that was followed to formulate the workshops' content, assessment, and delivery. Finally, we present the microcontroller based system that was used as an instrument to implement the workshops.

Participants:

The undergraduate Electrical Engineering Program in the Electrical and Computer Engineering (ECE) Department consist of 165 credits that should be completed in a period of 5 years. The curriculum provides students with a general education background in mathematics, science, and humanities. The program has four areas of emphasis: Applied Electromagnetics, Communications and Signal Processing, Control Systems, Electronics, and Power. Most students in the DCS course are in their fourth or fifth year of their course plan and are specializing in the area of Control Systems.

Some of the students in this course have already taken the microcontrollers course, which is one of the core courses in the curriculum. At this point, students have basic knowledge on the use of microcontrollers but they do not have the required skills to create an embedded controller. Due to this, one of the objectives of this work was to develop a set of workshops to teach the fundamentals of an embedded control system regardless whether the students had a solid background in microcontrollers or not. These workshops support the *Digital Control Systems* course project and were taught alongside the class lectures.

Methodology:

Streveler, et al, present an approach combining Outcome Based Education (OBE) and engineering design methods to align course content (curriculum), assessment (evaluation methods), and delivery (teaching strategy)[13] . In that approach, it is recommended to begin with the course requirements or specifications, emphasize metrics, and then prepare prototypes that meet the requirements. This work follows a *Backward Design* approach as presented by Wiggins and McTighe's[14,15] and the *How People Learn* framework presented by Bransford, et.al[16]. In the following sections we will describe the activities of the backward design approach: content, delivery, and assessment of the workshops that allowed the successful implementation of the proposed MCS approach in the DCS course project.

<u>Workshop Content</u>

In this study, the workshop content was designed to assist participants in accomplishing the ABET student Outcome E of the DCS course[17,18] which is expressed as: *Implement a digital controller using a digital computer and software*. According to the OBE framework[13], the content of each workshop was designed in four stages: (1) *Desired Outcomes*, (2) *Curricular Priorities*, and (3) *Learning Objectives*. The first two stages, provided a baseline to determine the expected student outcomes and define student's *Learning Objectives* that must be accomplished.

Desired Outcomes: Outcomes were established Following Streveler's OBE methodology[13]. The instructor identified the main requirements for the workshops according to the laboratory experiments characteristics and the course general objectives. Table 1 shows students' outcome analysis that resulted from answering the guiding questions[13].

Table 1 - Student Outcomes Analysis

What do we want students to know?	Students should understand the advantages of implementing a controller using a Microcontroller based System versus using high level implementing tools such as Simulink or Labview.
	Students should identify the basic components in a Microcontroller based control system.
	Students should understand how to use the software developing tools to program the Microcontroller.
	Students should identify the basic structures of the C Code programming language.
What do we want students to be able to do?	Students must be able to configure the main peripherals of the Microcontroller based control system.
	Students must be able to use C Code sample libraries to implement a digital controller using difference equations.
Who do we want students to be?	Students should be self-learners.
	Students must be courious about understanding how a microcontroller based control system work.

Specifically, student outcomes were focused on the knowledge of microcontroller characteristics and knowledge about C code language. Additionally, student outcomes should modify students' behavior by enhancing self-learning skills and curiosity about how digital controllers work in a real environment.

Curricular Priorities: Once we determined the expected student outcomes of the course workshops, the next step was to translate these characteristics into curricular priorities[13]. We proposed that the *enduring understanding* for students was a clearer perspective on what the main hardware and software characteristics of a microcontroller based control system are. *Important elements to know and do* refer to the concepts and skills learned in the implementation of the controller using an embedded system. Students at the end of the course must be familiar with the importance of using microcontrollers in the implementation of control systems. Table 2 shows the curricular priorities for the course workshops.

Table 2- Curricular Priorities for the Digital Control Systems Course Workshops

Enduring Understanding	Implementing a Digital Controller using Microcontrollers (MCU).
	Configure the main peripherals of the Microcontroller based control system.
	Use C Code sample libraries to implement a digital controller from difference equations.
Important Elements to Know & Do	Identify the advantages of implementing a controller using a Microcontroller based System versus using high level implementing tools such as Simulink or LabVIEW.
	How to design a computer program algorithm.
	Employ a user manual to solve a particular problem of any technology.
	Understand the working principle of the different sensors in the laboratory experiments.
Worth being Familiar With	The set of tools that ease the programming and debugging process of the Microcontroller.
	Microcontroller programming.
	Main characteristics of the TI C2000 microprocessor.
	C code main operations and programming structure.

Learning Objectives: Learning objectives were established according to the outcome analysis and curricular priorities determined in the previous section. The learning objectives were written following the cognitive domain of Bloom's Taxonomy[19], which involves knowledge and development of intellectual skills. This includes the recognition of specific procedural, patterns, facts, and concepts that serve in the development of intellectual abilities and skills. In the Digital Control Systems course workshops, students were expected to successfully complete the following course learning objectives:

1. Identify the main differences between implementing a digital controller using MCU's and high level implementing tools (Matlab, Simulink, etc.).
2. Identify the main components in a MCU based control system.
3. Identify the main components in a MCU C Code Program.
4. Explain the working principle of the different sensors in the laboratory experiments.
5. Develop a C Code program to read and write in the main peripherals of the C2000 microcontroller.

6. Develop a Graphical User Interface to read and write on the memory of the microcontroller on-the-fly.
7. Synthetize relevant information to develop a C Code program to implement a digital controller.
8. Test an MCU based digital controller with the Ball & Beam experiment.

Workshop Delivery

Workshops were given in the PICL and were two hours long each. Students were organized in pairs and were assigned a computer workstation and an MCS workstation. The instructor gave a tutorial where a step-by-step guidance was given according to the learning objectives of the session. Workshop content was divided in three different workshops and designed according to the desired learning objectives:

- The first workshop targeted learning objectives 1, 2, and 3 (the important concepts of embedded control systems). Students recognized the main differences between implementing a digital controller using an MCS and using high level tools. Also, in this workshop students learned basic operations in a C code programming through the use of the Code Composer Studio Development Software. Finally, students implemented a basic C Code blinking led program, which allowed them to familiarize with the Code Composer Studio Environment.

- The second workshop targeted objectives 4, 5, and 6 that relate to the configurations and a hands-on experience activity with the microcontroller stations. Students learned how to use the microcontroller peripherals. They were expected to learn about the working principle of each sensor of a Ball & Beam system and to read them using the microcontroller. Then, students learned to translate the signals coming from the peripherals to standard units (meters, radians, volts). Finally, students created a GUI to view the variables measured by the sensors.

- The third workshop targeted the last two objectives by implementing a real controller using difference equations and the Texas Instruments GUI Composer. This workshop synthetized the concepts learned in the previous workshops by implementing a digital controller using C Code. Specifically, students were expected to learn how to transform a z-domain transfer function to a difference equations and how to convert this difference equation into a C Code program to control a servomotor.

Workshop Assessment

Assessment activities were designed according to the learning goals established for each workshop. To achieve this, we used the predicates in Bloom's Taxonomy[19] to define course objective, evaluate how each item will be satisfied, and then determined assessment activities for each course objective. This guaranteed an alignment between course content and objectives[13]. Among the assessment activities are: diagnostic examinations, pre and post-tests, and oral exams. A description of each assessment activity is presented below. Assessment results are shown in the *Results* section.

Diagnostic Test: The objective of this test was to explore student's background on microcontrollers, programming languages, and control systems. It was given before the first workshop. A sample of the diagnostic test is provided in Appendix A.

Pre-Test and Post Test: Students received a pre-test (before the workshop) and one post-test (after the workshop) with identical questions. These tests measured the student outcomes fulfillment on each workshop. The results obtained in pre and post-tests indicated how this methodology is effective by aligning course content, assessment, and delivery. Examples of the pre and post-tests are included in Appendix A.

Oral Exam: At the end of the course project, students took an oral exam to assess their understanding on how they implemented the controller using both methods (Simulink and Microcontroller). A rubric was designed and used to assess this oral exam. A sample of the rubric is provided in Appendix B.

Microcontroller Based System (MCS) Workstation:

The MCS workstation integrate the Texas Instruments (TI) C2000 F28069 Microcontroller[20], the DRV8833 motor driver[21], and a custom made Analog Signal Conditioning Board. The MCS is enclosed in a box with all the ports needed to connect to the PICL experiments. This means that students do not need an extensive hardware knowledge to handle the MCS. A set of C language libraries with solutions to the most common control problems was developed. Also, this TI microcontroller uses a powerful tool called GUI Composer that helps students to create a Graphical User Interface (GUI) in a drag-and-drop environment. This GUI allows to watch the variables of the controller in real time and change the controller parameters on-the-fly if needed. The development process of the MCS was presented in the SACNAS 2014 Annual Conference[22] and is to appear in the IEEE 2015 Frontiers in Education Conference[23].

MCS Design

A general system overview of the MCS is shown in Figure 1.The Analog Signal Conditioner is required to convert the voltage signal levels from the Quanser® analog sensors to a range that could be read from the microcontroller (0-3.3V). A DC motor driver (DRV8833)[21] was configured and used to drive the B&B system motor from the PWM signals generated by the microcontroller. The Optical Encoders read the angular position of the motor. Finally, a Timer Interrupt Unit sends a signal to the CPU indicating when the control action should be performed.

The MCS uses a C2000 F28069 microcontroller. It operates at 80MHz and is equipped 16 Analog-to-Digital Conversion (ADC) channels with a resolution of 12 bits, 2 Quadrature Encoder read-modules (eQEP), 16 independent 32 bits PWM channels, Floating Point Unit (FPU), JTAG emulation tool, and other characteristics that make this microcontroller ideal for high capacity control purposes.

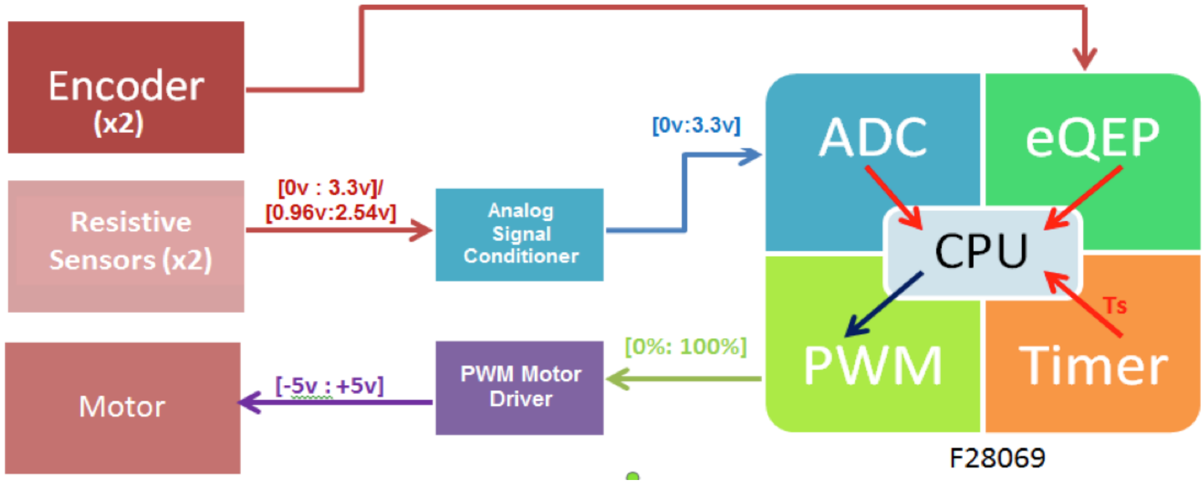

Figure 1 System Overview

System Assembly

The MCS workstation was packed in an enclosure with all the ports needed to make the connections with the Quanser® experiments and the power supply. This system should be able to handle different situations that may appear in practice (Overvoltage, bad connections, etc.). Figure 2 shows the final box assembly. The MCS is organized so that students may visually identify its main modules and manipulate them with little risk of damage.

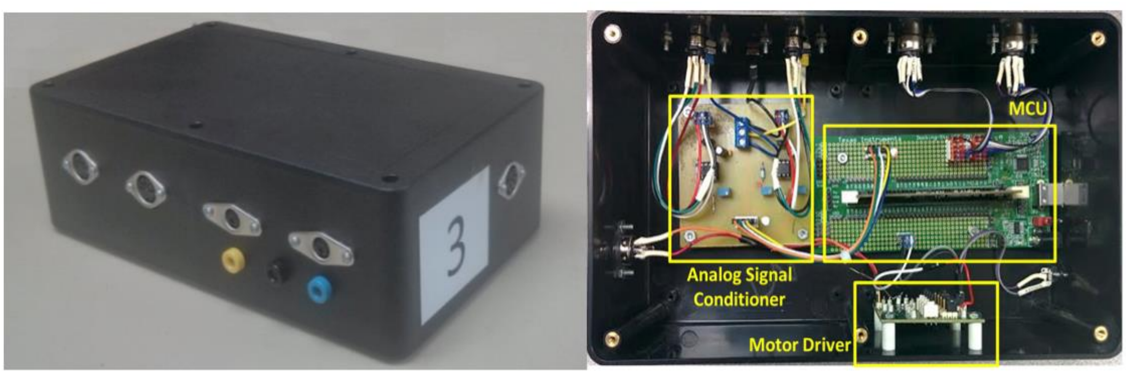

Figure 2. Final box assembly of the stations. Left: External view. Right: Internal View

System Implementation

One of the features of the Texas Instruments C2000 microcontrollers and Code Composer Studio is the debugging tool. GUI Composer is an extension of this software and allowed developers to create a Graphical User Interface (GUI) that access directly to the microcontroller memory using easy-to-use icons. Once student has developed the software, he or she can create a panel where all the variables can be changed and put a Graphic Panel where the defined variables can be watched in real time. Three sample GUI's were created to be used as templates for other projects: SRV-02 Proportional Controller, SRV-02 Lead-Lag Controller, B&B Lead-Lag Controller. The B&B Lead-Lag controller performance is shown on Figure 3 using GUI Composer. The student is able to change zeroes and poles and all the controller parameters, also, an "Enable" field was used to stop the system in case that the motor needs to be stopped.

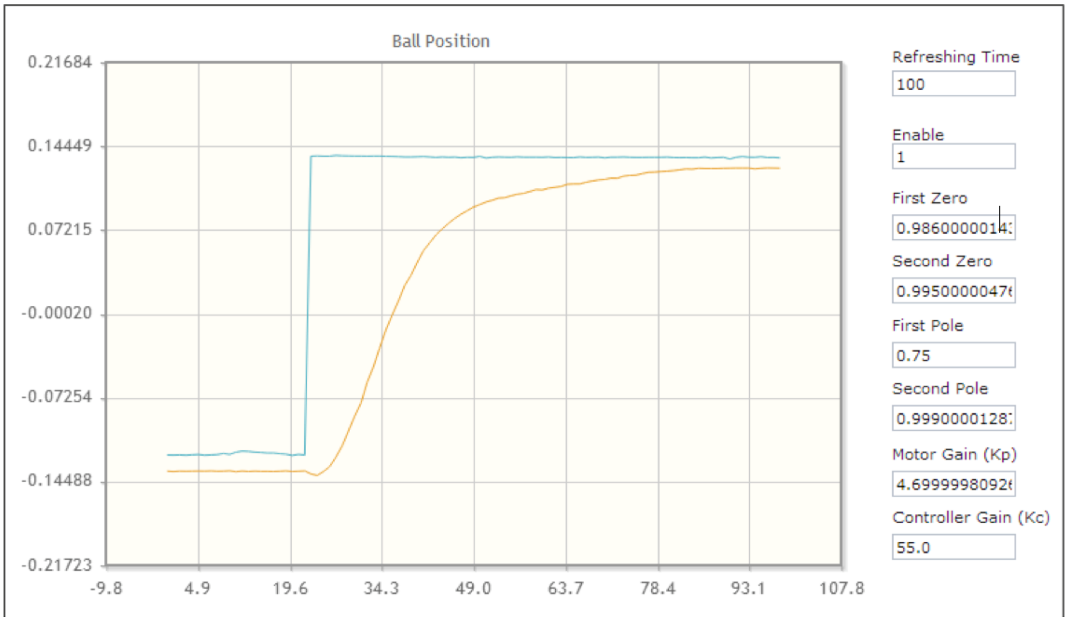

Figure 3. Ball & Beam Controller Performance using the MCS. Blue Line: Reference. Orange Line: System

Results

Assessment activities were designed considering the learning objectives and the student outcomes established in the previous analysis to guarantee alignment between the workshop content and delivery. At the beginning of the semester, students received a diagnostic test that explored their background in some relevant courses. Also, pre-test and post-test were administered for each workshop to determine learning gains. Finally, an oral exam was given to evaluate the student knowledge about the implementation of the controller using the MCS. Results from these activities are presented in the following sub-sections.

Diagnostic Test

The objective of this test was to explore student's background on microcontrollers, programming languages, and control systems at the beginning of each workshop. The questionnaire is provided in the appendix. The course started with a population of 28 students. Figure 4 reveals that although most of students took the microprocessors course, they did not get a high grade on it. This indicated that special attention must be paid on the first workshop.

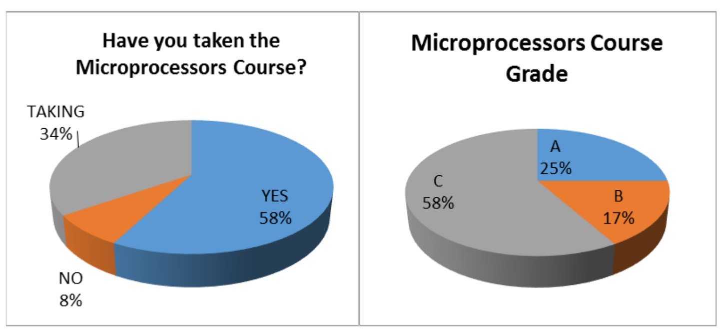

Figure 4. Diagnostic Test. Item 1.

Those who already took the microprocessors course were asked to specify in a scale of five their skills using microcontroller peripherals Figure 5 shows the diagnostic test results. These values were relatively low and were useful to emphasize some of the topics covered in workshops.

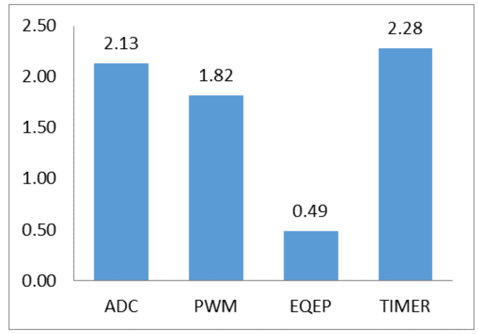

Figure 5. Diagnostic Test. Item 5

A relevant fact about students is their background in programming courses. Figure 6 indicates that all students have passed the programming course as a pre-requisite. This implies that students were expected to complete the assigned programming tasks.

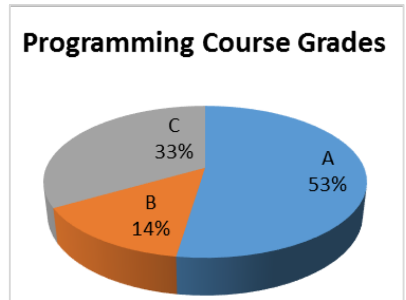

Figure 6. Diagnostic Test. Item 3

One of the questions in the diagnostic test was about students' experience using different programming languages. Students ,were asked to specify in a scale of five their experience using some of the most important languages used in Electrical Engineering. The best known programming language was Matlab, followed by C, and then by Assembly language (see Figure 7).

Finally, although most of the students have approved the microprocessors course, they do not have well understanding on peripheral configuration. Also, all of the students passed the programming course; but they do not have deep knowledge on the most common programming languages taught in the department. These results were a baseline to emphasize some of the topics covered on workshops. The following subsection shows the results obtained in workshops pre and post-test.

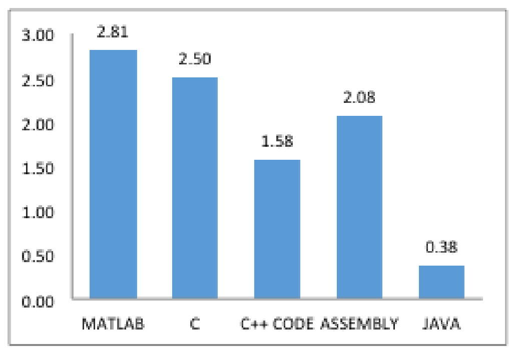

Figure 7 Diagnostic Test. In a scale of 5, what is your experience using the following programming languages?

<u>Pre and Post-Tests</u>

Students took three workshops two hours each in the laboratory. They received a pre-test before and a post-test after each workshop. Please refer to Appendix A for the test items. Tests results were analyzed by comparing students' performance before and after taking the workshop to determine learning gains. Our quantitative variables were the *Score Gain* (SG), defined as the mean difference between scores on each question, and the *Average Normalized Gain* (NG), defined as: $NG = SG/(Q - pre)$, were Q is the question value and *pre* is the media score obtained by the group in the pre-test question[24]. A desired *NG* of 30% was determined using a predefined value suggested by Hake[25]. He defined this value according to a pedagogical study that involved 6,000 students in 62 courses. Data suggested that a *NG* of 30% was the lower bound of what he called *"medium normalized gain"*. Results above this value could be considered as acceptable.

Workshop 1 - basic knowledge that students need to know about embedded control systems (objectives 1, 2, and 3). Table 3 summarizes the mean results obtained from this test; a total of 27 subjects took the workshop. Objectives 1 and 2 were accomplished; however, objective 3 shows a small *NG* value. This means that although the goal is accomplished, students find it difficult to understand the main components in an embedded control C code program.

Table 3. Pre and Post-Test analysis for Workshop 1

Question	1	2	3	4	Total
Objective	1	2		3	
Value	6	4	2	8	20
Pre-Test	2.67	0.58	0.33	2.92	6.5
Post-Test	5.25	2.88	1.54	4.50	14.16
SG	2.58	2.29	1.21	1.58	7.67
NG	78%	67%	73%	31%	57%

Workshop 2 - configuration of the main peripherals of the C2000 microcontrollers (objectives 4, 5, and 6). Students learned the working principle of the Ball & Beam (B&B) sensors, developed a C code program to read the sensor values, and created a GUI to watch them in an easy-to-use environment. Table 4 shows the obtained mean results from workshop 2. Questions 1, 2, and 3 covered the working principle of the B&B sensors and the microcontroller peripheral used to read them, for this reason, these questions evaluated objectives 4 and 5. Questions 4 and 5 assessed objectives 5 and 4 respectively. Results revealed that the goal was accomplished.

Table 4. Pre-Test and Post-Test analysis for Workshop 2

Question	1	2	3	4	5	Total
Objective	4-5			5	4	
Value	5	5	2	5	3	20
Pre-Test	2.52	1.26	0.11	0.48	0.26	4.63
Post-Test	3.59	2.70	1.52	1.85	1.11	10.78
SG	1.07	1.44	1.41	1.37	0.85	6.15
NG	43%	39%	75%	30%	31%	40%

Workshop 3 - the use of difference equations in order to create an embedded controller for the B&B system (objective 7 and 8). A total of sixteen (16) students were evaluated and Table 5 summarizes the obtained results. Objective 7 was assessed in all questions.

Table 5. Pre-Test and Post-Test analysis for Workshop 3

Question	1	2	3	4	Total
Objective	7				
Pre-Test	2.00	3.25	2.63	2.63	9.88
Post-Test	3.00	3.50	5.63	5.25	17.38
SG	1.00	0.25	3.00	2.63	7.49
NG	50%	33%	89%	78%	74%

This workshop revealed to be the most effective with a total mean *PL* value of 74%. Classroom observations indicated that students were motivated to keep using microcontrollers in future developments.

<u>Oral Exam</u>

A set of rubrics was developed to evaluate students in the Oral Exam. These rubrics were written according to the cognitive domain of Bloom's Taxonomy and ABET criteria[26,27] (See Appendix B). Objective 6 was evaluated by the instructor when students developed a GUI interface using Code Composer Studio and GUI Composer. All the students completed the requirements of this task. Objective 8 was evaluated by the instructor during the oral exam. All students developed the B&B controller using the MCU and the objective was accomplished.

Concluding Remarks & Implications

In this work we designed and implemented a methodology to integrate embedded systems in a digital control systems course. To the best of our knowledge, although there have been approaches in this area that use high level tools to help students in the learning process, there is no formal methodology to implement the use of embedded controllers in an educational environment.

A microcontroller based system was developed for the workshops. Experimental results indicated that the system has the same performance compared to the known classic methods (Simulink, LabVIEW). Also, the MCS demonstrated to be well designed since it was an effective tool for implementing the digital controllers of the student projects.

The workshops developed, followed an outcome-based education and a backward design approach. Pre and post-test revealed that the methodology was effective in aligning course content, assessment, and delivery.

Workshop experience provided a good understanding of embedded control systems to students. The process of programming the controller provided students a deeper understanding of how digital control systems are implemented in real world through embedded systems. Also, using Texas Instruments® tools helped in the debugging process. In the past, digital controllers were implemented using microcontrollers, but there were no formal debugging methods for troubleshooting.

This methodology could be used in the future in other engineering courses. Also, the MCS represents a multi-purpose platform that can become a commercial product of pedagogical interest that may be used to improve the learning process in a higher education setting.

Bibliography

[1] G. F. Franklin, M. L. Workman and D. Powell, Digital control of dynamic systems, Addison-Wesley Longman Publishing Co., Inc., 1997.

[2] G. H. Hostetter, Digital Control System Design. Holt, Rinehart and Winston, Inc., New York, New York, 1988.

[3] B. C. Kuo, Digital Control Systems (Holt, Rinehart and Winston, NY), 1980.

[4] C. L. Phillips and H. T. Nagle, Digital control system analysis and design, Prentice Hall Press, 2007.

[5] E. De Graaf and A. Kolmos, "Characteristics of Problem-Based Learning," *International Journal of Engineering Education,* vol. 19, no. 5, pp. 657-662, 2003.

[6] Q. Consulting, "Quanser Consulting Website-Ball & Beam Experiment," 2015. [Online]. Available: http://www.quanser.com/Products/ball_beam.

[7] G. Beauchamp and M. Vélez, "A Process Instrumentation and Control Laboratory," *ASEE Annual Conference Proceedings,* 1995.

[8] C. H. Choi, "A Linear Control Systems Course with Emphasis on Embedded Control," *American Society for Engineering Education (ASEE),* 2010.

[9] G. Beauchamp, M. Jimenez, R. Mulero and A. Ortiz, "Tradeoffs Implementing Digital Control Systems for Electrical Engineering Course Projects," *IEEE Frontiers in Education Conference (FIE),* pp. 1-6, 2012.

[10] P. Martí, M. Velasco and J. Fuertes, "Design of an Embedded Control System Laboratory Experiment," *Industrial Electronics, IEEE Transactions on,* vol. 57, no. 10, pp. 3297-3307, 2010.

[11] Y. Roshan and M. Moallem, "Developing a Course and Laboratory for Embedded Control of Mechatronic Systems," *American Society for Engineering Education,* 2011.

[12] M. Jimenez, G. Beauchamp, R. Mulero and M. Gonzalez, "Integrating Control Concepts in an Embedded Systems Design Course," *IEEE Frontiers in Education Conference (FIE),* pp. 1273-1278, 2013.

[13] R. Streveler, K. Smith and M. Pilotte, "Aligning Course Content, Assessment, and Delivery: Creating a Context for Outcome-Based Education," in *Outcome-Based Education and Engineering Curriculum: Evaluation, Assessment and Accreditation,* K. Mohd Yusof, S. Mohammad, N. Ahmad Azli, M. Noor Hassan, A. Kosnin and S. K, Syed Yusof (Eds.)Hershey, Pennsylvania: IGI Global, 2012.

[14] G. P. Wiggins and J. McTighe, Understanding by design, ASCD, 2010.

[15] J. McTighe and R. S. Thomas, "Backward Design," *Educational Leadership,* 2005.

[16] J. D. Bransford, A. L. Brown, R. R. Cocking and others, How people learn, Washington, DC: National Academy Press, 2000.

[17] E. A. C. a. others, "Criteria for Accrediting Engineering Programs," *ABET Report E1 11/19,* vol. 3, 2003.

[18] G. Beauchamp, "INEL 5508 Digital Control Systems Course Syllabus," UPRM Electrical and Computer Engineering Department, Mayaguez, PR., 2007.

[19] L. W. Anderson, D. R. Krathwohl and B. S. Bloom, A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives, Allyn & Bacon, 2001.

[20] Texas Instruments Incorporated, TMS320F28069 Technical Reference Manual, 2014.

[21] Texas Instruments Incorporated, DRV8833 User's Manual, 2014.

[22] J. F. Patarroyo and G. Beauchamp, "A Microcontroller Based System for Improving the Learning Process of Undergraduate Students in the Area of Control Systems," *SACNAS Annual Conference*, 2014.

[23] J. F. Patarroyo, G. Beauchamp and A. Santiago, "Design and Development of an Educational Microcontroller Based Control Station (Paper submitted)," *IEEE Frontiers In Education (FIE),* 2015.

[24] A. E. Kelly, R. A. Lesh and J. Y. Baek, Handbook of design research methods in education: Innovations in science, technology, engineering, and mathematics learning and teaching, Routledge, 2008.

[25] R. R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," *American journal of Physics,* vol. 66, no. 1, pp. 64--74, 1998.

[26] B. S. Bloom and D. R. Krathwohl, Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain, Longmans, 1956.

[27] Commission, Engineering Accreditation, "Criteria for Accrediting Engineering Programs," *ABET Report E1 11/19*, vol. 3, 2003.

Appendix A: Workshops Tests

Diagnostic Test

1) Have you taken the *Microprocessors I* course?
   a. Yes
   b. No
   c. Taking
   - If your answer is yes, indicate the grade obtained in this course: __

2) Have you taken the *Microprocessors Interfacing* course?
   a. Yes
   b. No
   c. Taking
   - If your answer is yes, indicate the grade obtained in this course: __

3) Have you taken the *Programming Algorithms* course?
   a. Yes
   b. No
   c. Taking
   - If your answer is yes, indicate the grade obtained in this course: __

4) Being 0 the lowest level of understanding and 5 the highest, indicate your knowledge level on the following programming languages.
   a. Matlab
   b. C Code
   c. C++ Code
   d. Assembly
   e. Java

5) Being 0 the lowest level of understanding and 5 the highest, indicate your knowledge level on the following microcontroller modules.
   a. Analog to Digital Converter (ADC)
   b. Pulse Width Modulator (PWM)
   c. Quadrature Encoder Unit (eQEP)
   d. Timer Interrupts

Test 1

1) Indicate 3 differences between implementing a digital controller using a MCU and using Simulink (6pts).

2) Indicate which are the main 4 modules of the microcontroller used in the Ball & Beam control (4pts).

3) Besides the microcontroller and power supply, which components are needed to control the Ball & Beam? (2 pts).

4) Explain the task done on each of the following sections of a basic C code microcontroller program (8pts).
   - General Declarations
   - Initializations
   - Infinite Loop
   - Timer Interrupts

Test 2

1) Explain the working principle of the sensor that measures the ball position in the Ball & Beam System. Which microcontroller module should be used to read this signal?

2) Explain the working principle of the sensor that measures the angle of the motor in the Ball & Beam system. Which microcontroller module should be used to read this signal?

3) Explain the working principle of an H Bridge motor driver (DRV8833).

4) Explain how the microcontroller could be used to generate an analogic output that moves the motor using an H bridge. Which microcontroller module could be used in this task?

5) Explain how to make an analog signal conditioning circuit for the sensor that measures the position of the ball in the Ball & Beam system.

Test 3

1) In a microcontroller based control program, which peripheral is used to define the sampling period?

2) In which part of the microcontroller program should we insert the digital controller statements to make it work at the defined sampling period?

3) Explain how to implement the following transfer function in the microcontroller using C Code language.

$$G(z) = \frac{Y(z)}{X(z)} = \frac{z}{z-1}$$

4) For the following system:

$$G(z) = \frac{Y(z)}{X(z)} = \frac{z^2 + 3.2z + 7}{z^3 + 2.7z^2 + 1.2z + 1}$$

   a) Indicate how many samples of the input should be stored to compute an output signal.
   b) Indicate how many samples of the output are needed.

Appendix B: Rubrics for Assessing the DCS Project Oral Exam

Group:_______ Name:____ Date:_________________

#	Item	Outcome	%	Good	Acceptable	Insufficient	Points	Total
1	Punctuality	7	20%	The student presents the report on time (80-100)	The student presents the report one day late. (70-79)	The student has two or more days without delivering his/her work. (0-69)		
2	Design of Controllers	3	10%	The student designed different types of controllers (P, PI, PID, Lead, Lag, Lead-Lag) (80-100).	The student designed a few types of controllers (70-79)	The student does not have a final controller design (0-69)		
			10%	Student evaluated the performance of the designed controllers (80-100)	Student gave a vague evaluation of the performance of the designed controllers (70-79)	Student is not capable of evaluating performance the designed controllers. (0-69)		
3	Simulations	8	10%	The student simulated the designed controllers in Simulink using saturation blocks. (80-100)	The student simulated some of the designed controllers in Simulink but did not use saturation blocks. (70-79)	The student does not simulate any of the proposed controllers (0-69)		
			10%	The student is capable of explaining whether the controller meets or not the design requirements (80-100)	The student barely explains whether the controller meets or not the design requirements (70-79)	The student cannot explain the design and simulation process.(0-69)		
4	Controller Implementation	4	7%	The student implemented the designed controller effectively on Simulink-Quarc (80-100)	The student implemented the designed controller on Simulink with some inaccuracies (70-79)	The student did not implement the designed controller on Simulink (0-69)		
			7%	The student used difference equations to develop a C Code program that performs the designed controller. (80-100)	The student developed a C Code program that performs the designed controller with errors. (70-79)	The student did not develop a C Code program that performs the designed controller. (0-69)		
			6%	The student explains how he/she used the block diagram of the system to develop an embedded digital controller. (80-100)	The student barely explains how to use the block diagram of the system to develop an embedded digital controller. (70-79)	The student is not capable of explaining the implementation process of an embedded controller. (0-69)		
5	Controller Performance	5	10%	The student implemented controller meets the design requirements using Simulink and the Microcontroller. (80-100)	The implemented controller works but does not meet the design requirements using Simulink and/or the Microcontroller. (70-79)	The implemented controller is unstable or it does not work. (0-69)		
			10%	The student can explain the discrepancies between the simulated and the real controller performance. (80-100)	The student barely explains the performance of the implemented controller. (70-79)	The student is not capable of justifying this behavior.(0-69)		
						Final Grade		

#	Course Outcomes	ABET Outcome
3	Design a single-input single-output feedback controller capable of achieving the design criteria for the system.	c
4	Implement a digital controller using a digital computer and software	e
5	Validate the performance of the closed-loop system	b
7	Preparation of a written report about the final project	g
8	Use modern engineering tools (MATLAB, labVIEW, PSPICE…) for the design and implementation of a process control and instrumentation system	k