

Evaluation of an Introductory Embedded Systems Programming Tutorial using Hands-on Learning Methods

Dr. Gregorio E Drayer, Georgia Institute of Technology

Gregorio (a.k.a. Greg) is electrical engineer and magister in systems engineering from Simon Bolivar University (USB) in Caracas, Venezuela. He received academic tenure in 2009 with the Department of Processes and Systems at USB. At the time of this submission, Greg recently earned his Ph.D. from School of Electrical and Computer Engineering, with a minor in Aerospace Engineering, at Georgia Tech, sponsored by the first International Fulbright Science and Technology Scholarship awarded to a Venezuelan by the U.S. Department of State. His advisor is Dr. Ayanna M. Howard, director of the Human-Automation Systems Laboratory. Greg is member of the Institute of Electrical and Electronic Engineers (IEEE) and the American Institute of Aeronautics and Astronautics (AIAA). He has served as referee for IEEE Transactions on Fuzzy Systems, the journal of the Faculty of Engineering at the Central University of Venezuela, and the International Conference on Environmental Systems.

Dr. Ayanna M Howard, Georgia Institute of Technology

Ayanna Howard is the Motorola Foundation Professor in the School of Electrical and Computer Engineering at the Georgia Institute of Technology. She received her B.S. in Engineering from Brown University, her M.S.E.E. from the University of Southern California, and her Ph.D. in Electrical Engineering from the University of Southern California in 1999. Her area of research is centered around the concept of humanized intelligence, the process of embedding human cognitive capability into the control path of autonomous systems. This work, which addresses issues of autonomous control as well as aspects of interaction with humans and the surrounding environment, has resulted in over 130 peer-reviewed publications in a number of projects – from scientific rover navigation in glacier environments to assistive robots for the home. To date, her unique accomplishments have been highlighted through a number of awards and articles, including highlights in USA Today, Upscale, and TIME Magazine, as well as being named a MIT Technology Review top young innovator of 2003, recognized as NSBE Educator of the Year in 2009, and receiving the Georgia-Tech Outstanding Interdisciplinary Activities Award in 2013. From 1993-2005, Dr. Howard was at NASA's Jet Propulsion Laboratory, California Institute of Technology. Following this, she joined Georgia Tech in July 2005 and founded the Human-Automation Systems Lab. She also served as Chair of the multidisciplinary Robotics Ph.D. program at Georgia Tech for three years from 2010-2013.

Evaluation of an Introductory Embedded Systems Programming Tutorial using Hands-On Learning Methods

Gregorio Drayer and Ayanna Howard

drayer@gatech.edu, ayanna.howard@ece.gatech.edu

School of Electrical and Computer Engineering

Georgia Institute of Technology

Abstract

The rapid advancement of low cost embedded systems invites engineering educators to deliver content and skills while engaging students in hands-on projects that may potentially make use of a variety of platforms. From proprietary to open source hardware and software, from microcontrollers to embedded operating systems (OS) devices, students today are challenged to accelerate their learning pace by working on real-world projects in a supervised environment. Currently, students rely on self-guidance in order to develop the knowledge base necessary for achieving the goals of their team projects with respect to embedded systems. This paper presents the results of an embedded systems programming tutorial piloted with a group of 15 undergraduate students from across the engineering disciplines and with a mix of sophomores through seniors. The tutorial included a series of three lecture modules prepared to introduce concepts on embedded systems. The modules were tightly coupled with hands-on exercises that employed the DE2i-150 development board, aimed to introduce students to the development of digital systems based on an Altera field programmable gate array (FPGA) in conjunction with an Linux-based embedded OS running on an Intel Atom processor. The first module provides an overview of the various inputs, outputs, sensors, and displays of the board. The second module introduces the embedded OS and guides students in establishing a high-speed Peripheral Component Interconnect Express (PCIe) link between the Atom processor and the FPGA. The third module focuses on implementing a custom C++ application written by students for real-time processing of inputs from four push buttons. Results show that the three lecture modules of 30 minutes each, coupled with the hands-on projects, offer a good introduction to the complexity of the DE2i-150 board. Surveys collected before the first module and after the third show a generally positive outcome. Recommendations for future efforts focus on incorporating more complex C++ applications concurrent with FPGA development.

1 Introduction

The “Internet of things”¹ challenges engineering educators to deliver content and skills while engaging students in hands-on projects that employ a variety of embedded computing platforms. From proprietary to open source hardware and software, from microcontrollers to embedded OS devices, students today have an opportunity to take more active control on their learning by working on real-world projects in a supervised environment. That is the goal of a multi-disciplinary design program at the Georgia Institute of Technology, called Vertically Integrated Projects (VIP) Program,² which offers undergraduate students a research and development opportunity to participate in team-oriented projects from their sophomore to senior years. Although the majority of these interdisciplinary teams are based on designing, programming, and deploying embedded systems in various application scenarios, there is currently no common curriculum module focused on embedded systems programming.

Currently, students are forced to rely on themselves to acquire the skills on embedded systems necessary for achieving the goals of their projects. This typically has resulted in a steep learning-curve, especially for new students and new teams that join the program. As such, we have developed an embedded systems programming tutorial that is applicable to the structure of the VIP program (i.e. a curriculum that can train students irrespective of their engineering discipline or class level). We believe this curriculum module will have broad impact on the academic community, at large, since we focus on extracting common knowledge that can be shared across a diverse mix of students.

This paper presents the results of our embedded systems programming tutorial³ piloted with the I-Natural VIP team, which consists of a group of 15 undergraduate students from across the engineering disciplines and with a mix of sophomores through seniors. The tutorial included a series of three lecture modules prepared to introduce concepts on embedded systems. The modules were tightly coupled with hands-on exercises that employed the DE2i-150 board,⁴ presented in Figure 1, aimed to allow students to develop digital systems based on an Altera FPGA in conjunction with an embedded OS running on an Intel Atom processor. Although there are other less complex boards for digital systems,⁵ the DE2i-150 allows for basic exercises on digital systems⁶ all the way to complex projects and other research.^{7,8}

This paper is organized as follows. Section 2 briefly describes the tutorial and its modules, while Section 3 explains the methodology used to evaluate the tutorial and performance of participants. Section 4 then presents the results obtained and finally Section 5 discusses the results and concludes the paper.

2 The Tutorial and Its Modules

This section briefly introduces the objectives and contents of each of the three modules. They were delivered in the classroom during 30 minutes each. Their goal was to provide a structured introduction on embedded systems to the participating students and enable them to continue on their own by elaborating on the tools and skills offered in the tutorial. The next subsections present such brief descriptions.

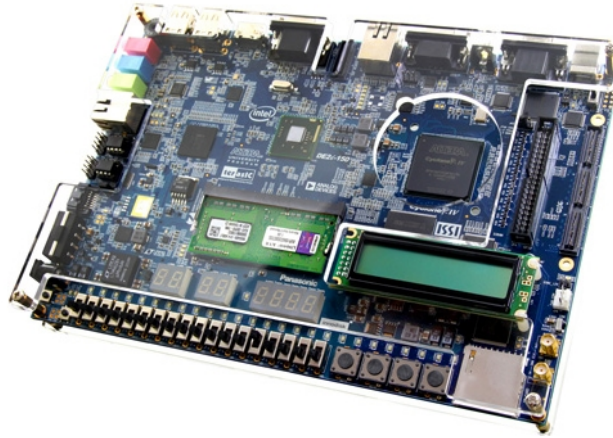


Figure 1: Altera/Intel DE2i-150 Development Board. Photo courtesy of TerasIC Technologies, Inc.

2.1 Module I

The first module was entitled “Introduction to the DE2i-150 Development Board” and made use of the Control Panel software developed by TerasIC Technologies for this particular board model. It also required the installation of the software Quartus II Web Edition, available at no cost from the Altera Corporation website.

Objectives of Module I To learn how to set up and power up the DE2i-150 development board, to have installed the USB-Blaster driver to program the field-programmable gate array (FPGA) with JTAG standard and active serial programming (ASP), to set up the DE2i-150 Control Panel that allows to “bring up” and test the board, to become familiar with its sensors and some of its input & output (I/O) devices and displays, and to explore state-of-the-art hardware for the development embedded systems.

Outline of Module I Getting started – materials and software; Layout of the board; USB-Blaster driver installation; Setting up the DE2i-150 Control Panel; Exploring the DE2i-150 board; Safe shutdown; and Summary.

2.2 Module II

The second module was entitled “Programming C in a Yocto Environment” and guided participants to navigate in an embedded-Linux environment, install drivers for the FPGA, and compile and run a C program.

Objectives of Module II To install a VNC client to access VNC server on the board from the laptop of students, to install a PCIe driver for high-speed communication between the Intel Atom

N2600 and the Altera Cyclone IV FPGA, and to compile and run a C program in a embedded-Linux environment.

Outline of Module II Getting started – materials and software; UltraVNC installation; Setting up VNC access to the board; Compiling a C program in Yocto; Installing the PCIe driver; Running the C application; Uninstalling the PCIe driver; Safe shutdown; and Summary.

2.3 Module III

The third module was entitled “Writing Your Own C Code” and consisted of writing and compiling custom C code for real-time interaction between the push buttons and LED’s of the DE2i-150 board.

Objectives of Module III To write custom C code for an application that enables interaction between buttons and LED’s, making use of (i) the Cyclone FPGA, (ii) the Atom processor, and (iii) PCIe high-speed communication; to analyze the behavior resulting from the custom code, and to identify its main functions.

Outline of Module III Getting started – materials and software; Setting up VNC access; Writing your C code; Compiling your C code; Installing the PCIe driver; Running your C application; Uninstalling the PCIe driver; Safe shutdown; and Summary.

3 Methodology

The evaluation of the tutorial was conducted through surveys given to the students before the first module and after the third. The questions aimed to explore the skills brought by students to the classroom and to have them perform self-evaluation of how their preparation to develop embedded systems may have improved after the third module.

The following subsections specify more details about the participants, and enumerate the questions included in each one of the surveys.

3.1 Participants

This tutorial was offered as an optional resource of the I-Natural team of the VIP Program. The I-Natural team is also a course and is composed of students from various areas of specialization, and ranging from sophomore to senior levels. The course numbers associated with the I-Natural VIP course are indicated by the major of the student, class level, and number of academic credits. These courses are ECE 2811, 381X, 481X (with the first digit indicating the level: 2 = sophomore; 3 = junior; 4 = senior and the last digit indicating the number of credits (X = 1 or 2)). Students may also use their I-Natural VIP participation for Senior Design credit. They are encouraged to

develop hands-on projects, from which the outcome may serve to approach or overcome a physical limitation of human users by means of human-system interfaces and robotic devices.

For this study, activities were optional for those students who had been part of the I-Natural team in the previous semesters. A total of 15 students agreed to participate by performing the activities of the tutorial. The composition of the group of students was determined through the pre-tutorial survey. Their involvement in this pilot project consisted in grouping them in teams of three and having them perform the exercises of the tutorial modules without mixing the teams. The pre-tutorial questions are presented in Subsection 3.2 and the post-tutorial questions are enumerated in Subsection 3.3. The results of the surveys is presented subsequently in Section 4.

3.2 Pre-Tutorial Survey Questions

The questions of the pre-tutorial survey collected initial information about the composition of the I-Natural team. They were the following:

1. What is your major, minor and year in school?
2. How much experience do you have with programming?
3. How much experience do you have in embedded systems design?
4. How much have you considered using an embedded system in any of your class projects?
5. Have you worked with embedded systems before? If, yes, please specify the course(s), projects developed, and devices used.
6. Have you worked with open-source embedded systems? i.e. Arduino, Raspberry Pi, etc. Please specify with which devices you have worked and enumerate the projects developed.

For Questions 2-4, students selected their response from a simple choice list of options. The options were: (a) A lot, (b) Some, (c) A little, and (d) None. Questions 5 and 6 included fields that offered students the opportunity to elaborate in their responses.

3.3 Post-Tutorial Survey Questions

The questions of the post-tutorial survey allowed for collecting feedback from the students about their experience conducting the exercises in the tutorial modules. The questions were the following:

1. How much will you consider using an embedded system in any of your future class projects?
2. How much has your confidence increased in using an embedded system?
3. How clear were the written instructions provided in the tutorial?
4. Was the amount of time provided sufficient to complete the tutorial modules?
5. How satisfied were you in achieving the objectives of the tutorial modules?

6. How much more capable do you feel at contributing to your VIP project with tasks on embedded systems?
7. Explain which module or specific task of the tutorial was the most helpful to you and why.
8. Explain what capabilities of the DE2i-150 board you would like to learn more about. Explain how you could employ the board on your VIP project.

The approach to the response of this survey was similar to the first. In this case, Questions 7 and 8 were open ended and allowed students to provide additional information.

4 Results

This section presents the distribution of responses to the questions of the surveys collected from the participants and described in Subsections 3.2 and 3.3. Subsection 4.1 and 4.2 illustrate the results of the pre-tutorial and post-tutorial surveys, respectively.

4.1 Pre-Tutorial Survey Results

The distribution of responses to Question 1 of the pre-tutorial survey are presented in Figure 2. This illustration serves to display the composition of the group of participants in terms of their major and minor areas of study, and their year in school. In this case the options reported were: Industrial and Systems Engineering (ISyE), Mechanical Engineering (ME), Computer Engineering (CompE), Biomedical Engineering (BME), and Electrical Engineering (EE), and Computer Science (CS).

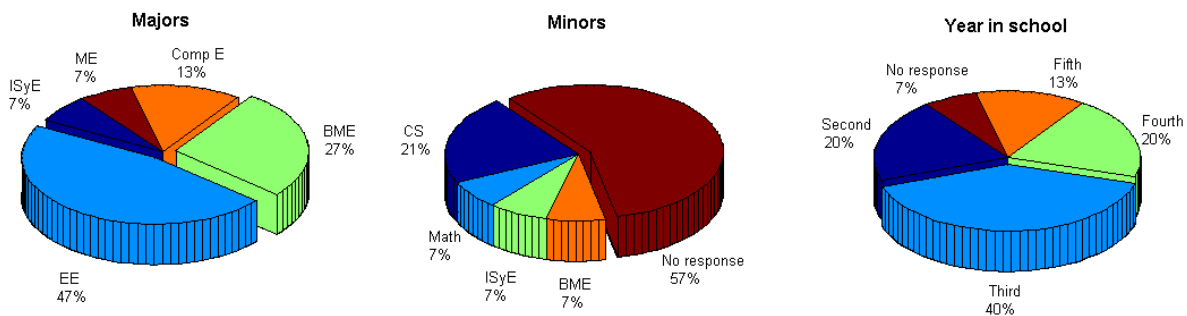


Figure 2: Pre-Tutorial Survey - Question 1: Composition of the group of participants

The experience of students relevant to programming and their familiarity with embedded system design by use in previous courses is illustrated with the distribution of their responses to Questions 2, 3, and 4 of the pre-tutorial survey. These results are shown in Figure 3 and labeled “Experience in Programming” and “Embedded systems experience and use consideration for class projects.”

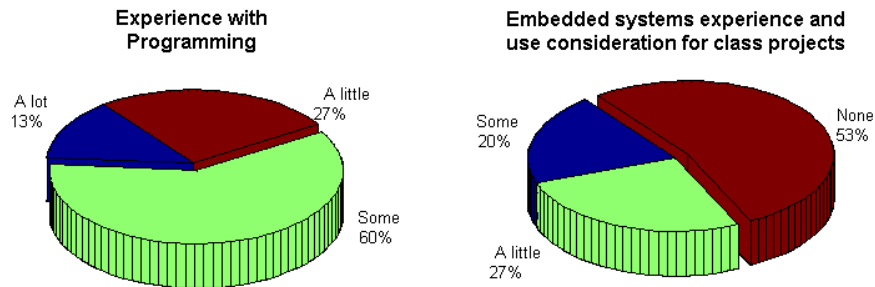


Figure 3: Pre-Tutorial Survey - Questions 2 through 4: Experience in programming and with embedded systems.

The distribution of responses to Question 5 and 6 of the pre-tutorial survey are shown in Figure 4. Their responses provide further details about the source of their previous experience and the particular hardware used in various projects.

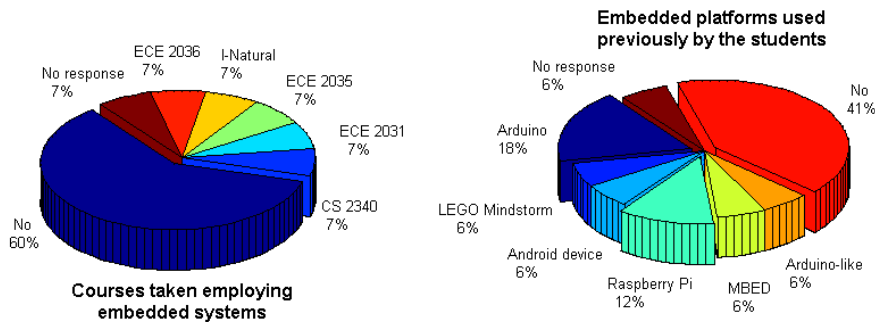


Figure 4: Pre-Tutorial Survey - Questions 5 and 6: Further details about the experience of participants and platforms used in previously.

4.2 Post-Tutorial Survey Results

The distribution of responses to Questions 1 and 2 of the post-tutorial survey provide a sense of the reception of the tutorial modules by the students, their increase in confidence in employing them, and their general motivation after completing the modules. These distribution are presented in Figure 5, with plots labeled “Considering embedded systems for future class projects” and “Confidence increase in employing embedded systems.”

Participants also had the opportunity to evaluate the tutorial itself and its modules by responding to Questions 3, 4, and 5. The distribution of their responses to these questions are presented in Figure 6.

Questions 6 and 7 of the post-tutorial survey were included in an effort to encourage students to appreciate the usefulness of the modules while conducting a self-evaluation of the skills they

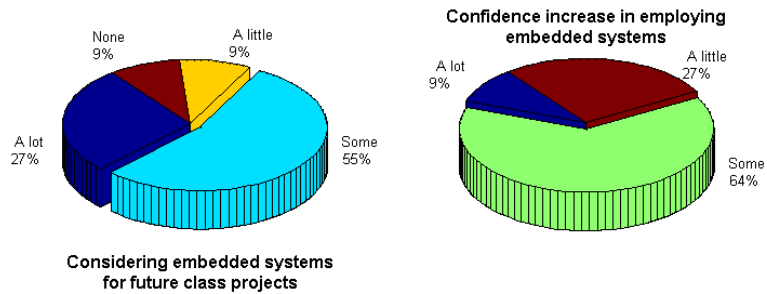


Figure 5: Post-Tutorial Survey - Questions 1 and 2: Reception and motivation.

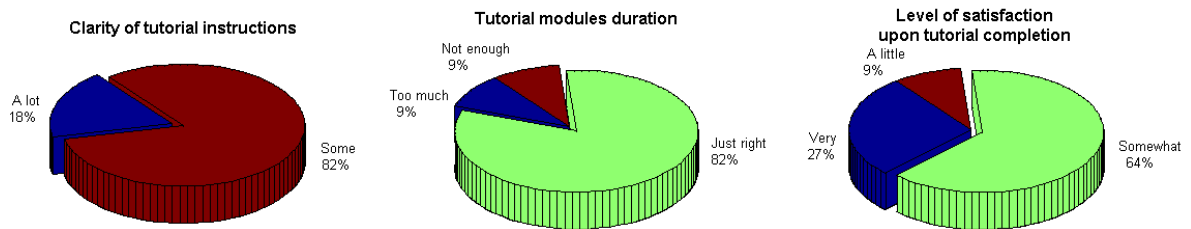


Figure 6: Post-Tutorial Survey - Questions 3 through 5: Evaluation of the tutorial modules by participants.

acquired. Their responses are reported in Figure 7 and contains their assessments of new skills acquired and on the usefulness of individual tutorial modules.

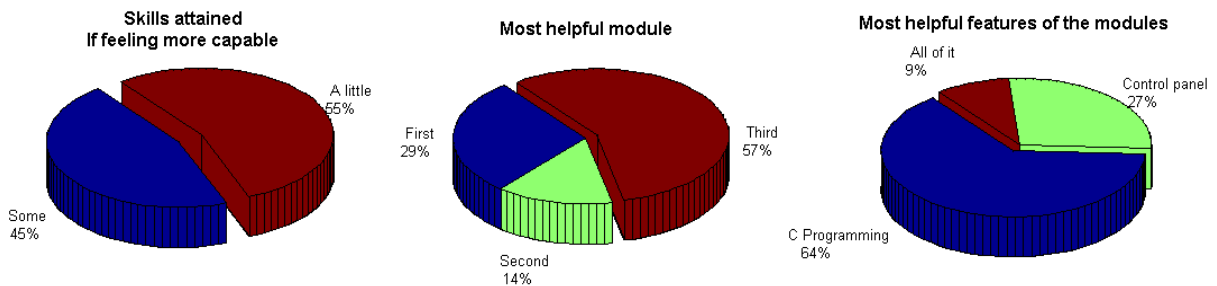


Figure 7: Post-Tutorial Survey - Questions 6 and 7: Skill transfer and module effectiveness according to participants.

Finally, and more specific to the development board DE2i-150, participants provided responses to the question exploring which features of the board were of greater interest to them after completing the third tutorial module. The distribution of their responses is presented in Figure 8.

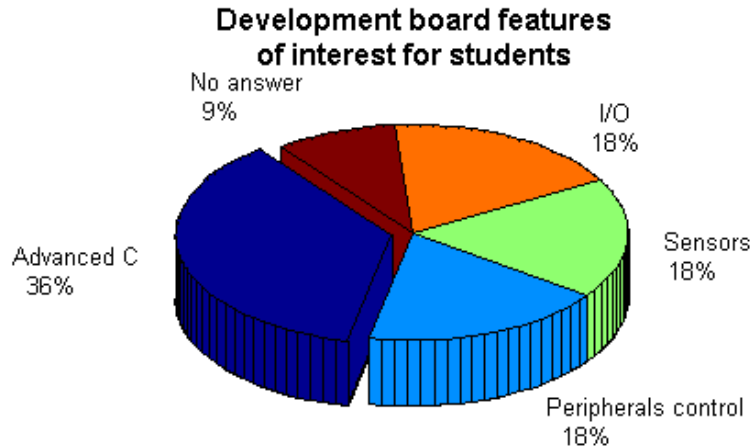


Figure 8: Post-Tutorial Survey - Question 8

5 Discussion

In general, the evaluation of the tutorial can start by considering the results presented in Figures 2, 3 and 5. With regards to the composition of the group, Figure 2 reports that the majority of the participating students, or 40%, are in their third year in school, with a symmetric percentage of 20% of students in their second and fourth year. Also by observing Figure 2, the majority of the students specializes in electrical engineering, seconded by biomedical engineering, and followed by computer engineering. Not all of the participating students is decided about a minor the majority of those who had decided had chosen computer science for their minor. Given this composition, the exposure to computer programming reported in Figure 3 is encouraging, with 60% of students having “some” experience and 13% reporting “a lot.” Even though an important majority of the participating students had some skills in computer programming, their experience in developing and designing embedded systems was considerably limited, as shown in Figure 3, which reports that only 27% of students have “a little” experience and seldom considered employing embedded systems in their class projects before the tutorial. A more detailed view of the experience of the experience of students can be obtained by observing Figure 4, where almost two thirds of the participants reported not having taken any course employing embedded systems. Of those who had, the majority took place in electrical and computer engineering or computer science courses, employing hardware such as Arduino, Raspberry Pi, and LEGO Mindstorms. However, by observing Figure 5, after completing the tutorials, a greater number of students seems to consider employing embedded systems in their class projects; 27% of students selected “a lot” and 55% consider it to “some” extent. Such a short tutorial appears to have considerably increased the confidence of participants in approaching projects that involve embedded systems: to 9% of them their confidence increased “a lot;” 64% increased “some;” and 9% increased “a little.” All participants reported positive changes in their confidence to some degree; none of them reported a non-positive (*i.e.* zero) change of confidence.

Other interesting details in the evaluation of the tutorial can be extracted from Figure 7. In this case, all participants reported feeling at least a little more capable in developing embedded systems, with 45% considering themselves “some” more capable. This figure also allows observing detail about which of the tutorial modules was more helpful and why. Surprisingly, most participants considered that the second module was the least helpful. One reason for this might be that the third module reuses some of the same steps taught in the second module to achieve its goals, giving the impression to students that perhaps it could have been merged into a single module. This can be evidenced by observing the interest of participants in the features taught in the third module; the most helpful feature corresponds to the C Programming exercises contained in both the second and third modules. Still, somewhat unexpected was the helpfulness of the first module. This module aimed to explore the capabilities and features of the DE2i-150 board. Nevertheless, it proved to have been helpful in providing an overview of the board and its workings. This is further evidenced in the interest that participants showed in expanding their knowledge on other capabilities of the board, as shown in Figure 8.

As for the tutorial structure and contents, Figure 6 offers an evaluation of the modules by the participating students. From these results it can be observed that students considered that the tutorial instructions were somewhat clear at least, with 18% of them evaluating the clarity of the instructions as “a lot.” One may think that the possible defect in clarity would have been caused by the limited amount of time allocated for the tutorial. However, the vast majority of participants considered that the duration was “just right;” only 9% did not think that 30 minutes was enough to complete the modules. These results challenge future facilitators of this tutorial to improve the delivery of its content and improve the contents themselves by expanding the amount of C programming or by including exercises that employ the peripherals of the board. Even though these results challenge the facilitators in the future, the level of satisfaction upon completion of the tutorial was generally high, with 64% being “somewhat” satisfied and 27% being “very” satisfied.

6 Conclusion

As new technologies, software tools, and electronic devices become available, students are increasingly challenged to acquire skills for the development of embedded systems. Both lecturers and students face the necessity to deliver or learn a diversity of programming languages, development approaches, and design methodologies. This paper presented the evaluation of a tutorial that employs the DE2i-150 Development board to introduce undergraduate students to the development of embedded systems. Results show a moderate success for the tutorial and the opportunity for improvements by including more programming modules that make use of peripherals of the DE2i-150 Development Board. As a pilot, the tutorial and this paper provide a stepping stone for instructors who may want to give continuity to this effort by preparing more elaborated modules for the introduction of undergraduate students to the discipline of embedded systems.

Acknowledgement

Curriculum development activities were supported by a gift made by the Intel Foundation to the School of Electrical and Computer Engineering at the Georgia Institute of Technology.

References

- ¹ Luigi Atzori, Antonio Iera, and Giacomo Morabito. The internet of things: A survey. *Computer Networks*, 54(15):2787 – 2805, 2010.
- ² Randal Abler, Edward Coyle, Rich DeMillo, Michael Hunter, and Emily Ivey. Team-based software/system development in the vertically-integrated projects (vip) program. In *Advanced Information Technology in Education*, pages 287–294. Springer, 2012.
- ³ Gregorio Drayer and Ayanna Howard. Intel curriculum on embedded systems, 2013. <http://humanslab.ece.gatech.edu/IntelCurriculum/>. Retrieved on February 14, 2014.
- ⁴ Intel Embedded University Program. Altera university program: De2i-150 fpga development kit. Online, 2013. <http://www.intel.com/content/www/us/en/education/university/embedded-university-program/curriculum/de2i-150-fpga-dev-kit.html>. Retrieved on January 3, 2014.
- ⁵ Altera University Program. De0-nano development and education board. Online, 2012. <http://www.altera.com/education/univ/materials/boards/de0-nano/unv-de0-nano-board.html>. Retrieved on January 3, 2014.
- ⁶ William Kleitz. *Digital Electronics with VHDL, Quartus II Version*. Pearson Prentice Hall, 2006.
- ⁷ Tian Gao. *FPGA of Acceleration of Stochastic Simulation*. PhD thesis, Cornell University, 2014.
- ⁸ Andreas Knirsch and Ing Joachim Wietzke. Can2wifi: Project report. Technical report, Cornell University, 2013.