Hands-on Teaching of Embedded Systems Design Using FPGA-Based tPad Development Kit

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Abstract

Modern embedded systems design relies on heavy use of Intellectual Property (IP) and involves both hardware and software design. Moreover, three is an increasing unitization of a diverse set of I/O ports in embedded systems including video, audio, Ethernet, etc. In order to reflect these trends in education in a hands-on manner, a platform is needed that allows fast integration of hardware and software, rapid prototyping capability, and rich IP library covering processor cores, I/O interface standards, arithmetic and signal processing functions, etc. The t-pad development kit, by Terasic, which is based on the DE2-115 development board, designed around the Altera's Cyclone IV FPGA, provides a suitable platform for hands-on education of modern embedded systems design. We have developed a series of example-driven hands-on tutorials to guide students to a comprehensive embedded system design flow in a bottom-up fashion. These tutorials were developed and verified by summer interns from Cañada College who spent Summer 2011 at San Francisco State University. The tutorials are currently being used in an embedded systems design course at SFSU. A course project realizing a complex embedded system in teams of no more than four students is an integral part of this course. The results show that using this platform not only generates excitement and motivation in students, but also enhances their learning and teaches them skills of modern embedded systems design.

Keywords

Development kit, Embedded Systems, FPGA, Intellectual Property, tPad

1. Introduction

Design of modern embedded systems involves hardware and software co-design, System-On-Chip (SOC) integration, use of Intellectual Property (IP), and various I/O standards. Due to the diverse required background, providing students with an educational experience of the holistic design of a modern embedded system is very challenging. Often students are taught different aspects of an embedded system in different courses without an opportunity for students to experience the complete design flow in a hands-on manner. Hands-on methods are proven to be the most effective for engineering teaching [1].

FPGA provides an ideal platform for low-cost and rapid prototyping of SOC (also referred to as System-On-Programmable-Chip (SOPC) [2]). Nowadays FPGA's come with embedded processors in the form of either hard or soft processor cores. Hence, such FPGAs provide an ideal platform for course projects in an embedded system design course for hands-on education.

A modern embedded system has diverse set of I/O devices (audio, video, camera, touch panel display etc). Offering so many options to student course projects is challenging. tPad development kit by Terasic [3] offers a cost-effective solution to this need, by offering an FPGA-based board that is equipped with a rich set of I/O ports from simple sliding switches, pushbuttons, and LEDs to more advanced interfaces such as touch panel LCD display, camera, video and audio I/O, Ethernet, USB, etc. All these come with required IPs to be able to quickly utilize these resources in a design. The tPad uses the Altera's Cyclone IV FPGA, which is supported by the Altera's Electronic Design Automation (EDA) tools [4].

We have setup a design flow and a set of example-drive tutorials that guide students in the use of the EDA tools and the tPad. The design flow and tutorials were developed by four students from Cañada College during an internship at SFUS in Summer 2011. This setup is used in teaching an embedded systems design course at San Francisco State University (SFSU) in Fall 2011. The course is a project-based course where students are encouraged to make use of the tPad features to realize a complex embedded system. The results indicate that the developed methodology enables effective teaching of comprehensive aspects of embedded systems design in a hands-on manner. It not only creates excitement and motivation among the students, but also enhances their learning.

2. tPad Development Kit

tPad is an FPGA development kit that is equipped with a rich set of I/O ports and interfaces. It contains the Altera Cyclone IV FPGA, LCD touch panel display, camera, video, audio, VGA, Ethernet, USB, and IR interfaces. Hence, it provides comprehensive design platform for embedded and multimedia-based systems. This platform includes hardware, Altera's EDA tools, intellectual property (IP), and reference designs for developing embedded software and hardware in a wide range of embedded applications. This is an ideal platform for hands-on education of embedded systems in classroom environments.

3. Embedded Systems Design Flow

Fig. 1 shows the design flow used for embedded systems design using the Altera EDA tools and the tPad development kit. Quartus tool is used for designing custom hardware. Nios II soft-core processor is an IP which is a reconfigurable core processor. The system level hardware implementation using Nios II processor, customs hardware, and hardware IPs is realized in Qsys tool. The software for the Nios II processor is developed using C/C++ and is compiled using Eclipse tool. Finally the software and hardware are linked together and downloaded to the tPad FPAG board.

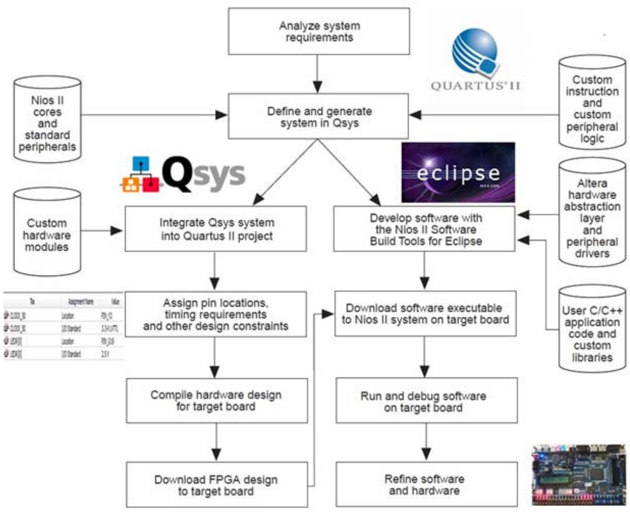


Fig. 1: Embedded System Design Flow [5]

4. Use of Intellectual Property (IP)

The tPad comes with a library of IPs supporting the interface to various I/O ports. The IPs are available to designers in the form of custom HDL codes as well as components for system integration in Qsys environment. Moreover, Altera University program offers a rich set of IPs to support use of the tPad development board. These IPs include clock signals, PLL, audio and video IP suites, bus bridges and communication, memory, and I/O.

5. Example Driven Tutorials

The industry tools come with very comprehensive manuals that are not targeted for student audience. We have developed a series of self-study tutorials that will guide the students through the entire design flow. The first tutorial deals with an introduction to the development kit and its features. The second tutorial focuses on the hardware-only design flow. It introduces the hardware design flow using a binary adder example that takes numbers from the sliding switches and displays the result on the seven-segment displays and the LCD. Students are asked to modify this example and convert the adder to an Arithmetic Logic Unit (ALU). In the next tutorial, the studnets realize the same binary adder example using hardware-software co-design flow by using the flow in Fig. 1. Students are asked to change the design to an ALU by minor modification of the hardware and software. The last tutorial is targeted to teach the use of the touch LCD. The tutorial provides the same example of the binary adder (processor-based) except that the results are shown on the touch panel LCD and the input numbers are set by the touch. Again as a practice, students are asked to modify the design from an adder to an ALU.

We are using the above tutorials in teaching embedded systems design course. The provided tutorials give student a quick start in using the board and tools. Students are provided with additional homework early in the semester that requires them to read and practice the tutorials.

6. Course Projects

Embedded systems design course at SFSU is a master level course which can also be taken by senior-level undergraduate students. The course is a project based, and students are required to forms teams of no more than 4 students and carry out the design of a fairly complex embedded system using the tPad and the Altera tools. The minimum requirements of the project are as follows: it must have both hardware and software components and it must utilize the touch panel LCD for user interaction. Students are also encouraged to have video components in their projects. Students submit their project proposals by the end of the first month in the semester and they receive feedback on design alternatives, solution selection process, setting realistic design specifications, and use of IPs and standards. Examples of proposed course projects include: real-time color recognition and tracking, touch based video recorder, touch based video mixer, real-time speech recognition, porting ucLinux operating system to tPad, function generator with touch interface, real-time GPS tracking system, and edge detection.

7. Course Project Implementation

The tPad and the developed design flow and tutorials were used for the first time in the embedded systems design course in Fall 2011 semester. 50% of the final grade was allocated to a semester long course project. The purpose of the project was for students to gain skills in designing embedded systems. The project was supported by the tutorials prescribed with the class homework. All projects were required to be done in student groups of no more than four.

The project was required to be a complex embedded system (e.g. involving video and touch interface) by doing hardware/software partitioning at high level and implementing the design in an FPGA. The hardware part would be described using HDL (Verilog or VHDL) and the software would be described in C language. The design implementation to FPGA would be done using EDA tools by Altera Inc. and on the DE2-115 tPad development kit.

Projects were team projects and students were asked to form teams of no more than four students. Students were required to submit project proposals early in the semester to be reviewed by the instructor for necessary changes and adjustments. The minimum requirements for project specifications were as follows: 1) it had to have both hardware and software components (i.e. processor based system); 2) it had to involve some sort of video component at least in the form of generating a video display output on the tPad LCD; 3) it had to make use of the touch display sensor to offer some touch control options for the user. The video component requirement was typically met by satisfying the minimum requirement above, but it was encouraged to include more video content, for example by use of the CMOS camera sensor of the board or by feeding external video through the video input port. Moreover, students were encouraged to make use of various I/O ports available on the DE2-115 tPad board.

36 students formed 13 teams and proposed the projects shown in table I. All project proposals met the earlier mentioned minimum specification requirements. Students' progress in the project was assisted by a series of hands-on homework assignments on various features of the tPad board that students had to use in their projects as well. These homework (HW) assignments were based on a simple Arithmetic Login Unit (ALU) implementation. In the first HW, the ALU was realized using the hardware-only approach and with inputs set by the sliding switches and the output displayed on the LCD character display. In the next HW, students were asked to realize the same ALU by a hardware/software partitioning approach using the Nios II processor. In the next HW, students were asked to modify the design so that the ALU output can be display on a LCD monitor connected to the VGA port. In the following HW, students were asked to direct the output of the design to the LCD display of the tPad board. Finally in the last HW, student were asked to add touch icons on the LCD display for controlling the operation of the ALU so that the sliding switches can be replaced by the touch buttons on the display. Such step-by-step progress in these HW assignments prepared student to take a bigger challenge in their course projects on their own. Students were required to video record a demo of their design for each HW assignment and post it on YouTube for others and instructors to see and evaluate. Students were also asked to deliver a midterm oral project progress review presentations to receive feedback from the instructor and other students. Such coaching and monitoring actions helped students to successfully finish their project on time.

As project deliverable, the students were required deliver an oral presentation, project demonstration, and video clip of their project demo on YouTube, and written project report. The project activities created great level of excitement among the students and increased their creativity in their approaches. In a few instances, students had to change their project definition from initially proposed ideas, because of facing technical issues in working with some I/O ports that enough resources and/or technical support was not available for. In these cases, student changed their project to simple game projects as shown in table I. These game projects still met the minimum required project specification stated earlier.

Most students found it very useful to examine existing demonstrations provided by Terasic Inc in order to understand how to integrate various I/O devices at both hardware and software level. Students also were encouraged to make use of existing open-source hardware and software IPs provided by Altera and Terasic Inc.

Table I: Course projects

Project Title	Team size	Video component	Touch interface	Other I/O
Color recognition and tracking	3	LCD Display and camera input	User input	VGA port Camera
Video edge detector	4	LCD display and camera input	User input	Camera
Video Mixer	2	LCD display, camera input, and video input	User input	Camera Video In
Photo gallery	3	LCD display	User input	SD card port
Notepad with self-orientation	2	LCD Display	User input	Digital Accelerometer
Music player	2	LCD display	User input	Audio Out
Picture and Video Mixer	4	LCD Display and camera	User input	Camera
Paint box	4	LCD display	User input	None
Waveform capture and loader	3	LCD display	User input	None
Arkanoid game	3	LCD display	User input	None
Egg gobbler game	2	LCD display	User input	None
Tic Tac Toe game	2	LCD Display	User input	None
Bomb blaster game	2	LCD display	User input	None

8. Course Project Assessment Results

In order to obtain a quantitative assessment of the usefulness of the tPad board and the tools and the experience of the students in the course projects, a survey was designed. The students were asked to fill out the survey at the end of the semester after the final presentation of their projects. The survey was composed of 15 questions as shown in Fig. 2. Students were asked to rate their level of agreement with each question in a five point scale: strongly agree, agree, neutral, disagree, and strongly disagree. The survey was conducted anonymously to help students express their opinions honestly.

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
1. The tPad board enhanced my interest in the course.					
2. The tPad board enabled me to develop embedded system design skills.					
3. The tPad board enhanced my creativity in the course project.					
4. The tPad board was easy to use.					
5. There is enough resources available for learning how to design with the tPad board.					
6. The software tools are easy to use.					
7. The Altera and Terasic free IPs are easy to integrate to a design.					
8. I will consider using the tPad board in my future embedded system design projects.					
9. The course project gave me the experience of designing a modern embedded system design.					
10. The course project created a teamwork environment.					
11. The experience of the course project has prepared me for jobs in industry.					
12. I experienced the IP based design through the course project.					
13. I learnt how to construct a video pipeline in an embedded system.					
14. The course project should be developed on top of an operating system after porting an embedded operating system to the board.					
15. Overall, I am satisfied with my experience in the course project.					

Fig. 2: Questionnaire for assessment of effectiveness of tPad board and course projects in learning enhancement.

The student responses to each question are depicted in Fig. 3. The response to each question is analyzed below.

Question #1: All students agreed that the use of the tPad board enhanced their level of interest in the course.

Question #2: Majority of the students strongly agreed or agreed that the tPad board enabled them to develop embedded system design skills. Only 10% of the students were neutral about this.

Question #3: Majority of the students strongly agreed or agreed that the tPad board enhanced their creativity in the course project. Only 16% of the students were neutral about this.

Question #4: Although majority of the students strongly agreed or agreed that the tPad board was easy to use; however a sizable number of students seem to disagree with this or remain neutral. This can be attributed to lack of student friendly tutorials on using different features and I/Os of the board and lack of detailed documentation on the demonstration examples and the open-source IPs.

Question #5: Majority of the students agreed that there are enough resources available to learn how to design with the tPad board; however, similar to the previous question, some students disagreed with this or remained neutral. This is due to the same reason of lack of detailed and student friendly documentation on use of various I/O ports as well as lack of detailed documentation on the provided demonstration examples.

Question #6: The responses found to be quite divided on this question. This is because most students found that the software tools were not stable. A task that they could run once, it might not run another time. This issue was faced frequently in the step of downloading the design to the board. It might be because we were using the free edition of the tools with no technical support; however, this is something that the tool industry needs to consider.

Question #7: Majority of the students agreed or strongly agreed that the open-source IPs available from Altera and Terasci Inc are easy to integrate to a design; however some students remained neutral or expressed disagreement with this. This could be because of incompatibility of some IPs with latest versions of the tools.

Question #8: Majority of the students agreed that they would consider using the tPad board in their future design projects.

Question #9: A strong majority of the students agreed that the course project gave them the experience of designing a modern embedded system. There was no disagreement about this.

Question #10: A strong majority also agreed that the course project crated a teamwork environment. The few students who disagreed with this might have felt left out in the project development.

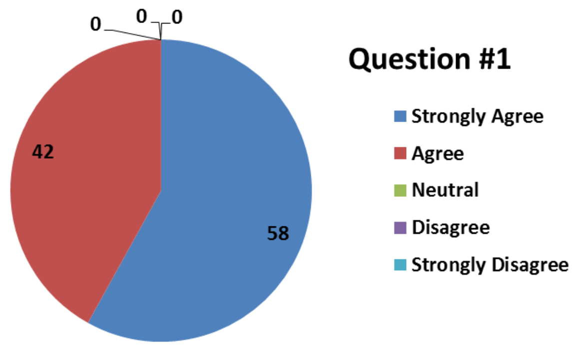
Question #11: Majority of the students felt that the experience of the course project prepared them for jobs in industry. There was no disagreement with this statement.

Question #12: Majority of the students agreed that they gained the experience of IP based design through the course project. That is because all projects involved use of various IPs, reflecting the way modern embedded systems are designed.

Question #13: A strong majority of the students agreed that they learnt how to construct a video pipeline for an embedded system. The video pipeline refers to a cascade of IPs needed to take a frame from a pixel buffer memory and display it on the output LCD display. This topic was covered in detail in the lecture and the students practiced it though both HW and course projects.

Question #14: Majority of the students felt that the course projects should be developed on top of an operating system after porting an embedded operating system to the board. As the embedded system design software gets more complex and involves multi taking, it becomes very challenging to develop all the code and debug at the hardware abstraction layer (HAL). The operating system creates a higher abstraction layer where the developers do not need to worry about hardware details and can focus on the algorithm and hardware independent software development. There are several open-source real-time operating systems available for embedded systems, such as ucLinux [2]. In future, efforts will be made to port this operating system to the tPad board and develop projects based on that.

Question #15: A strong majority of the students expressed their overall satisfaction with their course project experience.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Neutral
Disagree
Strongly Disagree
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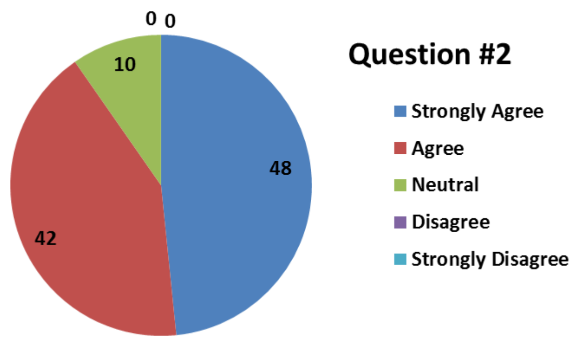
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Neutral
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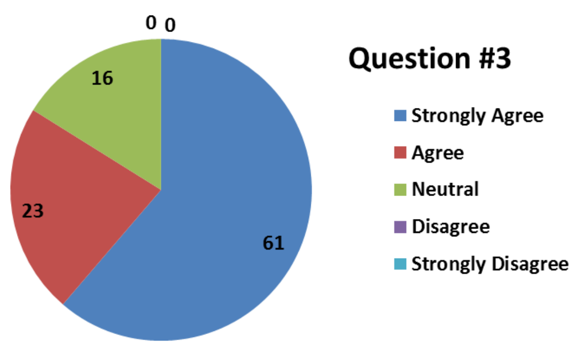
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Agree
Neutral
Disagree
Strongly Disagree
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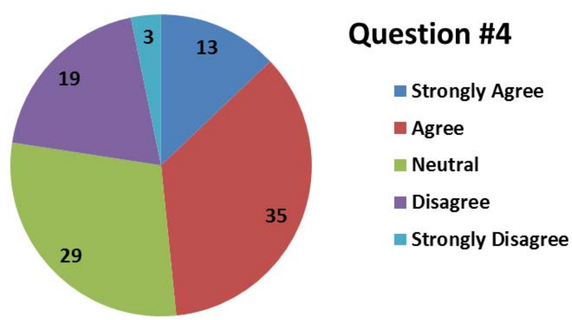
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Neutral
Disagree
Strongly Disagree
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35
29
19
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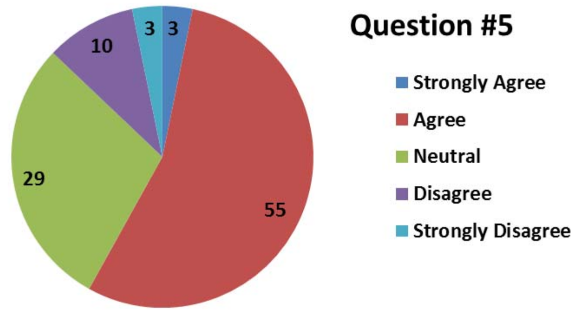
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Agree
Neutral
Disagree
Strongly Disagree
3
55
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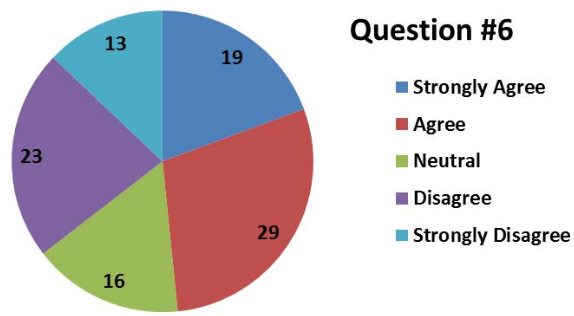
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Neutral
Disagree
Strongly Disagree
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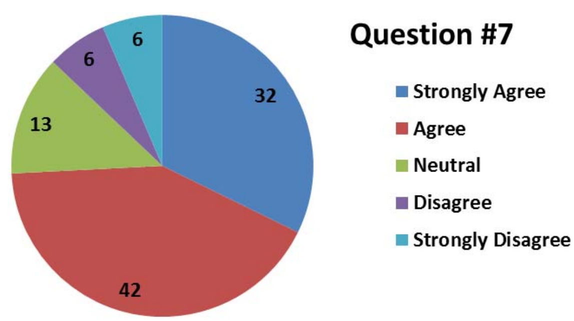
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Agree
Neutral
Disagree
Strongly Disagree
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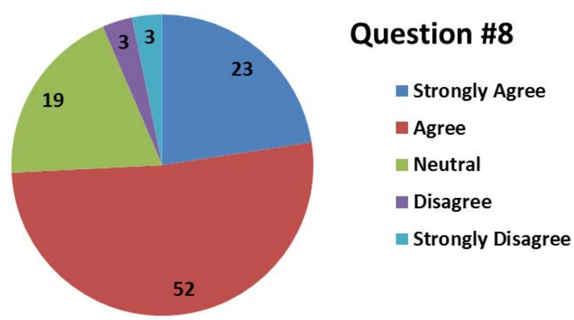
Question #8
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Agree
Neutral
Disagree
Strongly Disagree
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52
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3
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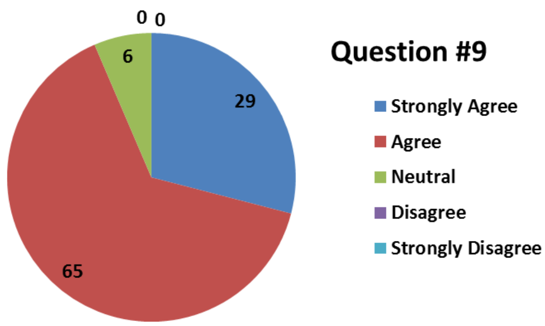

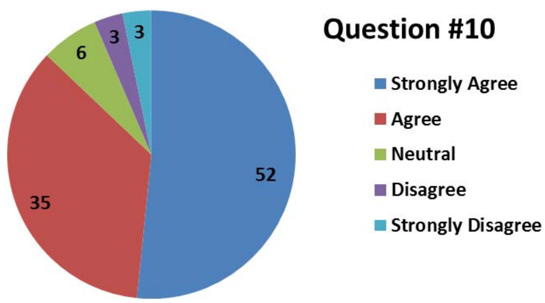

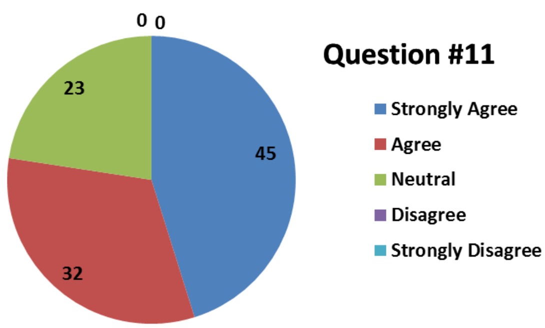

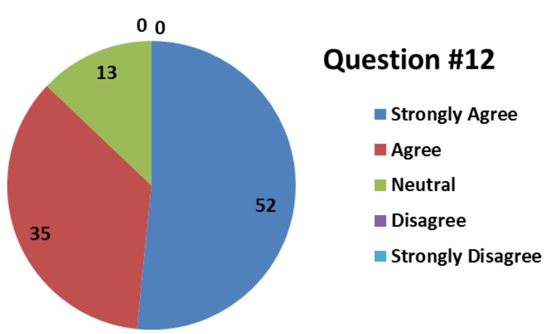

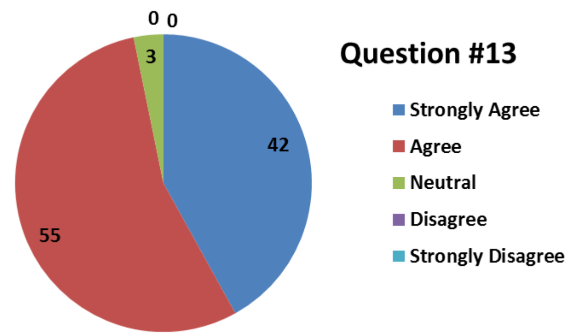

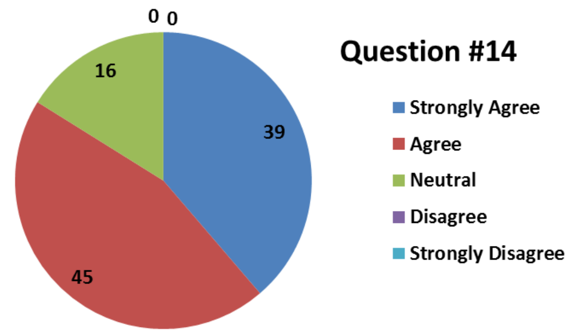

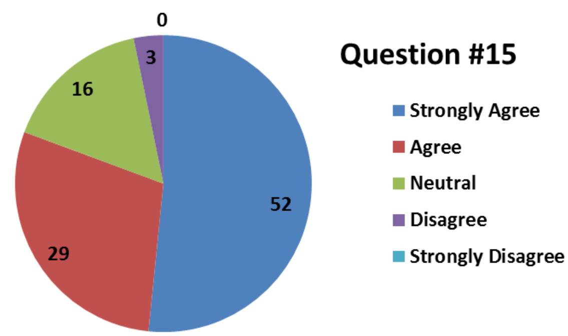

Fig. 3: student responses to the questions of the survey questionnaire.

9. Conclusion

The tPad is very useful development board for teaching embedded systems design in a hands-on manner. We presented our experience and finding using this board and the related software tools and resources in teaching an embedded system design course at SFSU. The usage of these tools was facilitated by a series of student friendly tutorials and course projects. Our findings are very positing and encouraging and can be used as a model for other universities to follow.

10. Acknowledgment

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11. References

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