Teaching Embedded Systems in the Context of Internet of Things (IoT)

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Introduction

The global adoption of Internet of Things (IoT) technology in a wide range of industry sectors has enabled a seamless confluence of our cyber and physical worlds [1]. The rapid proliferation of IoT devices is attributed to advances in key enabling technologies, among which communication and networking are paramount. As embedded systems converge with ubiquitous connectivity, it gives rise to an IoT ecosystem that drives a digital transformation, inspires innovation, and fuels economic growth. The resulting change in the technology landscape is creating a shift in demands of the Electrical and Computer Engineering (ECE) workforce. This emphasizes the need to reassess ways in which ECE programs prepare graduates in bridging the skills-gap.

This paper documents the process of integrating IoT-based activities in an *Embedded Systems* course at Seattle University, for two consecutive years. In the first iteration, the course included a two-week long project that had students work in teams of two to build a voice-based control system using custom *Alexa* skills, in other words, a DIY Amazon Alexa device for voice-controlled robots. Over the duration of this project, students encountered concepts related to wireless communication, computer networking, cloud computing, and network security, among many others. In the second iteration, computer vision and image processing, in addition to the above-mentioned concepts were used to implement a hand-gesture-based control system.

Survey and focus group results provide qualitative feedback on students' learning experiences. A comparative study on the differences between implementations and resulting feedback from both iterations of the course is presented. Observations and lessons learned contribute to the body of knowledge on curricular enhancement using IoT and help identify best practices for teaching Embedded Systems in a world that is more connected now, than ever before.

Background and Motivation

IoT is a technology that uses physical objects or "things" embedded with communication capabilities, enabling intelligent data exchange among such devices or between these devices and internet-enabled systems. The "Thing" in the Internet of Things can be defined as an embedded computing device, or an embedded system, that transmits and receives information over a network [2]. Based on a market update by IoT Analytics, the number of IoT devices that are currently in use worldwide exceeds 7 billion and this number is expected to grow to 10 billion by 2020 and 22 billion by 2025. The global market for IoT is estimated to reach $1,567 billion by 2025 from $130 billion in 2018 [3]. The positive reinforcement provided by these statistics is a driving force for continued efforts towards providing IoT education and training to future graduates.

In the context of undergraduate courses in Embedded Systems, engineering educators are progressively adopting ‘connected’ hardware platforms and a variety of tools that facilitate seamless hardware-software co-design. As an example, an IoT-based learning framework that consists of modules with integrated computing devices and instruments was proposed for an *Embedded Systems Analysis and Design* course [4]. The goal was to map abstract concepts and theories into practical, hands-on experiential knowledge. Although the paper delves into details of the framework, it lacks concrete examples of the labware designed for the course. Another example documents the challenges faced in teaching Embedded Systems in the context of IoT, specifically using ARM-based microcontrollers [5]. In conclusion, it was suggested that two different approaches may be used in designing the embedded system course, to simplify teaching: one to include extensive use of Application Programming Interfaces (APIs) provided by manufacturers and the second approach is to teach the course with the systems approach without focusing on hardware, instruction set, and assembly language. Along the same lines, an example of introducing IoT technology in an embedded networking course, specifically using the Texas Instruments (TI) ARM-based Connected Launchpad is documented in [6]. The design of an Embedded Systems Laboratory to support rapid prototyping of robotics and IoT is documented in [7]. An interesting and creative approach was used to disseminate the information needed for both traditional laboratory experiments and student design projects; an extensive Wiki site called the “mbed cookbook Wiki” was used to provide useful information such as interface wiring details and driver and code examples for breakout boards used in various projects. Using breadboarding, a wide range of robots and embedded devices were successfully prototyped, mostly using cloud compilers for software development.

The work in this paper is part of an ongoing project that focuses on the holistic integration of IoT-based activities in both core and elective undergraduate ECE courses. Towards this end, enhancements for courses at all levels of the academic program i.e. freshman-, sophomore-, junior-, and senior-levels have been designed and implemented in the past three years. This paper discusses the experience gained in developing and implementing IoT-enhancements for an *Embedded Systems* course at Seattle University, for two consecutive years. Laboratory components in the course utilize the MRK+Line robotics kit, based on the DIGILENT chipKIT Pro MX4 development board, which uses a Microchip PIC32MX microcontroller, based on the MIPS architecture. Hardware and Software platforms used exclusively for the IoT projects will be introduced in the following section.

Implementation

IoT-based activities for the *Embedded Systems* course were planned and implemented for two quarters; fall 2017 and fall 2018. This course is required for students pursuing a BS in Electrical Engineering with a Computer Engineering Specialization at Seattle University, and an elective for students in the Electrical Engineering program. The course is open to both juniors and seniors, provided they meet the prerequisite of *Microprocessor Design.*

It should be noted that this paper exclusively addresses the IoT-based enhancements to the *Embedded Systems* course, roughly lasting between one and two weeks towards the end of the quarter. In both instances, the IoT projects were designed to be in contrast with the main class project in that the latter was designed and taught as a gradual development that involved experimentation, deliberation, reflection, and a close-to thorough study of its theoretical underpinnings from the field of computer architecture. The former, on the hand, were designed to be fast implementations where students would get a taste of quick deployment that incorporates networking, signal processing, and machine learning without having the luxury of delving into detail on those topics. The reader may note that some of the student feedback was critical of this approach, demanding more time for the IoT projects as well as the term-long class project. The learning objectives for the IoT project were to gain exposure to the interacting components of an IoT system, learn up-to-date technical skills on the fly, and get further practice understanding and modifying existing code for a particular project deliverable.

Fall 2017: Voice-Based Control System

In fall 2017, 19 students worked in teams of two to create *Alexa* skills for voice-controlled robots. The project made use of technological tools such as the Raspberry Pi 3 embedded-microprocessor board, the MATRIX Creator microphone-array board, a "D1 Mini" Arduino-compatible Wi-Fi board (from Espresso, WeMos, AdaFruit, SparkFun, or other suppliers), Amazon's Alexa Voice Services (AVS), including the "skill"-generation environment and AVS Device SDK, along with AWS Lambda and node.js (for remote voice control) to allow the students to make their own version of the Amazon Echo. General purpose components such as loudspeakers, cables, display, mouse, and a keyboard for the Raspberry Pi were also used.

Students were provided with instructions on how to become an AVS Alexa "skill" developer, how to copy the Amazon app onto the Raspberry Pi board, and how to install and configure the MATRIX Creator software. Students were then shown how to run the web server and communicate with AVS securely through it. At the end of this procedure, students were able to talk to Alexa through their MATRIX Creator boards and the *ngrok* tunnel, an open-source secure-tunnel Internet utility, and control robots using voice commands.

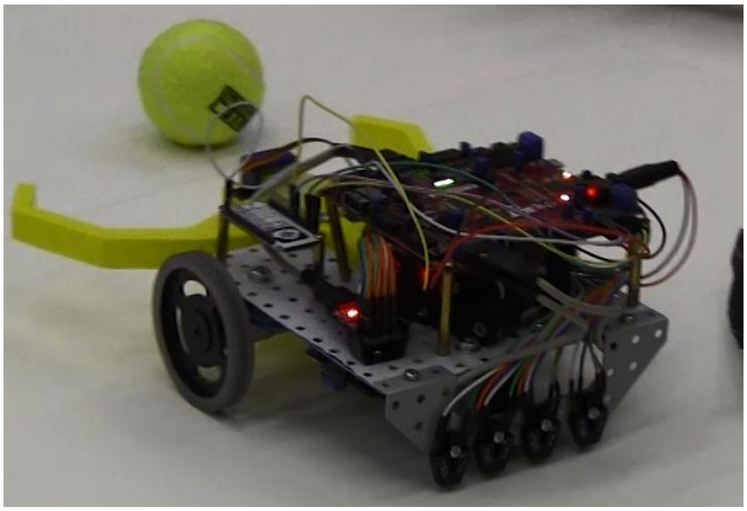

Figure 1: The voice-controlled robot

Some students used voice control to start and stop the robot, but a more popular choice was to make the robot do a victory dance. More adventurous teams created a robot-motor-control application for a cell phone that controlled the robot over Wi-Fi and implemented a denial-of-service attack on another team, to demonstrate the importance of network and device security.

Fall 2018: Hand-Gesture-Based Control System

In fall 2018, 24 students worked in teams of three to design and implement a hand-gesture-based control system, utilizing *OpenCV*, an open-source library for computer vision and a webcam. This project incorporated image recognition into the IoT activity of remotely controlling a Wi-Fi module through a public URL. Commands delivered from the image-recognition module on the host computer to the Wi-Fi module through an *ngrok* channel enable the operator to exert control over any device connected to the input/output pins of the module. The project incorporated many technological components and various IoT-, embedded-systems-, and machine-learning-related concepts and techniques. Among the tools and devices used were *OpenCV*, an *Arduino*/*ESP 8266* Wi-Fi module, and *ngrok*. Students wrote or edited Python and C code in a variety of environments such as *spyder* (within *Anaconda*), *Arduino Sketch*, and the standard development environment, *IDLE*, for Python.

Students were provided with instructions on the installation of *OpenCV*, and a detailed explanation of the steps involved in recognizing hand gestures. The image processing steps involved included conversion to grayscale and applying blurring, both to reduce the amount of detail in the image and reduce processing load, followed by thresholding via Otsu's binarization [8], [9], contour-finding, and convexity-finding, as shown in Figure 2. The remainder of the process was up to the team. There were challenges in finding the appropriate background with which the system can work, the degree of convexity that is correctly interpreted by the system, and so forth.

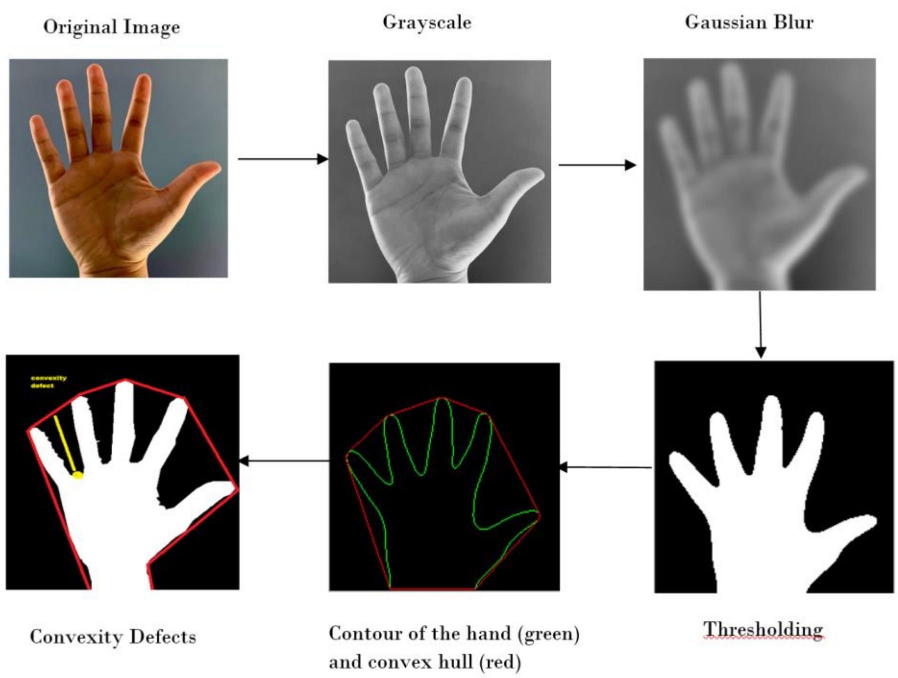

Figure 2: Sequence of Image Processing steps for hand-gesture recognition

The project was both successful and a good learning opportunity in the incorporation of many relevant technologies and in the fact that all teams got their gesture-recognition systems working. There were also challenges. For example, students found out that what was in the background could have a big negative effect on the recognition system's performance. There were occasional challenges with software versions, installations, and some threshold values for image recognition, but all groups completed all aspects of the project.

Security Considerations

The process for building either project involved setting up the Wi-Fi board and the *ngrok* tunnel as common steps. After this, the tools and procedures varied according to the mode of human–machine interaction each project focused on. In addition to these details, the projects contained an explicit cybersecurity component through the use of the secure tunnel created with the *ngrok* utility. Without this component of the project, the custom Amazon Echo-like setup would be susceptible to use from anywhere in the world (anywhere on the Internet, by anyone). Since the Mirai and Reaper botnets made big news almost three years ago, cybersecurity has become another crucial aspect of teaching computer engineering, and especially IoT [10]. The botnets, or their corresponding worms, did this by taking over, in the case of Mirai 100,000, 1 million, or 2.5 million IoT devices (according to varying estimates) [11], [12] and taking down high-usage sites such as Amazon, Twitter, Netflix, Spotify, and GitHub. Reaper is believed to have actively taken over fewer nodes, but also to have the capability of bringing into its queue around 2 million devices at any time [13].

As a result, universities across the country and the world are embracing cybersecurity education as part of teaching computer engineering, computer science, and electrical engineering [14-16]. Problems are being identified [17] and resources are being created [18]. Although the IoT projects described here were not designed for a cybersecurity course but a beginning embedded-systems course, and hence does not attempt to meet the requirements outlined in resources such as in [16] and [17], the authors wanted to include some awareness of the vulnerability of IoT devices. Furthermore, since the devices used in the project were only briefly on and connected to the Internet, they were not expected to carry the level of cybersecurity concerns of always-connected devices. Including some measure of cybersecurity in the project and making the project teams carry out the steps necessary to implement that small measure of security were considered sufficient to raise awareness in this beginning course.

Assessment

A post-activity survey was administered to students in both fall 2017 and 2018 sections of the *Embedded Systems* course. An online tool was used for the fall 2017 survey, and the response rate was 63.15 percent (12 out of 19 students responded). Eight students were reported to have successfully completed the activity with little or no help from the instructor, while four students received significant help from the instructor. The fall 2018 survey was paper-based, and it received a response rate of 100% (all 24 students responded). Thirteen students were reported to have successfully completed the activity with little or no help from the instructor, while eleven students received significant help from the instructor. Results from the survey are summarized in Table 1 and Figure 3.

Table 1: Statistics of student responses to IoT-activity specific survey statements*

Survey statement	**Fall 2017 (12 respondents)**			**Fall 2018 (24 respondents)**		
1:Disagree; 2: Somewhat agree; 3:Agree; 4: Strongly agree	**Mean**	**Median**	**Mode**	**Mean**	**Median**	**Mode**
Q1: This activity introduced me to the basics of IoT technology.	3.42	3	3	2.96	3	3
Q2: This activity has encouraged me to explore other applications of IoT.	3.08	3	3	2.96	3	3
Q3: This activity has enhanced my interest in the field of Electrical and Computer Engineering.	3.25	3	3	3	3	3
1:Not likely; 2: Unsure; 3:Likely; 4: Extremely likely						
Q4: To what extent do you anticipate using what you've learnt in your future career?	3	3	4	2.67	3	2

* We included the mean even though it's not recommended by statisticians for Likert data because it seemed to add to the interpretability of the median and mode which alone would give the impression that the results were too similar across the board

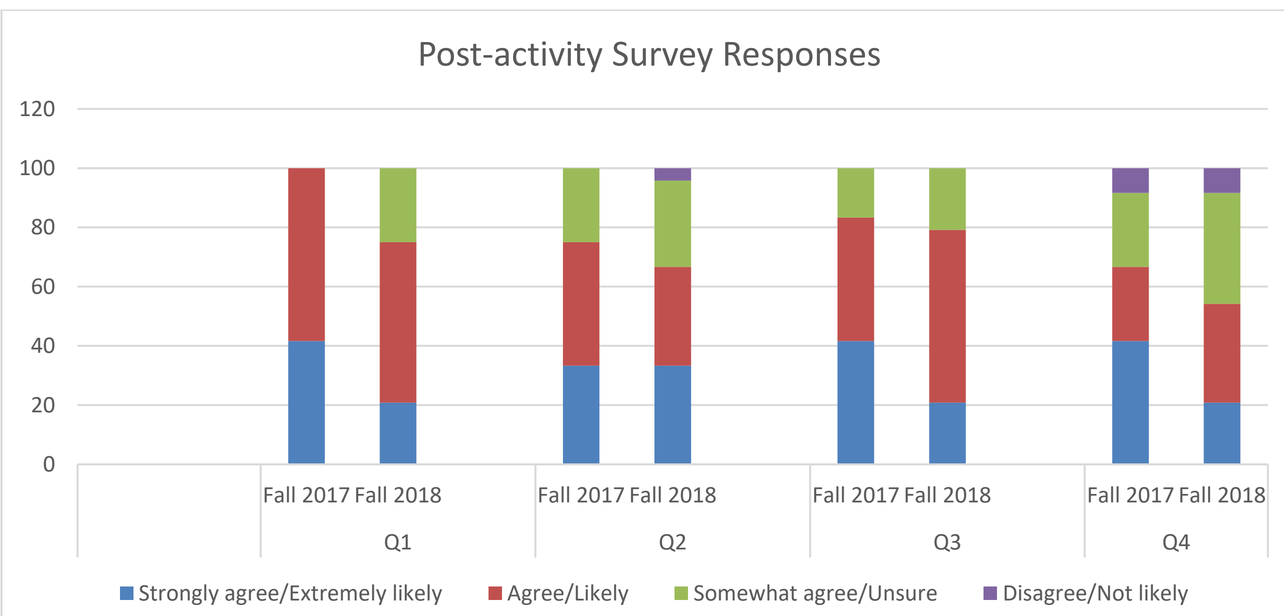

Figure 3: Comparison of post-activity survey responses for fall 2017 and 2018

In both instances, overall student responses were very positive and encouraging. All students were able to complete the activity/project. Few students took time to provide constructive feedback for improvements to the project. The repeated suggestions centered around introducing the IoT project early in the quarter as a way to provide more time for creative solutions and a deeper understanding. An interesting observation is that students who marked "Successfully completed with significant help from the instructor" were much more likely to rank the latter questions high with respect to increased interest (Q3) and anticipated use of IoT (Q4). A couple of hypotheses worth exploring are – *Did the added connection to the instructor increase the students understanding of IoT and its role in their future careers*? Or perhaps, *were these students less familiar with IoT and therefore increased their learning and interest more from their baseline understanding than the more experienced students?*

Selected verbatim comments from the surveys for both instances are listed below:

- *"Add more to the customization of the IoT portion. Just using the provided example project is not nearly as fun as creating something yourself. I feel as though that the provided example should have been a lab and then the project should incorporate more coding yourself using their API in a more custom way. Or coming up with something yourself." Fall 2017*
- *"Introduce it earlier in the quarter. Was a lot to do in a short time period. Smaller teams would help too because it ended up being too many people working on one piece of code to have everyone contribute meaningfully." Fall 2017*
- *"Adding more layers of creativity." Fall 2018*
- *"Integrating IoT into more of the projects we did in class." Fall 2018*
- *"Embedded systems should be brought to students more. (More classes, more projects and research)." Fall 2018*
- *"Loved the computer vision expansion! Overall, I liked the project." Fall 2018*

In addition to the paper-based survey in fall 2018, students were invited to participate in a one-hour focus group, facilitated by an external assessment consultant. Four students volunteered to participate. While the students offered suggestions that echo those from the post-activity student survey – wanting more time for creativity and depth of learning, they also wanted to be clear that they were excited to have the opportunity to learn IoT technology in their courses. Details of the focus group discussions are provided below:

1. Describe your initial knowledge about IoT coming into the course?

The students were asked to rank their knowledge or IoT coming into the course. The students brought in some baseline knowledge from their previous work as juniors.

IoT knowledge	0 = none	1 = some	2 = lots
Hardware and software platforms		3	1
Integration knowledge	3		1
Computer networking	1	3	
Communications protocols	1	3	

2. Did you learn what you expected to learn?

The students remarked that the IoT projects were a bit of a surprise and were announced after mid-terms. Explicit expectations were not provided and the students agreed that the project in the course was too guided. They felt they were “just following the steps” and that they would have benefited by some degree of creative freedom. One student provided the analogy that it was like climbing to the top of the diving board and we are ready to dive but there was no time to go forward. Another student remarked that the code should be a platform or example that gets you going but you should have the time to build on it. The students recognized that there was a lot of content in both courses and that the department would need to decide if it were possible to let go of some of the older content to make room for IoT.

3. Do you anticipate using what you’ve learned in your future career?

One student was already using it in their senior design (Capstone) project and could see applications for their future career. Another student remarked that while the code was given to them, they did learn how to use it. Another student commented that if not professionally then they could see using it as a hobby. They last student was not sure at first noting that “it’s kind of scary – ethically teaching computers to do things” – but then could see possibly engaging in a career in embedded devices.

4. Anything else you would like to add.

The students provided some suggestions for improvement which echoed the comments of the Fall 2018 Survey about making time for creativity and depth of understanding.

- The students suggest using the first four weeks of the quarter to provide the needed background learning before learning to code. They requested a more dynamic project. The current project felt tacked on to the already full curriculum and did not have room for creativity. They suggested that guided projects could be used at the beginning of the quarter and lead to more creative projects at the end of the quarter.
- The students wondered if IoT could be integrated across the Embedded Systems course since that course is already well-established.
- Finally, they all wanted to let the ECE department know that they found it very exciting to have the opportunity to learn IoT. One student remarked that “No one was sorry that we had an IoT project.”

Observations and Challenges Encountered

The feedback about spending more time on the project and allowing more creativity are good constructive comments that highlight an aspect of the course that requires careful consideration. The course is rather packed with information to the extent that even some intended core material did not fit into the quarter. Nonetheless, this project is a relevant and key part of the course as well, meaning that some tough decisions need to be made about what important material to include and exclude. Fortunately, questions like this are being raised by our study of implementing IoT projects in this course now, because the course itself will be undergoing major changes during summer 2019. New hardware and a new architecture will be considered and tested. We expect to use this opportunity to integrate the IoT components more thoroughly into the *Embedded Systems* course.

Although both projects were fun and informative, both students and the instructor felt the need for more time to be spent on the project. This goes both for the time students spend working on the project and for the instructor's thoroughness of familiarity with the hardware and software and with what can go wrong. Inconsistent behavior has been observed even though student teams were supposed to be following the same set of setup instructions. In order to know whether these inconsistencies in the results are due to the hardware and software or due to student errors, the instructor plans to spend time running over at least one of the projects multiple times with various sets of hardware the summer before the next time the course will be offered.

Conclusion

Embedded Systems form the cornerstone of Internet of Things applications and solutions. As engineering educators, it is imperative that we strive to constantly update course content and delivery mechanisms to reflect the rapidly changing innovations in technology. This work documents our experience in designing and implementing IoT-based enhancements to our *Embedded Systems* course, for two consecutive years. The fall 2017 project focused on voice control of robots, while the fall 2018 project was centered on hand-based gesture control. In both instances, overall student responses were positive and encouraging.

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