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Work in Progress: Enhance Undergraduate Electrical Engineering Education with CPS/IoT Infusion

Dr. Liang Hong, Tennessee State University

Dr. Liang Hong received the B.S. and the M.S. degrees in Electrical Engineering from Southeast University, Nanjing, China in 1994 and 1997, respectively, and the Ph.D. degree in Electrical Engineering from University of Missouri, Columbia, Missouri in 2002. Since August 2003, he has been with the Department of Electrical & Computer Engineering at Tennessee State University where he is now Full Professor. His research interests include cognitive radio, security of communication systems, networked control system, wireless sensor networks, wireless multimedia communications and networks, and engineering education.

Prof. Lee Keel, Tennessee State University
Dr. Charles David McCurry, Tennessee State University

Charles D. McCurry joined Tennessee State University as an Assistant Professor in the Electrical & Computer Engineering Department in 2015. He obtained his B.S. (1995) in Electrical Engineering, M.E. (2005) in Electrical Engineering and Ph.D. (2011) degree in Computer Information and Systems Engineering from Tennessee State University. From 2011 - 2015, He worked as a system and control engineering consultant employed by Booz Allen Hamilton with the Air Force Research Laboratory (AFRL). His academic research interest which correlated with his work at AFRL involve the areas of human and machine teaming, cyber-human systems, human and system Integration, control and intelligent control systems, machine learning and artificial intelligence applications, and system engineering design

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Abstract: Electrical engineers serve a vital function in our modern world. Currently, undergraduate electrical engineering (EE) students are in high demands to be hired with the highest median annual earnings. However, minorities continue to be underrepresented in science and engineering fields as reported by the National Science Board, Science & Engineering Indicators. This work-in-progress project presents our attempts to tackle the challenges and improve undergraduate training in EE program. Considering that the next generation electrical engineers should be exposed to the latest technology and have significant technical and scientific capabilities, deep interdisciplinary understandings, and soft skills such as self-learning abilities and communication competence, Cyber-physical systems (CPS)/Internet of Things (IoT), the feasible and effective platforms to present the undergraduate EE students with various sub-disciplines of EE, are infused throughout our four-year curriculum with a series of project-based and problem-oriented learning modules. The pedagogy of vertical integration is implemented to cut across artificial course boundaries. The feedback from the initial implementation is very positive and encouraging. The students enjoy what they learned and have more confidence and motivation to pursue advanced studies and careers in CPS/IoT area.

Background and motivation

Due to our insatiable desires for more electronics functionalities and higher performance communications, computing, and automation, electrical engineers serve a vital function in our modern world. Currently, undergraduate electrical engineering (EE) students are in high demands to be hired with the highest median annual earnings. According to U.S. Bureau of Labor Statistics, the overall employment of electrical and electronics engineers is projected to grow 3 percent from 2019 to 2029, about as fast as the average for all occupations [1]. However, minorities continue to be underrepresented in science and engineering fields as reported by the National Science Board, Science & Engineering Indicators [2]. Hence, it is essential to enhance undergraduate EE education in historically black colleges and universities (HBCU) and minority serving institutes (MSI) to achieve the goal of diversifying and improving minority students' interests and academic achievements.

Over the last two decades, the modern EE systems have changed significantly due to the increased complexity and technology advancements [3]. The next generation electrical engineers should have significant technical and scientific capabilities, deep interdisciplinary understandings, and soft skills such as self-learning abilities and communication competence [4]. To satisfy these requirements, the successful EE education needs to continuously expose students to the latest technology, provide them opportunities to practice, and involve them in innovative projects. Cyber-physical systems (CPS) [5], an integration of computation, networking, and physical processes, and its instance, Internet of Things (IoT) [6], a network of uniquely identifiable physical objects or "things" embedded with electronics, software, sensors and connectivity, emerge as feasible and effective platforms to present the undergraduate EE students with various sub-disciplines of EE such as engineering graphics and programming, data and signal processing, communications and computing, semiconductors, power, controls, embedded systems and many others.

Currently, CPS/IoT are expanding and growing itself to many different application domains such as military applications and operations, healthcare, industries, telecommunications, energy productions and distributions, transportation, surveillance, sustainable agriculture, and emergency responses to natural and human-made disasters [7]. According to the reports published by Future Market Insight [8] and McKinsey Global Institute [9], the global CPS market is estimated to reach a valuation of US $137,566 million by the end of 2028 [8], the IoT will have an estimated market size of up to $11.1 Trillion per year in 2025 [9], and the CPS/IoT areas will be a prominent source for new hires in the engineering field. On the other hand, the growth of CPS/IoT is outpacing the current workforce with necessary knowledge and skills. According to research from Gartner, insufficient staffing and lack of expertise is the top-cited barrier for organizations currently looking to implement and benefit from CPS/IoT [10]. Therefore, infusing CPS/IoT into EE curriculum offered at HBCU and MSI will not only train the future electrical engineers with the tools and skills required to meet the growing needs, but also achieve the goal of diversifying and improving the quality of the workforce.

Recognizing the high potential of CPS/IoT for teaching and student learning in EE program, many universities are beginning to offer CPS/IoT projects or courses into undergraduate education. For examples, Helps introduced first-year IT students to CPS concepts, with an emphasis on IT aspects of the field [11]. Cohenour used the IoT to motivate learning enthusiasm in engineering technology and management students [12]. Jung and Vernaza used CPS as a platform for rapid hardware and software development class [13]. Dickerson developed a course to prepare undergraduate engineering students for the CPS/IoT era [14]. However, these attempts only introduced CPS/IoT in unconnected pieces with separate courses whose relationship to each other and to the engineering process were not explained. Students were given a number of very specific topics inside the context of course materials without being aware of the extension of these topics into the larger world of EE subject materials. Therefore, why these concepts and knowledge were being learned and/or how they would eventually be used remained unclear to the students.

In order to improve the presentation of minorities in high-demand engineering areas with latest technology and bridge the gap between the undergraduate EE education and the industrial demands of entry-level electrical engineers with CPS/IoT expertise, this work-in-progress reports our attempts to tackle the challenges by infusing the fundamental, contemporary and multidisciplinary CPS/IoT concepts with a series of project-based and problem-oriented learning modules throughout our four-year curriculum. The pedagogy of vertical integration is implemented to cut across artificial course boundaries. The learning modules are designed to let students realize that the courses are part of a flow that contributes to a unified knowledge base, draw out their understanding of engineering and mathematics fundamentals, transform factual information into usable knowledge, and consolidate their perceptions of new information through integrated real-world applications.

Since the proposed approach is implemented in a HBCU, this paper mainly describes our trial to increase the presentation of minority students in the state-of-the-art engineering areas. However, the proposed approach is general. It can be adopted by every EE program that has interest.

The rest of the paper is organized in the following manner: First, the development of a coherent and coordinated sequence of courses with appropriate breadth and depth to support a broader range of EE fields that promote undergraduate interest and competence in CPS/IoT area is described. Then, the development of course modules with project-based learning that emphasizes hands-on experience via real-world related project is explained. After that, the learning outcome and assessment are presented. Finally, conclusions are drawn and future work are proposed.

Vertical curriculum integration with CPS/IoT infusion

CPS/IoT in real-world are very complex and large systems that expands to a broad range of EE fields. In order to promote undergraduate students' interest and competence in CPS/IoT fields, a coherent and coordinated sequence of courses must be developed with appropriate breadth and depth. The basic engineering principle, "divide and conquer" strategy [15, 16], is applied to address the complexity of the problems involved in CPS/IoT. The students are first motivated and introduced with the big picture of CPS/IoT systems and their applications. Then the decomposition of the systems into different EE subject fields and the connection of each component are explained. After that, the students master each small task in corresponding courses with the reinforcement of the big picture and the relationship of these components. Once the students understand the fundamental knowledge of signal and systems and digital and analog circuits in sophomore and junior years, they learn how to effectively "divide" complex problems, refine the decomposition, and integrate the pieces. Finally, the students compile, synthesize, and apply the various techniques that they have learned in previous courses into actual solutions to real-world problems through capstone projects.

Curriculum integration is a methodology widely used by educators to implement the "divide and conquer" strategy and improve students' education experience [17, 18]. In this project, vertical integration [19] is employed. The importance and curricular need for vertical integration was first expressed by Bordogna [19] as part of a keynote address at a National Science Foundation (NSF) conference. The implementation of vertical curriculum integration in this project includes a series of courses from introductory to intermediate to advanced courses (as shown in the following), and hands-on experience in CPS/IoT area that start as well-structured introductory theories and experiments at the lower levels of the curriculum and proceed as increasingly complex open-ended design projects at the upper levels of the curriculum. The projects in an upper level course build upon a previous knowledge built in a lower level course. The series of vertically-integrated and real-life problem-oriented topics are expected to cut across artificial course boundaries and introduce fundamental, contemporary and multidisciplinary CPS/IoT concepts.

Eleven (11) courses in our EE curriculum are selected and revised so that they infuse CPS/IoT concepts, theories, paradigms, hands-on exercises, and research into instruction. Efforts are taken to link the knowledge and skills taught in upstream courses to the objectives in the downstream courses through a series of real-world laboratory exercises and research in a variety of CPS/IoT areas under the support of EE subject materials. In this way, students develop practical skills and learn research technique that prepare them for advanced studies and for CPS/IoT related career in the public and private sectors.

The details of the curriculum integration are:

1. Students in introductory courses, ENGR 1020, Engineering Freshman Seminar, and EECE 1151, MATLAB-based Engineering Graphics, start with an overview of CPS/IoT, its enabling technologies, constituents of device, example of commercial devices, and the fundamental concepts and skills of data visualization with engineering graphics tools provided by MATLAB [20], a programming language commonly used by engineers. They then learn basic software programming skills and the associated algorithmic, computational problem solving methodology in ENGR 2230, Engineering Programming.
2. Students in intermediate courses, EECE 3200, Linear Systems, and ENGR 4400, Probability and Statistics, learn CPS/IoT in more details. They gain proficiency in understanding the concepts such as frequency spectrum, the statistical analysis of data, and the construction of predictive models for data trend forecasting. After that, they learn how to identify the modern digital techniques of wireless communications, explain the main modulation, encoding, and transmission techniques used in specific communication systems in EECE 3500, Communication Systems. They also learn how to use and apply appropriate tools to simulate and program CPS/IoT platform for message sending and receiving through EECE 3061, Advanced Programming Laboratory.
3. Students in advanced courses study and design practical IoT systems for applications in intelligent transportation system. They learn system engineering based design process in ENGR 3250, Introduction to System Engineering, and EECE 4310, Software Engineering, to define the system requirements, design the system's architect and algorithms, implement the system and conduct testing. In these two courses, the students also gain proficiency to effectively "divide" complex problems, refine the decomposition, and integrate the pieces. The students also learn how to identify and design close-loop control systems and networked control system in EECE 4000 and EECE 4001, Control System and Control System Lab. Finally, by applying the learned principles, the students exam the traffic in mid-Tennessee area and design intelligent transportation system to effectively manage the interstate highway traffic flow through Capstone Design Projects in ENGR 4500/4510.

Course module development with project based learning

For each course mentioned above, lectures, exercises and/or lab exercises, and course projects are developed with the project based learning pedagogy in a variety of CPS/IoT areas and at different levels (introductory, intermediate, and advanced).

Project based learning is a teaching and learning strategy that works effectively for engineering students. In project based learning, real-world relevant problems are introduced to students to provide the context for learning. Students who work cooperatively in teams to solve complex problems are the center of learning and the instructor becomes a facilitator [21, 22]. Seeing how a practical problem can be solved using knowledge they learned not only motivates the students for deep learning and improves their higher-order thinking skills, but also fosters growth in teamwork and collaborative problem-solving skills [23].

The course materials are developed with a general module style format that has clearly stated objectives, theories, hands-on experiences, and assessment. It is an integrated package including lecture notes for theoretical background, review questions and quizzes, assignments, and hands-on exercises with real world applications in the laboratory session. The hands-on experience in lab exercises and projects are organized at two difficulty levels: basic and advanced. The basic level hands-on lab depends on the knowledge learned in the lecture and lets the students to interact with data generated from the real world. Step-by-step guidelines and explanations are provided for lab implementation. Advanced level course projects are constructed to be open-ended and inquiry-based. They challenge students to acquire more theories and develop comprehensive applications for complicated cases in their capstone projects. The real-world related lab exercises and course projects use Tennessee Department of Transportation (TDOT) Traffic Management Center (TMC) facilities. Data are collected by both the students and the sensors deployed by TDOT TMC. All hands-on exercises and projects involve collaborative learning where student group pose their own questions and design methods, collect and analyze data, and present their results as text, poster, or oral presentations. Upon the completion of each course module, students are motivated to initiate their own projects for applications in various CPS/IoT areas. Figure 1 outlines the objectives and contents of a sample course module. The details of this course module and student deliverables could be found in our previous work [24].

Module name: IoT transceiver

Objectives:

- To understand the theoretical background and applications of Orthogonal frequency division multiplexing (OFDM) based IoT transceiver
- To connect mathematical symbols and block diagrams with the computer simulation of the OFDM based IoT transceiver
- To understand the software defined radio (SDR) concept and its implementation
- To interact with real-world wireless signals over-the-air in real-time and understand the real-world issues and non-idealities at various stages of the system with SDR platform
- To formulate real world problems and develop comprehensive solution

Learning materials:

1. Class notes with theoretical background and applications of OFDM and IoT transceiver
2. Review questions and quizzes
3. Assignments
4. Basic Level Hands-on Lab
    Pre-lab: computer simulation of the OFDM based IoT transceiver
    Lab: Image transmission with software defined radio platform
5. Source codes, sample results, and multimedia video demo for learning material 4
6. Advanced Level Real-World Relevance Projects
    Project 1: Transmit and receive the traffic data collected by TDOT Region 3 TMC
    Project 2: Transmit and receive the soil and water data collected by TSU Smart Agriculture Field
7. Extra readings with related tutorial papers and other online resources

Figure 1. Objectives and contents of sample course module

Table 1 shows the selected CPS/IoT related courses with sample labs and course projects for real-world related hands-on experience.

Table 1. CPS/IoT Related Courses with Sample Labs and Course Projects

Course Name	**Sample labs and course projects**
ENGR 1020: Freshman Engineering Seminar	1. Bluetooth low energy communication between an IoT device and a smartphone app. 2. Record the vibration intensity of an IoT device.
EECE 1151: MATLAB Based Engineering Graphics	1. Plot temperature data generated by an IoT device and identify the outlier. 2. Plot the traffic data collected by TDOT TMC.
ENGR 2230: Engineering Programming	1. Calculate the velocity of vehicles based on the GPS position data. 2. Control 4-digit 7-segment LED to display number based messages.
EECE 3061: Advanced Programming Laboratory	1. Use microcontroller to interface with sensors to play a multi-tone siren. 2. Connect to TDOT TMC data via Internet and then trigger events in the real world when certain conditions are met in the environment.
EECE 3200: Linear Systems	1. Analyze the frequency spectrum of a signal sent and received by software defined radio boards. 2. Extract signal of interest in the presence of noise with digital filter design.
EECE 3500: Communication Systems	1. Modulate high frequency sinusoid carrier by the data stream using phase shift keying technique. 2. Image transmission with software defined radio platform.
ENGR 4400: Probability and Statistics	1. Report the relationships between the columns in the structured dataset by computing the statistical correlations in the dataset 2. Extract information from vast amount of TDOT TMC traffic data by dividing the data into meaningful groups through statistical models.
ENGR 3250: Introduction to System Engineering	Students follow system engineering development life cycle to develop various CPS/IoT related systems based upon industry and society needs
EECE 4000/4001: Control Systems/Control System Lab	1. Design a state space model for formation control problems. 2. Modify the formation control to a leader follow problem.
EECE 4310: Software Engineering	Students follow the software development life cycle to implement various CPS/IoT related software system such as smart home and 3D printer monitoring
ENGR 4500/4510: Capstone Design Projects I and II	Students conduct independent projects related to the intelligent transportation system design using the authentic TDOT TMC data

Assessment of students learning

In order to obtain insights of the effectiveness of the CPS/IoT infused curriculum on student learning in undergraduate EE subjects and the long-term outcomes, assessments are taken at both formative and summative levels with the guidance of the following questions:

1. Do the modules meet their goals of providing students skills required in CPS/IoT careers?
2. Is there increase in students' competencies using the learning modules?
3. Does the curriculum integration promote students' capability to solve complex real-world problems related to CPS/IoT?
4. Is there increase in the number of students who join the workforce and /or pursue advanced degree related to CPS?

The formative assessments are conducted at each course with CPS/IoT infusion. The outcomes and impacts of the course modules are monitored via student surveys as indirect measure and course assignment evaluations by instructor as direct measure. The student surveys reflect their opinions on the course and their learning. Rubrics are developed for each course module on exercises and/or lab exercises, class projects, and independent projects to provide direct measurements that quantify students' achievements on the educational objectives presented in the module outline. Each rubric includes the outcome indicators that align with some of the new ABET students learning outcomes "1 through 7" and the levels of achievements for the experience of CPS/IoT. For each instructional outcome, four levels of achievements are designated. A score of 1 to 4 that represents unsatisfactory, developing, satisfactory, and exemplary levels is given based on their assignment performance, lab report, and presentation. Rubric based assessment gives a quantitative judgment of student knowledge. It requires little extra work in the grading process, requires no additional training for faculty to use, and avoids complete reliance on students' self-reporting through surveys [25]. The sample rubrics and student surveys could be found in our previous work [24].

Formative assessments help the instructors determine how well the outcomes are achieved and answer the first three guidance questions. It also allows the instructors to monitor the problems and then fine-tune the course modules. Since the start of this project in Fall 2019 semester, all the course modules were assessed at least one time. Table 2 shows the average results of direct measure for courses listed in Table 1 that were taught in 2019-2020 academic year. The results are the average percentages of students who performed at a satisfactory or exemplary level for each of the new ABET student learning outcome. The target is 70% or more of the students demonstrate a satisfactory or exemplary level. It is clear that all the student learning outcomes were met with large margin. The results for future academic years will be collected and compared with those for 2019-2020 academic year.

Table 2 – Average results of direct measure

ABET Student Learning Outcomes	1	2	3	4	5	6	7
Average percentages of students who performed at a satisfactory or exemplary level	82	90	87	82	79	83	89

The results from student surveys are also positive and encouraging. Students are highly interested and excited in the CPS/IoT topics. It shows that the developed course modules are successful in teaching the advanced techniques with hands-on experience in CPS/IoT domain.

In order to have a better answer to the four questions listed at the beginning of this section, more comprehensive assessments in longer period need to be conducted. When the freshmen enrolled in Fall 2019 complete the entire curriculum (expected in Spring 2023), the summative level assessment can evaluate the overall effectiveness of the vertical integration of CPS/IoT. At that time, through the analysis of the amount of CPS/IoT materials implemented in respective courses, number of students participated, grades, graduation rates, and specific aspects of project activities, how successful the CPS/IoT infusion could improve student learning and motivate the students to pursue advanced studies and careers in CPS/IoT areas will be revealed.

Conclusions and future work

This paper presents an on-going effort that enhances undergraduate training in EE program through curriculum integration of CPS/IoT and improves the presentation of minorities in high-demand engineering areas. The fundamental, contemporary and multidisciplinary CPS/IoT concepts with a series of project-based and problem-oriented learning modules are infused throughout our four-year curriculum. The pedagogy of vertical integration is implemented to cut across artificial course boundaries. The learning modules are designed to let students realize that the courses are part of a flow that contributes to a unified knowledge base. The assessment and feedback from the initial implementation of the course modules are very positive and encouraging. The students enjoy what they learned and are excited with the hands-on experience to solve real-world problem. They feel that their experiences give them confidence and motivation to pursue advanced studies and careers in CPS/IoT area.

The future work include identification and correction of weakness and deficiencies in the course modules, more comprehensive assessments in longer period, and comparison between two student groups, one will use the developed educational module and the other one will not. Survey will also be conducted to study how integration of hands-on experience and advanced CPS/IoT topics will increase minority retention and the number of minority students pursuing graduate degrees and careers in CPS/IoT area.

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