Considerations for an Internet of Things Curriculum

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Abstract

Educating the next generation of engineers to be able to design and develop the rapidly increasing need for Internet of Things (IoT) and Cyber Physical System (CPS) devices is imperative. The goal of this study is to determine the state of this educational need. This paper presents a: (1) mapping study to learn about existing research and proposed courses educating students to build IoT and CPS systems; and a (2) Programs Review for CPS/IoT-related courses currently being offered at the top 50 universities ranked by Collegechoice.net. The resulting courses from the mapping study and programs review are extensively analyzed and mapped to the NIST Network of Things primitives and the ACM/IEEE Computer Science Knowledge Areas. In addition to highlighting specific projects, the goal of this paper is to assist in the effort to build or adapt programs that academic institutions currently offer to meet the current and future IoT/CPS training and employment needs.

1. Introduction

The trend for Internet of Things (IoT) and Cyber Physical Systems (CPS), (e.g. smart products and services), are becoming more prevalent every day. IoT applications are already being leveraged in diverse domains such as medical services field, smart retail, customer service, smart homes, environmental monitoring and industrial Internet. Consequently, there will be a significant increase in spending on the design and development of IoT applications and analytics. According to analyst firm Gartner, there were 8.4 billion connected things in 2017 (excluding computers, cellphones and tablets), and this number is set to grow up reaching 20.4 billion deployed IoT devices by 2020 [1]. Spending in this market is expected to increase substantially, with the International Data Corporation (IDC) calculating that the worldwide market for IoT solutions will reach $7.1 trillion in 2020 [2]. The most significant increase in spending on IoT will be in the business-to-business (B2B) IoT systems (e.g. manufacturing, transportation, utilities etc.). This spending will reach $267B by 2020 [3].

This increased spending explicitly implies a need of well-trained engineers to design and implement these "smart" products ranging from ambient intelligence systems for health-care to environmental monitoring to detect volcanic eruptions. A search on Indeed.com in August 2018 for jobs that mentioned "IoT" resulted in 6,407 job opportunities in the United States alone. This doesn't include open positions in data analytics testing, algorithms, machine learning, or security, which are important disciplines in the design and implementation of CPS / IoT as well. In fact, the Bureau of Labor and Statistics predicts a 30 percent increase in jobs related to those technical domains by 2026.

This success and demand puts the burden and challenge on higher education to prepare the next generation of engineers with the skill set necessary to build these complex systems. Universities are being confronted to provide working knowledge of a new engineering discipline that adapts to the reasons why IoT and CPS are different than existing engineering disciplines. This is no easy task as it can be difficult for educators to keep up with the rapid pace of development as well as impart this knowledge onto students [4].

The goal of this paper aims at advancing the effort to build or adapt IoT/CPS training within academic programs / institutions in order to meet the urgent employment needs. The paper presents a mapping study which reviews research on the current college level courses offered on CPS/IoT education. A mapping study is a type of literature review where the main purpose is to classify the research identified as well as identify where the research is lacking [5]. Specifically, a mapping study is performed to learn about a topic, synthesize new knowledge on the topic, or address a deficiency in existing literature by being a facilitator for further research. In addtion to the mapping study we also investigated the current courses being offered on educating IoT at the top 50 ranked academic institutions

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in the world. The courses found from the search are then mapped to the NIST Network of Things (NoT) primitives and the ACM/IEEE Computer Science knowledge areas (KAs).

The remainder of this paper is structured as follows: Section 2 discusses a background on IoT primitives and the IEEE/ACM KAs of Computer Science. Section 3 describes the mapping study and the programs review that we conducted. In Section 4, we present a mapping of the retrieved CPS / IoT courses to the IoT primitives; while in Section 5 we discuss the mapping to the Computer Science KAs. Finally, the conclusions and recommendations are presented in Section 6.

2. Background

2.1. Internet of Things

The IEEE Internet of Thing (IoT) Community defines the IoT as: "...a self-configuring and adaptive system consisting of networks of sensors and smart objects whose purpose is to interconnect "all" things, including every day and industrial objects, in such a way as to make them intelligent, programmable and more capable of interacting with humans" [6]. The term "Internet of Things" was coined by Kevin Ashton in 1999 to refer to uniquely identifiable objects / things and their virtual representations in an Internet-like structure [7].

An IoT is representation of an NoT. Because of the upward trend of IoT/NoT applications in many domains, it is useful to have a consistent language to build NoTs [8]. A NoT can be described by five primitives proposed by NIST Special Publication 800-183 [8]:

1. Sensor is "an electronic utility (e.g. cameras and microphones) that measures physical properties such as sound, weight, humidity, temperature, acceleration". Properties of a sensor could be the transmission of data (e.g. RFID), Internet access, and/or be able to output data based on specific events.

2. A communication channel is "a medium by which data is transmitted (e.g., physical via Universal Serial Bus (USB), wireless, wired, verbal, etc.)".

3. Aggregator is "a software implementation based on mathematical function(s) that transforms groups of raw data into intermediate, aggregated data. Raw data can come from any source". Aggregators have two actors for consolidating large volumes of data into lesser amounts:
   (a) Cluster is "an abstract grouping of sensors (along with the data they output) that can appear and disappear instantaneously".
   (b) Weight is "the degree to which a particular sensors data will impact an aggregator's computation".

4. Decision trigger "creates the final result(s) needed to satisfy the purpose, specification and requirements of a specific NoT". A decision trigger is a conditional expression that triggers an action and abstractly defines the end-purpose of a NoT. A decision triggers outputs can control actuators and transactions.

5. External utility (eUtility) is "a hardware product, software or service which executes processes or feeds data into the overall data flow of the NoT".

Note that any specifically purposed NoT may not include all five. For example, you could have a NoT without sensors. The easiest way to think about IoT is that the "things" are what make IoT unique. Many people question whether IoT is just the next buzz word or is there a science behind it. IoT is an acronym of three letters: (I) (o) (T). (o) does not matter. (I) existed long before the IoT acronym was termed, and the (T) is the letter in the IoT acronym that matters the most. Thus, the five primitives define five Lego-like building blocks for any IoT-based system. The primitives are essentially the (T)s. We need to educate the next generation of computer scientists and engineers on the (T)s [9].

2.2. Knowledge Areas of Computer Science

ACM and IEEE-Computer Society have a long history of sponsoring efforts to establish international curricular guidelines for undergraduate programs in computing on roughly a ten year cycle, starting with the publication of Curriculum 68 [10] 50 years ago. The latest IEEE/ACM Curriculum Guidelines for Undergraduate Degree Programs in Computer Science was published in 2013 [11]. In Computer Science terms, one can view the Body of Knowledge as a specification of the content to be covered and a curriculum as an implementation. IEEE/ACM body of knowledge is composed of 18 KAs (see table 1). Knowledge Areas are not intended to be in one-to-one correspondence with particular courses in a curriculum. A curricula can have courses that incorporate topics from multiple KAs.

Voas and Laplante recommended a set of topics to consider when creating new curricula or topics to consider when modifying existing computer science curricula [12]. Further, if you are looking more at

Table 1. IEEE/ACM Computer Science KAs 2013

1	algorithms and complexity	10	networking and communications
2	architecture and organization	11	operating systems
3	computational science	12	platform-based development
4	discrete structures	13	parallel and distributed computing
5	graphics and visualization	14	programming languages
6	human-computer interaction	15	software development fundamentals
7	information assurance and security	16	software engineering
8	information management	17	systems fundamentals
9	intelligent systems	18	social issues and professional practice

CPS issues than IoT concerns, modifying a systems engineering, electrical engineering, or mechanical engineering curricula might be worth pursing as well.

3. Mapping Study and Programs Review

We conducted a review study with the goal of discovering how IoTs are currently being taught (or proposed to be taught) in academia. The study was done in two parts:

1. A Mapping Study: In the first part we searched the Engineering Village database to learn about existing research and proposed courses educating students to build IoT and CPS systems. Engineering Village is a comprehensive database that aggregates 12 engineering literature and patent databases providing coverage from a wide range of trusted engineering sources. The search was done in February 2018.

2. Programs Review: In the second part, we reviewed CPS/IoT-related programs at the top 50 universities ranked by Collegechoice.net (an aggregate of US News & World Report and the National Center for Education Statistics) and TopUniversities.com (international universities) for IoT and CPS course offerings as of December 2017.

It is worth to mentioning that the term "IoT in Education" is two faceted; because of its use as a technological tool to improve academic infrastructure and as a course or subject from which to teach fundamental concepts of computer science [13]. An example of the first facet is a research study focusing on utilizing IoT in education described a tool to manage student attendance with RFID readers at the school, library, cafeteria, dormitory entrances and to monitor student activities in these locations [14]. In our study herein, we focus on the second facet of the term. During the first part of the study, papers that focused on the first facet were excluded. That said, there are much fewer research papers presenting studies, that we were looking for in this mapping which focus on educating the next generation of engineers and computer scientists to design and build IoT and CPS products.

The search string used for the first part of the review consisted of two parts - C1 and C2, defined as follows:

1. C1 is a string made up of keywords related to Internet of Things such as "Internet of Things", "IoT", "Network of Things" and "NOT", "Cyber Physical Systems".

2. C2 is a string made up of keywords related education such as "education" and "course".

Eq. (1). Boolean expression search criteria C1 AND C2

An example of a search done in the electronic databases is shown below: ("Internet of Things" OR "IoT" OR "Network of Things" OR "NoT" OR "Cyber Physical Systems") AND ("Education" OR "Course").

This resulted in 309 articles. To determine whether a study should be included, the following exclusion criteria were used: (E1) study that not not a peer reviewed (e.g. opinion, viewpoint, keynote, discussions, editorials, comments, tutorials, prefaces, and anecdote papers and presentations in slide formats without any associated papers); (E2) study that is not in English; (E3) Study is focused on the first facet of term but not the second as we discussed previously.

After reviewing the papers' titles and the meta-data, 54 papers were downloaded to be considered. After reading the abstract of each of the papers, 30 articles were rejected on the basis of the exclusion criteria. The remaining 24 papers were read entirety and only 11 studies remained to be considered that meet the inclusion criteria. Each of the 11 remaining papers discussed one potential course to teach IoT.

While reading the papers and reviewing the courses retrieved from the two parts of the study; the primitives and CS KAs were documented. The following analysis presented in this study is based on the findings from this review.

3.1. Overview of courses from the Mapping Study

Of the 11 studies identified, all were published within the past 6 years (Figure 1). Nearly half of the courses discussed in the 11 studies are US based with others located in Italy, Spain, India, UK and China. Eight of the courses targeted mainly undergraduate students. The list of the courses are shown in table 2. Interestingly, 8 of these courses were proposed to be offered in electrical engineering or electrical and computer engineering programs. The remaining four courses reside in engineering science, computer and information science and software engineering programs.

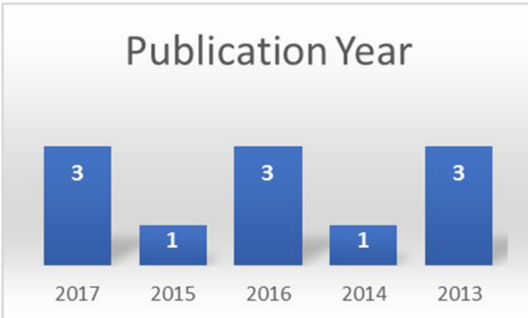

Figure 1. Year-wise distribution of selected studies.

Table 2. List of Courses Extracted from the Mapping Study

	Course Name	Article Source
1	Ambient Intelligence System Design	[15]
2	Systems administration	[16]
3	Cyber-Physical Systems	[17]
4	Internet of Things	[18]
5	Ambient Intelligence: Technology and Design	[19]
6	Smart Sensors and Internet of Things	[20]
7	My Digital Life	[21]
8	A CPS project in a Microprocessor System Design	[22]
9	Pervasive Computing Systems	[23]
10	Cyber-physical Systems	[24]
11	Embedded Systems Design	[25]

3.2. Overview of courses from the Programs Review

We reviewed CPS/IoT-related course offerings at the top 50 US based and international universities ranked by collegechoice.net (an aggregate of US News & World Report and the National Center for Education Statistics) and TopUniversities.com (international universities) as of December 2017. We searched relevant programs for courses focusing on the understanding, design, and/or implementation of Internet of things, cyber physical systems, and network of things. Twenty-eight of those universities had courses with a CPS/IoT focus, most of which were in graduate programs (see table 3). Eight of the courses were offered as both: undergraduate and graduate. In addition, more than half of those courses were taught in electrical and computer engineering programs [9]. We posted the list of courses / universities via the link: goo.gl/UUtN8T .

Table 3. Number of IoT / CPS courses at the top 50 ranked universities. [9]

Universities with IoT/CPS courses	Total IoT/CPS courses	Undergrad courses	Graduate courses
28	45	18	35

4. CPS /IoT courses and the IoT primitives

We reviewed the descriptions and structure of the IoT/CPS courses taught at the top 50 universities to determine the primitive focus of those courses. We carefully examined the course syllabus, description and materials for each of the 45 courses. We then mapped each course to the NoT primitives that it focuses on. For example, in an "embedded systems" course, the description stated:

*"Lectures will cover theoretical concepts of embedded and **cyberphysical systems** including discrete and continuous dynamics, hybrid systems, state machines, concurrent computation, embedded systems architecture and scheduling. Lab involves programming embedded applications for the **decentralized software services** architecture using C# and the Microsoft **Robotics** Software Development Kit (SDK) together with the hardware image processing and tracking capabilities of the Kinect **sensor**."*

This course was mapped accordingly to covering the "sensor", "communication" and "decision trigger" primitives. We posted the mapping matrix for the reviewed 45 courses to the IoT primitives via the link: We posted the list of courses / universities via the link: goo.gl/8VmGTV .

The results showed that only 11 percent of the 45 courses seem to cover all five primitives (see Figure 2). These courses, Interconnected Embedded Systems, Networked Cyber-Physical Systems, Internet of ThingsIntelligent and Connected Systems, and Body Sensor Networks in the Internet of Things, appear to be introductions to IoT and CPS technical and design understanding.

When we analyzed the combined list of courses from top 50 universities and the 11 courses from the retrieved studies, we found that the primitive most covered in the courses was the "e-utility" primitive with almost 25% of the courses covering that primitive in its content (see Figure 3).

Overall, the courses described had a variety of scenarios to teach each NoT Primitive. Notably, courses that covered the NoT primitives involve projects to design and implement devices for remote controlled systems or smart home devices. A smart home

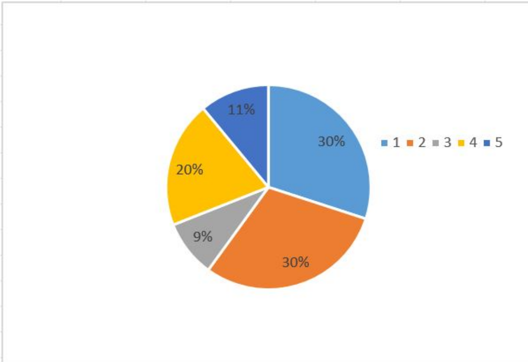

Figure 2. Number of IoT primitives covered in the courses at the top 50 ranked universities.

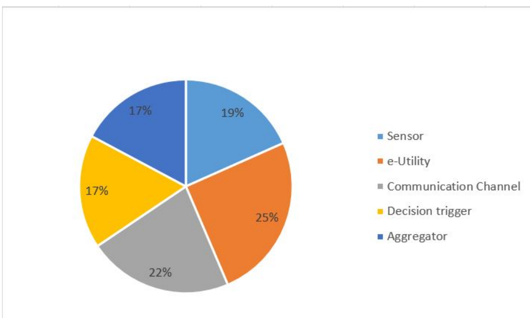

Figure 3. Distribution of NoT primitives in IoT courses from the top 50 universities and the literature

may use ambient intelligence. A course on ambient intelligence (AMI) would gave students access to smart home devices where they would design and implement an AMI system to involve sensing, reasoning about the sensed data (aggregation) on the cloud (eUtility), communicating the data using web protocols and architectures, and actuation (decision trigger) and interaction with the user [15]. Another course may focus on the design of a generic remote controlled system which utilizes robot cameras and gyroscopes (sensors) on mobile phone (eUtility), wireless communication of the data to and from robot, aggregating and reasoning about the data to perform robot movement (actuation) [16]. A cyber-physical system project had students focus on automation of industrial processes using an autonomous guided vehicle (AGV). The design of an AGV needs to consider sensor information to determine if the AGV is near a start and stop point by communicating and aggregating data stored on a cloud or server (eUtility) and triggering a decision [17].

5. CPS /IoT courses and Knowledge Areas of Computer Science

Most of the analyzed courses focused on IoT and CPS development. For example, an AMI system utilize pervasive technology and refers to the capacity of an IoT system to sense the environment and to respond to the presence of people. Pervasive computing are the microprocessors that facilitate the consistent communication connection in AMI systems.

In other words, AMI builds upon pervasive computing, and human-centric computer interaction design (KA: *human-computer interaction*). Environments that use AMI have these properties [26]:

- Identity recognition of individuals
- Awareness of an individuals presence
- Context awareness (e.g. traffic, weather)
- Activity recognition
- Individual needs adaptation

An excellent example of AMI are Ambient Assistant Living (AAL) technologies. These are technologies designed to assist autonomous aging such as detecting falls or medication reminders [27]. Another example is using ambient technologies to detect and absorb carbon dioxide from emissions to help control global warming [28].

The course and project descriptions were analyzed to map each course from the mapping literature study to the IEEE/ACM computer science KAs. The results are shown in Table 4. Noting that although there does not seem to be a pattern or consistency in the KAs covered, it is clear that that IoT/CPS skill set matches well with the IEEE/ACM computer science KAs.

The KAs for the courses were determined by the learning objectives and/or projects, depending on what was provided by the research. For example, one of the learning objectives for the Microprocessor Systems Design course were to write a pair of networked programs to exchange data between the embedded system and a computer. This objective clearly maps to KAs: *networking and communications* and *software development fundamentals*.

In general the course objectives were to have the students learn to design and manage complex/distributed systems (KA: *parallel and distributed computing*). Many of the projects assigned in the courses focused on practical programming (KA: *Software development fundamentals* and *algorithms and complexity*) of the IoT/CPS system. In another project, the students developed an android-based remote system for teleoperating a mobile robot controlled by means of a Raspberry Pi. The software developed by the students used the mobile phone gyroscope which translated the left and right tilt movements of the smartphone into motion commands to be followed by the robot.

Other interesting projects were in the area of smart things (e.g. cities and houses) as well as in the area of environmental monitoring (e.g. air, water, and soil quality; health quality, monitoring flood, volcanic eruptions, and traffic etc.)

Table 4. Course mapping to IEEE/ACM Comp Sci KAs

Course Name Article Source	KAs
Ambient Intelligence System Design [15]	(2) (6) (9) (10) (12) (13) (14) (15) (16)
Systems administration [16]	(1) (2) (3) (5) (9) (10) (11) (12) (14) (15) (17)
Cyber-Physical Systems [17]	(1) (2) (3) (7) (8) (9) (10) (12) (13) (16) (18)
Internet of Things [18]	(10) (12) (14) (15) (17)
Ambient Intelligence: Technology and Design [19]	(6) (8) (10) (12) (14) (15) (16) (18)
Smart Sensors and Internet of Things [20]	(2) (7) (10) (12) (15)
My Digital Life [21]	(1) (2) (15) (18)
A CPS project in a Microprocessor System Design [22]	(2) (9) (10) (12) (15)
Pervasive Computing Systems [23]	(8) (9) (10) (11) (12) (15) (16)
Cyber-physical Systems [24]	(15) (16) (18)
Embedded Systems Design [25]	(9) (10) (12) (15) (16)

6. Recommenations and Conclusion

It is clear that established engineering programs need to provide engineering students with the skills, tools, and training to design, implement, verify and validate these complex IoT and CPSs. The goal of this study was to determine the state of established higher education courses focused on developing skills to design and develop IoT and CPS systems.

The current state according to this mapping study indicates that course offerings in this area are at the beginning stages. This is not surprising considering the challenge academic programs have in adding courses and/or establishing new programs in general. Thus, it may be more practical for traditional curriculum to adapt the conventional courses to include the tools and training to address the need to develop the skill-set of the next generation of engineers and computer scientists for designing and building effective IoT and CPS systems. For example, an effective approach is to create learning modules that would address specific learning objectives. The modules would highlight CPS/IoT concepts using appropriate tools and hands-on exercises that could easily fit into existing courses such as embedded systems, systems administration, computer security, software architecture, and software construction. Virginia Tech created CPS security-focuses learning modules for this purpose [29]. Another approach is to create elective courses where students implement practical CPS or IoT systems as a course project similar to those described in this mapping study.

Accordingly, the path of least resistance to create a new program is by modifying existing programs since many of these courses may already exist at the institution and only require slight modifications. This appears to be the most efficient way to create new CPS/IoT educational program that is relevant, timely, and available now.

The future probably calls for a new engineering discipline for the 21st century, possibly called IoT Engineering or Network Engineering. Just as electrical engineering emerged in the late 19th century with the invention of the electric motor. In the meantime, there is no doubt that a complete CPS/IoT curriculum will require core set of competencies from multiple disciplines, existing engineering and/or computer science programs.

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