A Case Study to Develop a Graduate-level Degree Program in Embedded & Cyber-Physical Systems

Fadi Kurdahi, Mohammad Abdullah Al Faruque, Daniel Gajski, Ahmed Eltawil
Center for Embedded & Cyber-Physical Systems
University of California, Irvine
Irvine, CA 92697-2625
{kurdahi, alfaruqu, gajski, aeltawil}@uci.edu

ABSTRACT

University of California Irvine is developing an interdisciplinary graduate-level Masters degree in Embedded & Cyber-Physical Systems (MECPS) that will be managed by the Center for Embedded and Cyber-Physical Systems (CECS). In this paper, we present this case study and highlight our systematic approach to creating this MS degree program based on the demand from the students and the industries. As part of our methodology, a survey was conducted among applicants and current MS students in both Electrical Engineering and Computer Science disciplines. Moreover, a market study was performed by the University Extension to estimate the CPS-related job market in the United States of America.

Categories and Subject Descriptors

K.3 [**COMPUTERS AND EDUCATION**]: Computer and Information Science Education and Miscellaneous

General Terms

Embedded Systems, Design Methodology

Keywords

Cyber-Physical Systems, Embedded Systems, Education, Graduate Program

1. INTRODUCTION AND RELATED WORK

As systems grow in scale, complexity, and integration levels, there is a need to move towards a science of embedded systems, addressing the foundational aspects of design [1, 2]. Now that we have a better understanding of the basics of embedded systems, it is equally important to branch out to the application of such systems. This requires addressing domain-specific issues and the scale-up in complexity introduced by what is referred to today as cyber-physical systems. Generally speaking, Cyber-Physical Systems (CPS) are systems-of-systems that tightly couple their cyber (i.e. computation, communication and control), and physical components (sensing and actuation) in the context of applications such as (but not limited to): automotive and transportation, manufacturing, power distribution grid, medical and healthcare, robotics, civil infrastructure, avionics, etc. [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. Thus, these cyber-physical systems marry knowledge from the fields of embedded systems, networking, sensors, real-time systems and control as well as domain-specific knowledge to realize systems that are of untapped complexity and scale (see Figure 1). At the national level, CPS has been promoted in major funding initiatives as presented in several reports from funding agencies (e.g., [22, 23, 24]), and on a global scale, the European Union has allocated over $7 Billion to fund research in the area of embedded and cyber-physical systems as part of their Vision 2020 initiative. Japan has also launched similar initiatives. Essentially, the following domains have been identified as major thrust areas in CPS (although other areas are constantly being added to the list):

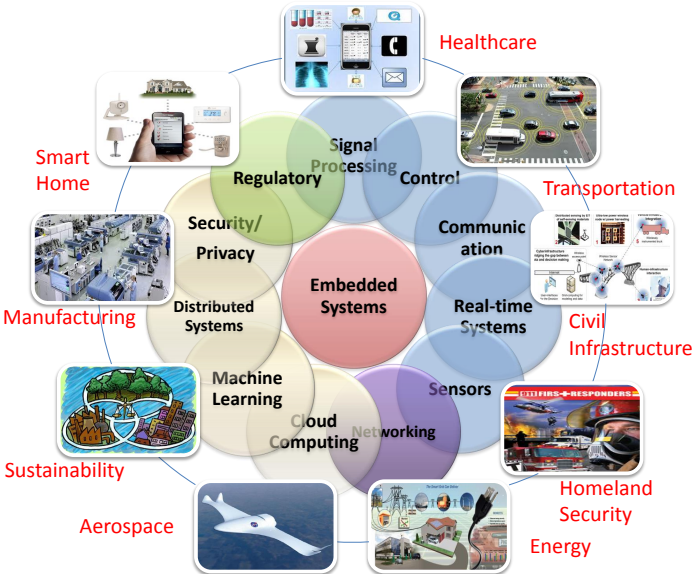

Figure 1: The Interdisciplinary Nature of ECPS.

1. **Advanced Manufacturing:** smart production equipment, processes, automation, control, and networks; new product design.
2. **Transportation/Automotive:** intelligent vehicles and traffic control, intelligent structures and pavements.
3. **Smart Infrastructure:** smart utility grids and smart buildings/ structures, civil infrastructure, smart homes.

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4. **Health Care:** body area networks and assistive systems, elderly home care and monitoring, networked implantable devices.
5. **Emergency Response and Cyber-Enhanced Security:** detection and surveillance systems, situational awareness, communication networks, and emergency response equipment.
6. **Sustainable development:** Water, pollution, waste, etc.

1.1 Overview of the proposed degree program

In a key report commissioned by NIST [22], it was stated that "*... ... a key visionary element of the future of education for CPS is the availability of recognized educational programs that offer the fundamentals of CPS though a multidisciplinary curriculum.*" The report goes on to recommend several transformative ideas, one of which is to "*... ...reward Masters' programs in CPS*". The report also points to a major barrier which is the "*... ...Lack of a CPS degree that cuts across multiple disciplines, hindered by stove piped nature of university structure.*" Motivated by the same vision, we initiated this degree as the first in the US to focus on both Embedded and Cyber-Physical Systems (ECPS). The degree will be managed by the Center for Embedded and Cyber-Physical Systems (CECS) at the University of California, Irvine (UCI) [25]. CECS and its activities naturally fall at the intersection of Engineering and Computer Science disciplines, and thus can inherently overcome the hindrances observed by the NIST report. Graduates are expected to have an integrative knowledge of systems fundamentals that include software, hardware, sensing, actuation control and hands-on knowledge through practical projects in a targeted application domain.

In recent years, we find that as undergrads work on senior design projects they get familiar with Embedded and Cyber-Physical Systems and gain an appreciation for the domain. Indeed, many of these students state that hands-on knowledge of systems is a highlight of their educational experience at UCI, and want to see more of it in the future. The proposed MECPS program directly addresses that point through the project students are required to do to fulfill their MECPS graduation requirement.

The interdisciplinary self-supporting Masters Degree in Embedded & Cyber-Physical Systems (MECPS) consists of a pre-sequenced pace of 7 foundational courses plus two project courses leading to a final project. Courses will carry 4 units of instruction and will be developed specifically for this program and delivered in a blended format. The courses comprising the degree will be a mix of on-ground and online components. To begin the program, all the courses will require a residential component. In the future, we will consider the possibility of having some courses in a blended or online format if deemed pedagogically sound. The blending format will vary from course to course depending on the amount of foundational versus hands-on components in each course. Ideally, much of the foundational knowledge will be delivered online while hands-on sessions will be face-to-face. Depending on the class size, some of the face-to-face sessions may be held using group interaction systems such as Google hangout.

2. STUDENT DEMAND FOR THE PROGRAM

The demand for advanced degrees in Electrical Engineering (EE), Computer Science (CS) and related fields has grown significantly in recent year. As an example, the number of applicants to the graduate programs in the EECS department in the Henry Samueli School of Engineering at UCI has more than doubled in the past 4 years. About 2/3 are MS applicants. Only 5% of these applicants are admitted to the MS program. A quick search showed that about 1/4 of the Fall 2014 applicants indicated ECPS as one of their interests even without having an ECPS program in place! Thus it is clear that there is significant demand for the program and there exists an excellent pool of applicants to which this program can be presented. We will specifically target applicants who have some industry exposure (whether as working professionals or interns, or having done practical work in their undergraduate years). Additionally, the degree will be offered to the industries through the University affiliates programs.

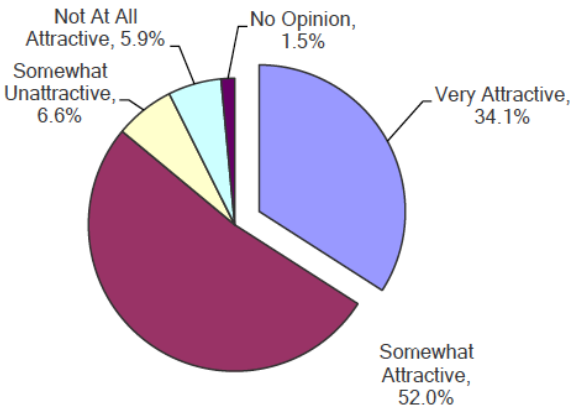

Figure 2: Survey Question: Based on the program description above, in your opinion, how attractive would the described Master's degree program in ECPS be to a prospective student.

The applicants and current MS students at UCI were surveyed to indicate how attractive such a program would be to them. 34.1% responded as "very attractive", another 52.0% responded as "somewhat attractive". To frame this in the proper context, the MS applicants and students' interests cover an extremely wide scope, from computer algorithms to solid-state devices. The fact that over 1/3 of them rated such a program as very attractive is indicative of the expected popularity such a program would have once implemented.

2.1 To Online Or Not To Online

When prompted to provide feedback about the desired proportion of on-campus classroom instruction versus online instruction, most respondents favored a majority of face-to-face instruction. Based on this feedback, we believe a blended format is an ideal venue where courses will be heavily technology enhanced, but without eliminating classroom interaction.

3. OPPORTUNITIES FOR PLACEMENT OF GRADUATES

We expect students to have an integrative knowledge of systems fundamentals that include software, hardware, sens-

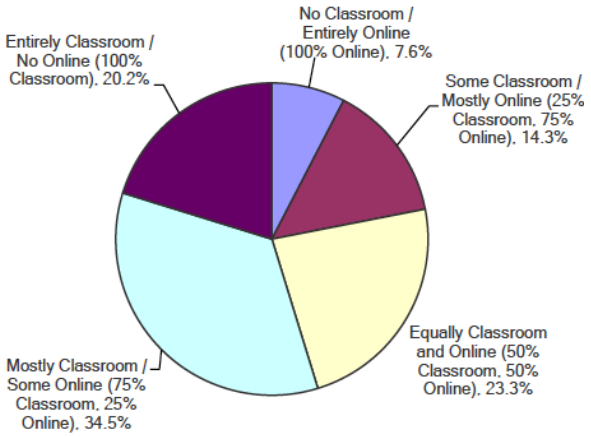

Figure 3: Survey Question: If the Master's degree in ECPS were offered with an online instructional component, how much of the program would you expect to be conducted in a traditional campus/classroom format on campus, and how much would be offered in an online format? Please select the response that most closely represents your opinion.

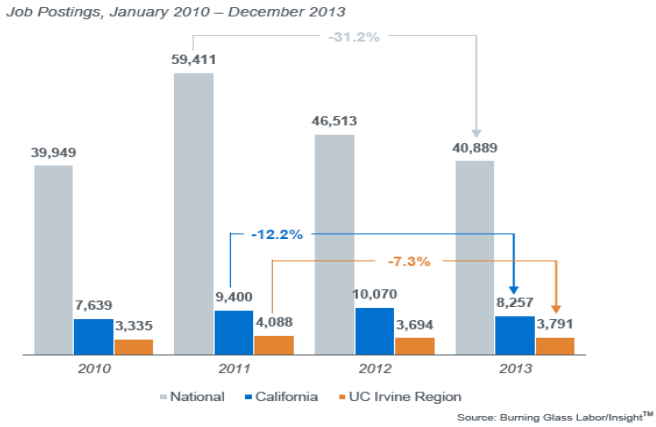

Figure 4: Historic trends in demand for CPS and related skills.

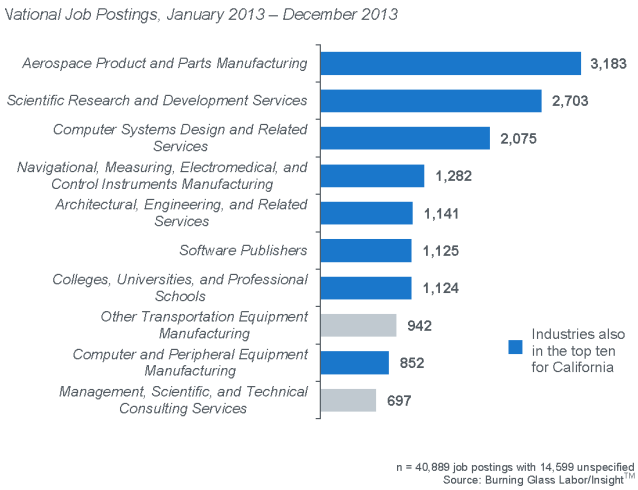

Figure 5: Top industries in the US for CPS and related skills.

ing, and actuation control. Students will also acquire hands-on knowledge through practical projects in a targeted application domain. Owing to its interdisciplinary nature, program graduates will be able to seek employment in electronics, aerospace, automotive, biomedical, manufacturing, robotics, defense, and construction industries.

The placement potential for the program's graduates is quite broad. A job market survey study was conducted by the University Extension. The graph in Figure 4 shows historic trends in demand for CPS and related skills. These skills include: systems engineering, embedded systems, robotics, mechatronics, control system design, or data communications. While a decline is observed nationwide in job demands, it is still a very healthy field with over 40000 job postings nationwide in 2013. More importantly, the job market in the local markets (California and UCI region) shows an even healthier trend with jobs in the UCI region increasing between 2012 and 2013 to around 4000 postings. Figures 5 - 8 highlight the skills, companies, regions and industries that are likely to hire MECPS graduates. The report further expects that 50-75% of the enrollees to be international students. Thus, many of the program's graduates may be candidates for the global job market, where even more significant growth is expected. Salary information further accentuates the attractiveness of the proposed degree. The same study concludes that "..students receive higher starting salaries, over $100,000 at jobs that require CPS skills".

3.1 Importance To The Discipline

Embedded systems are not apparent as computing apparatus, however they control the functionality and features of systems that exist around us in almost every appliance or device that we interact with on a daily basis. Cyber-physical systems are built around embedded systems and can be found in cars, for example, controlling almost every subsystem: breaks, steering, entertainment and many other. They are also found in set top boxes, airplane automatic pilot, pacemakers, building thermostats, and robotic manufacturing system to mention but a few. Today 90-95% of computing devices are in embedded systems and are expected to grow by 10% per year, reaching 20-200 billion computing devices in 2020, or about 30 devices per every living human on the planet. The value of embedded systems is correspondingly increasing as more functions are migrated to these systems. Today, they comprise 20% of car's value but will increase to 35-50% by 2020. The significance of embedded and cyber-physical systems on the economy is hard to overlook, the worldwide market for embedded systems in 2010 was about $100 billion, and $121 billion in 2011, and increasing at 7% Compound Annual Growth Rate (CAGR) per year to about $195 billion in 2018. Figures 5 and 6 show "approximately" postings and jobs related to ECPS. According to the Bureau of Labor Statistics, Network and Information Technology is projected to account for about 55% of all Science, Technology, Engineering and Math (STEM) jobs between 2008-2018, and amounting to over 760,000 jobs. The expected growth rate is twice the rate for all occupations in the US economy. From a worldwide prespective, It

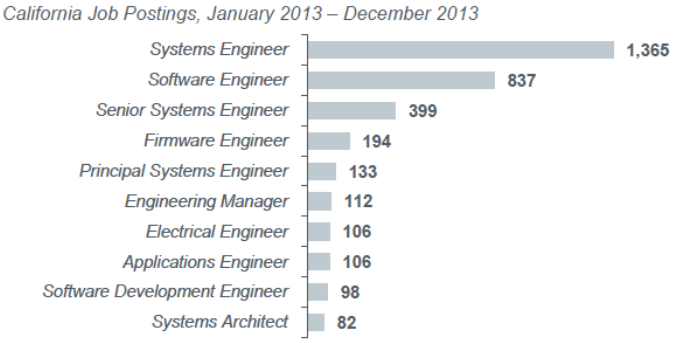

Figure 6: Top titles for jobs that require CPS an related skills.

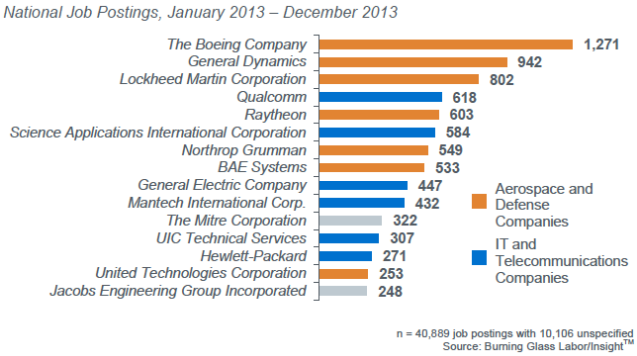

Figure 7: Top employers in the CPS for CPS and related skills.

is expected that the economy of ECPS and affiliated industries, or what is now referred to as the Internet of Things (IoT) will exceed $6-14 Trillion into the next decade [26, 27, 28, 29]. These numbers give us confidence that graduates who are trained in this domain will not have trouble finding jobs, and ones with high paying salaries at that. Figures 7 and 8 show "present day" postings and jobs that could be related to ECPS.

3.2 Ways in which the program will meet the needs of society

The importance of ECPS in serving the needs of society cannot be overstated. Figure 1 highlights the pervasiveness and ubiquity of such systems. Today it is hard to imagine a moment in as person's life on this planet where he or she is not interacting with such a system. Dubbed as systems that "you can trust your life to," cyber-physical systems are present in our everyday lives and are slated to become ubiquitous in the foreseeable future. From the smart grid that powers homes, to medical and health care monitoring systems, to electric vehicles and automotive telematics, to civil infrastructure, emergency response systems, and manufacturing, the need for skill sets in ECPS to help design, maintain, improve, use and assess such systems is an indispensable component in society's quest for a safer, more dependable, comfortable and generally happier status. As we increasingly entrust our well-being to automated systems, the need for integrative skills in ECPS will become more acute.

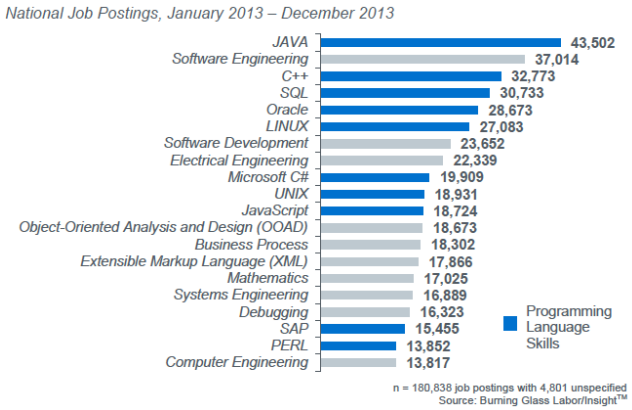

Figure 8: Possible/present day specialized skills for CPS program graduates.

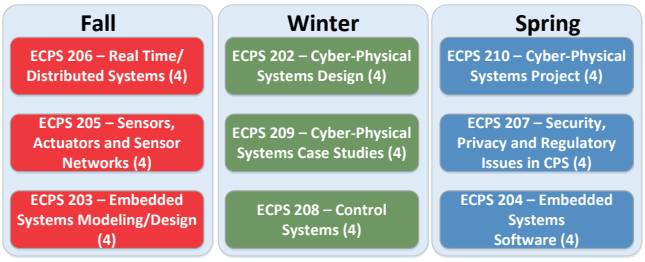

Figure 9: Sample program of study.

4. THE PROGRAM OF STUDY

The interdisciplinary Masters Degree in Embedded & Cyber-Physical Systems (MECPS) consists of a pre-sequenced pace of 7 foundational courses plus two project courses leading to a final project. As a prerequisite, students are expected to have completed a BS in Electrical Engineering (EE), Computer Engineering (CpE), Computer Science (CS), and Computer Science & Engineering (CSE) as shown in Figure 11. Courses will carry 4 units of instruction and will be developed specifically for this program and delivered in a blended format. The courses comprising the degree will be a mix of on-ground and online components. To begin the program, all the courses will require a residential component. In the future, we will consider the possibility of having some courses in a blended or online format if deemed pedagogically sound. The blending format will vary from course to course depending on the amount of foundational versus hands-on components in each course. Ideally, much of the foundational knowledge will be delivered online while hands-on sessions will be face-to-face. Depending on the class size, some of the face-to-face sessions may be held using group interaction systems such as Google hangout.

Figure 9 shows a one year plan of study. The two year plan is a part-time program for industry professionals (see Figure 10).

5. CONCLUSIONS

A case study on developing a graduate level Masters degree program in Embedded and Cyber-Physical Systems is presented in this paper to address industry demands. Driven

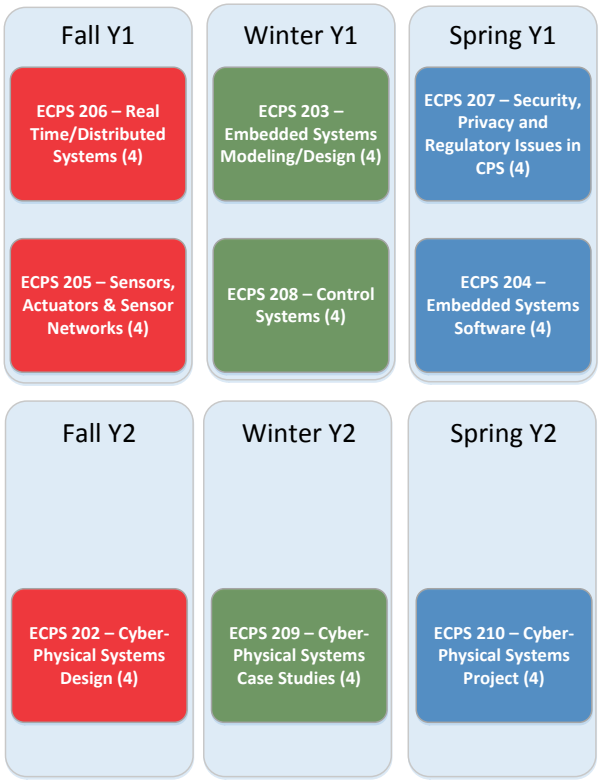

Figure 10: Sample two years program of study.

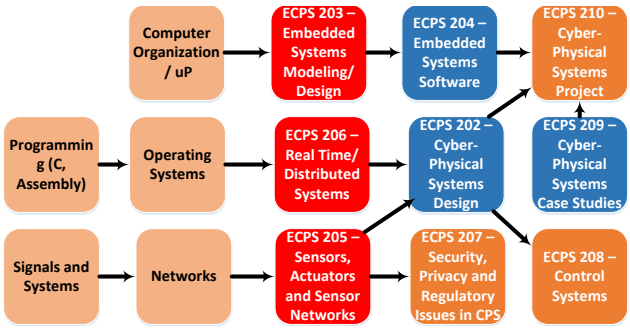

Figure 11: MECPS courses and prerequisites.

by the staggering estimates of economic impact and prospective job market size, the proposed MECPS program proposed is developed, in part, to serve the needs of domestic and international students, and working professionals among whom the leaders of the Embedded & Cyber-Physical Systems are especially likely to come. In future, lessons learned from the operation of this degree program will be shared with the ECPS community so that other universities worldwide may benefit from our experience. Our cyber-physical systems education is complementary to other initiatives, e.g. [30, 31, 32, 33, 34, 35, 36].

6. REFERENCES

[1] Sang C. Suh et. al (eds.). Applied Cyber-Physical Systems. *Springer*, 2014.

[2] Transparencymarketresearch. `http://www.transparencymarketresearch.com/embedded-system.html`., 2014.

[3] Edward A Lee. Cyber physical systems: Design challenges. *Object Oriented Real-Time Distributed Computing (ISORC), 11th IEEE International Symposium on*, pages 363–369, 2008.

[4] NSF. Cyber-Physical Systems (CPS). `http://www.nsf.gov`., 2014.

[5] DARPA. Adaptive Vehicle Make (AVM) Program. `http://www.darpa.mil`., 2014.

[6] NIST. Foundations for innovation: Strategic R&D opportunities for the 21st century cyber-physical systems - connecting computer and information systems with the physical world. *Technical report, NIST*, 2013.

[7] Rajesh Gupta. Programming models and methods for spatiotemporal actions and reasoning in cyber-physical systems. *NSF Workshop on CPS*, 2006.

[8] Paulo Tabuada. Cyber-physical systems: Position paper. *NSF Workshop on Cyber-Physical Systems*, 2006.

[9] Ragunathan Raj Rajkumar, Insup Lee, Lui Sha, and John Stankovic. Cyber-physical systems: the next computing revolution. *Proceedings of the 47th Design Automation Conference*, pages 731–736, 2010.

[10] Gabor Karsai and Janos Sztipanovits. Model-integrated development of cyber-physical systems. pages 46–54. Springer, 2008.

[11] Jeff C Jensen, Danica H Chang, and Edward A Lee. A model-based design methodology for cyber-physical systems. *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pages 1666–1671, 2011.

[12] Gabor Simko, Tihamer Levendovszky, Miklos Maroti, and Janos Sztipanovits. Towards a theory for cyber-physical systems modeling. *Proc. 3rd Workshop on Design, Modeling and Evaluation of Cyber Physical Systems (CyPhy 2013), Philadelphia, USA, April*, pages 08–11, 2013.

[13] Peter Marwedel. *Embedded system design: Embedded systems foundations of cyber-physical systems*. Springer Science & Business Media, 2010.

[14] Edward Ashford Lee and Sanjit Arunkumar Seshia. *Introduction to embedded systems: A cyber-physical systems approach*. Lee & Seshia, 2011.

[15] Arquimedes Canedo, Eric Schwarzenbach, and Mohammad Abdullah Al Faruque. Context-sensitive synthesis of executable functional models of cyber-physical systems. *ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS)*, pages 99–108, 2013.

[16] Janos Sztipanovits, Xenofon Koutsoukos, Gabor Karsai, Nicholas Kottenstette, Panos Antsaklis, Vijay Gupta, Bill Goodwine, John Baras, and Shige Wang. Toward a science of cyber–physical system integration. *Proceedings of the IEEE*, 100(1):29–44, 2012.

[17] Arquimedes Canedo, Jiang Wan, and Mohammad Abdullah Al Faruque. Functional modeling compiler for system-level design of automotive cyber-physical systems. *IEEE/ACM International Conference on Computer-Aided Design (ICCAD)*, pages 39–46, 2014.

[18] Lui Sha, Sathish Gopalakrishnan, Xue Liu, and Qixin Wang. Cyber-physical systems: A new frontier. pages 3–13. Springer, 2009.

[19] EMBEDDED COMPUTING. Cyber-physical systems. 2009.

[20] Radhakisan Baheti and Helen Gill. Cyber-physical systems. *The impact of control technology*, pages 161–166, 2011.

[21] Mohammad Abdullah Al Faruque and Fereidoun Ahourai. A model-based design of cyber-physical energy systems. In *2014 19th Asia and South Pacific Design Automation Conference (ASP-DAC)*, 2014.

[22] NIST. `http://www.nist.gov/el/isd/cps-020613.cfm`., 2014.

[23] Whitehouse. `http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd-report-2010.pdf`., 2010.

[24] CPS-VO. `http://cps-vo.org/`., 2014.

[25] Center for Embedded and Cyber-Physical Systems (CECS). `http://www.cecs.uci.edu/`., 2014.

[26] CISCO Corp. `http://www.cisco.com/web/about/ac79/docs/innov/IoE_Economy.pdf`., 2013.

[27] Freescale Corp. and ARM Corp. `http://cache.freescale.com/files/32bit/doc/white_paper/INTOTHNGSWP.pdf`., 2014.

[28] GE Corp. `http://www.ge.com/docs/chapters/Industrial_Internet.pdf`., 2012.

[29] Goldman-Sachs Equity Research. `http://www.goldmansachs.com/our-thinking/outlook/internet-of-things/iot-report.pdf`., 2014.

[30] Dorsa Sadigh, Sanjit A Seshia, and Mona Gupta. Automating exercise generation: A step towards meeting the MOOC challenge for embedded systems. *Proceedings of the Workshop on Embedded and Cyber-Physical Systems Education*, page 2, 2012.

[31] Kerstin Bauer and Klaus Schneider. Teaching cyber-physical systems: A programming approach. *Proceedings of the Workshop on Embedded and Cyber-Physical Systems Education*, page 3, 2012.

[32] Walid Taha, Robert Cartwright, Roland Philippsen, and Yingfu Zeng. A First Course on Cyber Physical Systems. *Workshop on Cyber-Physical Systems Education (CPS-Ed)*, 2013.

[33] E Atkins and J Bradley. Aerospace Cyber-Physical Systems Education. *AIAA Infotech@ Aerospace*, 2013.

[34] Aniruddha Gokhale, Gautam Biswas, Nilanjan Sarkar, Shivakumar Sastry, and MS Branicky. CPS-Laboratory-as-a-Service: Enabling technology for readily accessible and scalable CPS education. *First Workshop on Cyber Physical Systems Education, CPSWeek*, 2013.

[35] Edward A Lee, Sanjit A Seshia, and Jeff C Jensen. Teaching embedded systems the Berkeley way. *Proceedings of the Workshop on Embedded and Cyber-Physical Systems Education*, page 1, 2012.

[36] Steffen Peter, Frank Vahid, Daniel D Gajski, and Tony Givargis. A Ball Goes to School-Our Experiences from a CPS Design Experiment. *1st Workshop on Cyber-Physical Systems Education (CPS-Ed)*, 2013.