Education and training challenges in the era of Cyber-Physical Systems: beyond traditional engineering

Martin Törngren
KTH Royal Institute of Technology
10044 Stockholm, Sweden
+46-8-7906307
martint@kth.se

Saddek Bensalem
Univ. Joseph Fourier
Univ. Grenoble Alpes, VERIMAG,
F-38000 Grenoble, France
saddek.bensalem@gmail.com

John McDermid
Univ. of York
Department of Computer Science,
Deramore Lane, York, YO10 5GH; UK
john.mcdermid@york.ac.uk

Roberto Passerone
DISI - Univ. of Trento
Via Sommarive 9, 38123 Trento, Italy
roberto.passerone@unitn.it

Alberto Sangiovanni-Vincentelli
Univ. of California at Berkeley
515 Cory Hall, Berkeley CA 94720
alberto@eecs.berkeley.edu

Bernhard Schätz
TUM/Fortiss
80805 Munich, Germany;
schaetz@in.tum.de

ABSTRACT
Education and training face several challenges as our society is evolving to become increasingly dependent on Cyber-Physical Systems (CPS). We present and discuss how education is impacted, leveraging mainly a cross-domain investigation of CPS challenges of the EU CyPhERS project. In particular, the investigation revealed challenges that go beyond engineering education and that were found to be common across domains; (i) the need to consider and to include a broader set of stakeholders including policy makers and the general public to raise awareness of CPS technology implications (opportunities, risks and challenges), (ii) emphasizing human centered perspectives including sustainability and privacy in CPS education to make sure we end up with a human centric CPS-based society, (iii) improving the status of teaching, and (iv) supporting educational platforms and life-long learning capabilities. We conclude by discussing implications for educational systems.

Categories and Subject Descriptors
K.3.2 [Computer and Information Science Education]; K.4.1 [Public Policy Issues]; K.4.2 [Social Issues]; K.4.3 [Organizational Impacts]; K.6.1 [Project and People Management].

General Terms
Management, Design, Economics, Security, Human Factors.

Keywords
Cyber-physical systems, Embedded systems, Engineering education, Technological paradigm shifts, Life-long learning

1. INTRODUCTION AND MOTIVATION
The increasing connectivity, significance of software-defined functionality and an increasing penetration of electronics and software into virtually all facets of our lives, results in a society which is becoming dependent on smart devices that are part of and form inter-connected Systems of Systems, [3]. Different research communities refer to these systems by different names, such as Cyber-Physical Systems (CPS), Internet of Things (IoT), Ubiquitous Computing, the Fog and the Swarm, but all share the same paradigm of immersive and distributed sensing and computing. In this paper, we will refer to these technologies collectively as CPS.

It is clear that there is a large demand for CPS engineers. For example, according to an investigation by ARTEMIS and ITEA2, the global market of Digital Technology is currently estimated at USD 3,300 billion, corresponding to approximately 50 million jobs, and is predicted to have continued strong growth [1]. The term Digital Technology was used in [1] to account for software, embedded software, IT services, internal IT as well as hardware encompassing semiconductors, PCs, tablets, servers, storage, and peripherals.

The nature of CPS, however, implies a paradigm shift in the way systems are designed. Distinguishing "embedded" from "IT" used to be simple, as were the corresponding curricula. However, the connectivity and software intensiveness in all sorts of new applications imply that the traditional separation into various disciplines and domains is no longer adequate. Given this evolution, it is not surprising that CPS education is facing challenges in view of a growing demand from industry and public administrations, and considering innovation opportunities that lie in systems oriented services and products (cross discipline and domains). University programs are not producing the numbers of CPS specialists required and need to improve when it comes to balancing the skills provided.

The paradigm shift motivates extra efforts for revising education programs. Indeed, university educators are actively engaged in discussing how to reform programs to educate the CPS engineers of tomorrow, see for example [4], [6], [7], [8]. Balance and synergy lie at the core of developing CPS programs, [5].

Beyond engineering education, the large-scale implications of CPS imply that other educational and training efforts are important to make it possible to develop “CPS based societies”. In this paper we summarize and discuss such educational related findings, obtained mainly within the EU Project CyPhERS, an effort to create a CPS roadmap and agenda for Europe, [2].

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The main findings of CyPhERS were intended to define actions that could help to ensure sustainable and smooth adoption of CPS. CyPhERS took a broad perspective of CPS; the main findings relevant to education are as follows:

- Training and education require inclusion and consideration of a broader set of stakeholders including policy makers and the general public, in order to raise awareness of CPS opportunities, challenges and risks.
- Programs should be human-centered and should address sustainability and privacy to ensure that we develop a CPS ecosystem that is useful to humans and society.
- Improving the status of teaching.
- Stronger needs for life-long learning and continued education for engineers and other stakeholder. The needs are emphasized by the pace and variety of technological development, for example the integration of consumer electronics with industrial electronics. In addition, there are needs to support the development of educational platforms.

The paper is laid out as follows. Section 2 provides information about the investigations carried out. Section 3 summarizes the main findings, whereas Section 4 discusses these findings. Section 5 concludes the paper with recommendations for further work.

2. UNDERLYING INVESTIGATIONS

The findings described in this paper draw mainly on the CyPhERS project, [2]. The CyPhERS project was an EU-funded support action intended to establish a strategy and roadmap for CPS in Europe (see [10] for the final recommendations). CyPhERS had a broad remit covering, for example, technology trends and the impact of CPS on markets, e.g. identifying potential for disruption, including displacing incumbent suppliers.

Some of CyPhERS' work was generic, e.g. considering trends in technology, whereas some was domain specific. For example, the project considered smart grids, manufacturing, healthcare, road transportation and smart cities as application domains for CPS.

The core members of the CyPhERS project drew on their own expertise, but sought insight from a wide range of sources. As a consequence the project ran several workshops, carried out state-of-the-art surveys, and undertook in depth analysis, including SWOT analysis, for the five selected domains.

The findings in the selected domains were different in detail, but there was clear commonality in the core issues they identified. The findings were also supported by industrial and academic views expressed at a number of the workshops. The project produced recommendations to the EU on actions that could be taken to strengthen and protect the position of Europe in CPS, and the five domains investigated in more detail.

While the findings from the CyPhERS project were centered on a European perspective, the investigations also partly covered Asia, USA and Australia, by involving experts from these areas.

3. MAIN FINDINGS

3.1 Societal level training and preparation

The widespread adoption and penetration of CPS will affect most daily tasks and actions performed by any person. CPS will also in effect impact most aspects of a society, for example in terms of legislation, insurances, investments, governmental procurements, and privacy.

One of the key findings is that training and education consequently require the inclusion and consideration of a broader set of stakeholders than just engineers and system developers. A very broad set of stakeholders need basic understanding (and thus some form of education) about CPS!

If used effectively, CPS will enhance our daily lives and contribute to a sustainable society. If used and/or designed inappropriately, they may lead to unacceptable risks, for example causing shut-down of critical systems for transportation, energy provision and/or healthcare. They may also cause accidents and loss of energy and information. Because societies will rely on CPS it is of paramount importance not only that they are effectively engineered, but also well understood and appropriately used.

Decisions makers will, for example, be involved in risk assessments and trade-offs regarding choices in procuring CPS-based systems. Without basic insights, certain vulnerabilities and risks may be disregarded or devalued. A typical example of this would be decision makers for smart cities and transportation systems.

Awareness of CPS is also likely to increase the likelihood of CPS-based innovation and societal improvements. Involving the general public to a larger degree may also help to limit the "digital divide".

The immense opportunities offered by CPS, and the trade-offs involved (for example referring to data sharing vs. privacy, openness vs. security threats), would benefit from elaboration and investigation involving end-users. Essentially, "any system could be built" – the question is – what type of CPS-based societies would we like to create? For this purpose we recommend larger scale demonstrators and pilots to involve end-users.

To raise CPS awareness, education and training for a broader set of stakeholders needs to be addressed, ranging from early schooling to continuing education (see further Section 3.4).

The engineering training and education needs to focus on CPS traits and the characteristics of SoS, including:

- Increasing openness, adaptability and autonomy, in contrast with traditionally closed systems, with single jurisdiction, limited adaptability and autonomy [2];
- The extensive inclusion of off-the-shelf (OTS) parts perhaps with limited knowledge about their pedigree;
- Continual evolution, as individual CPS are upgraded;
- The ability to integrate across domains, e.g. to link smart grid with (charging for) electrics vehicles.

There is also a need of specialist training for system integrators and architects focusing, inter alia, on emergent properties, control of system configuration, system audit and monitoring.

3.2 Sustainable technologies

Electronics is already being embedded "everywhere" in our societies, and the CPS evolution will pave the way for even more electronics. CPS further creates important business opportunities for largely automated technological systems.

The implication is that economic, social and environmental sustainability must be considered now in order to ensure that planning, adoption and deployments of CPS sufficiently consider such aspects, in turn ensuring that humans remain in the center stage of a CPS-based society.

Important sustainability considerations that should be part of an all-around education program include

- Scarcity of earth's natural resources. Incentives to drive sustainable solutions towards a circular economy are important, [14]. CPS technology can contribute by providing including architectures and modularization schemes to support this.
- Management and maintenance of systems, mastering and limiting their complexity. Software and network based systems easily contribute unintended (and difficult to control) complexity into systems.
- Privacy, security, safety and reliability/availability considerations, and their trade-offs with usability and performance.
- Technological systems are all too often developed by technicians with limited understanding of behavioral science, user experience, cognition and psychology. This results in systems that are hard and annoying to use. We cannot afford this to scale to societal CPS systems. Research, innovation, development and deployment activities must therefore include expertise encompassing the understanding of humans (anthropology, sociology), together with engineering, business and legal aspects.

The presented topics are important both for research and education. There is a general need to bring sustainability issues including forward in engineering education.

3.3 Promoting the status of teaching

Teaching has a low status in universities in Europe, and also in proceeding schools (high-schools and earlier), and, consequently is not rewarded with the attention it deserves, [12]. This issue was recognized unanimously in workshops with academia (with our sources drawn from Europe, US and Australia). Similar concerns have been raised by national authorities, [11]. It is interesting to note that this issue was often met with surprise from industrial stakeholders, who however expressed very strong support in improving the situation.

The lowered status of teaching might originate from marketing and performance strategies imposed on higher education institutions, [13]. Initiatives to improve the status of teaching and management of teaching are therefore urgently needed.

3.4 Educational platforms and life-long learning

There is a need to create new teaching and training approaches leading to a new generation of scientists and engineers qualified and interested in working in CPS.

CPS is a dynamic field that requires an increased emphasis on multidisciplinary skills and significant enhancements in engineering curricula, renewed emphasis on systems sciences and engineering. Due to their rich infrastructure and set of basic services, future CPS can accelerate the construction of innovative added-value services. To exploit these opportunities, we need dynamic training programs for engineers, operators, and users of these systems to create pathways for keeping the workforce on top of new developments as they emerge.

Engineers must experience practical, cross-discipline technologies to familiarize themselves with the necessary - often more technical and practical than theoretical - capabilities to enable these innovations. Thus, the establishment of private-public cooperation and open source initiatives for the operation of educational platforms, facilitating experimentation with new technologies and interdisciplinary learning, including technology kits for CPS labs, "open labs", "hacker spaces" and "maker spaces".

An educational platform for CPS, as illustrated in Figure 1, should incorporate theory, CPS labs as well as more realistic industrial testbeds. In such a platform the Lab component plays an important role in dealing with the identified concepts and new technologies of CPS in preparing trainees for the real world. It exposes training engineers to practical experimentation and interdisciplinary learning throughout labs and CPS design projects, with adequate hands-on experiments.

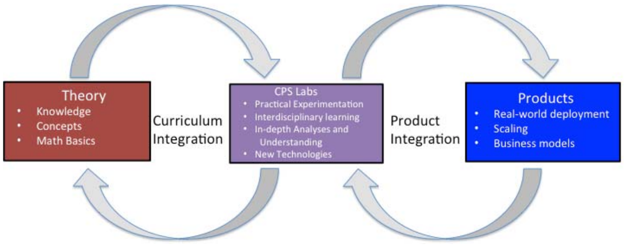

Figure 1. Educational Platform for CPS.

Due to the disruptive nature of CPS and the fast innovation cycles in information and communication technology, the half-life of state of the art knowledge in several involved disciplines and technologies is short. To ensure the necessary re-qualification, an academic-industrial alliance should engage established engineers in life-long learning through alumni-programs or training courses offered by academic and industrial educational institutions and supported by industry.

It is clear that there needs to be another shift in education and training in that it can no longer be viewed as a focus from (say) ages 15 to 25; instead it needs to start from early school and continue in a life-long learning scenario.

4. DISCUSSION

The validity of the findings is sustained by the coverage of five domains (which we believe to be representative), multiple world-wide regions, academic and industrial viewpoints.

The findings were also compared to other investigations, see e.g. the ITEA ARTEMIS-IA High-Level Vision 2030, [16], the German Agenda CPS, [9] and additional investigations referenced in the CyPhERS deliverables (for example in Deliverable D5.2), [3]. In particular, other investigations identified needs for life-long learning, finding (iv). Findings (i) – involvement and training of a broader set of stakeholders, and (iii) – status of teaching and educational platforms, appear to be unique to our investigation in the context of CPS education. While finding (i) is implied by some investigations, it is rarely spelled out explicitly. While some aspects of human centered perspectives are frequently highlighted, issues such as privacy and sustainability appear to be less often identified.

Networking and collaboration will be instrumental in meeting CPS challenges, and this is also true for education and training. We notice stronger trends within and across industries / industrial domains to create learning networks and to increase collaboration with academia. Learning networks can help addressing several of the findings by bringing stakeholders together, focusing on common challenges (such as sustainability and low status of teaching), and by joining efforts in order to strengthen, for example, continued training.

We identify a consequent need for initiatives (e.g. through public funding) to support large scale "collaboration networks" that can remove barriers by incentivizing collaboration among disjoint groups of CPS stakeholders.

The complexity of CPS – not only with respect to each of the technologies involved, but also specifically with respect to the engineering-challenge of systems of that scale and heterogeneity – requires education and research in both theoretical foundation and pragmatic engineering. Besides the foundational scientific knowledge, engineers need to learn practical engineering knowledge and skills in a structured setting including state-of-art technologies, tools and best practices. Incentives for academic and industry stakeholder should be provided to stimulate the cross-fertilization of pragmatic and theoretic knowledge by including corresponding courses in the academic curricula.

Incentives, policies and mechanisms for life-long learning need to be further developed. This should, as far as possible, build on opportunities made available by internet based learning (e.g. MOOC approaches), where the physical and hands on aspects of CPS will require specific considerations and further work.

It is likely that CPS will involve a technological paradigm shift, with potentially drastic implications for existing organizations and regions. Perhaps the greatest "defense" against the threat of disintermediation, is the agility on the part of developing organizations and societies to identify and exploit opportunities, matching the pace of innovation. Public (and private-public) initiatives can help by supporting innovation and education and training initiatives that can keep regions at the forefront in critical areas of CPS design, development and application.

5. CONCLUSIONS

Excellence in education, a skilled work force including leaders and decision makers will be of paramount importance for grasping CPS opportunities and dealing with their implied risks.

Our investigation reveals important needs to strengthen education and training among a broader set of stakeholders including policy makers and the general public, in order to raise awareness of CPS opportunities, challenges and risks.

Educational and training programs also, to a larger degree than hitherto, need to address sustainability and to ensure that we develop a CPS ecosystem that is useful to humans and society. We also believe that ethics as a topic needs further consideration in this vein.

The CPS technological shift implies that the amount of knowledge and skills required for product and service engineering is increasing along with the needs to continuously update your knowledge. There is a consequent need to develop incentives and mechanisms for life-long learning and to promote the development of educational platforms.

Finally, there is an urgent need to strengthen the conditions for and status of teaching.

Further work needs to address how in detail to move on from our findings to concrete actions.

6. ACKNOWLEDGMENTS

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