Guest Editors' Introduction: Education for Cyber–Physical Systems

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Cyber–physical systems (CPSs) are integrations of physical systems with computations. Their design poses many challenges. For example, CPS design is interdisciplinary by nature, crossing the boundaries of many engineering disciplines. In addition, there is a potential mismatch between the discrete nature of today's computing systems and typically continuous physical systems, and CPS design has to meet and adhere to many constraints and take many objectives into account. As a result, education for the CPS design is quite challenging. In this context, the special issue on education for CPS aims to provide educators, industrial representatives, and researchers with a view on the needs and share solutions for embedded and CPS education. The special issue addresses questions such as "How can we ensure that students will be able to work in interdisciplinary teams?," "What skills and capabilities are required by the engineers of tomorrow?," "How should the corresponding educational programs be formed?," and "How can effective pedagogic methods be introduced in this domain?"

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In response to the call for papers for this special issue, we received ten submissions. After a rigorous peer-review process, we have selected six articles for publication. The curated papers encompass both high-level curriculum design aspects as well as project-based experiential learning. The cross-cutting thread through all the six papers is the impact of the unique multidisciplinary aspects of CPS on education. The first paper of this special issue deals with continuing education in a university–industry cooperative network focusing on CPS. The next two papers discuss the challenges of introducing CPS and the Internet of Things (IoT) concepts in existing engineering and technology management curriculum, respectively. The final three papers focus on hands-on projects to cover different aspects of the CPS education from control algorithms and security to autonomous driving. The central theme of all these papers is enabling the students to translate their fundamental theoretical knowledge to real-world applications in nonidealized settings.

In "The Role of Competence Networks in the Era of Cyber–Physical Systems—Promoting Learning and Knowledge Creation," Törngren et al. (KTH Royal Institute of Technology, Sweden) provide a comprehensive overview and reflection of the CPS educational and knowledge creation challenges drawn from the 11 years of experience in the Innovative Center for Embedded Systems (ICES) network. The ICES is a KTH Industry

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cross-disciplinary and multidomain competence network for students, practicing engineers, managers, and academic faculty. The distinguishing aspect of this article is its focus on lifelong learning that addresses competence provisioning for both the developing and the existing professionals through industry–academia collaboration.

In "Future Engineering Curricula: Balancing Domain Competence with CPS Readiness," Nair et al. (Amrita School of Engineering and National Institute of Technology, Tiruchirappalli, India) demonstrate the possibility of adapting a conventional engineering program to seamlessly integrate the specialized and highly multidisciplinary skills of the CPS education. They propose a mixed curriculum comprising core courses in engineering, science, and mathematics with elective courses in CPS, for example, power/energy systems and automotive-related elective courses in an undergraduate electrical engineering program.

Following the same theme, in "Introducing IoT Subjects to an Existing Curriculum," Amador Nelke and Winokur (Holon Institute of Technology, Israel) share their experience of introducing an IoT course in a Bachelor of Sciences program in Industrial Engineering and Technology Management. Contrary to the previous article where CPS is introduced in an engineering program, the students in this program have little or no background in electrical and software engineering. Hence, the authors illustrate the challenges as well as their qualitative, quantitative achievements in providing the students with the necessary theoretical knowledge and practical experience to cooperate with the IoT engineers in multidisciplinary projects.

In "A Programmable Open Architecture Testbed for CPS Education," Gosh et al. [Technical University of Munich (TUM), Germany; Indian Institute of Technology (IIT) Kharagpur, Kharagpur, India; University of North Carolina (UNC), Chapel Hill, NC, USA] present a novel programmable, networked, and low-cost CPS testbed. This testbed allows the students to design, run, and validate wireless control algorithms on different networked CPS configurations that can be easily specified, implemented, and analyzed. The testbed conveniently illustrates the interdependency between the control theory and its implementation on the underlying embedded system platform.

In "Project-Based CPS Education: A Case Study of an Autonomous Driving Student Project," Ueter et al. (TU Dortmund, Dortmund, Germany) embark on educating graduate computer science and computer engineering students to solve complex engineering problems in the context of CPS. Through a project-based course on autonomous-driving, the students are exposed to the cross-cutting relevant aspects of a modern CPS system, including real-time systems, automatic control, and complex data processing.

Security aspects are frequently considered too late in the design process. Therefore, we are very happy that the final article "Cyber–Physical Systems Security Education Through Hands-on Lab Exercises" by Konstantinou (Florida State University, Tallahassee, FL, USA) explains how to foster interest in CPS security education with hands-on laboratory exercises. The author argues that an interdisciplinary approach, crossing the boundaries in particular between computer science and engineering, is required to obtain adequate CPS security solutions. The author's laboratory exercises are designed to impart theoretical knowledge and also to acquire practical skills via experiential learning.

Apart from the contributed articles, the special issue also includes a survey on the CPS education by the guest editors. The survey addresses the central question "How can we educate students such that they will be able to design CPS systems?" and provides a framework of the different approaches adopted by the universities across the world to create CPS-ready graduates.

We would like to acknowledge all the authors for their contributions and thank all of the anonymous reviewers for their rigorous work. Their insights were invaluable in bringing this special issue to fruition. This issue would not have been possible without the tremendous support of the Editor-in-Chief, Joerg Henkel, who encouraged this special issue proposal on education for CPS. We express our sincere gratitude to Sara Dailey for her support throughout the editorial process.

It is our pleasure to offer this selection of exciting articles to you. We hope that you will enjoy reading them and will be inspired in your future teaching and curriculum design in the broad spectrum of the CPS. ■

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