SCIENCE CHINA
Information Sciences

• **INSIGHT** •

Special Focus on Advanced Technology of Software
May 2016, Vol. 59 050102:1–050102:2
doi: 10.1007/s11432-016-5547-3

Intelligent CPS: features and challenges

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Received November 7, 2015; accepted February 1, 2016; published online April 8, 2016

Citation Yang G, Zhou X S. Intelligent CPS: features and challenges. Sci China Inf Sci, 2016, 59(5): 050102, doi: 10.1007/s11432-016-5547-3

Cyber–physical systems (CPS) have become a hot research area in the past few years [1]. Existing studies focus on unified model construction, service-based design methods, integrated support tools, and verification methods in specific application areas [2–4]. We designate this as CPS 1.0. With the new features and requirements from intelligent manufacturing [5], intelligent transportation, and smart grid [6], as well as the rapid development of Mobile Internet and Cloud Computing techniques, CPS is stepping into version 2.0.

In this new version, the scale of cyber–physical systems will become much larger, the running environment will be more open, and the system behaviors should be more autonomous [7]. Furthermore, spatial–temporal features and human–machine cooperation will become crucial concepts that characterize CPS 2.0 [8, 9]. With these characteristics, we believe that "intelligence" will steer the development of CPS in the coming 2.0 era. The new features of CPS 2.0 pertaining to "intelligence" include:

Adaptive system modeling. Applications (e.g., intelligent manufacturing) in the CPS 2.0 version will be more personalized and demand-driven. We should thus construct flexible and unified models to adapt to varied application contexts [10].

Dynamic organization reconstruction. It is to meet the spatial–temporal dynamics of intelligent manufacturing, such as its working process and physical environments.

Cyber–physical–social cooperation. CPS 2.0 highlights the participation of humans, as well as the adaptive cooperation between cyber, physical, and social spaces. With human in the loop, the system will be able to adapt itself to evolving application requirements [7].

Autonomous behavior evolution. Regarding the use of CPS in varied and large-scale application areas (e.g., intelligent manufacturing, smart cities, smart grid, smart transportation, etc.), CPS should be equipped with capabilities such as autonomous evolution and autonomic management.

As a result of the significant changes in the scale of applications, the running environment, and the system behaviors, the above four features will be prevalent in the upcoming CPS 2.0. However, to achieve this vision, there are numerous open theoretical and technical challenges remaining to be addressed, as presented below.

The fusion of cyber–physical–social features in model construction. The development of intelligent industry largely depends on the fusion and collaboration of human and machine intelligence. In this situation, the traditional computer–communication–control (3C) fusion methodologies and models will not be enough. New human-in-the-loop models should be studied, these not only deal with the fusion of heterogeneous features from cyber, physical, and social spaces, but also ad-

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The authors declare that they have no conflict of interest.

dress the new issues such as intelligent behavior characterization (e.g., system self-adjustment and auto-optimization) and model construction based on process data.

The adaptability of run-time services. In the next-generation cyber–physical applications and systems, system behaviors evolve along with changes of application requirements. For example, the organization and running style of intelligent production lines (each being an autonomous entity but needing collaboration) dynamically adjust and optimize according to the personalized customization requests from product orders. The capacity to dynamically deploy and reconfigure the CPS software layer adaptively is a crucial feature. The methodology to support application-driven "3C" soft fusion and the dynamic cooperation and efficient implementation of autonomous entities, as along with the multi-objective optimization regarding the cooperation of entities in complex applications, will become essential research challenges in the study of intelligent CPS [11, 12].

The verifiability of autonomous behaviors. The temporal–spatial consistency, the safety and emergence support capability, and the reliability of intelligent CPS are closely related to its activities and associated parameters in the physical process. Compared with traditional computing systems, the process of the system state evolution of intelligent CPS will become more complex, and its verification methods will be more challenging [13]. The heterogeneity of system components poses challenges to teh assessment of the performance and correctness of the CPS as a whole. Many issues are raised, such as how to support formal analysis and online simulation of the core features of intelligent CPS and how to achieve combined verification of the integrated behaviors of intelligent CPS.

The opportunities of the services offered by CPS 2.0 are countless and will change over the lifetime of these systems. Our research group has been devoted to the study of CPS in recent years. We proposed the adaptive, situation-driven CPS model construction method [3] and developed the CPS running platform with the support of CPS-service and CPS-agent. These methods have been further verified in the application of intelligent production lines in the field of industry control.

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