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A Survey of Cyber-Physical Systems

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***Abstract*—Cyber-Physical Systems (CPSs) are characterized by integrating computation and physical processes. The theories and applications of CPSs face the enormous challenges. The aim of this work is to provide a better understanding of this emerging multi-disciplinary methodology. First, the features of CPSs are described, and the research progresses are summarized from different perspectives such as energy control, secure control, transmission and management, control technique, system resource allocation, and model-based software design. Then three classic applications are given to show that the prospects of CPSs are engaging. Finally, the research challenges and some suggestions for future work are in brief outlined.**

Keywords – cyber-physical systems (CPSs); communications; computation; control

I. INTRODUCTION

Cyber-Physical Systems (CPSs) integrate the dynamics of the physical processes with those of the software and communication, providing abstractions and modeling, design, and analysis techniques for the integrated whole[1]. The dynamics among computers, networking, and physical systems interact in ways that require fundamentally new design technologies. The technology depends on the multi-disciplines such as embedded systems, computers, communications, etc. and the software is embedded in devices whose principle mission is not computation alone, e.g. cars, medical devices, scientific instruments, and intelligent transportation systems [2]. Now the project for CPSs engages the related researchers very much.

Since 2006, the National Science Foundation (NSF) has awarded large amounts of funds to a research project for CPSs. Many universities and institutes (e.g. UCB, Vanderbilt, Memphis, Michigan, Notre Dame, Maryland, and General Motors Research and Development Center, etc.) join this research project [3, 4]. Besides these, the researchers from other countries have started to be aware of significance for CPSs research. In [5-7], the researchers are interested in this domain, including theoretical foundations, design and implementation, real-world applications, as well as education. As a whole, although the researchers have made some progress in modeling, control of energy and security, approach of software design, etc. the CPSs are just in an embryonic stage.

The rest of this paper is outlined as follows. Section II introduces the features of CPSs. From different perspectives, the research processes are summarized in Section III. Section IV gives some classic applications. Section V outlines the research challenges and some suggestions for future work and Section VI concludes this paper.

II. FEATURES OF CPSS

Goals of CPSs research program are to deeply integrate physical and cyber design. The diagrammatic layout for CPSs is shown in Figure 1. Obviously, CPSs are different from desktop computing, traditional embedded/real-time systems, today's wireless sensor network (WSN), etc. and they have some defining characteristics as follows [7-10].

- *Closely integrated*. CPSs are the integrations of computation and physical processes.
- *Cyber capability in every physical component and resource-constrained*. The software is embedded in every embedded system or physical component, and the system resources such as computing, network bandwidth, etc. are usually limited.
- *Networked at multiple and extreme scales*. CPSs, the networks of which include wired/wireless network, WLAN, Bluetooth, GSM, etc. are distributed systems. Moreover, the system scales and device categories appear to be highly varied.
- *Complex at multiple temporal and spatial scales*. In CPSs, the different component has probably inequable

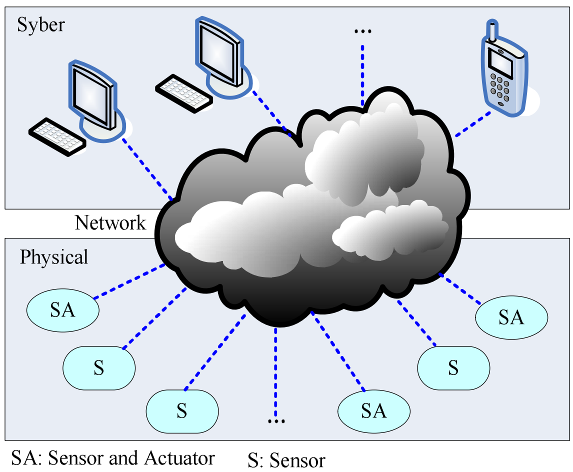

Figure 1. Diagrammatic layout for CPSs

granularity of time and spatiality, and CPSs are strictly constrained by spatiality and real time.

- *Dynamically reorganizing/reconfiguring*. CPSs as very complicated systems must have adaptive capabilities.
- *High degrees of automation, control loops must close*. CPSs are in favor of convenient man-machine interaction, and the advanced feedback control technologies are widely applied to these systems.
- *Operation must be dependable, certified in some cases*. As a large scale/complicated system, the reliability and security are necessary for CPSs.

III. REASEARCH PROCESS

Since 2007, American government has treated CPSs as a new development strategy. Some researchers from various countries discussed the related concepts, technologies, applications and challenges during CPSweek and the international conference on CPS subject [11]. The results of this research mainly concentrate in the following respects [7].

A. Energy Control

One of the features of CPSs is distributed system. Though the vast majority of devices in CPSs need less energy, the energy supply is still a great challenge because the demand and supply of energy is inconvenient.

In [12], a control strategy is proposed for realizing best trade-off between satisfying user requests and energy consumption in a data center. In [13-15], these papers concern the basic modeling of cyber-based physical energy systems. A novel cyber-based dynamic model is proposed in which a resulting mathematical model greatly depends on the cyber technologies supporting the physical system. F. M. Zhang *et al* [16] design optimal and adaptive discharge profile for a square wave impulsive current to achieve maximum battery life. J. Wei *et al* and C. J. Xue *et al* [17, 18] develop an optimal lazy scheduler to manage services with minimum energy expenditure while not violating time-sensitive constraints. In [19], a peak inlet temperature minimization problem is formulated to improve the energy efficiency. J. R. Cao *et al* [20] present a clustering architecture in order to obtain good performance in energy efficiency.

B. Secure Control

Now, the research for secure control mainly includes key management, identity authentication, etc. In [21], the existing security technologies for CPSs are summarized, and main challenges are proposed. C. Singh *et al* [22] explore the topic of the reliability assurance of CPSs and possibly stimulate more research in this area. T. T. Gamage *et al* [23] give a general theory of event compensation as an information flow security enforcement mechanism for CPSs. Then a case study is used to demonstrate this concept. In [24], a certifcateless signature scheme for mobile wireless CPSs is designed and validated. Y. Zhang *et al* [25] present an adaptive health monitoring and management system model that defines the fault diagnosis quality metrics and supports diagnosis requirement specifications. J. Wei *et al* [26] exploit message scheduling solutions to improve security quality of wireless networks for mission-critical cyber-physical applications.

C. Transmission and Management

CPSs need to conduct the transmission and management of multi-modal data generated by different sensor devices. In [27], a novel information-centric approach for timely, secure real-time data services in CPSs is proposed. In order to obtain the crucial data for optimal environment abstraction, L. H. Kong *et al* [28] study the spatio-temporal distribution of CPS nodes. H. Ahmadi *et al* [29] present an innovative congestion control mechanism for accurate estimation of spatio-temporal phenomena in wireless sensor networks performing monitoring applications. A dissertation on CPSs discusses the design, implementation, and evaluation of systems and algorithms that enable predictable and scalable real-time data services for CPS applications [30]. Now, the exiting results are still rare, and there are many facets to be studied.

D. Model-based Software Design

Now, the main model-based software design methods include Model Driven Development (MDD) (e.g. UML), Model-Integrated Computing (MIC), Domain-Specific Modeling (DSM), etc [31, 32]. An example, abstractions in the design flow for DSM, is shown in Figure 2. These methods have been widely applied to the embedded system design [34, 35]. On the basis of these, some researchers conduct model-based software design for CPSs in the following aspects: event model, physical model, reliability and real-time assurance, etc.

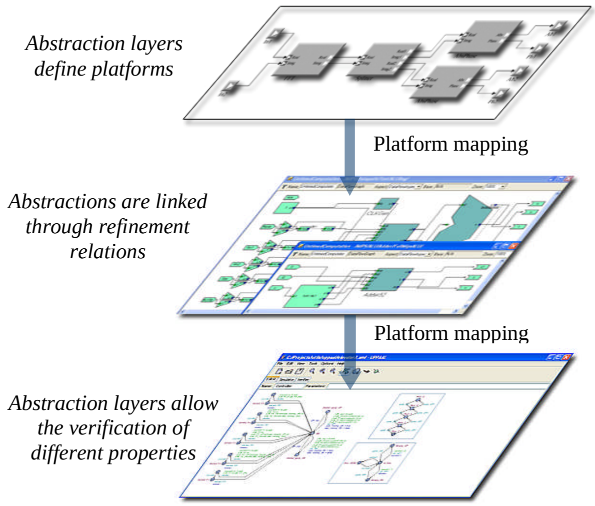

Figure 2. Abstractions in the design flow for DSM [33]

1) Event model. E. A. Lee *et al* [36] make a case that the time is right to introduce temporal semantics into programming models for CPSs. A programming model called programming temporally-integrated distributed embedded systems (PTIDES) provides a coordination language rooted in discrete-event semantics, supported by a lightweight runtime framework and tools for verifying concurrent software components. In [37], a concept lattice-based event model for CPSs is proposed. This model not only captures the essential information about events in a distributed and heterogeneous environment, but it also allows events to be composed across different boundaries of different components and devices within and among both cyber and physical domains. In addition, A CPS architecture along with a novel event model for CPS is developed [38].

2) Physical model. In [39], a methodology for automatically abstracting models of CPSs is proposed. The models are described using a user-defined language inspired by assembly code. For mechanical systems, Y. Zhu *et al* [40] show how analytical models of a particular class of physical systems can be automatically mapped to executable simulation codes. S. Jha *et al* [41] present a new approach to assist designers by synthesizing the switching logic, given a partial system model, using a combination of fixpoint computation, numerical simulation, and machine learning. This technique quickly generates intuitive system models.

3) Reliability and real-time assurance. E. A. Lee [42] emphasizes the importance of security, reliability and real-time assurance in CPSs, and considers the effective orchestration of software and physical processes requires semantic models. From the perspective of soft real-time and hard real-time, U. Kremer [43] conducts the research that the role of time in CPS applications has a fundamental impact on the design and requirements. In CPSs, the heterogeneity causes major challenges for compositional design of large-scale systems including fundamental problems caused by network uncertainties, such as time-varying delay, jitter, data rate limitations, packet loss and others. To address these implementation uncertainties, X. Koutsoukos *et al* [44] propose a passive control architecture. For improving reliability, T. L. Crenshaw *et al* [45] describe a simplex reference model to assist developers with CPS architectures which limit fault-propagation. A highly configurable and reusable middleware framework for real-time hybrid testing is provided in [46].

Though the model-based software design has an early start, the present development of CPSs progresses at a fast enough rate to provide a competitive challenge.

E. Control Technique

Compared with other control applications, the control technique for CPSs is still at an elementary stage. F. M. Zhang *et al* [2] develop theoretical results in designing scheduling algorithms for control applications of CPS to achieve balances among robustness, schedulability and power consumption. Moreover, an inverted pendulum as a study object is designed to validate the proposed theory. N. Kottenstette *et al* [47] describe a general technique: passivity and a particular controller structure involving the resilient power junction. In [48], a design and implementation of CPSs for neutrally controlled artificial legs is proposed. In [49], J. L. Ny *et al* approach the problem of certifying a digital controller implementation from an input-output, robust control perspective.

F. System Resource Allocation

Until now, the relative research for system resource allocation mainly focuses on embedded/real-time systems, networked control systems, WSN, etc [50-52]. Towards the complicated CPSs, this work is in the beginning stage. V. Liberatore [53] gives a new train of thought on bandwidth allocation in CPSs. In [54], the model dynamics are presented to express the properties of both software and hardware of CPSs, which is used to do resource allocation. K. W. Li *et al* [55] research the problem of designing a distributed algorithm for joint optimal congestion control and channel assignment in the multi-radio multi-channel networks for CPSs. The ductility metric is developed to characterize the overload behavior of mixed-criticality CPSs in [56].

IV. CLASSIC APPLICATIONS

Applications of CPSs include medical devices and systems, assisted living, traffic control and safety, advanced automotive systems, process control, energy conservation, environmental control avionics and aviation software, instrumentation, critical infrastructure (e.g. power, water), distributed robotics, weapons systems, manufacturing, distributed sensing command and control, smart structures, biosystems, communications systems, etc.[9, 10]. The classic application architecture of CPSs is described in [38]. Now, some application cases for CPSs have been conducted in [57-64]. Here, three examples (Health Care and Medicine, Intelligent Road and Unmanned Vehicle, and Electric Power Grid) are used to illuminate the classic applications of CPSs [8, 9].

A. Health Care and Medicine

The domain of health care and medicine includes national health information network, electronic patient record initiative, home care, operating room, etc. some of which are increasingly controlled by computer systems with hardware and software components, and are real-time systems with safety and timing requirements. A case of CPSs, an operating room, is shown in Figure 3.

Figure 3. A case of CPSs: An operating room [8, 9]

B. Electric Power Grid

The power electronics, power grid, and embedded control software form a CPS, whose design is heavily influenced by fault tolerance, security, decentralized control, and economic/ ethical social aspects [65]. In [8, 9], a case of CPSs, electric power grid, is given as shown in Figure 4.

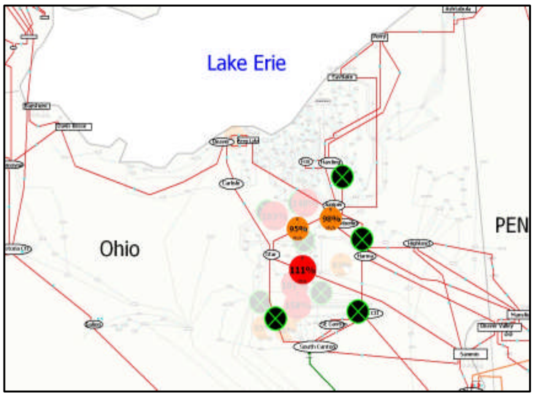

Figure 4. A case of CPSs: Electric power grid [8, 9]

C. *Integrate Intelligent Road with Unmanned Vehicle*

With the development of sensor network, embedded systems, etc. some new solutions can be applied to unmanned vehicle. We are conducting a program that intelligent road and unmanned vehicle are integrated in the form of CPSs. Figure 5 shows another case of CPSs: Integrate intelligent road with unmanned vehicle.

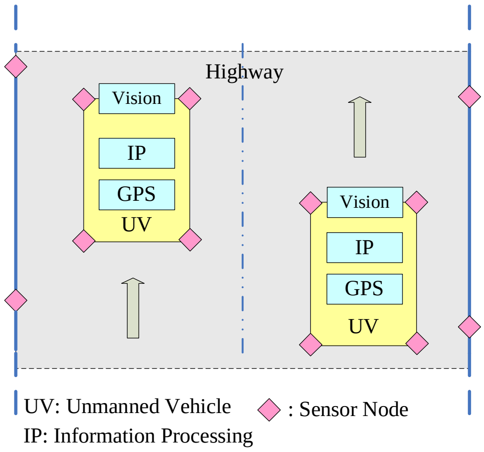

Figure 5. A case of CPSs: Integrate intelligent road with unmanned vehicle

V. RESEARCH CHALLENGES

CPSs as a very active research field, a variety of questions need to be solved, at different layers of the architecture and from different aspects of systems design, to trigger and to ease the integration of the physical and cyber worlds [66]. In [10, 42, 66-68], the research challenges are mainly summarized as follows:

1) Control and hybrid systems. A new mathematical theory must merge event-based systems with time-based systems for feedback control. This theory also must be suitable for hierarchies involving asynchronous dynamics at different time scales and geographic scope.

2) Sensor and mobile networks. In practical applications, the need for increased system autonomy requires self-organizing/reorganizing mobile networks for CPSs. Gathering and refining critical information from the vast amount of raw data is essential.

3) Robustness, reliability, safety, and security. It is a critical challenge because uncertainty in the environment, security attacks, and errors in physical devices make ensuring overall system robustness, security, and safety. Exploiting the physical nature of CPS by leveraging location-based, time-based and tag-based mechanisms is to realize security solutions.

4) Abstractions. This aspect includes real-time embedded systems abstractions and computational abstractions, which needs new resource allocation scheme to ensure that fault tolerance, scalability, optimization, etc. are achieved. New distributed real-time computing and real-time group communication methods are needed. In addition, the physical properties also should be captured by programming abstractions.

5) Model-based development. Though there several existing model-based development methods, they are far from meeting demands in CPSs. Computing and communications, and physical dynamics must be abstracted and modeled at different levels of scale, locality, and time granularity.

6)Verification, validation, and certification. The interaction between formal methods and testing needs to be established. We should apply the heterogeneous nature of CPS models to compositional verification and testing methods.

VI. CONCLUSIONS

In the last few years, this emerging domain for CPSs has been attracting the significant interest, and will continue for the years to come. In spite of rapid evolution, we are still facing new difficulties and severe challenges. In this literature, we concisely review the existing research results that involve energy control, secure control, model-based software design transmission and management, control technique, etc. On this basis, some classic applications used to show the good prospects. Then, we propose several research issues and encourage more insight into this new field.

ACKNOWLEDGMENT

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