Advances in Cyber-Physical Systems Research

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Abstract

Cyber-physical systems (CPSs) are an emerging discipline that involves engineered computing and communicating systems interfacing the physical world. The widespread applications of CPSs still face enormous challenges because of the lack of theoretical foundations. In this technical survey, we review state-of-the-art design techniques from various angles. The aim of this work is to provide a better understanding of this emerging multidisciplinary methodology. The features of CPSs are described, and the research progress is analyzed using the following aspects: energy management, network security, data transmission and management, model-based design, control technique, and system resource allocation. We focus on CPS resource optimization, and propose a system performance optimization model with resource constraints. In addition, some classic applications (e.g., integrating intelligent road with unmanned vehicle) are provided to show that the prospects of CPSs are promising. Furthermore, research challenges and suggestions for future work are outlined in brief.

Keywords: Cyber-physical systems, optimization, embedded systems, unmanned vehicle, wireless sensor networks

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1. Introduction

Cyber-physical systems (CPSs) perfectly integrate computation with physical processes, and provide abstractions, modeling, design, and analysis techniques for the integrated whole [1]. CPSs require computing and networking technologies to embrace not merely information, but also physical dynamics. The interactions among control, computing, network, and physical systems require new design technologies. The technology depends on multiple disciplines, such as computing science, control theories, and communication engineering. In addition, software is embedded in devices, the principle mission of which is not computation alone. CPSs range from relatively small systems, such as aircrafts and automobiles, to large systems such a national power grid [2].

Since 2006, the National Science Foundation (NSF) has awarded large amounts of funds to a research project titled "Science of Integration for CPSs." Many universities and institutes (such as UC Berkeley, Vanderbilt, Memphis, Michigan, Notre Dame, Maryland, and General Motors Research and Development Center) have joined this research project [3][4]. Analogously, in 2004 the European Union (EU) began the Advanced Research & Technology for Embedded Intelligence and Systems (ARTEMIS) project, which aims to tackle the research and structural challenges faced by the European industry by defining and implementing a coherent research agenda for embedded computing systems [5]. In addition to these efforts, researchers from other countries, such as China and Korea, have begun to be keenly aware of the significance of CPSs research.

In 2007, the American government named CPSs as a new development strategy. Researchers from various countries discussed the related concepts, technologies, applications, and challenges during CPS Week and the International Conference on CPS [6]. In [7][8][9][10], researchers expressed interest in this domain, including theoretical foundations, design and implementation, real-world applications, and education. Recent research advances mainly concentrate on the following respects: energy management, network security, data transmission and management, model-based design, control technique, system resource allocation, and applications. As a whole, although researchers have made some progress in modeling, control of energy and security, and approach of software-based design, among others, CPSs remain in the embryonic stage.

Wireless sensor networks (WSNs), CPSs, and the "Internet of things" (IoT) are emerging disciplines that have attracted and engaged many researchers and vendors. The integration among these disciplines accelerates their applications and produces new challenges. In recent years, great achievements have been made in these emerging fields. These achievements promote the development of CPSs. In spite of rapid evolution, we continue to face new difficulties and challenges, such as security, data integrity, and privacy.

The goal of the CPS research program is to deeply synthesize physical and cyber (computing, communication, and control) design. Obviously, CPSs are different from desktop computing, traditional embedded/real-time systems, and WSNs; however, they have some defining characteristics as follows [11][12][13]:

- *Cyber capability in every physical component and resource constraint*. The software is embedded in every embedded system or physical component, and the system resources (e.g., computing and network bandwidth) are usually limited.
- *Closely integrated*. CPSs deeply integrate computation with physical processes.

- *Networked at multiple and extreme scales*. CPSs, the networks of which include wired/wireless network, Wi-Fi, Bluetooth, and GSM, among others, are distributed systems. Moreover, the system scales and device categories appear to be highly varied.
- *Complex multiple temporal and spatial scales*. In CPSs, the different components likely have unequal granularity of time and spatiality. CPSs are strictly constrained by spatiality and real-time capacity.
- *Dynamically reorganizing/reconfiguring*. CPSs, as very complicated and large-scale systems, must have adaptive capabilities.
- *Closed-loop control and high degrees of automation*. CPSs favor convenient man–machine interaction, and advanced feedback control technologies are widely applied to these systems.
- *Operation must be dependable and certified in some cases*. Reliability and security are necessary for CPSs because of their extreme scales and complexities.

The remainder of this paper is organized as follows. We review the recent research advances from different perspectives from Section 2 to Section 7. Section 8 describes the classic applications for CPSs. Section 9 outlines research challenges and some suggestions for future work. Section 10 concludes this paper.

2. Energy Management

One of the features of CPSs is the distributed system. Although the vast majority of devices in CPSs need less energy, the energy supply continues to be a great challenge because the demand and supply of energy is inconvenient. From an engineering perspective, the overarching goal of CPS design is to minimize specific cost functions (such as power consumption and fuel consumption) subject to various system resources, performance, and reliability.

Gupta *et al*. [14] discussed the various approaches for energy-sustainable computing in CPSs, and identified major research directions. In [15], a control strategy was proposed for realizing the best trade-off between satisfying user requests and energy consumption in a data center. Zhang *et al*. [16] developed a dynamic battery discharge model, and designed an optimal and adaptive discharge profile for a square-wave impulsive current to achieve maximum battery life. Wei *et al*. [17] and Xue *et al*. [18] developed 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 was formulated to improve energy efficiency. Cao *et al*. [20] presented a clustering architecture in order to obtain good performance in energy efficiency. For resource-constrained CPSs, Zhang *et al*. [21] proposed an adaptive health monitoring and management system model that defines the fault diagnosis quality metrics and supports diagnosis requirement specifications. Based on the model, the evaluation results showed that the technique reduces the overall system resource consumption without adversely impacting the diagnosis capability.

References [22][23][24] were concerned with the basic modeling of cyber-based physical energy systems for distributed sensing and control. A novel cyber-based dynamic model was proposed in which the resulting mathematical model greatly depends on the cyber technologies supporting the physical system. Concretely, the cyber-physical generator-turbine-governor (G-T-G) set module shown in **Fig. 1** provides a cyber-physical representation of a power plant. The physical process is modeled as a closed-loop continuous-time dynamic model as follows:

$$\begin{cases} J_G\dot{\omega}_G + D_G\omega_G = P_T + e_T a - P_G \\ T_u\dot{P}_T = -P_T + K_t a \\ T_g\dot{a} = -ra - \omega_G + \omega_G^{ref} \end{cases} \tag{1}$$

where P_T and P_G are the mechanical and electrical powers of the turbine and the generator, respectively; and e_T, J_G, D_G, T_u, and T_g stand for the coefficient of the valve position, the moment of inertia of the generator, its damping coefficient, and the time constants of the turbine and generator, respectively. The state variables ω_G and a correspond to the generator output frequency and the valve opening, respectively, and ω_G^{ref} represents the set point value of the speed governor.

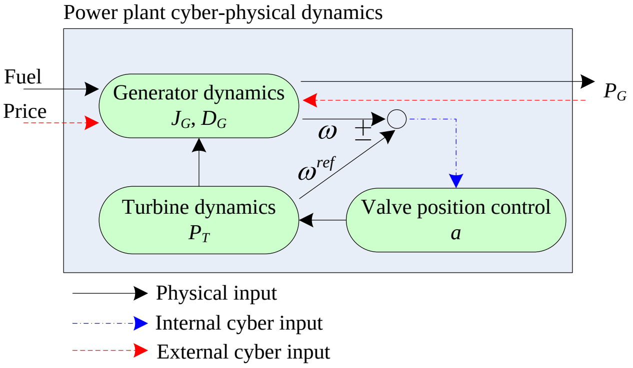


Fig. 1. Cyber-physical G-T-G set module

For the cyber-physical load module, the physical load is represented by its cyber model as follows:

$$J_L\dot{\omega}_L + D_L\omega_L = -P_L - L \tag{2}$$

where L stands for the real energy consumed by the load, P_L is the electrical energy delivered by the network to the load, and J_L and D_L refer to the effective moment of inertia and the damping coefficient of the aggregate load, respectively.

According to the aforementioned two models, this work has great potential for managing tradeoffs among multiple objectives such as flexibility, efficiency, environmental sustainability, and distributed QoS because a cyber-based dynamic model lends itself to distributed sensing and actuation within this complex system. However, we should go a step further to ensure the accuracy, reliability, and safety of this scheme.

3. Network Security

Research in network security mainly includes key management and identity authentication, among others. In [25], the existing security technologies for CPSs were summarized, and the main challenges were identified. Singh *et al*. [26] explored the topic of reliability assurance in cyber-physical power systems, and stimulated more research in this area. Gamage *et al*. [27] provided a general theory of event compensation as an information-flow security-enforcement mechanism for CPSs, and a direct current circuit example was used to demonstrate the proposed concept. In [28], a certificateless signature scheme for mobile wireless CPSs was designed and validated. Akella *et al.* [29] presented a semantic model for information flow analysis in CPSs, and described an approach to perform analysis, including both trace-based and automated analyses through process algebra specification. In [30], a novel measurement method was proposed for data stream privacy in distributed CPSs. This method improves the trade-off between privacy and the accuracy of reconstruction of aggregate information from shared perturbed data.

Jiang *et al.* [31] exploited message-scheduling solutions to improve security quality of wireless networks for mission-critical cyber-physical applications. In their proposed system, each confidentiality-sensitive and periodic real-time message is defined as a tuple $M_i = (P_i, s_i, l_i, v_i)$, where s_i is the message size, P_i is the message period, l_i is the confidentiality level to be assigned, and v_i is the security impact value of message M_i. The risk-free probability of security-critical message M_i with confidentiality level l_i is given as

$$P_{risk-free}(l_i) = \begin{cases} 0 & \text{if } l_i < l_i^{\min} \\ \exp[-\lambda(l_i - l_i^{\min})] & \text{if } l_i^{\min} \le l_i < l_i^{\max} \\ 1 & \text{if } l_i^{\max} < l_i \end{cases} \quad (3)$$

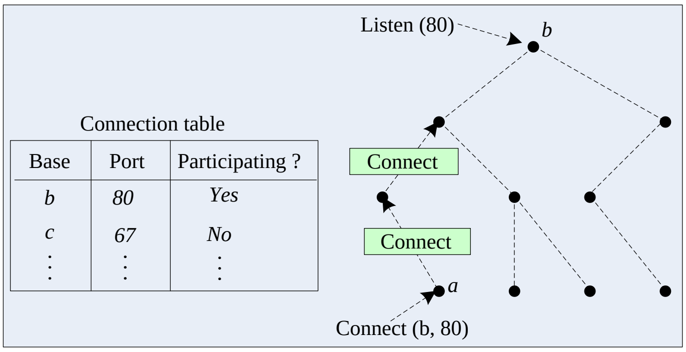
where $l_i^{\max}$ and $l_i^{\min}$ are maximal and minimal confidentiality level requirements specified by message user, respectively, and λ is the security risk coefficient that can be adjusted according to different risk models. However, some security services, such as integrity and authorization services, are not incorporated, and noncritical messages are not included in this model.

4. Data Transmission and Management

CPSs need to conduct the transmission and management of multimodal data generated by different sensor devices. Kang *et al.* [32] proposed a novel information-centric approach for timely, secure, real-time data services in CPSs. In order to obtain the crucial data for optimal environment abstraction, Kong *et al.* [33] studied the spatiotemporal distribution of CPS nodes. Real-data-based simulation was used to verify the efficacy and efficiency of proposed approaches. A dissertation on CPSs discussed the design, implementation, and evaluation of systems and algorithms that enable predictable and scalable real-time data services for CPS applications [34]. Ehyaei *et al.* [35] showed that their new physical-based interpolation scheme could be implemented on commodity sensor platforms. Ahmadi *et al.* [36] presented an innovative congestion control mechanism for accurate estimation of spatiotemporal phenomena in WSN monitoring applications. In short, results for data transmission and management in CPSs are still rare, and many facets need to be studied.

Taking the case of [36], we provide a further analysis on data transmission and management. Ahmadi *et al.* designed the congestion control components running locally on every node as a part of the transport layer. Every connection in the protocol is represented by a base station address and a port number. To initiate the connection, the base station calls the listen function provided by the transport layer interface to listen to a specific port. Any node willing to join the connection calls to connect with the base station address and corresponding port number (see **Fig. 2**).

This work employs adaptive aggregation as a congestion-control mechanism that minimizes estimation error of physical phenomena. The proposed scheme eliminates congestion with an estimation error an order of magnitude smaller than traditional rate-control approaches.



Base	Port	Participating ?
b	*80*	*Yes*
c	*67*	*No*
⋮	⋮	⋮

Fig. 2. Spatio-temporal data send mechanism

5. Model-based Design

In recent years, some researchers have conducted model-based design for CPSs in the following aspects: event model, physical model, reliability, and real-time assurance, among others. Model-based software design methods include model-driven development (MDD) (e.g., UML), model-integrated computing (MIC), and domain-specific modeling (DSM) [37][38]. As an example, abstractions in the design flow for DSM in [39] are shown in **Fig. 3**. These methods have been widely applied to embedded-systems design [40][41]. In this subsection, we discuss different model-based design methods for CPSs.

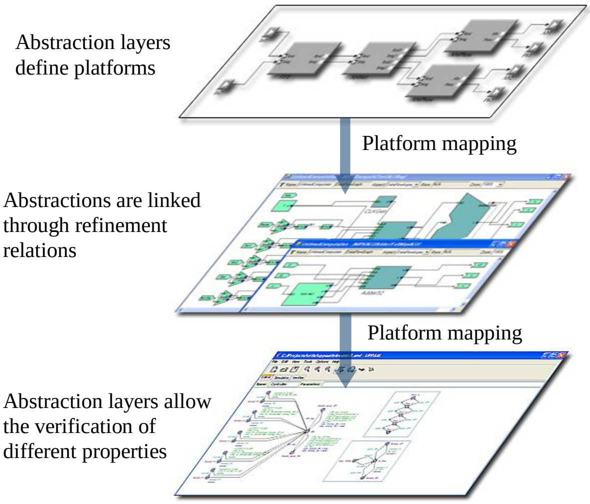


Fig. 3. Abstractions in the design flow for DSM

5.1 Event Model

Lee *et al*. [42] posited 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. Tan *et al*. [43] proposed a concept-lattice-based event model for CPSs. This model not only captures the essential information regarding events in a distributed and heterogeneous environment, but also allows events to be composed across different boundaries of different components and devices within and among both cyber and physical domains.

In [44], a CPS architecture, along with a novel event model for CPSs, was developed. The spatiotemporal event is defined as the occurrence of interest, which describes the state of one or more objects either in the cyber-world or the physical world according to attributes, time, and location. Therefore, a generic event is given as

$$\varepsilon_{id}\{t^{o}_{\varepsilon_{id}}, l^{o}_{\varepsilon_{id}}, V_{\varepsilon_{id}}\} \tag{4}$$

where ε is the event type identifier, id is the event ID, $t^{o}_{\varepsilon_{id}}$ is the event occurrence time, $l^{o}_{\varepsilon_{id}}$ is the event occurrence location, and $V_{\varepsilon_{id}}$ is the set of event occurrence attributes.

An event can be further classified as physical event, physical observation, sensor event, cyber-physical event, or cyber event, among others. For example, a cyber event instance ID and 6-tuple event instance properties are given by [44]:

$$E(CCUid, Eid, i)\{t^{g}_{E}, l^{g}_{E}, t^{eo}_{E}, l^{eo}_{E}, V_{E}, \rho_{E}\} \tag{5}$$

where E($CCUid$, Eid, i) is the cyber event instance of CPS control unit (CCU) $CCUid$-based on cyber event ID Eid, $t^{o}_{E(CCUid,Eid,i)}$ and $l^{o}_{E(CCUid,Eid,i)}$ are the time and location when the CCU generates the event instance, $t^{eo}_{E(CCUid,Eid,i)}$, $t^{eo}_{E(CCUid,Eid,i)}$ and $V_{E(CCUid,Eid,i)}$ are the estimated event occurrence time, location, and attributes, respectively, and $\rho_{E(CCUid,Eid,i)}$ is the confidence level of the CCU regarding the particular cyber event instance.

This work provides a good foundation for further builiding a formal temporal analysis of event detection latency and designing an end-to-end latency model for CPSs.

5.2 Physical Model

Thacker *et al*. [45] presented a methodology for automatically abstracting models of CPSs. These models are described using a user-defined language inspired by assembly code. For mechanical systems, Zhu *et al*. [46] showed how analytical models of a particular class of physical systems could be automatically mapped to executable simulation codes. This mapping has the potential to significantly reduce the cost and time needed to develop simulation codes for CPSs. Jha *et al*. [47] presented a new approach to assist designers by synthesizing the switching logic, given a partial system model, using a combination of fixed-point computation, numerical simulation, and machine learning. This technique is able to quickly generate intuitive system models.

5.3 Reliability and Real-time Assurance

Lee [48] emphasized the importance of security, reliability, and real-time assurance in CPSs, and suggested that the effective orchestration of software and physical processes requires semantic models. From the standpoint of real-time assurance, Kremer [49] conducted research on the role of time in CPS applications, as well as its 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, and packet loss. To address these implementation uncertainties, Koutsoukos *et al*. [50] proposed a passive control architecture. A highly configurable and reusable middleware framework for real-time hybrid testing was provided in [51]. Reference [52] addressed the issue of defining and evaluating consistency between the heterogeneous models used for the design of such complex systems and a base architecture for CPSs. Ahmadi *et al*. [53] designed a novel modeling technique, called the sparse regression cube, to perform reliable hierarchical modeling for open CPSs.

For improving reliability, Crenshaw *et al*. [54] described a simplex reference model to assist with constructing CPS architecture that limits fault-propagation. The simplex reference model consists of the following components: external context, domain model, machine, and safety requirements. The plant states are defined as *Recoverable*, *Safe*, and *Unsafe*. As time passes, the state of the plant evolves, forming a trajectory *T*, as shown in **Fig. 4**. For the control domain, a point in the system trajectory at time *j*, under control policy *U*, starting with initial condition x_k is represented as $T(x_k, U, j)$. This method improves the reliability of unreliable data.

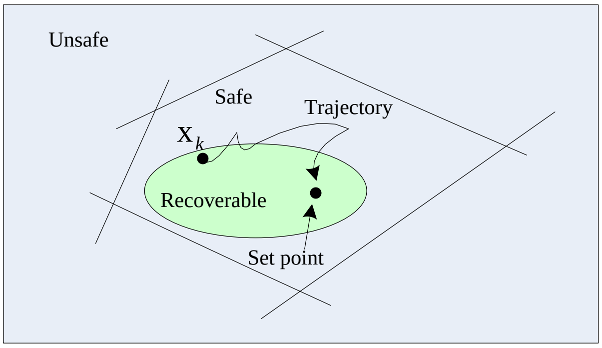


Fig. 4. State of the plant

To sum up, although the model-based design has an early start, the present development of CPSs has progressed at a fast enough rate to provide a competitive challenge. The existing theories and methods cannot meet the demands of CPS design.

6. Control Technique

Compared with other control applications, the control technique for CPSs remains at an elementary stage. Zhang *et al*. [2] developed theoretical results in designing scheduling algorithms for control applications of CPSs to achieve balance among robustness, schedulability, and power consumption. Moreover, an inverted pendulum, as a study object, was designed to validate the proposed theory. Kottenstette *et al*. [55] described a control theoretical framework based on the concept of passivity for designing a control network that can tolerate, for instance, denial-of-service attacks on networks used in the closed loop. In [56], a design and implementation of CPSs for neutrally controlled artificial legs was proposed. Ny *et al*. [57] approached the problem of certifying a digital controller implementation from an input–output, robust control perspective. In [58], the sandboxing controllers for CPSs were proposed. For sandbox approach, hardware failure is not considered in design; thus, practical systems may need to incorporate redundancy. In order to develop new, systematic methods for CPSs, Murray *et al*. [59] achieved the control design using slow computing. The proposed control architecture of this method is shown in **Fig. 5**.

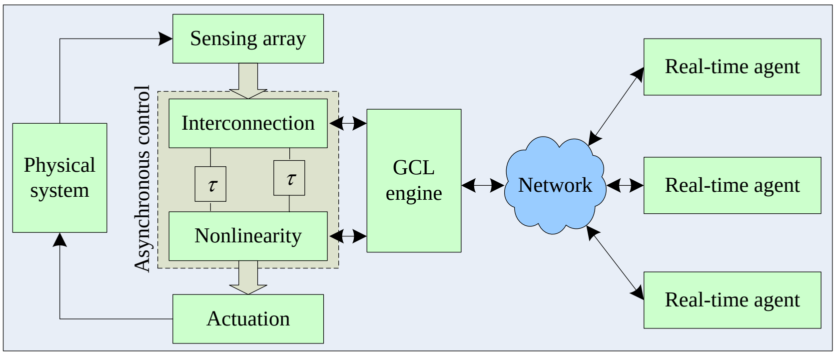


Fig. 5. Control architecture using slow computing

Currently, many more breakthroughs are needed for control theories. For example, the mathematical theory supporting event-based systems together with time-based systems and asynchronous dynamics at different time scales and geographic scope are necessary to deepen research.

7. System Resource Allocation

Thus far, the involved research for system resource allocation focuses on embedded/real-time systems, networked control systems, and WSNs [60][61][62]. For complicated CPSs, the work is in the beginning stage. Liberatore [63] inspired a new train of thought on bandwidth allocation in CPSs. In [64], model dynamics were presented to express the properties of both software and hardware of CPSs used to adjust resource allocation. Li *et al*. [65] researched the problem of designing a distributed algorithm for joint optimal congestion control and channel assignment in multiple-radio, multiple-channel networks for CPSs. In [66], a ductility metric was developed to characterize the overload behavior of mixed-criticality CPSs; the high-criticality tasks meet their deadlines by stealing cycles from low-criticality tasks. Yoshimoto *et al*. [67] introduced an arbiter by job skipping in real-time computing systems, and formulated an optimization problem that minimizes the weighted sum of performance degradation indices of plants under the schedulability and the stability constraint.

In [68], we gave the resource constraints in CPSs from the standpoint of multidisciplinary optimization (see **Fig. 6**). In order to reasonably schedule tasks and adequately utilize system resource from the global perspective, a system performance optimization model with resource constraints is proposed as follows:

$$\max_{f_1,\ldots,f_N} J = \sum_{i=1}^{N} \lambda_i J_i(f_i) \tag{6}$$

$$\text{s.t.} \begin{cases} \sum_{i=1}^{N} c_i f_i \le U_R \\ f_i \ge f_{\min,i} \\ \sum_{i=1}^{N}{}_{i\in \mathrm{S}(p)} f_i \le C_p \end{cases} \tag{7}$$

where J is the performance function, λ_i is the weight coefficient, f_i is the frequency for periodic task, c_i is the task execution time, U_R is the upper bound of CPU utilization, p is the information channel, C_p is the channel capacity, and $f_{\min,i}$ is the lower bound of frequency.

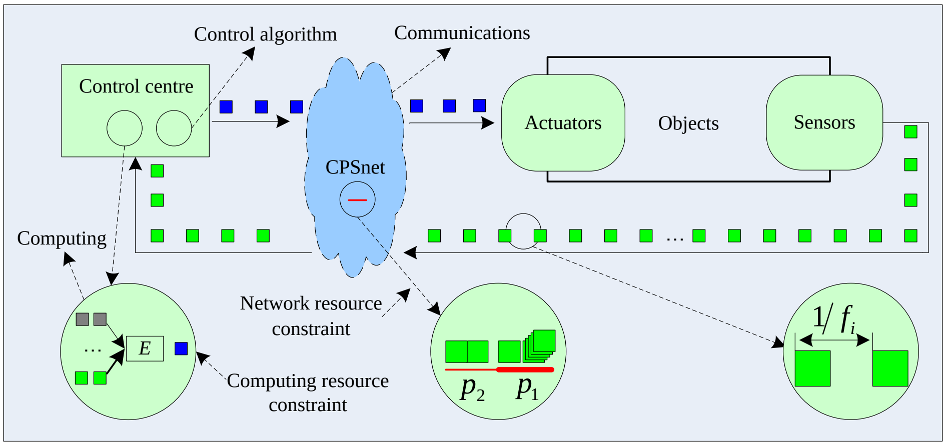


Fig. 6. Considered resource constraints in CPSs

For the above model, we adopted the particle swarm optimization (PSO) algorithm to seek an optimal solution with resource constraints. Because the PSO is metaheuristic, it makes few or no assumptions regarding the problem being optimized, and can search very large spaces of candidate solutions. In recent years, PSO has been widely used for continuous parameter optimization problem, combinatorial optimization, and neural network training [69].

8. Applications

8.1 Application Domain

The 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 (such as power and water), distributed robotics, weapons systems, manufacturing, distributed sensing command and control, smart structures, biosystems, and communications systems [11][12]. The classic application architecture of CPSs is described in [44]. Some application cases for CPSs were conducted in [70][71][72][73]. Here, two examples (healthcare and medicine, and electric power grid) are used to illuminate the classic applications of CPSs.

The domain of healthcare and medicine includes national health information networks, electronic patient record initiatives, home care, and operating rooms, among others, some of which are increasingly controlled by computer systems with hardware and software components; they are real-time systems with safety and timing requirements. A case of CPS, an operating room, is shown in **Fig. 7**.

The power electronics, power grid, and embedded control software form a CPS, the design of which design is heavily influenced by fault tolerance, security, decentralized control, and economic/ethical social aspects [74]. Another case of CPSs, an electric power grid, is given in **Fig. 8**.

Fig. 7. A case of CPSs: operating room [11]

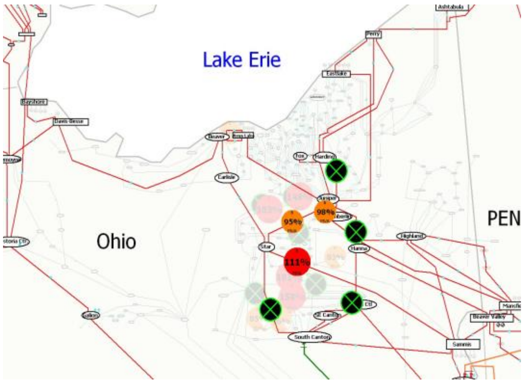


Fig. 8. A case of CPSs: electric power grid [12]

8.2 Another Case of CPSs: Unmanned Vehicle with WSNs Navigation

Currently, we are conducting a project where intelligent road and unmanned vehicle are integrated in the form of CPSs. With the development of WSNs, and embedded/real-time systems, some new solutions can be applied to an unmanned vehicle. **Fig. 9** shows a proposed prototype of an unmanned vehicle with WSNs navigation [73][75]. This system is mainly made up of WSNs and unmanned vehicles. Many sensor nodes (such as IEEE 802.15.4/ZigBee) construct wireless networks that are dynamically reorganizing and reconfiguring. The unmanned vehicles with sensor nodes obtain data from WSNs, and further process information to determine the behaviors of vehicles. In addition, GPS and vision systems for unmanned vehicles serve as auxiliary locations, whereas the unmanned vehicles primarily realize navigation depending on WSNs.

By means of WSNs navigation, an unmanned vehicle is able to move anywhere on a flat surface. We assume that the unmanned vehicle moves from a starting point to an ending point. Before experiment, the location information about ending point should be sent to unmanned vehicle, which conducts path planning to determine the optimal trajectory. In the process of running, wireless sensor nodes belonging to unmanned vehicle exchange real-time data with the WSNs nodes. In this way, using the dynamic programming achieves a rational trajectory. According to the current position of unmanned vehicle, wireless sensors for communications continually keep switching. If a sensor goes wrong, this fault is solved by occasionally reorganizing and reconfiguring the WSNs. Using this prototype platform, we can study different perspectives, as shown in **Fig. 10**.

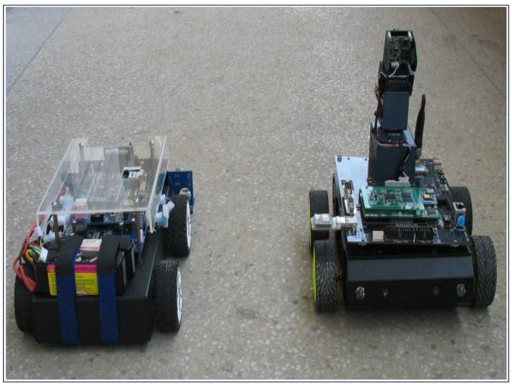


Fig. 9. Proposed prototype of unmanned vehicle

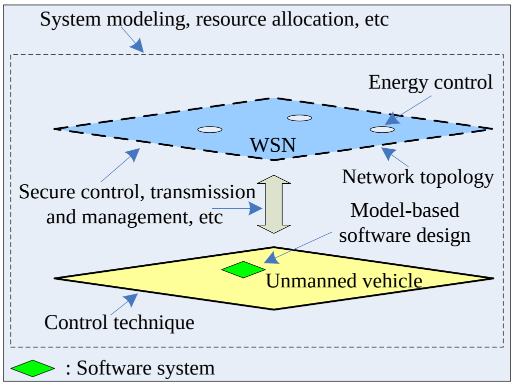


Fig. 10. Study from different perspectives

9. Research Challenges

CPSs are a very active research field, and the convergence of sensing, control, computing, communication, and coordination in CPSs, such as modern airplanes, power grid, transportation systems, and medical device networks, poses enormous challenges because of their complexities. A variety of issues need to be solved at different layers of the architecture and from different aspects of system design to ease the integration of the physical and cyber worlds [76]. Currently, the existing research challenges are summarized from various viewpoints in [12][48][77][78][79][80]. **Fig. 11** depicts the main challenges of CPS design. We outline the key issues involved from different perspectives, as shown in **Table 1**.

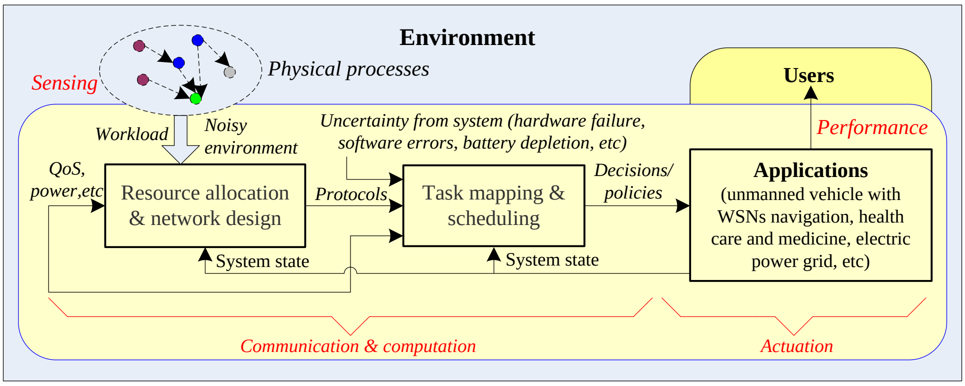


Fig. 11. Challenges of CPS design

Table 1. Key issues involved from different perspectives

No.	Challenges	Notes
1	Codesign tools	The tools supporting the simulation and codesign, as well as achieving automatic development process from modeling to code, are necessary. Unfortunately, the existing tools are not suited for CPS design involving multple disciplines.
2	Real-time performance	For example, as the speed of unmanned vehicle with WSNs navigation increases, we must ensure that real-time performance meets the specific application requirements. However, many factors, such as hardware platform and design methods, affect response time.
3	More progress in WSNs, embedded systems, and others	More breakthrough progress should be made in the key back-up technologies for CPSs, including WSNs and embedded system.
4	Control and hybrid systems	We must propose a new mathematical theory merging 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 scopes.
5	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 are essential.

6	Robustness, reliability, safety, and security	Robustness, reliability, and safety, among others, are critical challenges because of uncertainties in the environment, such as security attacks and errors in physical devices. Exploiting the physical nature of CPSs by leveraging location-, time-, and tag-based mechanisms can realize security solutions.
7	Abstractions	This aspect includes real-time embedded systems abstractions and computational abstractions that need a new resource allocation scheme to ensure that fault tolerance, scalability, and optimization 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.
8	Model-based development	Although several existing tools support model-based development, they are far from meeting CPS design requirements. Computing, communications, and physical dynamics must be abstracted and modeled at different levels of scale, locality, and time granularity.
9	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.

10. Conclusions

In the last few years, this emergence of CPSs has attracted significant interest, and will continue to be of interest for the years to come. Building CPSs requires a new science of characterizing and controlling dynamic processes across heterogeneous networks of sensors and computational devices. In spite of rapid evolution, we continue to face new difficulties and severe challenges, such as interdisciplinary integration and novel design methodology. Basically, the widespread applications of CPSs require breakthroughs in the research of theoretical and technical support.

In the current article, we have reviewed the existing research results that involve energy management, network security, data transmission and management, model-based design, control technique, and system resource allocation. On this basis, some classic applications were used to show the good prospects for CPSs. These prospects include a new solution applied to an unmanned vehicle by integrating intelligent road with the vehicle in the form of CPSs, which is currently being carried out by our group. We have also proposed several research issues and challenges in order to encourage more insight into this new field.

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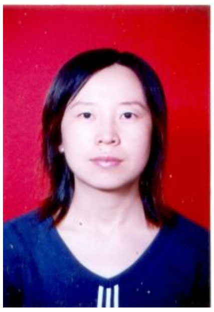

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