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An Overview and Some Challenges in Cyber-Physical Systems

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Abstract | Technological advances in computing, communications, and control, have set the stage for a next generation of engineered systems, called cyber-physical systems (CPS). These systems can potentially be important in overcoming many challenges in energy, environment, transportation, and health care. In this paper, we discuss some of these grand challenges that necessitate further advances in CPS. We also provide a partial survey of some important research issues, and an overview of several research efforts that have been undertaken toward the development of CPS.

Keywords: *Cyber-physical systems.*

1 Introduction

Cyber-physical systems (CPS) are currently of interest in academia, industry, and government due to their potentially significant impact on society, environment, and economy. In general, CPS refers to the next generation of engineered systems that require tight integration of computing, communication, and control technologies to achieve stability, performance, reliability, robustness, and efficiency in dealing with physical systems of many application domains such as transportation, energy, medical, and defense.[1–5] It is expected that CPS can potentially revolutionize how we interact, operate, and construct many engineered systems which our modern society critically depends on, such as automobiles, aircraft, power grid, manufacturing plants, medical systems, and buildings.

The emergence of CPS has been enabled by significant advancements in many technology areas. Thanks to today's micro-scale and nano-scale design and fabrication technologies, many fundamental enabling hardware components for the next generation of engineered systems are becoming available and beginning to be used in many systems. Examples are sensors, actuators, and processors that are small, cheap, fast, and energy efficient. Advances in system software, from high performance computing systems to real-time embedded systems, programming languages with high-level abstraction, and software engineering for complex software design and development, are also key enablers for CPS. Through the Internet, billions of computers are connected across the globe. The emergence of wireless networking has made feasible connectivity of mobile nodes.

There are also societal and industrial demands driving CPS. The growth of traffic in both ground and air has increased significantly over recent decades and is causing congestion problems in today's transportation system infrastructure. Fossil fuels which are today's main energy source are becoming depleted, and the high volume of carbon dioxide gas emissions has led to dramatic changes in global climate. Growing global population and corresponding growing demand for technological systems, such as power, transportation, water, and medical systems creates further challenges.

In the United States, the President's Council of Advisors on Science and Technology (PCAST) has placed CPS at the top of the priority list for federal research investment.[6] Also, in the US, the National Science Foundation (NSF) has launched a new program on CPS in 2009, and has funded almost 150M USD of research projects since then. Similar efforts in the EU can be found in the Advanced Research & Technology for EMbedded Intelligence and Systems (ARTEMIS) program.[7] Also, many conferences and workshops on CPS have been organized, such as CPS Week since 2008, a multi-conference event composed of several conferences such as ICCPS, RTAS, HSCC, IPSN, and HiConS. Of these, the ACM/IEEE International Conference

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on Cyber-Physical Systems (ICCPS) is a new conference that is co-sponsored by the ACM and the IEEE that was launched in 2010.

From a historical point of view, this trend of convergence of computing, communication, and control technologies is not new. In fact, an early effort in the past was to build an anti-aircraft gun system during World War II.[8] Recently, real-time embedded control systems in a small form factor have been widely deployed in small home appliances, cars, airplanes, power plants, environmental monitoring systems, and industrial manufacturing systems, etc. Due to technological advancements, for example in wired and wireless networks, there have arisen new capabilities, which in turn have given rise to new opportunities and thus new challenges. We discuss these challenges in more detail in the next section.

This paper is organized as follows. In Section 2, we discuss some of the grand challenges motivating the CPS revolution in several application domains, and then in Section 3 some research issues to overcome those challenges. In Section 4, we overview many research efforts over the past decade that are relevant to CPS. We conclude in Section 5.

2 Challenges and Opportunities for Cyber-Physical Systems

The U.S. National Academy of Engineering has compiled a list of fourteen grand challenges for engineering.[9] In this section, we discuss some challenges that are particularly related to CPS. Also, we outline some research opportunities for CPS community in addressing such challenges.

Among the many challenging issues related to society, economy, and environment, CPS research is particularly relevant vis-a-vis safety, stability, performance, reliability, robustness, and efficiency, in areas such as transportation, energy, medical and healthcare, defense, manufacturing, and agriculture. Some representative grand challenges for CPS research are as follows:[2,10,11]

2.1 *Near-zero automotive traffic fatalities, minimal injuries, and significantly reduced traffic congestion and delays*

From the statistics of the National Highway Traffic Safety Administration, there are more than 5 million car accidents annually in the United States and more than 2 million injuries or fatalities.[12] The total number of vehicles including passenger cars, trucks, buses, and motorcycles has been continuously increasing for the past several decades, with growth accelerating in China and India. The latter two numbers are expected to increase dramatically for the next several decades or so. In several aspects, today's transportation infrastructure has reached its capacity limit causing congestion and delays on roads. At the same time, it is not viable or sustainable to construct transportation infrastructure to keep pace with the increasing number of vehicles. Instead, there is motivation to make the overall transportation system smarter for better safety, energy efficiency, and throughput. Toward this direction, research on CPS such as autonomous vehicles, intelligent intersection systems, wireless communication systems for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), etc., can play an important role in meeting the continuing challenges in transportation systems.

2.2 *Sustainable and blackout-free electricity generation and distribution*

In the United States, approximately 70% of electricity is generated from fossil fuels such as coal and natural gas, as shown in Figure 1, and half of these power plants are more than 40 years old.[10] This high dependency on fossil fuels for electricity generation contributes to more than 40% of greenhouse gas emission globally and it is further expected that electricity demand will grow by more than 75% by 2030.[5] Moreover, these aging power plants and electricity distribution infrastructure make the overall power grid less reliable. As an example, a power surge in western New York and Canada caused a series of cascading power failures resulting in a widespread blackout across eight states in the United States and Canada in 2003, which was the largest blackout in American history. In July 2012, India had the largest blackout in history, affecting more than

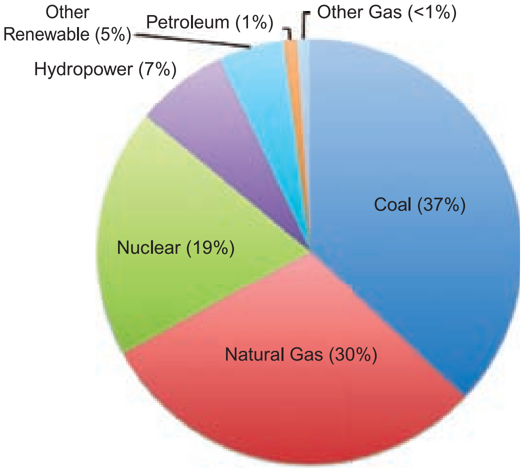

Figure 1: Electricity generation by source in the United States (2012).[13]

600 million people. Existing power grid systems are not reliable, environment friendly, or cost effective enough to be used continuously in the future. It is not a sustainable solution to continue to construct fossil fueled power plants and distribution infrastructure in the same manner that they have been built over the last century to meet ever increasing electricity demand. It is an important issue for many nations to transform today's power grid systems into smart grid systems for better reliability, efficiency, and eco-friendliness. CPS research in areas such as distributed sensing, monitoring, and control of power generation and consumption, electricity demand prediction and generation/distribution optimization, failure detection and recovery, etc., is critical for the next generation power grid systems.

2.3 *Clean and energy-aware buildings and cities*

Today, most cars run on gasoline, and most electricity is generated from fossil fuels. Such high dependency on these energy sources causes serious environmental issues and makes society and economy less sustainable. Thus, it is important to find solutions to reduce fossil fuel consumptions while satisfying overall energy demands of various energy consuming sectors such as transportation, industry, buildings, residences, and others. Automobile manufacturers are investing in research to build electric vehicles that can be competitive with existing gasoline vehicles in terms of price, efficiency, and performance. There are many university, industry, and government efforts to utilize alternative energy sources such as wind, solar, and geothermal for electricity generation. Along with these efforts, further research is necessary for improving overall efficiency in energy consumption. As an example, peak electricity consumption can be reduced significantly through technologies such as demand response, smart meters and communication systems for real-time price and usage information exchange between electricity suppliers and consumers. CPS research is an important component of such innovations.

2.4 *Smart, reliable, and flexible medical and healthcare systems*

According to the U.S. Department of Health and Human Services, a significant fraction of the population over 65 years old is living alone (19% men and 36% women), and more than 35% of the elderly population have some type of disability such as difficulty in hearing, vision, cognition, ambulation, self-care, or independent living.[14] Moreover, it is expected that the elderly population in the United States will continue to grow, as shown in Figure 2, eventually leading to great increases in the costs of taking care of the increasing elderly population. One major challenge is to find ways to provide cost-efficient and effective medical and health care services to the elderly at their homes.[3] Some representative examples of CPS research are smart sensor systems for real-time patient health condition monitoring and warning, telemedicine systems which enable remote healthcare service provision, semi-autonomous tele-operated home service robots that can assist with patient physical activities, etc.

Each year, approximately 98,000 fatalities result from medical errors in the United States alone, resulting in patient disability, decreased public confidence in the health care system, and increased health care costs.[15] Some common types of medical errors are surgical errors, diagnostic errors, medication errors, and patient handoff errors. A major portion of these errors can be reduced through CPS technologies. It is reported that the computerized physician order entry (CPOE) systems with automated clinical decision support systems (CDSS) contribute to 70% reduction in adverse drug events (ADE) in primary care.[16] Also, computerized decision support systems can assist clinicians to make proper diagnostic decisions based on information such as patient past medical history, diagnostic test results, etc. Information technology can also improve patient handoffs since it can mitigate errors caused by disorganized communication between caregivers. Further advances in embedded systems, real-time wireless networks, design and development techniques for safety-critical complex medical systems, safety verification and validation, etc., can accelerate the ongoing evolution of medical and healthcare systems toward safer, smarter, and more interconnected systems.

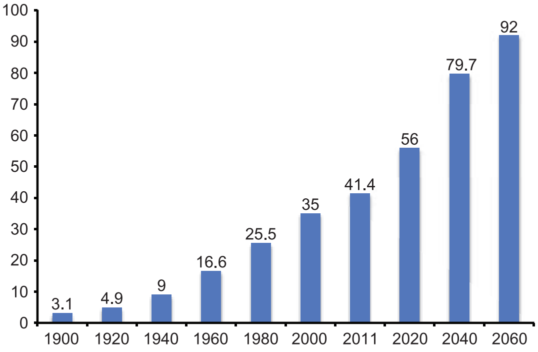

Figure 2: Number of persons 65+ (numbers in millions).[14]

2.5 *Other challenges*

In March 2011, a 9.0 magnitude earthquake in the northeastern coast of Japan caused serious damage to the nation. Approximately 28,000 were dead, injured, or missing. The World Bank has estimated a \$100–\$250 billion impact on the nation's economy. Hurricane Katrina that hit the United States in August 2005 left a comparably massive damage exceeding \$100 billion in economic loss and more than 2,000 killed or missing. Other recent examples of natural or man made disasters are the 2008 Sichuan earthquake in China, the 2011 volcanic eruption in Ireland, the Chernobyl nuclear power plant accident in Ukraine, the Deepwater Horizon oil spill in the Gulf of Mexico in 2006, and the September 11th attack on the World Trade Center in 2001.

As shown in Figure 3, the Food and Agriculture Organization of the United Nations estimates that there are over 920 million hungry people in the world.[17] The increasing global population is expected to further exacerbate food shortages. Recent economic growth in countries such as China and India has increased the overall food demand significantly, which in turn is expected to further increase the gap between food supply and demand worldwide.[18]

CPS technologies can potentially be useful in mitigating societal and economical damages caused by disaster events. Technologies for rapid evacuation management systems, large-scale distributed environmental and geographical monitoring, fast and reliable event prediction, estimation of damage propagation, integrated and coordinated traffic control capabilities, etc., can be important in mitigating the overall negative impacts of disasters. It is also expected that CPS research can play an important role in tackling the increasing food demand-supply gap by increasing food consumption efficiency and overall food production capability through technologies such as precision agriculture, intelligent water management, and more efficient food distribution.

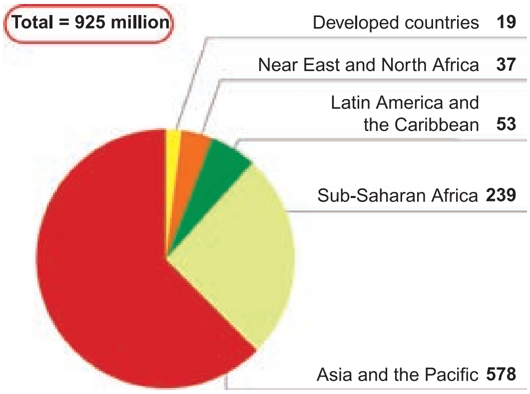

Figure 3: Number of hungry people in the world (2010).[17]

3 CPS Research Issues

As suggested in Section 2, the spectrum of potential application domains of CPS technologies is quite broad. Though specific research problems may vary according to applications, there are several common research issues cutting across many application areas. In this section, we discuss a sample of such fundamental research issues for CPS.

3.1 *Abstraction and architecture*

It is well known that well-designed abstractions and architectures are critical for the success of technology.[19] Representative examples that have catalyzed the Information Technology (IT) revolution of the 20th century are the Von Neumann Architecture, a basic design model for stored-program digital computers, and the Open Systems Interconnection (OSI) Model, an architecture for communication system design that has resulted in the success of today's Internet. Similarly, finding the right abstractions and architectures for CPS that can be applicable to diverse application domains can be critical for a successful CPS revolution in the present century. An example of research in this field can be found in,[19] where a layered architecture for networked control was proposed based on an extension of the OSI model, as shown in Figure 4.

3.2 *Computing and networking foundations*

The fundamental attributes of physical systems are *time* and *concurrency*. However, neither of these is properly modeled and handled in today's computing and networking systems. No widely used programming languages have temporal properties in their semantics. The thread, which is a programming abstract for concurrent execution, is known to be very difficult to use and problematic due to its counter-intuitive abstraction. Networking technologies that are widely used today introduce substantial delays and unpredictability. Computing hardware and software systems are designed and built for better throughput at the expense of predictability.[20] Thus, further research on computing and networking systems that can naturally integrate temporal properties of physical systems is an important research area.

3.3 *Hybrid systems and control*

One challenging feature of CPS is that there are tight interactions between the continuous dynamics of physical systems and the discrete dynamics of cyber

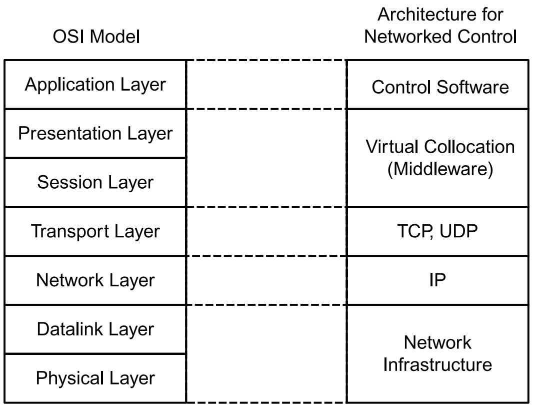

Figure 4: Mapping from the OSI model to an architecture for networked control proposed by Graham et al.[19]

systems. For a long time, mathematical formalism based on differential equations has been used successfully by engineers and scientists to model and analyze physical system dynamics. On the other hand, the theoretical foundation for cyber systems has been based on discrete mathematics such as automata theory, graph theory, etc. The advent of CPS has galvanized efforts at developing a new theoretical foundation, hybrid systems, that can capture both continuous and discrete dynamics at the same time, for system design and analysis. There has been significant progress over the last decade on hybrid systems research. However, there still remain many open problems such as reachability of hybrid systems with nontrivial continuous dynamics, discrete abstraction methods for decidable hybrid systems model generation, automatic synthesis of control algorithms for large scale hybrid systems, etc.

3.4 *Verification, validation, and certification*

During the design and development cycle of a new engineered system, certification and validation is one of the most time consuming, labor and cost intensive processes in general. This is particularly true for systems that require high dependability, such as airplanes, automobiles, medical devices, etc. As an example, certification consumes more than 50% of the resources invested in developing new safety-critical systems in the aviation industry. The situations is similar in the medical, automotive, energy, and other safety-critical industries. Further, as the complexity of CPS is significantly increasing, certification and validation process is becoming even more challenging and costly. To address this issue, there have been many CPS research efforts over the last decade. Model-based design, development, and verification is expected to play an important role in the drive towards efficient and cost-effective evidence-based certification. However, to realize the idea of this approach in practice, there are still many technical challenges that need to be overcome, such as new models for compositional system-wide verification, further advances on formal verification algorithms to handle nontrivial (industrial-sized) CPS system models, and model-driven design and development tools that will enable integrated verification and validation of overall CPS at the design state.

3.5 *Robustness, safety, and security*

As discussed earlier, many CPS applications are safety-critical systems, e.g., ground/air transportation systems, power grid systems, medical and healthcare systems, disaster monitoring and warning systems, etc. Hence, it is important to ensure overall stability of physical systems to avoid catastrophic situations. However, since there are various sources in the physical, sensing, networking, computational and actuation domains that can make systems behave anomalously, it is very challenging to achieve this goal in CPS. Several uncertainties exist in physical systems and their surrounding environment. Various types of failures can occur at any time and at any place in physical and cyber systems. There can also be security attacks from adversaries. Thus, achieving system-wide robustness, safety, and security is a major research challenge for CPS.

4 Overview of Cyber-Physical Systems Research

In this section, we provide a partial overview of some of the efforts that have been undertaken over the recent years to tackle some of the challenging CPS research issues.

4.1 *Stability, performance, and safety*

From the system theoretic point of view, stability, performance, and safety of CPS are the most important properties that need to be considered during the design of supervisory decision and control algorithms. However, due to the possible existence of a communication network in the loop of sensing, computing, and actuation, it is indeed a difficult problem to satisfy these properties. Networked control systems (NCS) is a research area that studies stability and performance of control systems where feedback loops are closed over networks, as shown in Figure 5. In the context of NCS, some fundamental questions are (i) How do network-induced packet delays and losses affect the stability of a system?, (ii) Under what conditions are networked control systems stabilizable?, and (iii) How does one stabilize a NCS?

Figure 5: Structure of networked control systems.

The relation between packet transmission delay and stability is studied and a sufficient condition is derived for the maximum packet transmission interval, called MATI, for stability of NCS by Walsh et al.[21,22] The stability of NCS is studied from the perspective of hybrid system analysis.[23] A more general approach toward the stability of NCS with nonlinear dynamics, disturbances, network scheduling protocols can be found in the work by Nesic et al.[24] The problem of stabilization of an NCS over a lossy communication channel has been studied in the frameworks of robust control[25] and optimal control.[26,27] Information and coding theoretic approaches for stability and stabilizability of an NCS can be found in several works[28–30] and the references therein. Finding an optimal location for control computation in an NCS is another interesting problem.[31]

Generally speaking, at a certain level, mathematical modeling and analysis framework for CPS is necessarily a hybrid issue due to the tight coupling between continuous and discrete dynamics. One of the simplest forms of hybrid systems is a system that switches between different operation modes to adapt to various changes, called a switching system. Extensive work has been done to study the issue of stability and stabilizability of switched systems.[32,33] A more general form of hybrid systems called hybrid automata (HA)[34,35] can potentially be useful in developing techniques for algorithmic verification of CPS properties such as safety and liveness. Safety verification of a given HA can be conducted through the computation of the reachable set of the HA from an initial condition. However, it turns out that exact reachable set computation of HA is an undecidable problem in general.[36] An important class of HA that has been shown to be decidable is timed automata,[37] whose investigation has laid an important conceptual foundation for the area of algorithmic verification of HA. Some other representative classes of hybrid systems that are decidable are initialized rectangular hybrid automata (IRHA)[36] and o-minimal hybrid system.[38]

For the case of HA with continuous dynamics in the form of a linear or nonlinear differential equation, there is no known algorithm that can compute the reachable set of such HA exactly. To avoid computational intractability, some approximation techniques have been proposed, such as linear phase portrait approximation[39] and polyhedral representation of continuous variable evolution.[40,41] Important notions with respect to decidability of such general classes of HA have been proposed by Girard et al.[42] called *approximate* similarity and bisimilarity, which are extensions of the well known notions of simulation and bisimulation in discrete systems. Recently, Pola et al.[43] have proposed an algorithm for construction of an approximately bisimilar symbolic model from a HA that is incrementally asymptotically stable. Based on this result, a software tool for automatic controller synthesis, called PESSOA,[44] has been developed. Other tools developed for reachable set computation and verification of HA areHyTech[39] and SpaceEx.[45]

4.2 *Sensing, computing, and networking systems*

Since computing and networking systems in CPS interact with the physical world, predictability (or timeliness) of these systems is an important property that should be provided. Real-time scheduling theory is the area that studies this issue in computing and networking systems. The foundational work is that of Liu and Layland on rate monotonic (RM) and earliest deadline first (EDF) scheduling algorithms, presented in 1973.[46] In this work, bounds on processor utilization are derived for a set of periodic tasks under which schedulability is guaranteed when a task set is scheduled by assigning priority statically based on the periodicity of a task in RM, or dynamically based on the absolute deadline of an instance of task in EDF. Since then, many other real-time scheduling algorithms have been proposed with better processor utilization bounds and faster response time for aperiodic tasks such as priority exchange server, total bandwidth server (TBS), constant bandwidth server (CBS), etc. In,[47] the authors have proposed a real-time scheduling theory, called feasible region calculus, for a task set consisting of aperiodic tasks with arbitrary arrival times, execution times, and deadlines. Other work on real-time scheduling theory includes resource sharing, real-time queueing theory, etc. For more detail on this field, we refer the readers to the works by Sha et al.[48] and Buttazzo.[49]

Along with advances in real-time scheduling theory, computing platforms for real-time and embedded systems have been developed and used successfully in many application areas.[50] However, due to the scale, structure, and behavioral complexities of today's and tomorrow's CPS, it is an important challenge to develop extensible, scalable, and adaptable software platforms that can operate in distributed, heterogeneous, time-critical, and safety-critical environment. The Common

Object Request Broker Architecture (CORBA) of the Object Management Group (OMG) is a well-known industry standard specification for software platforms, called middleware, which has been used mainly in distributed and heterogeneous enterprise computing environments. To enhance its applicability in time and safety-critical systems, OMG has developed an extension of CORBA, called Real-time CORBA, to support temporally predictable end-to-end interactions. As an implementation of Real-time CORBA, the ACE ORB (TAO)[51] has been developed and used in the Open Control Platform (OCP)[52] for complex and reconfigurable control system applications such as unmanned aerial vehicles (UAV). Another software platform that is capable of extensible, reconfigurable, and real-time use is Etherware[53,54] designed for large-scale networked control systems. Some other works are RUNES[55] and RTZen.[56]

In CPS, temporal predictability of communication systems is also an important issue for overall system-wide stability, performance, and safety. Achieving such real-time properties is much harder in wireless networking systems than in wired situations due to several issues such as interference between nodes, dynamically changing network topology, power, etc. The problem of real-time packet scheduling at an access point where packets are sent from multiple client nodes has been studied by Hou et al.[57] The setting of this problem is similar to the case of real-time task scheduling in computing systems except that packets are sent over the unreliable wireless communication medium. In this formulation, a schedulability condition is derived by considering the unreliability of wireless communication links and an optimal access point packet scheduling policy has been developed. Further details can be found in.[58–60]

Wireless sensor networks (WSN) involve several of the components related to CPS, such as sensing, computing, and communication. There are many important research issues of importance to WSN, such as connectivity, energy-efficient networking protocols and platforms. The connectivity problem is studied by Gupta et al.[61] and Penrose.[62] For energy-efficient networking, several medium access control (MAC) protocols have been proposed such as S-MAC[63] and B-MAC.[64] Routing is also an important research issue in WSN. Various routing protocols have been developed, including SPEED[65] and RAP.[66] Concerning WSN platforms, TinyOS[67] is a well-known open source operating system for WSN which has seen much implementation and experimention. Further details can be found in the work by Stankovic et al.[68] and the references therein.

4.3 *Modeling, design, and development*

Computing systems including hardware, software, and networking contribute significantly to the overall development cost, labor, and time involved in CPS. As an example, almost half of the production costs of today's automobiles are accounted for by computing system development. As noted earlier, the situation is no different in other industries. In tomorrow's CPS, due to the increasing complexity and heterogeneity of systems, it is expected to be even more difficult to design, develop, and debug computing systems, which will in turn result in significant increases in overall development costs.

Over the past decade, there have been many efforts by the CPS research community to tackle this issue. One effort is model-based design and development.[69,70] The basic idea of this approach has already been used successfully in several tools such as Simulink and LabVIEW, and has proven to be useful for the development of today's real-time and embedded control systems. However, to handle the increased complexity and heterogeneity of CPS, it is necessary to further advance technologies for model-based design and development beyond tools. Building a well-defined model that is composable, verifiable, and easy to design is a significant challenge. Lee has argued from the computer scientists' perspective that today's computing and networking abstractions are not appropriate for CPS modeling since they do not properly capture the passage of time and concurrency of a physical system and have identified some promising research directions for better abstractions vis-à-vis computing and networking systems for CPS.[20] Challenges to CPS modeling, and an overview of recent work are presented the work by Derler et al.[71] using the illustrative example of a fuel management system in aircraft. Recently, Edison et al. have introduced a programming model that captures the physical notion of time for model-based design of distributed real-time embedded systems, called programming temporally integrated distributed embedded systems (PTIDES).[72] Giotto, a programming language for real-time CPS, and Ptolemy II,[73] a modeling and simulation environment for heterogeneous systems, are also notable works in this direction of research. Other works on model-based design and development are model-driven architecture (MDA)[74] and model-integration computing (MIC).[75]

4.4 *Others*

There are several other important CPS research fields that are not covered in this paper, such as security, in-network information processing, etc. For more details on these subjects, readers are referred to other works for CPS security,[76–78] and for in-network information processing in sensor network.[79–81] In addition to these, some recent work on CPS applications can be found on the security of smart grid,[82] on energy efficient modeling and control of data center,[83] on medical and healthcare systems,[11] and on autonomous ground transportation systems.[84]

5 Concluding Remarks

In this paper, we have provided an overview of some grand challenges that call for further advances in computing, communication, and control technologies for tomorrow's cyber-physical systems. We have also presented a partial account of several research issues to overcome these challenges, and have surveyed recent research efforts in (i) stability, performance, and safety, (ii) sensing, computing, and networking systems, and (iii) modeling, design, and development. As is evident, there remain several important open problems. These present opportunities for exciting research for many years to come.

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