Characteristic, Architecture, Technology, and Design Methodology of Cyber-Physical Systems

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Abstract. Cyber-physical systems (CPS) involve in a variety of computing model integration and collaborative work. There are some problems such as ununified design methods, worse elasticity, high complexity, difficult to implement cyber-physical co-design and co-verification, etc. Aiming at the co-design of embedded components, sensing components, controlling components, communication components and physical components in heterogeneous environments, this paper proposes the characteristics, architectures, technologies, and design methodologies of CPSs. It's necessary to design CPSs in the model-driven design process to establish CPSs and confirm its correctness, support cyber-physical co-design and correctness by construction so as to avoid modifying repeatedly the design when problems are found in the system realization process, and provide the necessary theoretical and practical technical supports to establish CPSs.

Keywords: Cyber-Physical systems · Co-modeling · Component · Co-verification

1 Introduction

Cyber-Physical System (CPS) [1] is a new generation of multi-dimensional intelligent system integrated computing, communication and control, widely used in aviation, automotive [2, 3], chemical, pharmaceutical, infrastructure, energy [4, 5], health, manufacturing, traffic control [6], home [7], entertainment, robotics [8] and consumer electronics and other fields.

CPS is a multidimensional and complex system which combines computing, network and physical environment. As shown in Fig. 1, the real time sensing, dynamic control and information service of the large-scale engineering system are realized through the organic integration and deep collaboration of 3C technology (Computation, Communication and Control). CPS implements the integration of computing, communication and physical systems. It can make the system more reliable and efficient with real-time collaboration, and has important and wide application prospects. With ubiquitous environmental sensing, embedded computing, network communication and network control systems engineering, CPS has the function of computing, communication, precise control, remote cooperation and autonomy. It pays attention to the close combination

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and coordination of computational resources and physical resources, mainly used for some intelligent systems, such as robots, intelligent navigation, etc. In recent years, CPS has not only become an important direction of research and development of academic and scientific community, but also it is expected to become the industry field of the priority development of the business community. The development of CPS research and application is of great significance to accelerate the integration of industrialization and information technology.

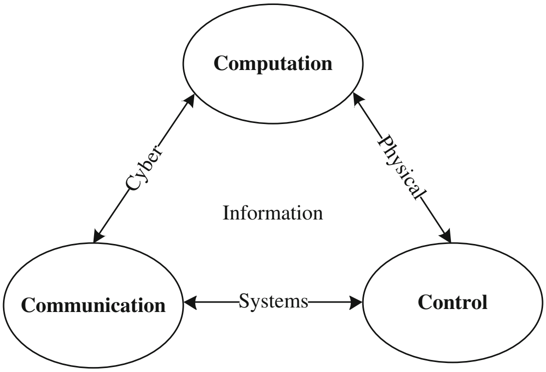

Fig. 1. 3C view of CPS.

In order to meet the CPS's idea of the integration of computing, communication, control and physical equipment, and make the engineering system more efficient, more efficient, more functional and superior performance, it needs to evolve the existing physical and information systems involved in the evolution of science and technology, and establish a scientific and technological infrastructure to meet the needs of CPSs.

In the process of CPS building, we have to face some challenges, such as re-arrangement of the abstract layer in the design flow, the development of new heterogeneous model combination based on the semantic foundation and the description of the different physical and logical modeling language based on the semantic foundation, research on the science and technology foundation of a system combination and integration which is model-based, accurate and predictable, development of new CPS open architecture which will allow us to build the national and global level CPSs, new flexible CPS design automation infrastructure, etc. CPS will change the way that people interact with the physical world, and its application is very wide, including smart grid systems, intelligent transportation systems, aerospace and electronic systems, intelligent medical systems, information appliances systems, environmental monitoring, intelligent building, industrial control, defense systems, weapons systems, etc. It will become an important driving force for the new technological revolution. CPS combines a variety of technologies, such as sensing, decision-making, execution, computing, networking, and physical processes. It is the key field of science and technology and economic development in the new century.

2 Characteristics

CPS is developed on the basis of embedded system, sensor technology and network technology. According to the actual needs, a complete CPS should have the following characteristics.

- **Reliability**. The physical reality of the world is always changing.CPS is working in such an environment. Therefore, CPS must have the ability to cope with the unexpected situation and subsystem failure. Reliability, as an important index of the system, has been widely recognized by people. Especially the requirement of CPS is more prominent. Only high reliability as a guarantee, CPSs involving people's lives and safety can safely be used by people.
- **Concurrency**. Concurrency is the basic feature of the event in the physical environment. At present, the computing mode is in order. And people seem to have been fully adapted to this mode. But CPS is a system that combines computing and physical processes. New concurrent computing software systems must be developed to meet the needs of CPS.
- **Real-time**. The real-time nature of the information world is that the same time that the event occurred in the physical world is also reflected in the information world. CPS has a constant interaction between computational process and physical process. It is needed to perceive the physical process and to intervene in the process of physics in real time. This puts forward the very high requirement to the system's real-time performance.
- **Massive information processing**. CPS is a multidimensional and complex system which combines computing, network and physical environment. The type and quantity of information that the system needs to receive and process is very large, e.g., smart grid CPS needs to receive the voltage, current, temperature and other information of each node. The number of these nodes is extremely large. Therefore massive computing is a common feature of CPS.
- **Distribution**. In CPS, there are a lot of embedded systems. They form a distributed computing network. However the capacity of each node is limited. Therefore CPS is a typical distributed computing system.
- **Autonomy**. The autonomy of the system is one of the most representative features of CPS. The system can respond to the changes of the external environment and make the appropriate response in time so as to ensure the normal operation of the system. And this kind of reaction can be carried out by human intervention.
- **Security**. For any valuable system, security is an indispensable prerequisite. Especially for the CPS which can affect the physical environment, it needs to enjoy a higher security.
- **Dynamic reorganization**. CPS faces a huge physical environment. In this physical environment, all kinds of resources are changing at a time. If we cannot make the system adjust itself according to the actual situation, i.e. effective dynamic reconfiguration, it is possible to make the system unstable or unsafe because of the depletion of some resources.

- **Heterogeneity**. In CPS there are a variety of devices, including sensors, processors, memory, etc. These devices may come from different manufacturers. They may use different instructions, and depend on different operating systems. How to ensure that these devices can achieve interoperability between the CPS is a problem must be solved. This also determines the CPS must have the characteristics of heterogeneity.

3 Related Terms

CPS is very easy to be confused with of Internet of Things (IoT), Machine-To-Machine (M2M), Sensor Network Wireless (WSN) and so on.

- **M2M**. From a narrow sense, M2M represents the communication between the machine and the machine. In a broad sense, it can also indicate the communication between people and machines. At present, most of the M2M refers to the communication between non information technology (IT) machine and other equipment or IT system.
- **WSN**. WSN refers to a large number of sensor devices through wireless communication way to connect and form a sensor network.
- **IoT**. IoT refers that through the Internet and other means of communication, computing systems, sensors, controllers and objects (or environment) are connected to form a network connecting human with things and things with things for informatization, remote management and intelligent control.
- **CPS**. CPS is a complex system which combines the computation, the network and the physical environment, and realizes real time sensing and dynamic control of physical devices or environments by computing, communication and control.

In summary, M2M emphasizes the communication between the machine and the machine, WSN focuses on the multi hop transmission of sensing information, CPS emphasizes the process of feedback and control, and IoT emphasizes the information perception and transmission of all things.

4 Architecture

Based on the environment perception, CPS is a controlled, reliable and extensible network physical equipment system with the capability of computing, communication and control. By the feedback loop of the interactive computational processes and physical processes, it realizes the deep integration and real-time interaction, adds or extends new functions, and detects or controls physical entities in a safe, reliable, efficient, and real-time manner. Physical devices in CPS refer to objects in nature. Therefore they not only refer to the cold equipment, but also include living organisms, such as people.

4.1 Composition Structure

Tan et al. [9] proposed a representative CPS composition structure. The composition structure is divided according to the different space. At the same time, it gives the detailed process of sensing event flow and control event flow. Through this structure, we can clearly understand the interaction between the physical world, the cyber space and the human space. The physical world is the basis of CPS. The information source of the whole system and the final feedback of the information all exist in the physical world. In the physical world, there are various devices which can interact directly with the physical environment. We can call the terminal device at the front end of the system Mote. These Mote constitute the front end of CPS in the physical world. The physical world front end of CPS consists of two parts: the perception part and the execution part.

CPS is full of all kinds of physical nodes in the physical environment. These heterogeneous nodes may be very close or thousands of kilometers apart. How to make these nodes communicate with each other and to support the interoperability between each other is the problem that CPS network needs to solve. Network for CPS, is the basis for the realization of information sharing. Compared to the common network layer of the computer network, CPS network construction is more difficult. CPS network not only needs to provide the basis for the application of resource sharing network, but also to shield the heterogeneity of a very large physical nodes and realize the seamless connection of the system. At the same time, it also provides users with the plug and play services. As a result, the CPS network has a higher demand for technology. In addition to the access control technology, routing technology, network transmission technology in the common computer network, CPS also needs some new technologies as the support, e.g., the description and semantic analysis technology of heterogeneous data generated by heterogeneous nodes, node localization technology caused by node mobility, new storage technologies for solving the massive data, network congestion technologies for solving massive data transmission, etc.

The third part of the structure of CPS is the CPS control unit. The event driven control unit receives the event and physical world information perceived by the sensing unit through the CPS network, and according to certain rules, deals with them and generates the processing information. These processing information will be transmitted through the CPS network to the implementation unit and the sensing unit, and complete the interactive process of the whole system.

4.2 Hierarchical Structure

In addition to the above described CPS composition structure, the CPS can be divided into a hierarchical structure model. According to the function of CPS equipment, the whole CPS is generally divided into physical layer, network layer and application layer.

- **Physical layer**. The physical layer mentioned here refers to the hierarchy of the system nodes in which the computing function is embedded into the physical process. In brief, physical devices that interact with the environment are collectively referred to as the physical layer. This layer includes sensing devices for environmental sensing, execution devices for reacting to environmental state, energy units for supplying energy to other devices, etc.
- **Network layer**. There are some differences between the network layer and the network in the composition structure. In the latter, it also includes database servers.

The main function of the network layer in the hierarchical structure is to carry out the network transmission. Network layer is to shield the heterogeneity of the physical layer units and provide support for CPS cell interconnect. In order to achieve better network transmission and solve the load problem caused by the large amount of data on the network, Krishna et al. [54] proposed the concept of CPI (Cyber-Physical Internet) to establish a network of computing physics similar to the Internet, so as to support the interconnection and interoperability of all devices in CPS.

- **Application layer**. It is the top layer. It is user oriented, responsible for the entire CPS presented to users. This layer encapsulates details of the physical layer and the network layer, and generates different application modules, such as monitoring module, data acquisition module, data display module, etc., so that users do not need to care about the details of the physical layer and the network layer, and directly focus on the business processing. The application layer is mainly to collect the task requirements and decompose the task reasonably, and then according to these sub tasks, query and configure resources, position and schedule resources to complete specific tasks.

5 Integrated Technologies

CPS requires a lot of technologies as the basis and support, such as computer system technology, embedded system technology, wireless sensor network technology, IoT technology, network control technology and hybrid system technology, etc. Although, based on the above technologies, but because of its inherent characteristics, and there are some differences between the above technologies and CPS. Therefore, in order to achieve a better CPS abstraction and modeling, to build a suitable CPS validation system, it is necessary to understand the existing technology in depth, and on this basis to improve and optimize.

5.1 Computer System Technology

The computer system mainly consists of two parts: hardware and software. CPS must also have the software and hardware components as well as the functions, such as CPU, memory and external device, operating system, language processing system, data processing system, etc. However, CPS has many differences from the common computer system in the specific design and implementation of the components. The design of the existing computer system is based on the goal of efficient data storage, conversion and processing. Differently, the ultimate goal of CPS is to realize the real-time and effective interaction between the computing process and the physical process. Therefore, the focus of CPS is on the system's real-time, security, reliability, confidentiality, adaptive and other characteristics. The common computer systems have not paid special attention to these characteristics. However, the existing grid technology, parallel computing technology in the computer system, to a certain extent, satisfies the requirements of distributed control and efficient computation of CPS, and provides a great technical support for the development of CPS.

5.2 Embedded System Technology

An embedded system is a system used to control or monitor machines, devices, factories, and other large scale equipment, i.e., it is a special computer system which is application-centered, based on computer technologies, software and hardware modifiable, strictly required on function, reliability, cost, volume and power consumption. It can be seen that the embedded system is mainly developed and designed according to software and hardware collaboration. The combination of computing unit and physical object in CPS can also be considered as a kind of generalized hardware and software collaboration, but different from the traditional collaboration of embedded systems. CPS requires hardware must contain information components. For traditional hardware and software collaboration, in order to get a stable integration environment, the function of embedded systems is enhanced by embedding a certain computing device and the corresponding software in the physical device. The integration of information and physics in CPS is to make the system better adapt to the uncertain and dynamic environment, and more attention is paid to the deep coupling of computing resources and physical resources, and how to effectively utilize existing resources and so on. Although there are some differences between embedded technology and CPS, CPS still need embedded technology as a support.

5.3 Wireless Sensor Network Technology

Wireless sensor networks consist of a large number of inexpensive micro sensor nodes deployed in the monitoring area, which form a multi hop ad hoc network system by wireless communication. The purpose is to sense, collect and process the information of objects in the network coverage area, and send it to the observer. Sensors, sensing objects and observers constitute the three elements of the wireless sensor network. The development of wireless sensor network technology promotes the development of CPS. The existing wireless network technology provides a good platform for the development of CPS. Unfortunately, wireless sensor network technology has limitations, e.g., when the node is put into the monitoring site, they are basically static in space, i.e., the monitoring position is fixed, and cannot make the corresponding adjustment according to the changes of the environment. At the same time, in addition to sensor nodes, CPS also contains actuator nodes, compared to the wireless sensor network, more complex. Because of the autonomy of the node (especially the actuator node), the topological structure of the structure must be dynamically configured in space and time, there should be a clear coordination and communication protocol between the nodes, and the universal solutions in different environments are necessary. In addition, CPS also needs to be improved through the network control strategy and battery equipment to extend the service life of the sensor nodes.

5.4 IoT Technology

Through radio frequency identification, infrared sensor, global positioning system, laser scanner and other information sensing equipment, according to the agreement, IoT connects the things to the Internet for information exchange and communication, so as to achieve a “thing-thing connected” or “object-object connected” network with intelligent identification, positioning, tracking, monitoring and management. There are some differences between IoT and CPS. First, CPS is aimed at the remote communication and control of physical components (including human), and IoT is aimed at the perception of the object state. Human use sensors to sense the state of objects, but they can’t control the state of the object. Second, in IoT, communication occurs mainly between objects and people or between objects and processors, and in addition to the above two kinds of communication, CPS has a communication between objects and objects, so as to achieve the goal of self-interaction between components. Although there is a difference between CPS and IoT, the development of the IoT technology has greatly promoted the realization of CPS. IoT can not only provide a “thing-thing connected” network communication environment for the realization of CPS, the involved radio frequency identification technology, wireless sensor technology, embedded system technology and nanotechnology can provide help for the realization of CPS.

5.5 Network Control Technology

Networked Control Systems (NCS) is a fully distributed, networked real-time feedback control system. It refers to a set of field sensors, controllers and actuators, and communication networks, used to provide data transmission between devices and enable users of different locations in the region to achieve resource sharing and coordination. Similar to CPS, NCS aims at interaction between objects. However, in CPS, in order to improve the real-time performance and accuracy, using decentralized control, on the basis of self-sensing control of each node, it realizes the system’s operation and decision based on the control mode of the central linkage adjustable feedback control, and by improving the performance of node autonomy, it achieves the system’s self-regulatory capacity and efficiency improvement.

5.6 Hybrid System Technology

Hybrid system is a kind of dynamic system composed of continuous subsystem and discrete subsystem. CPS is a hybrid system, and many models of hybrid systems can be applied to the research of CPS, such as discrete event model, computational intelligence model, game theory and so on.

6 Challenges and Problems in Design

As shown in Fig. 2, CPS specially emphasizes the process of sensing, transmission, processing, and control of user space, cyber space, information space and physical space. The real time, dynamic information control and information service of physical entities are highlighted. The basic feature is a perceptual feedback loop which can interact with the physical world. It influences the feedback loop through the computing process and physical process, achieves close interaction with the physical process, and thereby adds or expands new capabilities to the physical system. CPS is composed of complex and varied functions [10], and needs to be coordinated with communication, sensing, control and physical components. It makes it difficult to grasp the development of the system, and it is an urgent need and urgent task to discuss its efficient cooperative design method.

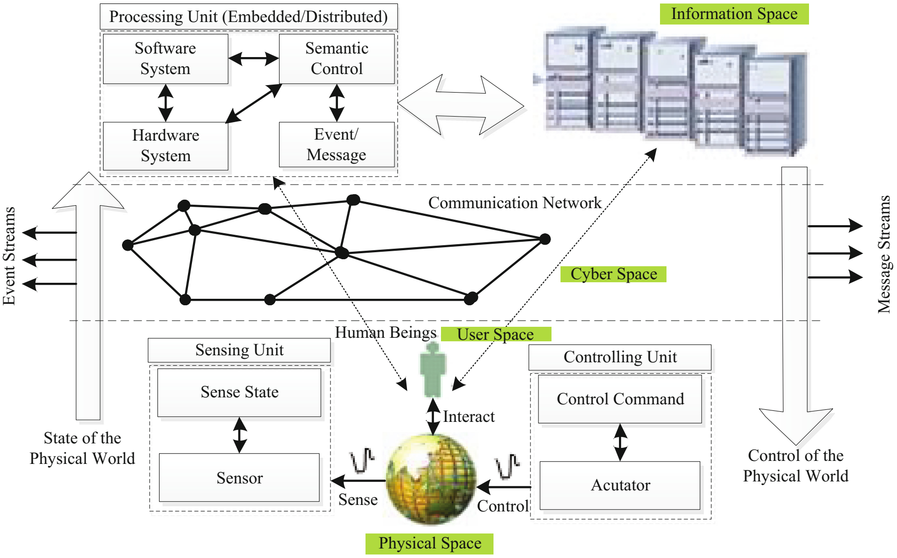

Fig. 2. Application system architecture of the CPSs.

The traditional embedded system is enclosed. It particularly emphasizes computational processing power. In addition to the I/O ports that are used to connect the basic external modules, there is no external extension interface. It cannot meet the design requirements of controllability, trustworthiness, extensibility of physical devices. A complete CPS is designed to be an interactive network composed of physical devices. It involves tn The collaborative work of heterogeneous units, such as humans, machines, things and so on, not just a single device. The combination of computing and physical entity units will be more compact. The physical component is different from the software component and hardware component. The safety and reliability of the system is higher than that of the general computing system [11]. CPS needs to be improved in terms of adaptability, automation, efficiency, functionality, reliability, security, availability, and so on [12].

The heterogeneity of CPS components is mainly reflected in three aspects:

- First, software components and hardware components are included in the embedded system. Their analysis, design, coding, testing methods are significantly different.
- Second, for the CPS components, such as embedded software components, embedded hardware components, sensing components, control components, communication components, and physical components, there is not consistent in terms of function,

computing model (continuous and discrete), description (text and graphics) and validation (formal verification, simulation and test), difficult to co-design.

- Third, the types, models and connection forms of these components used in different application environments are different. There is a large difference in scale. In design, the system needs to be more flexible (elastic). When the system is complex to a certain degree, if the direct programming is used for design, the system will increase the possibility of fault or even failure.

In view of the complex work of the collaborative design of CPS components, in order to meet the requirements of good performance, low cost and high reliability, and improve the quality and efficiency of the system development, the design needs to be carried out under the description that the design cycle can completed. Therefore, the first step in collaborative design of all kinds of components should be to establish a system model, which is an abstract description of the system. Its content mainly includes three points: the requirement analysis is transformed into a system implementation that is remodelable, verifiable, and visualized so that it is easy to verify whether the designed system is in conformity with the requirement analysis, and also easy to understand and modify the design; it can represent the structure and behavior of the system; it can represent the non-functional constraints of the system.

CPS collaborative design, including collaborative design between designers and among different models of sub components, is becoming an urgent problem to be solved. One of the most effective methods to solve this kind of complex problem is the theory of hierarchical and collaborative modeling [13], i.e., closely combined with the external physical environment factors of CPS, the complex problem is divided into several sub problems so as to solve one by one. Hierarchical cooperative modeling is to divide the complex system with multi computing models into some layers, link up the system structure and system behavior to be designed, and visually control the architecture so as to discover more details of needs and better solve the problem. In addition, the system design also follows a law that the sooner the verification, the sooner found the problem, the price paid is smaller. Effective system model and specification are conducive to the division of design and professional production, and is conducive to collaborative verification and correctness-by-construction, and thereby is conducive to saving design and production costs.

Based on the above analysis, CPS design is facing some problems and challenges.

- There is no uniform standard for analysis and design, e.g., their methods are not unified. From analysis and design to production and programming, there is not a consistent engineering method. This makes the impact of human factors in every process of product form is very serious.
- The results of analysis and design cannot be reused [14] when developing similar projects or products. The configuration in the process of design and after the completion of design cannot achieve flexible regulation from the general framework to the specific application, i.e., not remodelable [15].
- CPS design is a collaborative design process [16], e.g., collaborative design for a variety of heterogeneous computing models [17–22], including continuous systems, discrete systems, etc., and collaborative design of heterogeneous components,

including software, hardware, sensors, controllers, communication units, physical systems, etc. Single model or modeling method is difficult to meet the needs of the design of heterogeneous components in CPS [23, 24].

7 Design Methodology

7.1 Overview

In accordance with whether the formalization is supported, traditional embedded system modeling methods can be divided into formal and non-formal methods. The formal methods are described in terms of symbolic and mathematical language, including algebraic language such as OBJ, Clear, ASL, One/Two ACT, etc., process algebra language such as CSP, CCS, π calculus etc., temporal logic language such as PLTL, CTL, XYZ/E, UNITY, TLA, etc., and network language such as Petri Nets [25–28], UML, FSM, FNN [29], etc. The limitation of Petri Nets is that the complexity of the system will rapidly lead to the non-understanding of the system. Due to the lack of explicit support for concurrency and hierarchy, for complex systems, FSM may have "state explosion" and "migration expansion" phenomenon. The non-formal methods, such as structured method and object-oriented method, can basically describe the functional properties of the system, and simulation can be used to verify the correctness of the system. But the description ability of the non-functional attributes is limited, and it is not conducive to rigorous verification through mathematical methods.

According to the composition elements of the modeling objects, the modeling methods can be divided into process based, task based, and component based approaches. Component-based approaches [30–33] also include object-oriented (such as real-time UML), middleware (such as COBRA, EJB, SOM, DCOM and other business standards), actor-oriented [34], field-oriented, resource-oriented technologies.

According to the system description, the modeling methods can be divided into state-oriented (such as FSM and Petri Nets), activity-oriented (such as data flow diagram and control flow graph) [35], structure-oriented (such as component connection diagram), data-oriented (such as the entity relationship diagram and Jackson diagram) and heterogeneous model (such as the control/data flow graph).

According to the development methods, there are two kinds of methods including Top-Down (such as Simulink, SDL, StateCharts, etc.) and Bottom-Up (such as HDL, UML, IDL, ADL, Modelica, etc.). The former is suitable for system requirement analysis, high level architecture description and system evaluation. The latter is suitable for the description, design and verification of the low layer architecture.

These methods have played an important role in the traditional system design. However, in the collaborative design of CPS, they face new problems and insurmountable difficulties.

7.2 Key Methods

CPS is different from the usual pure software or hardware system, but integrated with software, hardware, sensing, control, communication, and physical systems [36–38]. Some functions can be achieved by software, can also be achieved through hardware, but also can be completed by the physical device. The challenge of CPS design is not only related to the computer software and hardware, and also involves a number of non-computer engineering problems, such as mechanical dimensions, power consumption and manufacturing cost, etc. Even for the problem of computer engineering, most systems also have special requirements for real-time, reliability, and multi rate problems. With the increasing application demand, CPS function is becoming more and more powerful, the system architecture is becoming more and more complex, and the requirements are also naturally improved like boats going up with the level of the water.

In order to support the design of CPS in the heterogeneous environment, OMG proposes a Model Driven Architecture (MDA) method, which is an open frame based on UML, MOF, XMI, CWM and so on, supports software design and model visualization, XML data storage and exchange, separates the commercial application logic from the supporting platform technology, and establishes the abstract model of the embedded software system. In the promotion of MDA, a variety of modeling and verification methods to support the collaborative design of embedded systems have emerged.

Model Integrated Computing (MIC) [30], proposed by Vanderbilt University, based on the use of UML/OCL meta model language, extends the use and scope in the system development, provides a flexible framework for the development of CPS, and can meet the requirements of the rapid development and application of engineering personnel in specific areas, e.g., military, aviation, chemical engineering, etc., without needing too many software development foundation. At present, the team also realized that the support of the heterogeneous model is the next research direction.

Sifakis et al. proposed the BIP (Behavior/Interaction/Priority) [31] CPS abstract modeling method based-on components. This method supports for the glue operation of heterogeneous components. The modeling results can be compiled into the specified platform C++ code. And the model checking theory is proposed for model verification. However, there is still a lack of modeling and verification platform support, also need to provide a further extension of the physical component modeling and verification.

After studying the characteristics and challenges of CPS in depth, Lee who is a leading figure in the CPS study, believes that the CPS can also be called a deep embedded system. And by summarizing the existing simulation control modeling method, he puts forward the concept of "cyber systems need to be physical" and "physical systems need to be cyber" to solve the modeling of physical entities and cyber entities and the interaction between them. In his method, the physical subsystem is packaged abstractly in a software system, so that the physical subsystem has the characteristics of interaction with the information layer. At the same time, he abstracts software components and network components, so that they have the time characteristics of the physical world in real time. Lee et al. [34] also proposes a system level, hierarchical and heterogeneous actor-oriented modeling language based on Ptolemy, using XML as the basic behavior and structure description language, realizing the modeling environment towards parallel, real time embedded applications. This method is mainly used to verify the model of embedded systems and CPSs. It does not have the comprehensive and compile function for the target system, and does not support the implantation of the new behavior model. Liu [39] further expands the CPS as the Cyber Physical Social System (CPSS), introduces cognitive and social domains into CPS, and realizes collaborative modeling of cyber, physics, cognition and social space. In theory, the modeling space of CPS is greatly expanded.

The researchers have come to realize the importance of CPS collaborative modeling and verification. DEVS [40] is a kind of discrete event system simulation theory which is built by Zeigler based on the study of general systems theory. It has simple operation semantics, and there is a simple corresponding relationship with the real system. However, DEVS is a kind of poor semantic system description method. Its advantage lies in the support of the system's structure, communication mechanism and time concept. The disadvantage is the lack of a description of the system behavior. The openness of model structure is low. And its abstract mathematical description from the specific modeling of the system is still a long distance. Liu [41] embeds StateCharts to DEVS, using these characteristics that StateCharts is suitable to establish the behavior model of the system and describe the conversion rules of states, to realize the complementary advantages. In this improvement method, a simple, intuitive system model can be established. This method can effectively improve the design efficiency of CPS and complete the automatic mapping of high-level modeling to the bottom layer code.

In addition, in the rapid development at the same time, Modelica is highly concerned by the industrial sector. Many of the relevant industry's top companies have launched their support programs. Under the support of Modelica, Taha et al. [42] completes the Acumen project, and proposes a modeling and verification method for hybrid systems. In this method, continuous functions are used to model continuous systems and discrete simulation. Tan [9] describes the connections between the CPS components using events, which are divided into temporal and spatial events, and establishes the hierarchical event model. Then the event model of concept lattice is proposed, and the event type, the internal attribute and the external attribute are defined. Compared with the time driven model [43, 44], the event driven model [45] can better reflect the interaction between components in CPS.

In the field of specific application, Parolini [46] proposes a control oriented model in which the computational network and the thermal network are used to construct the system model, so that the effective control of energy efficiency of data center is realized. Saber [47] divides the cyber physical energy system into stochastic model, intelligent dynamic load balance model and smart grid model, including energy, grid - based vehicles and heat units, maximizing the reuse and utilization of energy. Saeedloei [48] emphasizes the importance of the programming model, in which the methods such as co-induction, limiting factor and co-winding communication are used for logic programming of CPS, so that the formal modeling and verification of the reactor temperature control system are realized. Lin [49] uses agent-based modeling method to model the CPS system by using agent to eliminate the difference and represent the properties of information layer and physical layer in CPS system. These applications [50–54] are highly targeted, and have low open support and different description methods for different models. The validation of the collaboration is limited by their model openness.

8 Conclusions and Future Works

The above problems restrict the development of CPS theory and technology, and become the main bottleneck for many years to limit CPS to large scale applications. This makes most of the organizations and groups, who are engaged in the development of CPS applications, basically adopt the operation mode of small group and even small workshop, so that the development of more complex or large-scale system becomes very difficult or even impossible to carry out, or because of the changing needs of the system or the flow of team members, the project falls in failure. Therefore, an open modeling approach is needed to support the collaborative design of embedded, sensing, control, communication, physical and other components for modeling CPS, and an extensible consistent description method is provided to specify these heterogeneous components, and then to carry out the collaborative verification.

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