Cyber-Physical-Social System (CPSS) Architecture Framework and Methodology

Qing Li [a], Zhixiong Fang and Mengjin Qu
Department of Automation, Tsinghua University, Beijing 100084, China

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Abstract: With the development of the Internet of things, mobile Internet, cloud computing and other emerging information technologies, as well as the development of a new generation of artificial intelligence represented by big data and machine learning, the cyber physical system (CPS) formed by the integration of intelligent systems and physical systems is increasingly showing the characteristics of self-evolution and self-growth like human society. Although human is still the most important and leading part in the technology-society system under the current technical conditions, a new ternary integrated collaborative model is being formed between human and intelligent system and physical system, and more complex integration logic is being brought. This paper studies the architecture framework and methodology of ternary integrated cyber physical social system (CPSS), which provides a framework and method for analysis and design of this complex system of systems.

1 INTRODUCTION

With the development and revolution of industrial technology, information technology and management technology, the relationship between human and nature has undergone profound changes.

As shown in Figure 1, the first industrial revolution was marked by the realization of mechanization. Human beings began to deal with systematic industrial systems and assumed the main responsibility for the mechanical operation and control of industrial systems. The main interaction is between human and machine. With the second industrial revolution, electrification and automation upgraded the interaction between people and industrial systems to electromechanical manipulation and control, but still the physical way. The typical feature of the third industrial revolution is informatization. The application of information technology enables people to manage and control industrial systems at more levels. Machines are integrated with computer chips so that they can be operated in digital way. But this doesn't mean that electromechanical manipulation disappeared. It became the underlying logic. At this stage, the concept of cyber physical system (CPS) was proposed by the National Science Foundation (Shi, J., Wan, J., Yan, H., & Suo, H., 2011), but it is mainly classified into the category of industrial systems, forming a binary structure with people. The core of the fourth industrial revolution is intelligence. The development of the new generation of artificial intelligence makes the cyber system independent from the industrial system, and interacts with the industrial system to realize the evolution and emergence characteristics (Zhou, J. et al. 2018). People, cyber and industrial systems characterized by machines constitute the ternary structure of CPSS (Wang, F. Y., 2010).

With the development of emerging information technology represented by computer software and hardware, network and database technology, and especially the Internet of things, cyber-physical system (CPS) has become the basic architecture of technical system (Zhou, K., Liu, T., & Zhou, L., 2015), and is promoting the traditional technology-management system integration architecture of industrial system to a decentralized network architecture. However, generally, people still regard CPS as a whole to interact with human (Griffor, E. R., Greer, C., Wollman, D. A., & Burns, M. J., 2017).

[a] https://orcid.org/0000-0002-6013-1921

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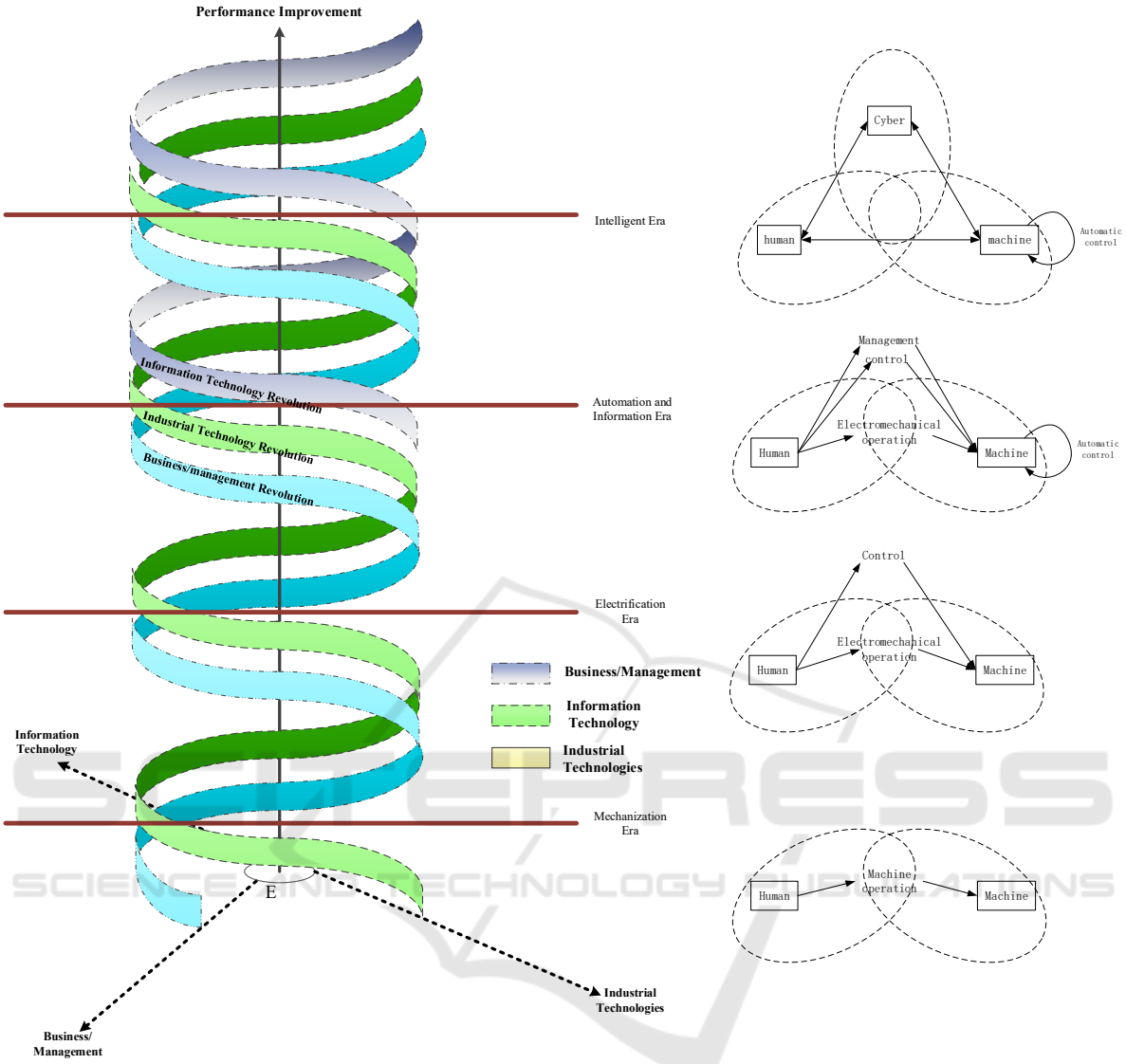

Figure 1: The integrated development of industrial technology, management technology and information technology, and the emergence of CPSS.

Because CPSS is developed on the basis of CPS, at present, many studies focus on the role of human in the whole CPSS system, the relationship and cooperation between people and CPS, and the possible system changes caused by artificial intelligence. Romero et al. (2016) analysed the change of the cooperative relationship between people as operator and machine, and put forward the classification method of human agent, artificial agent and hybrid agent on the basis of intelligent agent theory. Pacaux-Lemoine et al. (2018) put forward the ability classification method of human agent and artificial agent on this basis. The ability of each intelligent agent is divided into the ability of industry related knowledge and skills and the ability to cooperate with other agents, but the ability of human agent and artificial agent is not completely the same. Sowe et al. (2016) believed that there are differences between human and machine in motivation, predictability and perception, and Gil et al. (2019) also believed that human and machine do well in different fields. In terms of the relationship between people and systems, Calinescu et al. (2019) divided people's roles into three types: input provider, system contributor, and the consumer of services provided by the system. From another perspective, Yao et al. (2022) divided the roles played by people into three types: "human in the loop", "human on the loop" and

"human out of the loop", which respectively represent people who directly operate the physical system, people who indirectly control, supervise and analyse the physical system through the cyber system, and people who design, plan, make decisions, experience, use and evaluate the whole system. Bousdekis et al. (2020) proposed the framework of HCPS on the basis of industry 4.0, which constructs the digital twin model of human, physical entities and how they interact in the information world.

With the development of cloud computing, big data and machine learning, the new generation of artificial intelligence is changing this traditional philosophical paradigm. In quite a number of fields, artificial intelligence has been able to promote the independent development and evolution of CPS, and the emerging characteristics have already taken on some characteristics of the human world. Zhou et al. (2019) combed the process of information system from assisting human to being able to learn, recognize and make decisions independently from the perspective of intelligent manufacturing. The new generation of artificial intelligence makes CPS have the ability to evolve independently of human beings.

Currently, artificial intelligence cannot completely replace human intelligence, and human beings are still the leading factor in the development of the material world. However, in the interaction with the material world, human intelligence will be more and more influenced by the cyber system. The binary system composed of human (consciousness) and physics (matter) is developing into a ternary system in which human (consciousness), artificial intelligence (cyber) and physics (matter) interact, which will lead to a series of new problems in system cognition, control, decision-making and optimization. How to analyse, design and run such a system needs the support of architecture, methodology, system modelling and system evaluation.

On the basis of summarizing the industrial technology revolution, information technology revolution and management reform, this paper constructs the architecture of CPSS by combing the relevant research results of complex system architecture and analysing the meta model and conceptual model. On the basis of the architecture framework, this paper puts forward the main concerns for each dimension, and describes the relationship between these concerns, which provides a method for the analysis and design of CPSS.

2 CPSS AND ITS META MODEL

There are studies about meta model of CPSS to show what is it made of. Yilma et al. (2019) added social components on the basis of CPS meta model from Lezoche and Panetto (2018) to form CSS and CPSS to propose the first CPSS meta model. On this basis, Abera et al. (2020) added the relationship between social component and physical component to form the Physical-Social System, and showed that the CPSS system is composed of CPSS space and CPSS objects. He et al. (2021) proposed a meta model of cyber, physical and human, including events, entities and services, which determines the interaction scenarios of cyber, physical and human through events, and realizes the interaction among the three elements through services.

Based on the previous works, we proposed another meta model of CPSS, which focuses on relationships between systems, as shown in Figure 2.

CPSS has three basic units/subsystems:

- Social system is a network of relationships formed by people based on their subjective consciousness. Because people have the intelligence ability of perception, cognition and decision-making, they can act on their will to recognize and transform the physical world. A social system can be made of social subsystems.
- Physical system usually refers to the physical world corresponding to human society, which can be perceived, recognized and transformed by people. The physical system is usually related to the material world, and will be counteracted by human's activities. a physical system can be made of physical subsystems.
- With the development of automation technology and artificial intelligence technology, human beings gradually endow their perception, cognition, control and decision-making abilities to physical systems, and then cyber systems become independent systems. With the development of information technology, cyber systems have more and more abilities of perception, cognition and decision-making, which can act and react with the physical world independently, and realize self-evolution and self-growth without human participation in this process. With the development of artificial intelligence technology, the independence of cyber system becomes

more and more obvious. A cyber system can be made of cyber subsystems.

Physical system, social system and cyber system interact with each other, resulting in three binary systems:

- Human-machine system is an interactive system produced by the interaction of social system and physical system. It embodies the concept of the original dualistic philosophy of material consciousness. Human-machine system is a subject in the field of traditional industrial engineering. Human factor engineering is one of the important branches, which supports the development of industrial mode of mass production in the era of traditional mechanization. In smart manufacturing, the system that integrates the functions of an operator (or a group of operators) and a machine (or a group of machines) is usually called man-machine system. This term can also be used to emphasize the dynamic evolutionary system formed by the interaction and reaction between people and the external world.
- Cyber-physical system is a complex engineering system, which connects the cyber space with the physical world through a network of interconnected computing elements such as sensors, actuators and computing processing units. These systems are highly automated, intelligent and collaborative. CPS is the core concept of German industry 4.0 and a result of the interconnection of everything formed by the development of the Internet of things. According to Lee et al. (2015), CPS implementation is divided into 5 levels: Smart Connection Level, Data-to-Information Conversion Level, Cyber Level, Cognition Level and Configuration level, and each level defines relevant characteristics and attributes.
- Cyber-social system is usually considered as a social network that connects people through the Internet. With the higher and higher intelligence level of cyber system, the relationship between human and cyber system is evolving rapidly. The development of artificial intelligence has brought new problems and challenges in the interaction between human intelligence and artificial intelligence.

Although many scholars have begun to study the relevant architecture, model and technical issues of CPSS, there is little research on the positioning and complex interrelationship of cyber, physical and human, especially the evolution of the system caused by the interrelationship. There are still a lot of

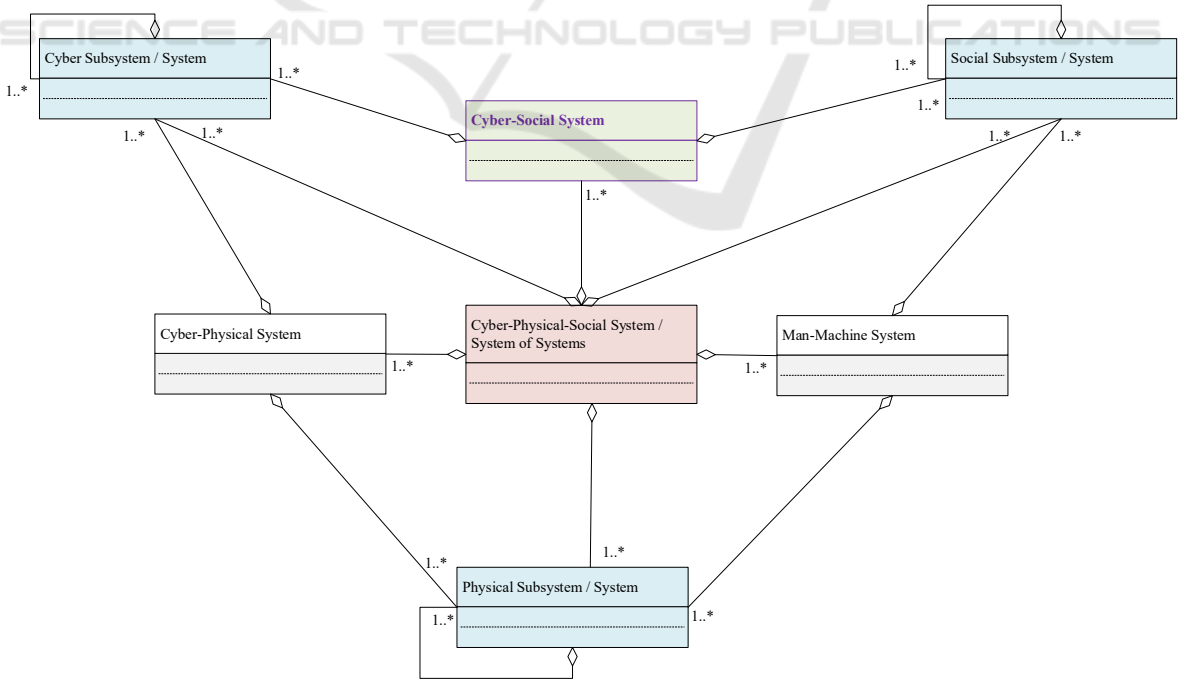

Figure 2: Meta model of Cyber-Physical-Social System.

theoretical and technical problems in the interaction between human intelligence and artificial intelligence. For example, after AlphaGo defeated Lee SeDol, it is unclear what role artificial intelligence plays in improving human Go Game skills; in automatic driving, there are still a lot of ethical and technical problems in the relationship between people's driving willingness and automatic driving algorithm.

The CPSS, which is composed of man-machine system, CPS and CSS, presents some new characteristics and new theoretical and technical problems:

- It leads to the change of the theoretical framework of philosophy and the transformation from the dualistic philosophy of material consciousness to the ternary philosophy of material, consciousness and cyber. And the cyber system has the ability to act and react independently with the material world.
- The balance of the relationship between human and the cyber system is deflecting, and people's dominant position is weakening. In many scenarios, for most people, they are passively accepting the command and scheduling of the intelligent system. Human society has gradually formed a situation that a small number of professionals research and develop artificial intelligence algorithms, while most people are served and dominated by artificial intelligence.
- As cyber plays an increasingly independent role in decision-making, there is no complete solution to determine its legal status. For example, there is no consensus on the legal status of auto drive system in traffic accidents
- Since there are still a lot of ambiguous relationships in CPSS, it is a challenge for the theory and method of system engineering to ensure the completeness and safety of system design during the design of CPSS.

In order to fully understand the main characteristics of CPSS and provide a framework and tools for the analysis and design of CPSS, it is necessary to build the architecture framework of CPSS.

3 CPSS ARCHITECTURE FRAMEWORK CONSTRUCTION

ISO/IEC/IEEE 42010 (2011) reveals the basic logic of building a complex system architecture description This paper builds the architecture framework of CPSS based on the basic idea of the standard, and the conceptual model is shown in Figure 3.

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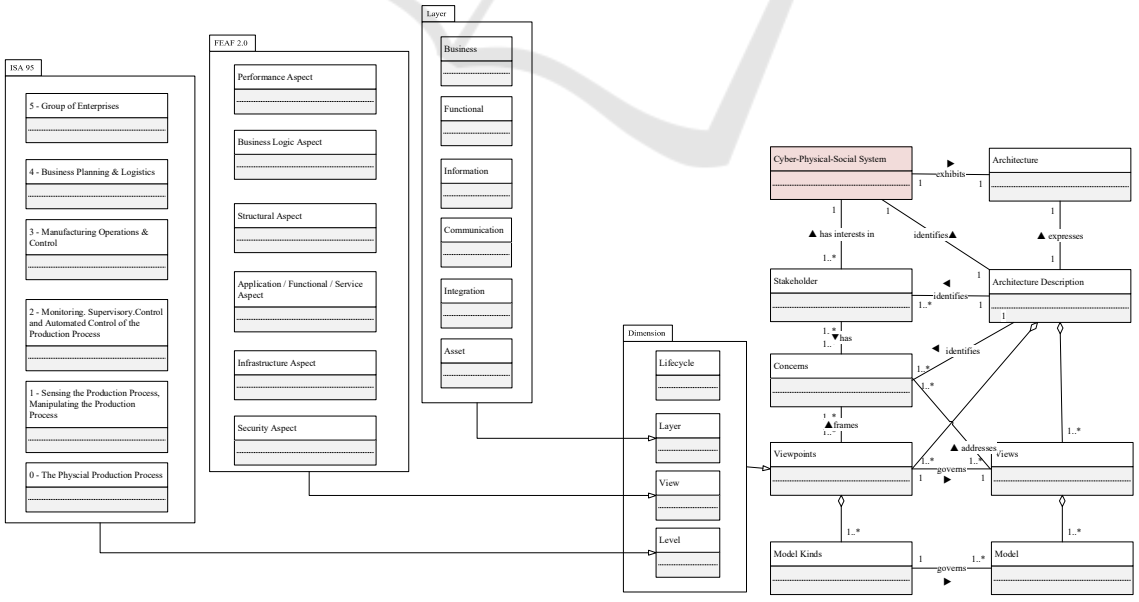

Figure 3: Concept model of CPSS architecture.

As shown in Figure 3, the right part is from ISO 42010, which reflects the construction logic of the architecture framework description. The architecture object is specified to CPSS. The construction of CPSS architecture is to start from the stakeholders related to CPSS. By analysing their concerns about CPSS, form the viewpoints and views of CPSS, and then build the description of CPSS architecture framework.

For a typical CPSS such as an intelligent manufacturing system, based on Reference Architecture Model for Industrial 4.0 (RAMI 4.0) (Hankel et al. 2015) and Industrial Internet Reference Architecture (IIRA) (Lin et al. 2015), the main viewpoints include layer, view, level and lifecycle.

Layers defined in RAMI 4.0 include business, functional, information, communication, integration, and asset. Based on the definition of ISA95 / ISO 62264 (ANSI/ISA-95, 2000), the level of enterprise and control system integration design includes 0-4 levels. In order to describe the systematic characteristics of the systems presented by enterprise groups and networked enterprises, we have added a fifth level. In addition, based on the idea of Federal Enterprise Architecture Framework (FEAF) 2.0 (OMB, 2013), the modelling analysis and model construction of CPSS can be based on the derived structure from performance, business, structure, application, infrastructure to security.

For integrated manufacturing systems, some architectural frameworks have long focused on the ternary relationship between people, machines / facilities and information. For example, Purdue enterprise reference architecture (PERA) (Williams, 1998) includes information architecture, manufacturing architecture as well as human and organizational architecture. As shown in the upper left of Figure 4, these three systems can be extended to correspond to cyber, physical, and social systems respectively. The idea of PERA is that every time the system changes from the current situation to the target, it needs to change the physical system, information system and organizational structure. As shown in the left middle of Figure 4, the manufacturing system supported by IMPACS (Integrated Manufacturing Planning and Control System) (Banerjee, 1997) is also composed of information technology, manufacturing technology and organization description.

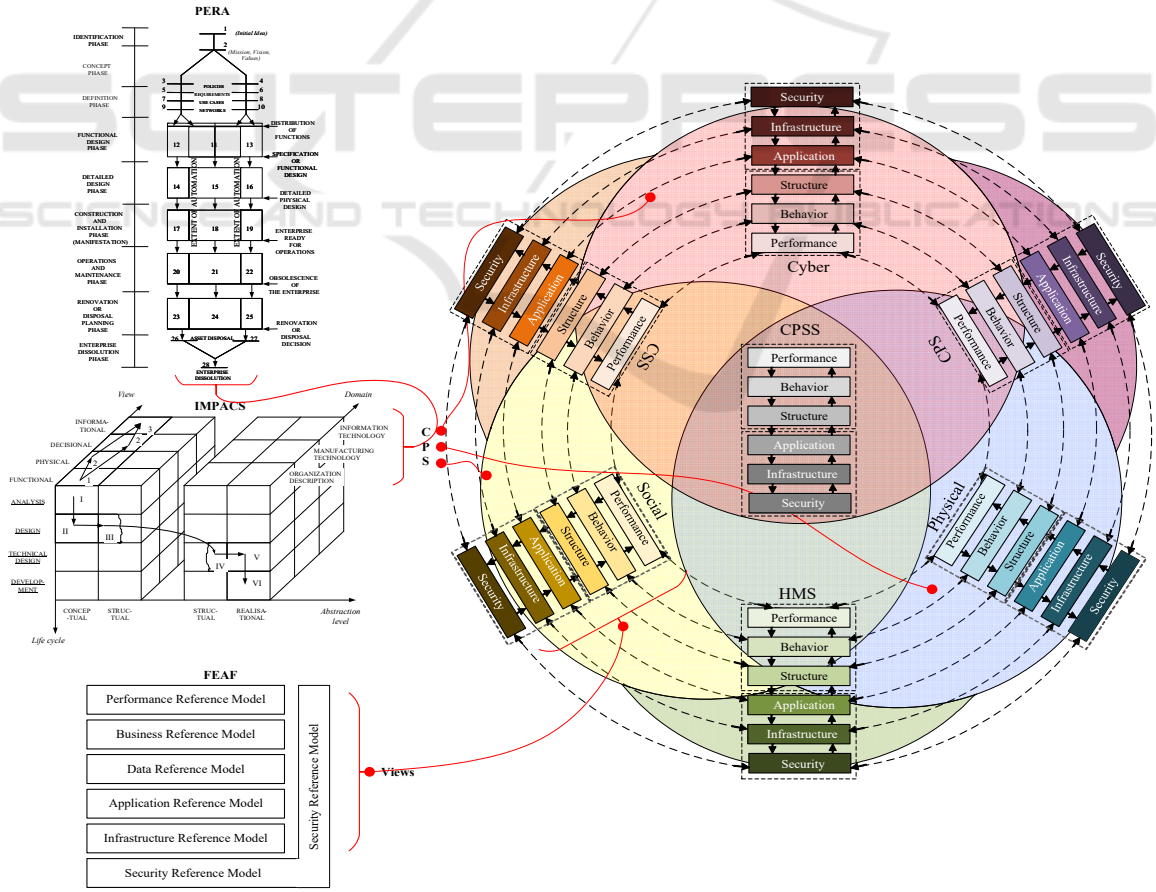

Figure 4: CPSS architecture framework.

As shown in the lower left of Figure 4, FEAF 2.0 constructs the hierarchical structure of system design and implementation. Performance, business and data constitute the business architecture of the system design: the strategic objectives stipulate the business logic, and the business logic exports the required data structure. Application, infrastructure and security constitute the technical architecture of the system. Because security needs to be considered at all levels and stages, application and infrastructure constitute the core of the technical architecture of the system.

Based on the above analysis, the architecture framework of CPSS is shown on the right side of Figure 4. The description of the architecture framework is similar to a Venn diagram, which highlights the new interactive system formed after the interaction of cyber system, physical system and social system. This idea comes from the meta model, PERA and IMPACS. Based on the changes of business system and technical system caused by the interaction of these systems, the CPSS system is analysed and designed. Different views in one system have relationships of dependence. And the same view in different systems are corresponding.

Following, we will analyse the concepts and logic of CPSS architecture from the perspective of system modelling:

- Performance view: Performance requirements are the basis for the construction of the whole system. Requirements come from many aspects, including laws and regulations, standards and specifications, strategic objectives, and the goals and needs of stakeholders such as customers. After decomposition, the performance requirements of CPSS can be divided into two parts: one is the professional ability of individuals, and the other is the ability of individuals to cooperate with other individuals. In the social system, as an independent individual, the performance requirements are reflected in people's knowledge, skills, physical strength and other abilities, as well as the ability to exchange information, make joint decisions and cooperate with others. However, the social system has a hierarchical structure, and many people form an organization. At this time, the performance requirements among people have become the performance requirements within the organization, and the communication and cooperation between organizations have new performance requirements. This is also the same in other systems. It should be noted that the communication and cooperation capabilities between people and physical objects, physical objects and cyber objects, people and objects, need to be considered in the composite system, such as the ability of people to understand and use machines and software, the ability of machines to understand and execute the instructions issued by people and information systems, and the ability of information systems to monitor and analyse the activities of people and machines. In each subsystem, the performance requirements of the top-level subsystems can be obtained through continuous decomposition. The performance of the subsystem depends not only on the performance of each individual, but also on the way of cooperation between individuals, that is, workflow and organizational structure. Therefore, the performance model also puts forward performance requirements for business logic and organizational structure.
- Behaviour View：The behaviour view builds a series of activity processes to meet the requirements of the performance view in design. The behaviour view can be classified into different layers. For each activity process, some measurement indicators are proposed to judge whether it meets the performance requirements. In addition to defining the whole activity process from triggering, running to ending, the behaviour layer also needs to define the roles and components that undertake some activities and functions in the activity process, and define the performance requirements of these roles and components, and then feed back to the performance model. Because different organizational departments, different kinds of physical components and information components may be involved in the whole activity process, in order to improve the performance of the process and meet the performance requirements, it is often necessary to put forward certain requirements for the structural relationship between people and organizations, the location relationship of physical components in the physical environment, and the data flow relationship between information components.
- Structure View：The structure view builds the personnel organization structure, physical structure and cyber structure to support the mechanism embodied in the behaviour view. Excellent personnel organization structure needs to ensure clear division of functions, responsibilities and authorities of personnel organization, full play of individual abilities and

efficient communication and cooperation of personnel organization. The placement, splicing and assembly of physical components in the physical environment should meet the constraints of the actual spatial structure and the business logic timing relationship requirements of the behaviour layer. The network structure should facilitate the information exchange between personnel and physical components, and the data structure should make the data storage cost low and easy to query.

- Application view: The application view focuses on the implementation of system activities. The application view aims at the behaviour view of the system, describes the specific technical implementation and participants of the activity process, and describes the dynamic structure of physical components, information components and personnel organization in the process. In the physical, cyber and social world, application views are often embodied as production systems and products, software application services, business process and workflow management systems.
- Infrastructure view: The infrastructure view focuses on the basic support of the system. The infrastructure view aims at the performance view, behaviour view, structure view and application view, and builds the basic support service capability model of the system to meet the performance requirements, behaviour operation requirements, resource and function structure requirements and application construction requirements. Infrastructure is often embodied in the physical, cyber and social world as energy system, transportation system, communication network, data resources, and human resources.
- Security view: Security is the core concern of CPSS. Security view is closely related to performance, behaviour, structure, application and infrastructure. According to the principles of FEAF 2.0, the modelling and analysis of security view has become a key field of system design.

By transforming Figure 4, we get the description of CPSS architecture framework as shown in Figure 5. Different from Figure 4, figure 5 highlights two new fields of CPSS, cyber–social system and cyber–physical–social system, which meet new theoretical and technical problems. On the other hand, it also points out other dimensions in the architecture: layer, level and lifecycle.

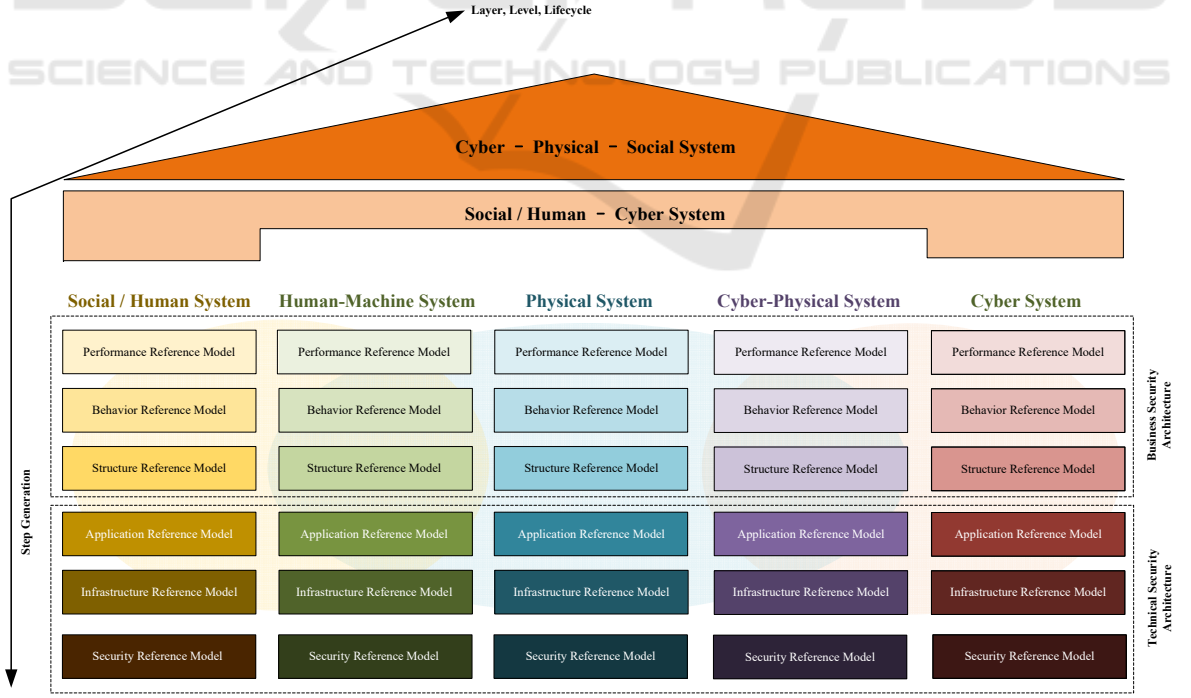

Figure 5: CPSS architecture framework description.

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4 STRUCTURAL APPROACH OF CPSS ANALYSIS AND DESIGN

In the previous section, we discussed the contents of the 6-tier views in CPSS architecture, and in this section, we discussed the specific contents that should be concerned about each subsystem involved, as shown in Figure 6. Here we discuss physical system, cyber system and social system, as well as cyber-physical system and cyber-social system, rather than man-machine system, because the relationship between social system and physical system, that is, the relationship between people and machines, has been studied for a long time, and will not be repeated in this paper. In addition, the integration of physical system and cyber system has become a trend in many scenarios, we cannot regard the interaction between human and physical system as the relationship between them, but the relationship between human and CPS.

We discuss the relationship between different systems in the order of levels:

- Performance view: In physical system, we generally hope that the system can handle a large number of physical entities and improve the operation speed and accuracy. The improvement of performance depends on the emergence and application of new materials, new energy, new equipment and new technology. In cyber system, the improvement of perception ability promotes the improvement of system autonomy, automation and decision-making ability. Because of the emergence of embedded devices such as sensors, physical system and cyber system can be combined to form intelligent CPS units and overall intelligent systems. Intelligent CPS also promotes the improvement of physical system performance. In the social system, people often pursue safety, wealth, freedom and achievement. In the interaction between people and cyber system, because of the improvement of the decision-making ability of cyber system, people and cyber system make decisions together to realize human-cyber collaboration.
- Behaviour view: The system supports the realization of performance through certain activity processes. The physical system completes its own tasks through a certain operation mode and process, and supports the data analysis, cognitive learning and decision-making control in the cyber system through the signal acquisition of the physical system. The decision-making results are transmitted to the physical activities through CPS. Social systems realize their goals and aspirations through a series of activities such as perception, decision-making and execution. Human decision-making and cybernetic system decision-making together constitute human-cyber collaboration. Human-cyber collaboration requires mutual understanding between human and cyber about behaviour and intentions and a resolution mechanism when decisions conflict.
- Structure view: Structure is the organization form of resources or functional components required by system activities. In physical systems, the operation of system activities requires the consumption of energy and materials, the support of functional facilities and other infrastructure, and will produce products. In cyber system, the analysis and storage of data need the support of physical resources of information technology infrastructure, corresponding big data analysis technology and algorithm model. Information infrastructure and physical equipment together constitute the intelligent unit and system component of CPS. In the social system, groups realize the distribution of tasks and functions of each person through a certain organizational structure, and there are economic, political, cultural and other social relations between people. Personnel interact with cyber system through human-computer interfaces such as brain-computer interface.
- Application view: Application is the integrated implementation of system activities. Mechanical, electronic and energy functional components together form a physical system to realize physical activities. In cyber system, intelligent algorithm is based on model knowledge and machine learning, which is the realization of data analysis and cognitive learning process. Intelligent units are combined with physical components to obtain intelligent applications, and intelligent algorithms integrate all intelligent units to obtain intelligent systems. In social system, people realize the arrangement of business activities through process management. The combination of human-computer interaction components and algorithms provides functional components for the combination of human activities and cyber activities.
- Infrastructure view: Infrastructures are the basic support for application running and the realization of system structure. In the physical world, the system platform is the location of physical system deployment, and the physical prototype is the realization of structural design. Big data, cloud computing and the Internet of things together constitute the industrial Internet.

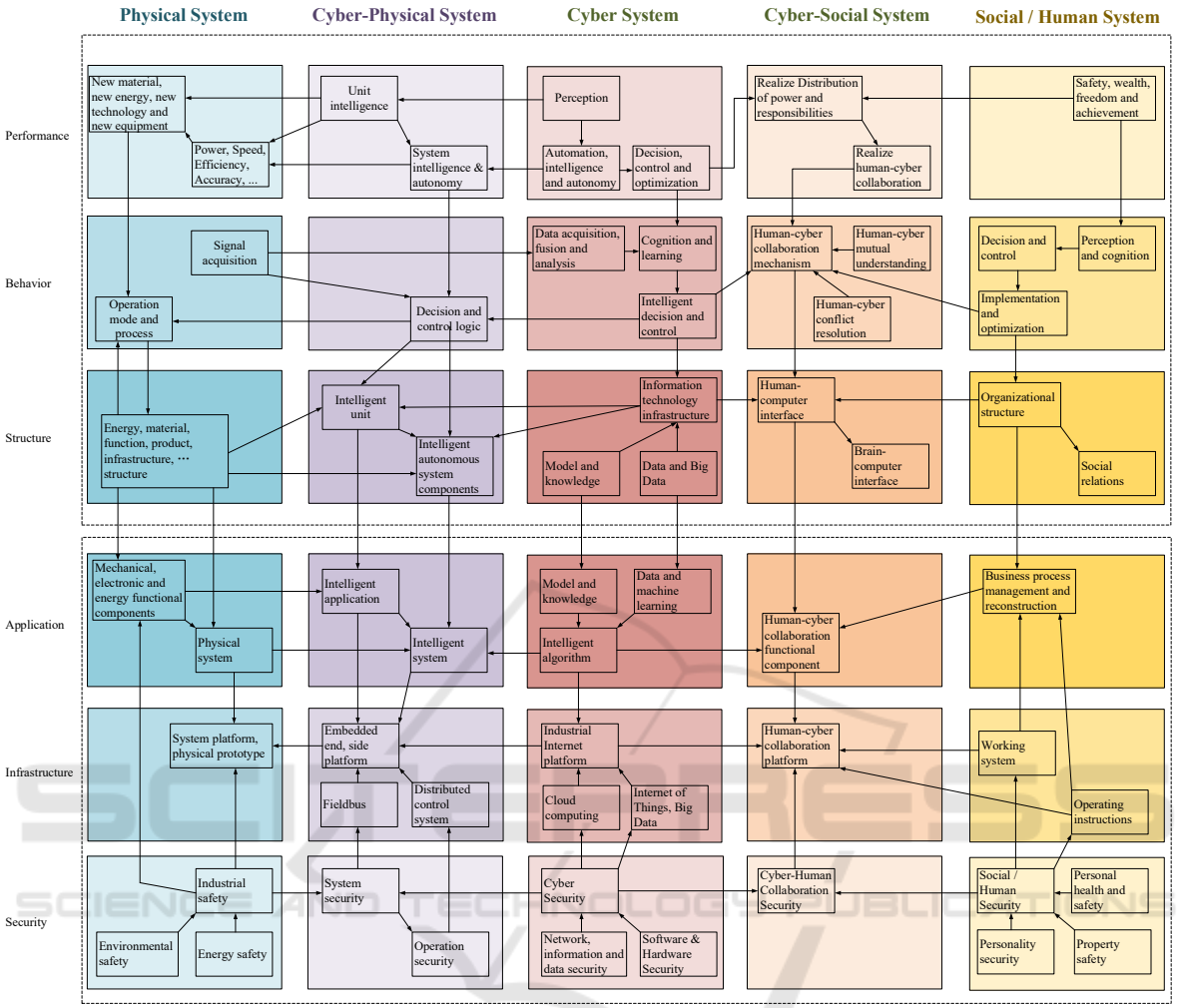

Figure 6: CPSS analysis and design.

It is a platform for algorithm model to learn and deploy. It is combined with the physical platform through embedded devices, fieldbus and distributed control systems. It is also organically combined with the working system and operating specifications of social systems through the human-computer collaboration platform.

- Security view: Security concerns the security factors at all levels of the system. Industrial safety includes energy safety and environmental safety, mainly focusing on the normal operation of system components. Cyber system mainly focuses on the security of data, network, software and hardware applications. System security and operation security focus on the control of cyber system over physical system. The social system mainly focuses on human life, health, property and personality. There are security problems in the cooperation between people and cyber about decision conflicts.

5 CONCLUSIONS

This paper studies the cyber-physical-social system developed with the new generation of artificial intelligence technology, constructs its reference architecture framework, and on this basis, puts forward the structured process of CPSS analysis and design.

As artificial intelligence increasingly presents the characteristics of self-learning, self-growth and self-evolution, and has the ability to explore, recognize and transform the material world independently, the ternary system composed of human, cyber system and physical system presents

new characteristics. Based on ISO 42010, this paper constructs the reference architecture of CPSS and clarifies the internal logic of ternary blending. The cooperation between human and cyber system will be the focus of future research, which will be related to the development of artificial intelligence technology and the mode of its role in production and life.

On the basis of CPSS architecture, it is necessary to build a structured process to clarify the methodology of analysis and design of CPSS ternary fusion system. This paper focuses on the impact of the introduction of intelligent technology into industrial systems on people and manufacturing, and constructs the analysis process and important concerns.

With the development of intelligent technologies such as autonomous driving, the architecture, methodology, modeling and analysis methods, security system construction and other technologies of CPSS need to be further developed in engineering practice.

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