Cyber-Physical-Social Systems: The State of the Art and Perspectives

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***Abstract*— This paper is to discuss the state, trend, and frontiers of development of cyber-physical-social systems (CPSSs) in China. The demand for developing CPSS is discussed in detail, followed by the Artificial societies, Computational experiments, Parallel execution (ACP) approach for CPSS and knowledge automation. The development of ACP based on CPSS in transportation, energy, information, Internet of Things, and Internet of Minds (IoM) is discussed to demonstrate the cutting-edge applications in CPSS. Finally, the blockchainized IoM technology and the concepts of parallel society are described. This paper will contribute to the transition from the current social construct to a futuristic intelligent society.**

***Index Terms*— Artificial societies, Computational experiments, Parallel execution (ACP), blockchain, cyber-physical-social system (CPSS), Internet of Minds (IoM), parallel systems, social computing.**

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I. Cyber-Physical Social Systems

The concepts of cyber-physical-social system (CPSS) was first coined in 2010 [1]. It integrates cyber space, physical space, and social space. CPSS emphasizes in-depth interaction among the physical world, cyber world, and social world. CPSS integrates social system and physical system by intelligent human–machine interaction in cyber-space, achieving management and control of such sociotechnical complex systems [2], [3].

II. Current State of the Art of CPSS

In the 1990s, the concepts of Open Complex Giant System and Integrated Integration Workshop were developed by the Chinese scientists and presented by Xuesen *et al.* [4]. These concepts were used for complex information processing and decision support. Based on these methods, the Artificial Societies, Computational Experiments, Parallel Execution (ACP) approach was invented at the Institute of Automation, Chinese Academy of Sciences, for management and control of complex systems [5]. By building a closed-loop feedback system of the physical complex system under investigation and its corresponding artificial systems, one can compute and test events that have occurred and are possibly going to occur in a software-defined "laboratory." In this way, the ACP approach provides the computational decision and verification support for the management and the control of the dual physical–artificial complex system.

Building the parallel systems relies on knowledge automation technology. Reference [6] provides the perspective that CPSS will result in a paradigm shift of intelligent systems and human societies into the parallel intelligent era. In the new intelligent era, the cyber space, physical space, and social space will be integrated seamlessly, and the knowledge automation is the technical foundation. The key technology of knowledge automation is to integrate the knowledge representations and machine learning techniques [7], [8]. Knowledge representations describe knowledge and transform it to a qualitative description and data structures. As an example, Li and Lin [9] proposed a new theoretical framework for machine learning named the Parallel Learning that is an effective system design to mine relevant information from the big data using knowledge from software-defined artificial systems.

A. CPSS in Energy

The concept of energy 5.0 was introduced in 2015, which is a parallel energy system that integrates social and energy systems [10]. In this paper, human and social factors are explicitly incorporated into energy systems to form a CPSS in energy. In this CPSS, the artificial energy system interacts with the physical system that guides the operation the campus energy system. In 2017, Xue and Yu [11] envisioned that the future of energy systems must be a fusion of cyber, physical, and social systems with considerations of environmental, social, and human impacts.

B. CPSS in Power Grid

De-Sheng and Fei [12] proposed to build a parallel power grid based on CPSS and ACP approach, where a physical power grid interacts with its corresponding artificial power grid. L. Cheng and T. Yu [8] proposed the construction of a smart energy dispatching robot based on CPSS, which creates a parallel system to mimic a realistic one for power dispatch.

C. CPSS in Smart Vehicles

Currently, the smart vehicle industry has attracted much attention from the industrial and the academic communities. The concept of "parallel smart vehicles" based on CPSS is proposed to remedy unsettling safety issues in autonomous driving [13]. By building a virtual artificial system for a real-physical road system to help guide the actual vehicles to pass through safely and efficiently.

D. CPSS in Management

Reference [14] proposed a parallel enterprise management system with its framework and applications. The authors also demonstrated that the parallel system can effectively improve the system security, reliability, and management efficiency in practice.

E. CPSS in Military Operation

Reference [15] proposed an idea of constructing a parallel command and control's system using CPSS. Liu *et al.* [16] have also proposed a command and control system in military operations using the CPSS and self-synchronization mechanism.

F. CPSS in Intelligent Transportation

Intelligent transportation transforms the passive and rigid traffic systems to active, intelligent, and adaptive ones. Currently, China is taking the lead of applying CPSS with social factors incorporated into the traffic system. In 2008, Wang [17] proposed the ACP method for establishing intelligent transportation systems. Guo *et al.* [18] analyzed the transportation big data in the context of CPSS-based intelligent transportation systems. Xiong *et al.* [19] constructed a CPSS-based intelligent transportation system with a proposed iterative search algorithm based on relevant rules to mine traffic information from social media data for traffic monitoring. Furthermore, the collection, cleaning, and fusion technologies of various types of big data with different granularities and precisions in social traffic were also discussed. He also developed a way to extract real-time traffic information from natural language voice and text. Hence, using social data, CPSS can predict traffic congestion and uncover causes to provide commuters with the shortest and the fastest traffic routes. Traffic CPSSs are becoming the frontier area in intelligent transportation systems.

G. CPSS in Antiterrorism

To response to antiterrorism situations, Wei *et al.* [20] designed an antiterrorism early warning system based on CPSSs, which includes antiterrorism database, critical situation detection, and an intelligent early warning system, in the social, cyber, and physical spaces.

H. CPSS in Intelligent Manufacturing

Recently, the mass-customized production model begins to prevail to meet the demand from a large number of customers, each with individual needs. Lei and Ming-Lun [21] built a CPSS system to connect different manufacturing resources within an enterprise for effective manufacturing. Cun-Ji *et al.* [22] proposed an idea that the manufacturing equipment and model can be upgraded to the "smart generation" by deploying smart manufacturing in the context of CPSS. Xi-Fan *et al.* [23] propose a big data-driven, active manufacturing. Jiu-Sheng *et al.* [24] proposed an idea for Zhejiang "smart manufacturing" one-stop platform based on blockchain.

I. CPSS in Smart Cities

Cassandras [25] introduced the idea of building a smart city based on CPSS, where intelligent transportation, smart energy, smart healthcare, environmental monitoring, and various social activities are integrated, to transform a traditional city into a smart system. Nowadays, more than 500 cities in China, including Fuqing [26], Shenzhen [27], and Xiong'an [28], have proposed and/or begun to construct their own smart city projects.

J. CPSS and Social Computing

The advance of information and communication technology (ICT) drastically increases the complexity of social, economic, and engineering systems. In 2005, the Chinese Academy of Sciences started the research in the area of social computing [29], [30]. Social computing is an interdisciplinary subject consisting of artificial intelligence (AI), computational, managerial, and social sciences [31]. In 2007, the ACP approach for social computing was proposed [32], [33]. It is believed that social computing based on ACP can study unconventional security issues in a virtual society environment [34]. Yong-He *et al.* [35] studied the e-learning model in a social computing environment. Wang *et al.* [36] proposed an approach to seamlessly integrate social computing and social manufacturing.

K. CPSS in Architecture

In the development of CPSS architecture, Wang *et al.* [37] proposed a tensor-based cloud computing framework, and Guo *et al.* [38] proposed a data-centric CPSS framework. Although there are some *ad hoc* research works on CPSS architecture, a unified model does not exist.

III. Recent Development of CPSS in the "Five-Grids-in-One" Research

Human has been building "grids" around Karl Popper's three worlds, which are the transportation grid, the energy grid, the information grid, the Internet of Things (IoT), and the fifth grid, the Internet of Minds (IoM) [39]. CPSS plays an essential role in establishing the "Five-Grid-in-One" theory to accelerate the integration of the five grids.

A. Transportation Grid

In recent years, with a rapid development and an increase in popularities for IoT, cloud computing, social media, and mobile communication technology, the global data show an explosive growth trend, and the modern society is facing a subversive data revolution. Intelligent transportation is an important application of the big data. The growth in popularity for Internet, social media, the deep coupling, and the strong feedback with the physical could change the application of environment and management decision-making model for intelligent transportation.

In the sharing economy, Uber and DiDi have shown that the modern urban traffic management and control are no longer limited to the statistical analysis and mining of a single field. This area has been extended to a comprehensive analysis, evaluation, and decision support in the social physical information system (CPSS) based on deeper and cross-domain analyses of the physical, network, and social spaces. In 2017, the Ministry of Transportation, China, issued an action plan to promote the developments of intelligent transportation systems (2017–2020). This plan explicitly calls for an acceleration in the integrated innovation and application of modern information technology that includes cloud computing, large data, and so on to improve digitalization, networking, and intellectualization of transportation systems. Big data provides a new driving force for developing an intelligent transportation system. Social media network is becoming increasingly important as an emerging source of traffic information. The traffic information contained in social media can be supplemented and cross-validated with the traffic information collected from the physical world to enrich the content of traffic information acquisition. Zheng *et al.* [40] analyzed the research framework, method, and direction of social transportation based on big data. Cao *et al.* [41] used websites and the social media to extract the public traffic opinions. Wang *et al.* [42] summarized the current research status and proposed crowdsourcing in intelligent transportation systems for the future. Lv *et al.* [43] used deep learning to study the problem of traffic flow prediction in large-scale road network and verified that the deep learning prediction method is better than the traditional methods.

Due to the reliabilities of detectors and data transmission, the collected data can be partially corrupted. Duan *et al.* proposed a traffic flow data compensation method based on the automatic encoder for noise reduction to optimize the implementation mechanism, the associated empirical results showed its efficacy of mitigating the problem of mass traffic data [44]. Since the transportation systems are too complicated and experiments are too difficult to carry out in an urban environment, Wang [45] introduced the theory of parallel transportation management and control systems. By building an interactive-and-evolutionary parallel system between the actual traffic system and the artificial traffic system, a closed loop of intelligent processing, which includes traffic information collection, fusion, and analysis, traffic scene modeling prediction, and control measure feedbacks, can be implemented, and the traffic management can be promote to a new level of intelligence (shown in Fig. 1).

With the developments of sensing, computing, and networking technologies, social media and mobile devices have recently experienced a rapid growth, generating a huge volume of social signal in nearly real time. In this era, the physical world and the virtual cyber space are deeply coupled and interactive. It is becoming a new norm in the modern operations of social organizations. Hence, it makes it difficult to manage complex social systems. The key to further improving the traffic CPSS is to build the virtual and soft parts of the intelligent system to make it quantized, computable, and real time. Using a closed-loop feedback that is made of a virtual and an actual system, they can merge to achieve a desired goal. Thus, realizing the test and the computing of past, current, and future events in the software-defined laboratory provides reliable supports for the management and decision-making process of a real traffic scenario. The development includes the following.

1) Data acquisition and sensing technology using single source is extended to environment awareness technology using multisource data fusion. A large quantity of sensors and data acquisition technologies has been deployed in the urban traffic environment, but a big gap between the real applications and the corresponding ideal states still exist. The emerging application of CPSS in transportation demands better accuracy and timeliness on the collected data. To make full use of the existing acquisition equipment, it is important to realize the complementary advantages of various collection of equipment and build an awareness system from multisensor data fusion.
2) The foundation of a new generation of transportation CPSS-control technology is to combine the physical reality and the virtual world. Network public opinion has become an important factor affecting individual traffic behavior. Simulation and virtual reality technology have played an important role in formulating management schemes, and virtual currency has been applied in the payment of intelligent traffic transaction and has shown great potentials. They represent the basic elements of an urban transportation system. In turn, they provide new opportunities and challenges for a new generation of traffic CPSS control technology.

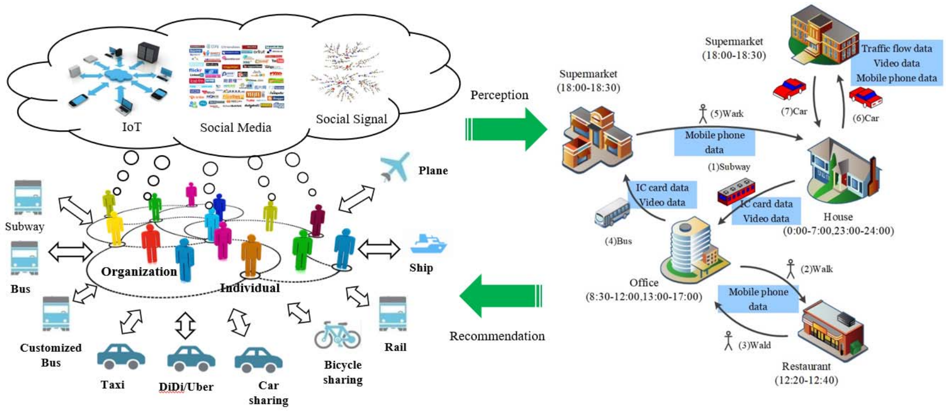

Fig. 1. Parallel transportation system based on CPSS.

3) Deep learning, knowledge discovery, AI, and other technologies will be widely used in transportation CPSS. More work will be replaced by computers, especially the CPSS knowledge automation being the core of knowledge acquisition, analysis, and learning, will likely become a new industry.

B. Energy Grid

The social energy system composes of a physical energy system, a physical social system, and a virtual system derived from the physical system. By using various sources of data, knowledge automation of a system can be achieved through sufficient interaction and a large scale of computation. Intelligence can be generated to control and manage a system. By applying knowledge and intelligence to a social energy system, real automation and intelligence of design and management of a social technology system can be realized. A general approach uses ACP method and parallel system to establish a proposed social energy system. Its features are illustrated in the following

1) Artificial System: For a conventional power system, the design and programming of the control and the management solutions generally consider the mechanism of the energy flow only. The social and informational nature of energy is often ignored. With the emergence of smart energy conversion, transport, and use patterns, energy system needs to embrace intermittent renewable energy by adapting rapid changes while meeting the demands of energy-saving and emission reduction. This requires a thorough understanding of the social information system with complexity and uncertainty of individuals, organizations, and social behaviors. To explore how society affects the energy system and improve design, operation, and maintenance of the social technology system, it is important to combine sociology, management, economics, anthropology, and behavior. Currently, the above-mentioned interaction and co-operation mechanisms have not been developed using the physical, social, and information attributes. Since a traditional power system simulation model only considers a small amount of social information, such as power demands, the described interaction, and co-operation mechanisms, cannot be realized in the conventional power system model. To create intelligence-based decision-making, CPSS of co-operation among the three components of the strategy should be adaptive in real time. Unlike a traditional deterministic or probabilistic simulation model, most variables cannot be predicted, so the system model needs to have a real-time adaptive capability. In the need of innovative theories and technologies, the concept of artificial energy systems based on parallel system is the current approach to social energy. The uncertainty of the CPSS and the complexity of human society generate a more complex system. Hence, the transitions from Newton's law to Merton's law and from control to guide become an urgent area of research.

The virtual artificial energy system will be established in the "network space" based on semantic modeling [46], data driven, or other modeling techniques, this system should run in parallel with the actual physical energy system to exchange feedback. In real time, a simulation system should also be able to reflect the reality of the corresponding physical system. In addition, a simulation system needs to provide optimal solutions to the physical system through parallel computing. Under this premise, it is believed that by introducing virtual artificial system into complex energy control system, it will give rise to a new era in the energy industry.

2) Knowledge Automation Through Interaction and Computation: A social energy system usually contains complex physical and information processes. The complexity of the social energy technology system is more than what an industrial automation can handle. This means that the traditional industrial automation methods, including manual control, single-loop control, multiloop control, distributed control system, manufacturing execution system, and enterprise resource planning, can no longer meet the needs of social energy. An artificial system that is derived from the social system and the energy system could play a central role in processing the big data and information from the energy and social systems. The data and information about a physical system have the characteristics of uncertainties, redundancies, and inconsistencies. Human alone on the other hand is incapable of processing and analyzing the information. Therefore, it is necessary to create a knowledge automation system [7] by adapting data-driven, multiagent system, and other AI systems and technology.

3) Social Technology Feedback Mechanism and Realistic Gamification: Through the interaction among society, technology, and artificial systems, a feedback mechanism can be obtained, either directly or indirectly. We found that any physical–social technology system can interact with multiple virtual human systems, for example, consumer behavior artificial system, organizational behavior artificial system, emergency artificial system, scheduling and optimization artificial system, real-time management artificial system, and so on. Each artificial system corresponds to a different application by generating different feedback responses for modeling and shaping the real physical society and energy systems. It is done through interactive and computational automation knowledge. This feedback can include a direct control of the technology system, indirect manipulation technology of distributed social agents, based on the effects of the social and economic entities, maximum transmission of public information, and even social data from individual behavior. From the philosophical perspective, [47] takes an effective and efficient feedback as a core feature of the game. In a social energy and technology system, a powerful and effective feedback mechanism improves the possibility of real gaming. In this case, the physical system will be shaped more rapidly and guided to a desired result. With a strong feedback mechanism, the social technology systems are expected to have an advanced closed-loop operational capability with stability, rapid systems convergence, and systems adaptive agility.

C. Information Grid

In the age of information mobile networks, the efficient organization and rapid dissemination of digital and bit-oriented information are becoming more and more important. Communications and networks, as the important components for the information industry, they can become tools for advancing technology, module upgrades revolution, and infrastructure support. They play an important role in economic development and industrial advancement. As real-world network systems are becoming more and more complex, so are the engineering or social aspects. The multidomain, dynamic, and unpredictable characteristics of the network system also become larger and more complex. As a result, it is increasingly difficult to predict and make comprehensive and accurate evaluations and corrections to the solution.

Therefore, the concept of parallel networks [48]–[50] is proposed based on the CPSS theory and ACP approach. It combines software-defined networks, network function virtualization, and so on. As a new network architecture, parallel network redefines the real-time information transmission and mutual optimization of the artificial network and the actual network. It redefines the control plane, forwarding plane, and application layer of the network system. Based on the concept of programmable network management software, parallel networks realize the real-time decision-making guidance with behavior optimization using different levels of requirement and service connotations. The purpose of a parallel network is not only independent of the network transmission speed and better mobile broadband experience but also to connect new industries and promote new services. That includes the advancements of autonomous driving, IoT, smart home, industrial automation, and so on.

As a key technology and infrastructure, this new network architecture can drive the developments of other industries and technologies. As information technology gradually penetrates various industries, the demands for enterprises, information management and analysis, data storage and calculation, data security, and transmission rate are increasing. The introductions of cloud computing and big data have accelerated the pace of industrial upgrades and increased the core competitiveness of enterprises. Cloud techniques can be improved in terms of reliability, transmission rate, security and other aspects. Artificial networks and computational experiments of parallel networks could provide evaluation and prediction schemes for easy implementations. The characteristics and advantages of parallel networks not only meet the basic needs of communication networks, services, security, and other aspects but also can drive and promote the developments of new technologies and new functions for industrial production, financial markets, transportation, and other industries.

1) Artificial Networks: Based on the modeling methods of artificial systems in parallel systems, artificial networks still adopts the agent-based modeling methods. The main characteristics of the agents are autonomy, social ability, self-adaptive ability of learning and evolution, mobility, and so on. It can be divided into three parts, that is, agent, agent environment, and social rules. Agent can be various network devices or network users in an artificial network system. Each agent has a unique internal state, behavior rules, thinking modes, and growth processes. These features are changing with time and the external environment. The agent environment is the space to survive and move, either as a reflection of a real network, a social environment, a virtual mathematical, or a computational process. It is generally characterized by the storage of social materials, the development of relevant regulations, standards, and various functional sites for designing human and biological survival and activities, and the networks they built. The choice of these places is determined by the impacts on the network behaviors. The social rules refer to the criteria, such as the steps of the agent, the environment, and agent-to-agent, environment-to-environment, and agent-to-environment. These rules manage simple data transmission and reception protocols, complex large-scale network system-management methods, algorithms to optimize performance, and so on.

For example, in the long-term evolution network, the aspects of network coverage, call setup and hold, mobility management, delay, system resources and others are divided according to the perceptual evaluation and the optimization analysis. All of them are defined by purpose, definition, calculation formula, and statistical granularity. By analyzing the constraint relationship among these indicators, the corresponding parameters and its threshold, tests are designed for different services, such as video, web browsing, and online music. Thus, the thresholds for ensuring user perception are obtained under different services. The corresponding relation table is given by the indicator threshold and the degree of user perceptions. Key indicators and its optimization that have a greater impact on user perceptions can be designed by studying the corresponding relation between the indicator threshold and the degree of user perception, which can be more accurately controlled to provide a powerful data support for a refined maintenance of the actual network system.

2) Computational Experiments: Before an actual network interacts with an artificial network, the artificial network performs calculations of the partial computational experiments using the existing data and parameters. The input parameters and the experimental results are stored in a mapping table. When the actual network needs a real-time guidance, feedback parameters are first determined. The feedback with the input parameters are stored in an artificial network mapped and compared using algorithms, such as the lookup table method to find which input parameter group obtains the highest fitting degree with the feedback parameters. After that, the experimental results are provided to the actual network in order to derive a real-time guidance. Computational experiments are designed based on the parameters of feedback from the actual network. Hence, the set of input parameters and experimental results can be updated in the mapping table. As the experiments become more complete, the real-time guidance for the actual network would become more accurate.

3) Parallel Execution: The model of the artificial network system is continuously improved to approximate the actual network. When an actual network is accurately described by an artificial network, various statistical calculation experiments can be performed on the artificial network to determine the management and control strategies of the actual network system. First, using parallel execution, quality of service is guaranteed for the user terminals in the network with limited bandwidth. When the network traffic is unevenly distributed, and the channel characteristics are fluctuating from channel fading and interference, flexible allocation and dynamic adjustments of the available wireless resources will achieve an optimal utilization of the wireless network. It prevents network congestion and minimizes the signal loading. Furthermore, the actual network system state is amended, and the artificial network state can also be adjusted; thereby, the network resource management is improved in terms of power control, channel allocation, scheduling, handover, access control, load control, end-to-end QoS, adaptive code modulation, and so on, and the optimized network performance is achieved.

4) Parallel Network Applications: With the developments of network communication, self-driving must be highly networked in the future. However, wired transmission is difficult and expensive because of its limiting mobility in self-driving environment. Wireless communication has become a trend. There are different kinds of wireless transmission, for example, infrared, Bluetooth, Wi-Fi, UWB, and Zigbee, which are suitable for short-range transmission. Especially, the transmission speed of UWB can reach to hundreds of Mb/s, but these technologies are only suitable for short-range transmission. The 4G network combined with 3G and WLAN can transmit high-quality video and images with a typical data rate of above 100 Mb/s. The arrival of 5G will improve the real-time performance of image transmission to satisfy the network requirements for self-driving vehicles. A self-driving car can experience obstacles and mechanical malfunctions on the road. If this information can be transmitted in a timely manner and displayed on a monitoring and control terminal, operators can make prompt decisions to avoid possible collisions. With the help of parallel networks, parallel vehicles [51], [52] take full advantage about the network optimization of parallel networks. First, artificial network systems are built in accordance with the actual network systems. Second, using various computational experiments on the artificial network system, dynamic operating state analysis and performance optimization of the actual network are realized (generated). Finally, the optimized operational recommendations are fed back to the actual system to improve system performance, maximizing the capacity efficiency and meeting the user network service requirements [52].

For IoT, based on the CPSS methods, there are some studies on the modulation technology of complex high-speed IoT communications. It is designed to be a novel multicarrier sequence anti-interference modulation scheme for mobile IoT communication to analyze the impact of virtual space on subcarrier interference. The transmission characteristics and performance indicators of IoT access technologies are analyzed and compared from data collection, transmission, and the analysis methods based on typical application scenarios. Finally, considering IoT network architecture, a new ACP-based network architecture and network optimization schemes are designed to enhance the network performance of IoT.

In conclusion, a parallel network combines the concepts of the software-defined network to improve the network flexibility and virtualization. It encapsulates the computing, storage, and switching routing hardware devices in resource pools, which can be flexibly scheduled and used, as it is needed to reduce the network cost.

D. Internet of Things

The concept and the architecture of the Social IoT (SIoT) is coined at the Institute of Automation, Chinese Academy of Sciences, which extends the traditional IoT sensing and actuation of "things," to the inclusion of social perception and prescription, as well as social computing technology. In SIoT, parallel system theory is the methodology and CPSS is a theoretical framework using a new generation of information technology architecture, including cloud computing, edge computing, software-defined networking, and software as a service. The ICT acts as the supporting platform for knowledge automation and social computing technology that implement the functionalities of SIoT. The architecture of SIoT is shown in Fig. 2.

E. Internet of Minds

IoM is a new intelligent-oriented knowledge network for intelligence based on IoT. The most striking feature of IoM is the capability of directly extending human and social intelligence. Currently, management and control of complex systems, especially social complex systems, require certain intelligence that exceeds the capacity of the human minds,

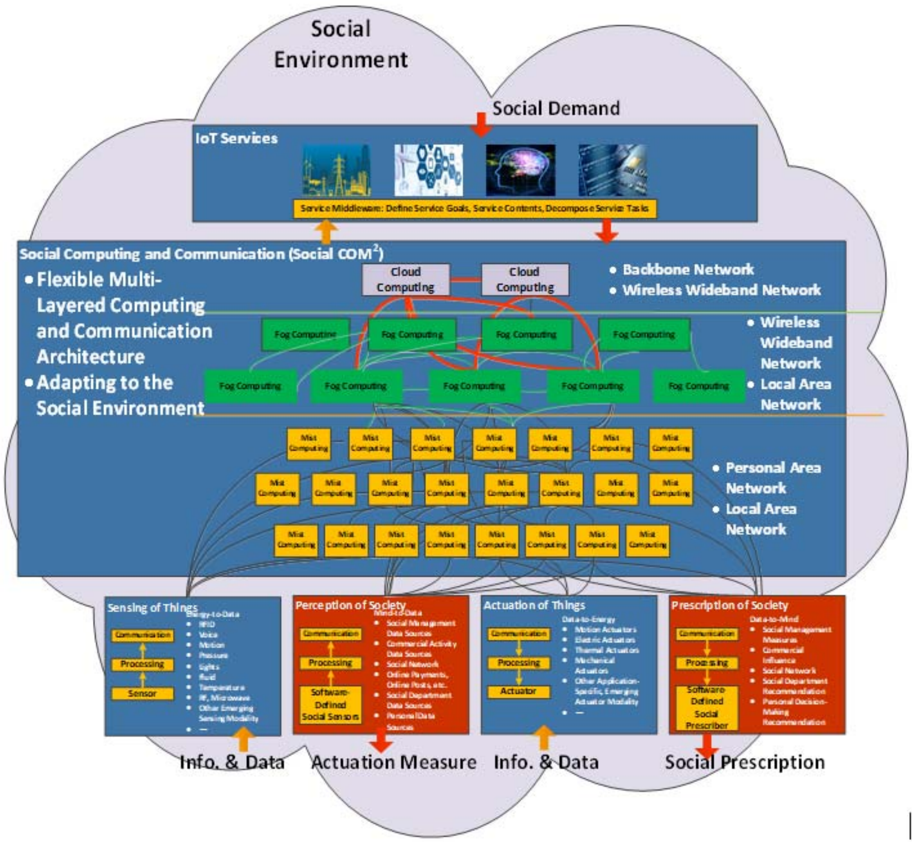

Fig. 2. SIoT.

which leads to the use of machine intelligence with knowledge automation. Currently, there exist many intelligent agents in our society although these agents may be interconnected through data links, they are not directly connected at the knowledge level due to a lack of intelligent connection mechanisms. IoM synergizes various intelligent agents in human society by connecting machine, as well as human, intelligence. Only after the realization of socialized intelligent knowledge interconnection, AI technology can form a true social ecosystem. IoM signifies a leap toward a socialized knowledge connectivity and intelligent integration. This is a leap from an independent and simple knowledge system to a complex connective knowledge system with linkage and integration. As a result, IoM is a critical enabler of CPSS operation.

The core issues that must be solved to establish IoM are the acquisition of knowledge, the representation of knowledge, the transmission of knowledge, the association of knowledge, and the use of knowledge. It should be emphasized that the five core issues are not isolated from each other but are closely linked and mutually related. The acquisition, representation, transmission, association, and utilization of knowledge are both ancient philosophical propositions and frontiers in AI science. The goal of building IoM is to complete the collaborative intelligence of the whole society and, thus, enable intelligent operations in CPSS.

IV. Blockchain in CPSS

Blockchain is a key technical framework for the CPSS-based parallel societies; it provides a solid foundation for both data and trust for the future in parallel societies featuring a combination of human–machine integration and virtual reality. Blockchain can offer a complete, novel, and self-consistent architecture for establishing decentralized autonomous societies and ecosystems in the bottom–up fashion.

The characteristics of blockchain technology can be summarized as "TRUE" (trustable, reliable, usable, efficient, and effective) and "Decentralized and Distributed, Autonomous and Automated, Organized and Ordered." Thanks to these characteristics, blockchain is widely believed to be one of the key components in CPSS-oriented revolution of intelligent industries, for example, the Industries 5.0 versus Industries 4.0. In the CPSS-based smart societies and digital economy, a parallel blockchain based on both blockchain technology and parallel intelligence, has the potential of bridging the gap between the physical world and the cyber-space. This could result in an online-to-offline (O2O) (or offline-to-online) parallel society. The O2O parallel society can be extended into the third social space, taking complex human and social factors into consideration. The resulting CPSS-based parallel blockchain can endow blockchain the capabilities for descriptive, predictive, and prescription intelligences through computational experiments and parallel optimizations between the actual blockchain and the artificial blockchain systems. Online big data can be easily integrated into a blockchain [53], [54]. Furthermore, blockchain can be used together with IoT. The Blockchain of Things can help digitalize physical devices and properties into a blockchain. For instance, one of the key applications for blockchain is intelligent connected devices. This helps monitor the entire lifecycle of physical devices in a secured and trusted environment. It realizes the data transmission, transaction and negotiation among devices, and the automated operations among devices using smart contracts [55], [56].

Blockchain-driven smart contract is also a key technique for the CPSS-based knowledge automation. Smart contract is not limited to the provisions of the physical contract guaranteed by the blockchain. It can be more flexibly predefined as the "IF-THEN" type of scenario-response rules that can further be extended to various unpredefined "WHAT-IF" type of scenario-deduction rules that can be executed automatically. Smart contract is important to study and simplify the complexity in CPSSs. From the perspective of game theoretic analysis, the human-in-the-loop-type social complexity is largely due to the uncertainties in human co-operation and coordination caused by empty threats and contingent actions [57]. Smart contract can be a large extent to help reduce and even eliminate the human-involved social complexities. This simplifies the "Merton" societies as the "Newton" societies and improves the efficacy and efficiency in the social coordination and co-operation [58].

V. Parallel Society

Parallel Society introduces the ACP-based parallel intelligence methods [32], [59], [60] into social management system. It combines technologies, such as multiagent modeling, social computing, virtual reality, machine learning, and social network analysis, using massive social sensors collected from big data. It is to build an artificial social system that reflects the person-role (job)-task-standard relationships in actual societal system by using software-defined objects (SDOs), software-defined relationships, software-defined norms, and so on. The artificial social system that can interact, coevolve, and have a closed-loop feedback with the actual social system becomes a "dynamic and growing laboratory" to implement computational experiments through economic. Any other strategies can be tested and evaluated before the social implementation. Thus, the "decentralized" computing guidance, management, and control for the actual social system can be realized [61].

The perception, modeling, analysis, decision, and feedback execution of actual social processes, cyber movement organizations (CMOs), social services, and resource planning are the cornerstones to realize the innovative social management and scientific control in the parallel societies [62]. The basic approach to build a parallel society system has the following three steps: 1) modeling and representation of an actual social system in order to construct an artificial social system using the bottom–up multiagent modeling methods; 2) computing and experimenting with events that happened in the past to adjust the parallel system behaviors and to quantify the impacts of a set of simple system parameters on a global complex system; and 3) control and managing parallel execution of actual and artificial systems. The ACP approach sufficiently exploits social and online information to quantify social group's wisdom. As a result, it guides, manages, and controls complex social systems via computational leverage. The CMOs oriented parallel social management integrates various social factors, such as people, places, events, objects, and organizations, to comprehensively perceive, model analyze ubiquitous social signals to provide bases for decision-making, and intelligent support for social management in a virtual–actual interactive way.

The idea of using social data to optimize the management and control of complex social processes has existed for a long time. In the 1970s, Chilean President Salvador Allende launched a cybernetic revolution in South America called "Project Cybersyn" [63]. Under the guidance of the British cybernetician, Stafford Beer, a national networking system with sufficient information exchange is constructed through a five-layer recursive structure of a feasible system model. This system transforms national administrative and long-term plans into daily decisions and real-time actions. Essentially, the communication and interaction among system elements are thought to be the means of system management. The system design is shown in Fig. 3. Due to a lack of modern data and computing technologies, it failed to achieve the desired result.

Nowadays, with the occurrence of the Internet and the development of various computing technologies, human beings are moving from the industrial era to the knowledge era and even to the intelligence era. The integration of mobile smart devices, AI, and social networks makes it possible to solve larger scale problems using fragmented information by mobilizing hundreds or thousands of netizens. Many organizations are undergoing dynamic changes under an open environment of the network. Online booking, design, production, manufacturing, sales, and logistics will lead to a new social management industry in the future. In the era of big data, with various new information technologies, the innovation of social service management has become a major issue concerning the prosperity and development of the security and stability for a country and society. Different sources of information, such as urban traffic conditions, weather changes, community dynamics, and popular discussion hotspots, can be quickly captured and analyzed through various devices or systems that perceive, measure, collect, and transmit data. It is possible to achieve real-time data collection, fusion, and analysis of open social signals. Using the ACP-based social computing, data mining, natural language processing, and machine learning, the social network analysis methods are integrated for analyzing social activities, social processes, social structures, social organizations, and social functions. Thus, real-time integrated and comprehensively systematic knowledge can be obtained to solve specific problems through structural analysis, semantic analysis, and sentiment analysis. Based on the interaction and parallel execution between the artificial and the actual system, the computational results (decisions) from the "dynamic and growing laboratory" are used to guide, manage, and provide feedback to the social personnel in a visual way. By analyzing different situations and deriving solutions in real time, the work and tasks can be completed remotely through multiparty collaboration, it therefore can transform the society. Parallel societies are reshaping people's lives, values, and service feelings through coordination of different elements, such as people, places, events, objects, and organizations.

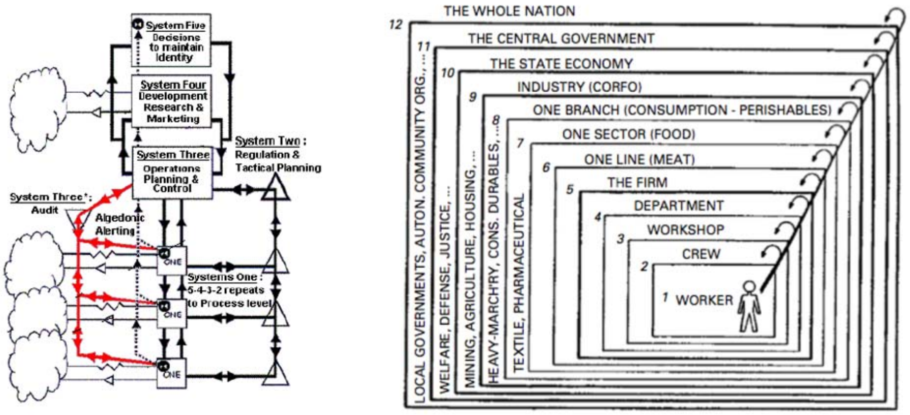

Fig. 3. System framework of Project Cybersyn [64].

Intensive, intelligent, and fully responsive social management architecture will be achieved using refined management, humanized services, diversified participation, and information support. Parallel societies are guided by social needs, centered around offline communities and online platforms, and supported by the ACP-based social computing methods. Of all the technologies, knowledge automation is the core to guarantee its realization. It relies on the Internet, IoT, cloud computing, and big data to perceive social situations. It combines multiparty social power and integrate social intelligence to manage social processes scientifically. In fact, the development from the information society to parallel societies is a process from data to intelligence, decentralization to intensiveness, and passivity to proactivity. Parallel societies will promote the transformation of the traditional social management structure of centralization, information asymmetry, and unequal interaction to an innovative social management structure of equal rights, information symmetry, and location equivalence. The core problem is to bridge the gap between the actual and the modeling behaviors and to use the Merton Law to predict and guide to a future state of a system. By effectively avoiding any uncertain, complex, and diverse situations in traditional social management, flexible, focused, and convergent parallel social management goals will be achieved.

VI. Conclusion

This paper first discusses the concept of CPSSs and its current development with the applications in transportation, energy, manufacturing, military command and control, smart vehicles, etc. The recent frontier research and development of CPSS in transportation grid, energy grid, information grid, IoT, and IoM are depicted in detail. As game-changing technology, the applications of blockchain in CPSS are also explored and explained.

In our vision for the future of CPSS, through intelligent and integrative coordination of social elements, the efforts made in CPSS will converge for building an intelligent, parallel human society that aims to promote an new and innovative social structure with equal rights, information symmetry, and balance in regional development, as well as to reshape people's lives, values, and service quality.

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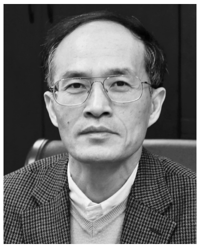

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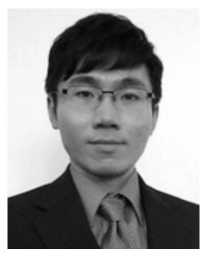

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