EDITORS: Xiao Wang, x.wang@ia.ac.cn, Fei-Yue Wang, feiyue.wang@ia.ac.cn

DEPARTMENT: AI AND CYBER-PHYSICAL-SOCIAL SYSTEMS

Metaverses and DeMetaverses: From Digital Twins in CPS to Parallel Intelligence in CPSS

Xiao Wang, *QAII, Qingdao, 266109, China and also CASIA, Beijing, 100190, China*
Jing Yang, *Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China*
Jinpeng Han, *Xi'an Jiaotong University, Xi'an, 710049, China*
Wei Wang, *Beijing Jiaotong University, Beijing, 100044, China*
Fei-Yue Wang, *Macau University of Science and Technology, Macao, 999078, China*

A total of 12 years have been passed since this Department was created in 2010 as the first academic forum dedicated to cyber-physical-social systems (CPSS), with the first CPSS research article on the field: "The Emergence of Intelligent Enterprises: From CPS to CPSS." What has happened and changed during the past decade? A brief reflection and review are presented here with a focus on digital twins in CPS versus parallel intelligence in CPSS, and their relationship to blockchain intelligence, smart contracts, metaverses, DAO, Web3, and decentralized science. The concept of DeMetaverses is thus introduced and interpreted as a DAO-based decentralized autonomous metaverse. The characteristics, mechanism, and impact of DeMetaverses are discussed with a vision for achieving an integrated human, artificial, natural, and organizational intelligence that would transform our world into "6S" societies.

In 2009, inspired by the statement that "Web 2.0 is a great lie in the course of Web history" and various dismal speculations, Xiao Wang, then Editor-in-Chief of *IEEE Intelligent Systems*, addressed the related issues and the potential of Web 2.0 for web science and engineering in his editorial[1] "Beyond X 2.0: Where Should We Go?," from web's historical developments to future Web 3.0 and Web 4.0. In his sequential editorial,[2] he discussed the relationship between virtual/mechanical avatars, mirror world, and parallel uuniverses in cybernetics, computer, and quantum physics. Apparently, many of his observations and comments[1,2] are still valid for today's sentiments and speculations to digital twins, metaverses, and Web 3.0 or Web3.

In his opening article for this Department, "The Emergence of Intelligent Enterprises: From Cyber-Physical Systems (CPS) to CPSS,"[3] Wang reintroduced his cyber-social-physical approach for complex systems and complexity sciences[4] as CPSS, and initiated the academic investigation and R&D in this new field. Today, CPSS is viewed as the abstract and scientific name for metaverses.[5]

Twelve years have passed and fruitful research results have emerged, where parallel intelligence published in 2004 and digital twins coined in 2010 have raised compelling implications for the research on CPS and CPSS. They have provided novel insights for addressing problems about the construction of digital intelligent societies, such as the integration and mining of massive data in Internet of Things devices, the separation between artificial systems and actual systems, as well as the coordination of multisource heterogeneous resources. The most critical difference between digital twins and parallel intelligence lies in their research infrastructure, that is, the former is CPS while the latter is CPSS. In addition, digital twins did not initially involve human factors, but parallel intelligence was primarily concerned with them.

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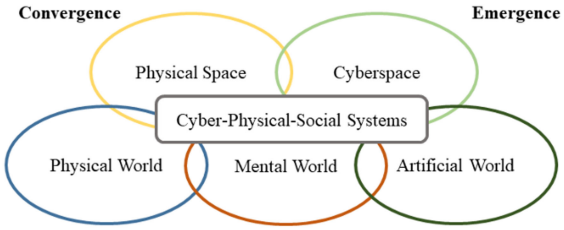

FIGURE 1. Basic philosophy and structure of CPSS.

RISE OF METAVERSES: FROM CPS TO CPSS

The term CPS describes intelligent systems characterized by a tight integration among computation, communication, and control in their operations and interactions with their task environment.[3] However, with the development of the Internet, human, social, economic, and ecologic factors have been fully incorporated into engineering systems. The theory of CPS is no longer adequate for dealing with human-in-the-loop systems. Consequently, the concept of CPSS involving human and social factors was introduced in the late 1990s for the effective and efficient operations of those systems.[4] Figure 1 illustrates the basic philosophy and structure of CPSS. CPSS is based on Karl Popper's theory of reality that manifests that our universe is composed of three interacting worlds,[3] namely physical, mental, and artificial worlds, so this revolutionary jump from CPS to CPSS is of great philosophical significance. The structure of CPSS provides a fulcrum for unifying the contradiction between emergence and convergence in complex systems. Human–computer interaction is an important research direction in the development of CPS and CPSS, aiming at making computers smart via receiving enough knowledge and reducing the human intervention in decision-making.[6]

The metaverses describe virtual worlds that not only are the exact reflections of the physical worlds, but also have the ability to infinitely expand, thus forming a superlarge space where the physical and virtual worlds interact and entangle with each other. From the engineering perspective, the metaverses have the typical characteristics of CPSS, which specially refers to three worlds (physical, artificial, and mental worlds) and two spaces (physical and cyber spaces), i.e., CPSS is equivalent to metaverses. The metaverses allow people in physical worlds to create and develop virtual worlds, and Web 3.0 is an innovative direction for the interactions between people and cyberspaces. In the future, the virtual worlds and cyberspaces will be as real as the physical worlds and physical spaces, and the mental worlds will also be deeply integrated into the virtual and physical worlds. The future production and lifestyle will

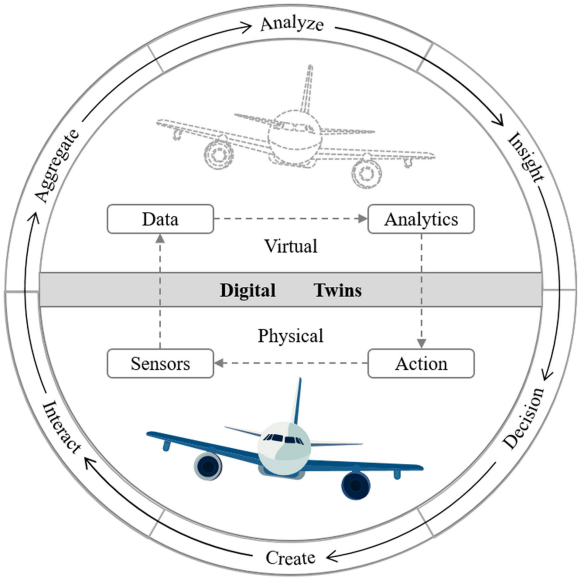

FIGURE 2. Basic framework of digital twins.

exist in a "complex space," which is half physical and half virtual.[1] Just like the emergence of imaginary numbers more than 400 years ago, people's understanding of numbers has been extended from real numbers to complex ones, i.e., real and imaginary numbers.

DIGITAL TWINS IN CPS

The first phase concerning the development of metaverse is generally regarded as digital twins, which include physical entities and their digital counterparts in CPS.[7] The digital twin, as an emerging technology, aims at obtaining a vivid digital representation of physical reality. The concept of digital twins can be traced back to the mirrored spaces model in 2003. The model was defined as a three-dimensional model for product lifecycle management that includes physical space, virtual space, and a link between them. The name "Digital Twins" was coined by the National Aeronautics and Space Administration in 2010 for the purpose of comprehendsive maintenance of flight systems. In 2011, the U.S. Air Force Laboratory explicitly proposed a digital twin paradigm for aircrafts. Since then, the application of the digital twin has been extended to diverse scenarios, such as smart cities, product R&D, and manufacturing.

As illustrated in Figure 2, digital twins provide a novel insight for integrating entities and information in CPS. Digital twins, first, construct virtual entities based on historical data and real-time sensing data of physical entities, and then make decisions for controlling systems by processing and analyzing the collected

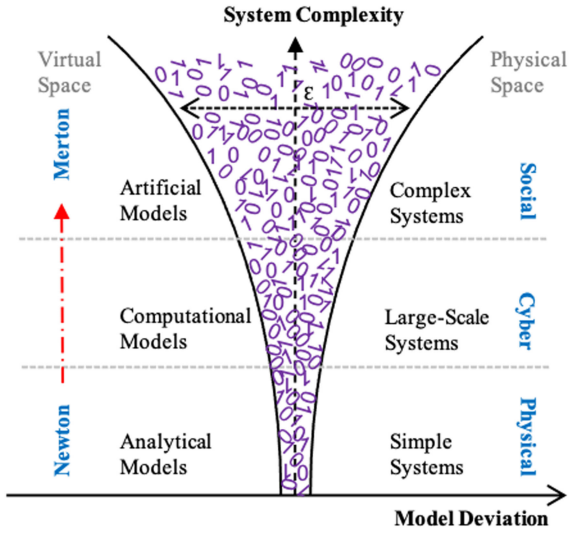

FIGURE 3. Modeling gap between actual systems and artificial systems.

data. The integration of entities and information are the cornerstone of digital twins, which play an essential role in the perception of physical elements, the construction of virtual models, the fusion of twin data as well as real-time interaction between virtual and real systems. The core idea of digital twins is in accordance with Newton's laws and CPS is a typical Newton's system, of which the behaviors can be precisely predicted and controlled. Therefore, digital twins are not capable of managing and controlling CPSS effectively, because human and social behaviors in CPSS cannot be predicted comprehensively and accurately.

PARALLEL INTELLIGENCE IN CPSS

Complex systems with the characteristics of uncertainty, diversity, and complexity in CPSS have a substantial cognitive or modeling gap between physical systems and their models, so those systems evolve into Merton's systems susceptible to external analysis, as illustrated in Figure 3. Merton's laws rather than Newton's laws are suitable for describing, predicting, and prescribing those systems. Merton's laws are composed of various self-fulfilling prophecy laws and can guide and influence Merton's systems.

On the basis of Merton's laws, the artificial systems, computation experiments, and parallel execution (ACP) approach was proposed as a parallel intelligence system for effective and efficient operations of complex systems in 2004. The basic idea of ACP is that parallel systems consisting of actual systems and one or more artificial systems are utilized for solving problems in complex systems.[8,9] Compared with digital twins, humans not only exist in physical spaces, they are also modeled into artificial systems as agents. Virtual humans interact with other digital avatars in artificial systems, thus serving as the guide of human behaviors and their states of mind in physical spaces. Parallel intelligence is thus capable of comprehensively dealing with environmental and human factors for effectively managing and controlling CPSS with openness.

In recent years, parallel intelligence and CPSS have been widely used in transportation, manufacturing, economy, ecology, and other fields,[10–13] as illustrated in Figure 4. Especially in the field of intelligent transportation, parallel transportation management systems have been established in 2010 and have been successfully deployed in many cities, which provides a possible way to alleviate traffic congestion in urban cities.

DAO-BASED DEMETAVERSES: THE EMERGENCE OF HANOI

DeMetaverses refer to DAO-based decentralized autonomous metaverses through the use of blockchain and Web 3.0 technologies, where virtual entities are stored, updated, shared, and exchanged between local nodes. Decentralized intelligence circulates between local nodes and is aggregated to produce an integrated human, artificial, natural, and organizational intelligence (Hanoi), which makes our societies trustable, reliable, useful as well as efficient and effective (TRUE).[5] Similar to decentralized science,[14] the main driving force of De-Metaverses is generated by Web 3.0 collectives and blockchain-based DAOs. Conversely, the development of DeMetaverses can in turn advance underlying theories and technologies, such as blockchain, Web 3.0, DAOs, and decentralized AI.[15] Crypto computing and confidential computing protect the security of data, not only in the storage and transmission process, but also in the use process.

Figure 5 illustrates the differences between Metaverses and DeMetaverses. In metaverses, humans only possess their own virtual avatars, while in DeMetaverses, they can also create virtual avatars with partners in the DAO and cooperate with existing avatars to run new avatars. DAOs ensure the efficient operation of activities and services in DeMetaverses. In a DAO, proposals can be launched by any members, like holders or contractors, through initiating a discussion within the community. The proposal will pass and be recorded by smart contracts if most members vote yes. Members who contribute significantly to the community will obtain some reputation values correspondingly and gain a specific advantage in the following votes. Tokens are circulated within the community as

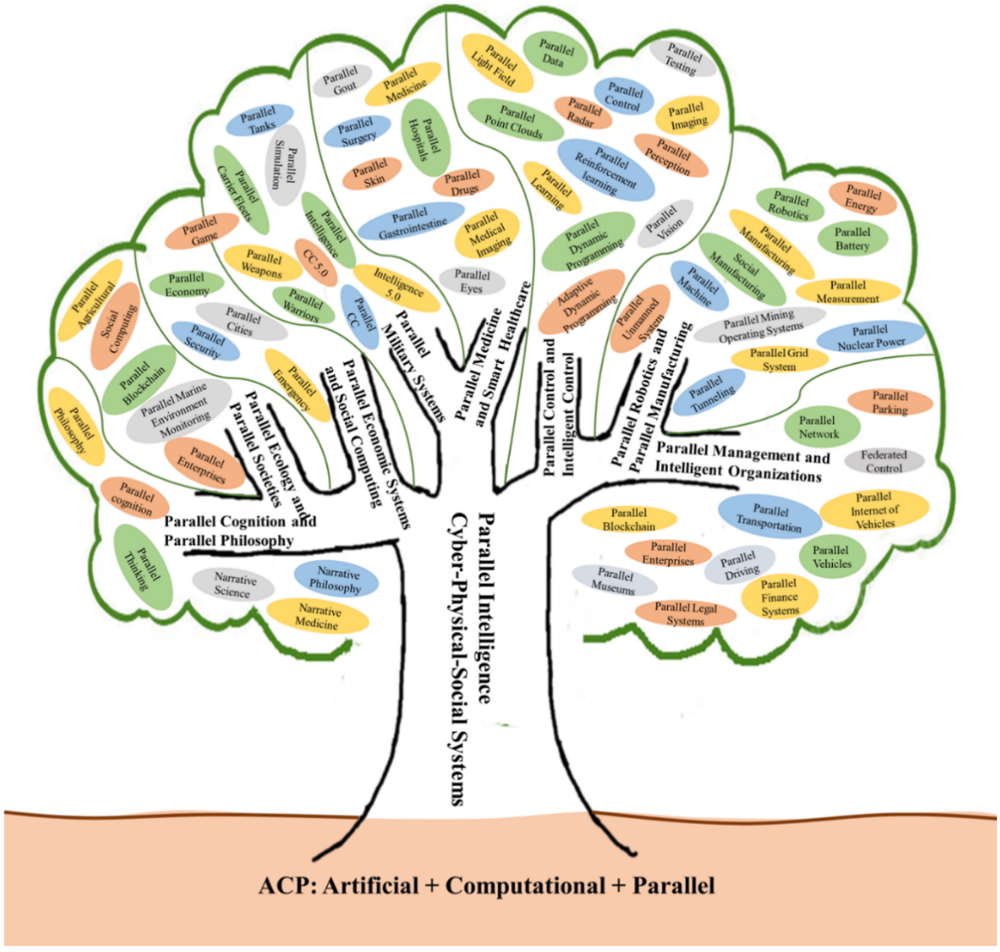

FIGURE 4. Applications of parallel intelligence and CPSS.

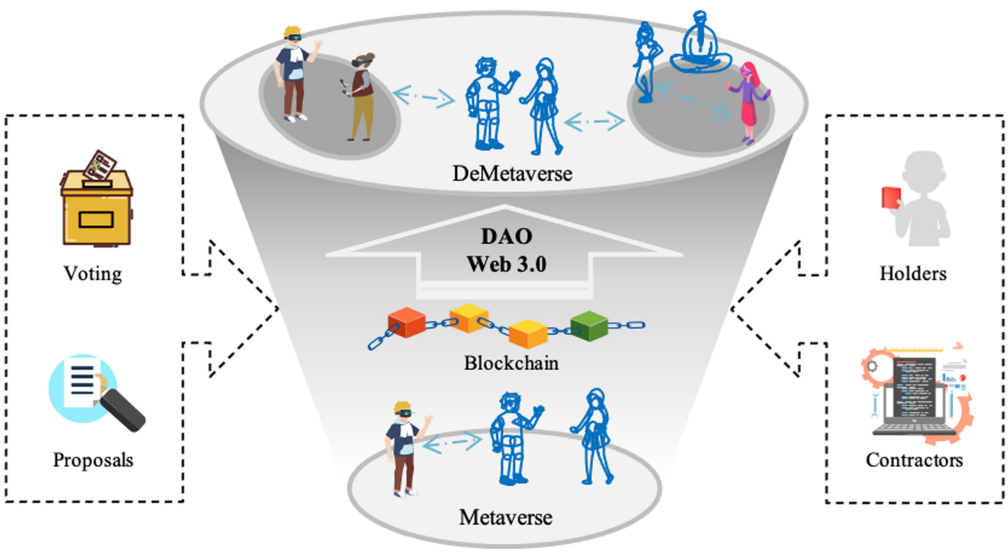

FIGURE 5. Metaverses and DeMetaverses. People in physical worlds versus digital avatars in virtual worlds.

assets to motivate members to complete the published tasks actively.

In future, with the promotion of DeMetaverses, we must live with three Bs: Being for the physical world, becoming of the mental world, and believing in the artificial world. A new profession, game engineers, will be born for translating everything we possess in physical spaces into cyberspaces, which enable us to play, work, and live in virtual worlds. Attention and trust will be widely produced and circulated as commercial commodities. Benefiting from the TRUE Tower of Hanoi, our worlds will be transformed into "6S" intelligent societies. Here, "6S" means safe in the physical world, secure in the cyber world, sustainable in the ecological world, sensitive to individual needs, services for all and smart in all.

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XIAO WANG is a research scientist and the president of QAII, also an associate professor with the Institute of Automation, Chinese Academy of Sciences, Beijing, 100045, China and also with the Qingdao Academy of Intelligent Industries, Qingdao, China. Her research interests include social computing, knowledge automation, parallel intelligence, autonomous driving and ITS, SciTS, and DAO-based computational social systems. She is a member of BoG of IEEE ITSS. Contact her at x.wang@ia.ac.cn.

JING YANG is a Ph.D. candidate with the State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China. Her research interests include parallel manufacturing, social manufacturing, cyber-physical-social systems, blockchain, and DAO. Contact her at yangjing2020@ia.ac.cn.

JINPENG HAN is currently a Ph.D. candidate with the School of Software Engineering, Xi'an Jiaotong University, Xi'an, China, as well as with the State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing, 710049, China. His research

interests include parallel security, security games, and parallel intelligence. Contact him at jinpeng.han@stu.xjtu.edu.cn.

WEI WANG is an English lecturer with the School of Languages and Communication Studies, Beijing Jiaotong University, Beijing, 100044, China. His research focuses on sociolinguistics and loanword phonology. Wang received his Ph.D. degree in linguistics from Jilin University, and was once a visiting scholar to Department of Linguistics, University of Toronto during the Ph.D. study. Contact him at weiwang3@bjtu.edu.cn.

FEI-YUE WANG is a chief scientist and the founding director of the State Key Laboratory of Management and Control of Complex Systems, Chinese Academy of Sciences, Beijing, 100045, China, since 2011, and also with the Macau University of Science and Technology, Av. Wai Long, Macao, China. His research interests include parallel intelligence, social computing, knowledge automation, blockchain and DAO, complex systems and complexity, and robotics and automation. Contact him at feiyue@ieee.org.