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Parallel intelligence in three decades: a historical review and future perspective on ACP and cyber-physical-social systems

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Abstract

Recent advances in human-in-the-loop or human-centric research have sparked a new wave of scientific exploration. These studies have enhanced the understanding of complex social systems and contributed to more sustainable artificial intelligence (AI) ecosystems. However, the incorporation of human or social factors increases system complexity, making traditional approaches inadequate for managing these complex systems and necessitating a novel operational paradigm. Over decades of work, a mature and comprehensive theory of parallel intelligence (PI) has been established. Rooted in cyber-physical-social systems (CPSS), PI adapts flexibly to various situations within complex systems through the ACP framework (Artificial systems, Computational experiments, and Parallel execution), ensuring system reliability. This paper provides a detailed review and a novel perspective on PI, beginning with the historical and philosophical origins of CPSS and proceeding to present both the fundamental framework and technological implementations of PI. PI-based Industry 5.0 is highlighted, where three pillars are adopted to help realize the supposed vision. Additionally, the paper outlines applications of PI in multiple fields, such as transportation, healthcare, manufacturing, and agriculture, and discusses the opportunities and challenges for imaginative intelligence. The continuous exploration of PI is expected to eventually facilitate the realization of "6S"-based (safe, secure, sustainable, sensitive, service, and smart) parallel ecosystems.

Keywords Parallel intelligence · Cyber-physical-social systems · Artificial systems · Computational experiments · Parallel execution · ACP · Industry 5.0

1 Introduction

The last few decades have witnessed how artificial intelligence (AI) technologies promoted the digitalization and intellectualization of the world. Driven by these technologies, social, economic, and ecological factors are continuously integrated into engineering

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Extended author information available on the last page of the article systems, contributing to the growing complexity (Saikia et al. 2023). However, when facing these new forms and complexity in both social and engineering dimensions, traditional approaches that primarily focus on physical systems or cyber-physical systems (CPS) become less efficient (Ding et al. 2020; Ren et al. 2023). Therefore, there is an urgent need to develop new thinking, new theories, and new technologies to meet these pressing challenges (Wang 2004c).

To address the above issue, cyber-social-physical systems (CSPS) (Wang 1999, 2023a), proposed by Fei-Yue Wang in the 1990s, are introduced to provide appropriate solutions, which can be interpreted as a universal framework for considering both human and social factors (Zhang et al. 2018). The CAST Lab of Intelligent Control and Systems Engineering Center (ICSEC) in the Chinese Academy of Sciences applies CSPS to the parallel management of transportation systems (Wang and Tang 2004), making it the first application of CSPS. Later in 2010, CSPS was renamed to cyber-physical-social systems (CPSS) (Wang 2010a). In the following year, cyber-physical-human systems (CPHS) (Albaba and Yildiz 2019) becomes a key research direction in the European Network of Excellence HYCON2 (Highly-complex and networked control systems), where multiple human-related issues are discussed. Comparing CPSS and CPHS, it can be observed that they share a similar definition in terms of concepts.

CPSS, as depicted in Fig. 1, is philosophically grounded in Karl Popper's theory of reality, making it distinct from CPS. According to this theory, the universe is comprised of three interconnected and coherent parts: the physical world, the mental world, and the artificial world. Among these worlds, the physical world contains objective matters and phenomena, and the mental world includes the consciousness and subjective thoughts of humans, while the artificial world involves human products that are recorded and stored through various platforms. Correspondingly, their mutual interactions can be mapped to physical space and cyberspace. Leveraging the structure, CPSS will effectively integrate massive resources and values, therefore bridging the gap between "emergence" and "convergence".

CPSS has widened the cognitive and modeling gap between model and reality, as it has broadened the scope of complex systems. Consequently, traditional "Newton's Laws" are no longer sufficient for describing and controlling the entities within CPSS (Wang 2016). To face this challenge, a shift in the focus on "Merton's Laws" is necessitated (as shown in Fig. 2). Named after the American sociologist Robert K. Merton, this theory

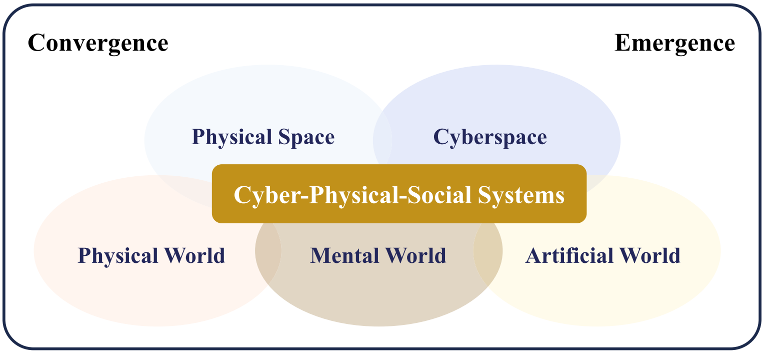


Fig. 1 The philosophical foundation and structure of CPSS

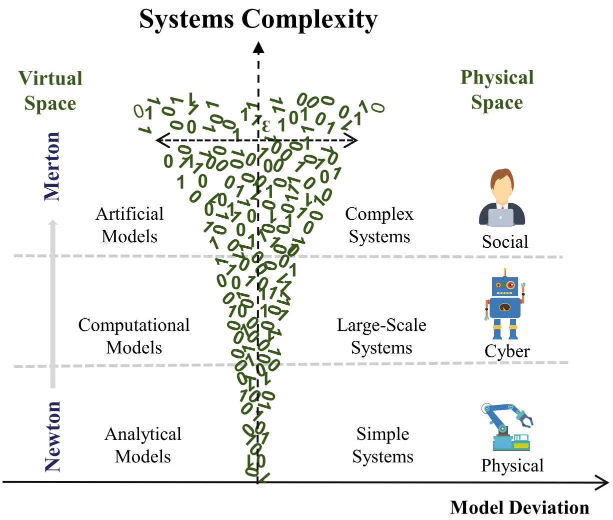


Fig. 2 The modeling gap: systems complexity VS model deviation

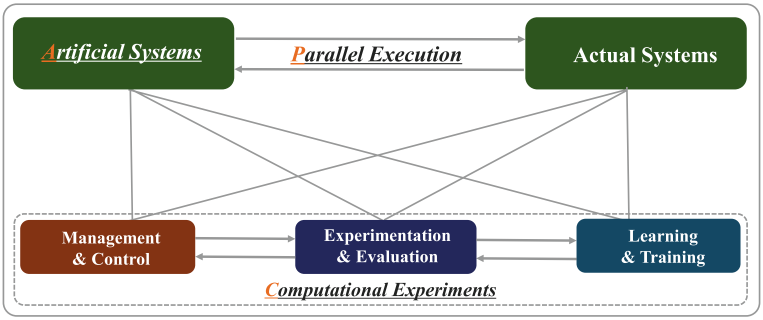


Fig. 3 The framework of the ACP mechanism

is conceptualized as the set of various human-related self-fulfilling prophecy laws (Wang 2012a), where human intelligence and machine intelligence will think in parallel and work together to realize the shared and predetermined objective. From the theoretical point of view, Fig. 3 presents the framework of ACP (“artificial systems, computational experiments, and parallel execution”) (Wang 2004a) as a promising approach for bridging the modeling gap, where “A” aims to build one or more digital models of actual systems, “C” involves designing diverse computational experiments, and “P” facilitates two-way feedback among different systems. Moreover, depending on the complexity level of practical situations and problems, the ratio between artificial and actual systems is not limited to *one* : *one*-they can be *one* : *n*, *n* : *one*, *m* : *n*, and so on.

Grounded in ACP and CPSS, parallel intelligence (PI) (Wang et al. 2016a, 2018c, 2023h; Wang 2022b) is therefore introduced, which can be regarded as the form of intelligence that emerges from the collaboration and interactions among actual, artificial, and social systems. After decades of development and evolution, a mature and integrated theory of PI has been developed and played significant roles in multiple domains, such as intelligent transportation systems, smart manufacturing, and intelligent healthcare. Consequently, this paper reviews the historical development and discusses the future perspectives of PI, and the main contributions are outlined as follows:

- Rooted in ACP and CPSS, a detailed historical review of PI is conducted to provide a more comprehensive and professional understanding of parallel systems.
- To facilitate in-depth exploration and research, both fundamental infrastructures and technological implementations of PI are outlined, along with the basic framework and some enabling technologies.
- Driven by PI, the concept of Industry 5.0 is discussed, where three technologies, three kinds of workers, and three operation modes are introduced.
- Successful applications of PI in different fields, including transportation, manufacturing, healthcare, and agriculture, are summarized. Also, the future perspectives on parallel industry and parallel societies are projected.

The remainder of this paper is constructed as follows. In Sect. 2, the historical origin of CPSS is presented. The basic framework and technical implementation of PI are introduced in Sect. 3, and the theory of PI-enabled Industry 5.0 is discussed in Sect. 4. Subsequently, the case studies of PI on multiple domains, such as parallel transportation, parallel healthcare, and parallel control, are presented in Sect. 5. Finally, the goal of parallel industry and parallel societies are highlighted in Sect. 6, while the conclusion and future perspectives are presented in Sect. 7.

2 The Historical Origin of CPSS

Figure 4 illustrates the historical evolution of CPSS. In the beginning, the advancement of information networks greatly propelled the development of CPSS. Then, the widespread of Internet applications around 2000 posed the challenge of information security. To provide solid solutions, Wang began to promote research on CSPS, especially on how to realize knowledge automation through CSPS. Simultaneously, the phenomenon of human flesh search (HFS) emerged in China, which was interpreted as a way to collect information and resources by leveraging the power of individuals. Driven by this situation, ICSEC intensified the research on CSPS, and the Open Source Intelligence Group (OSIG) was founded in 2000 for its innovative work on the CSPS-based HFS Cyber Movement Organizations

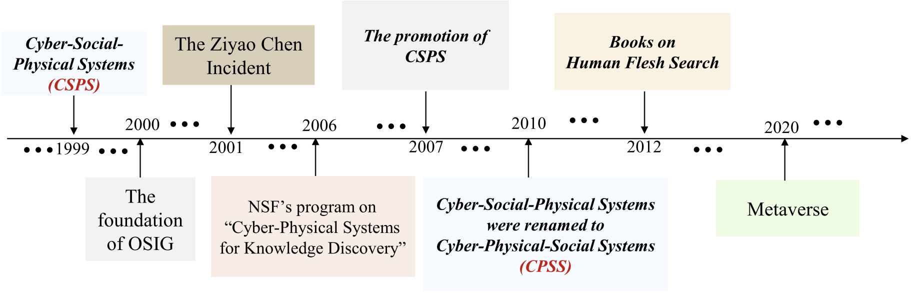


Fig. 4 The historical evolution of CPSS

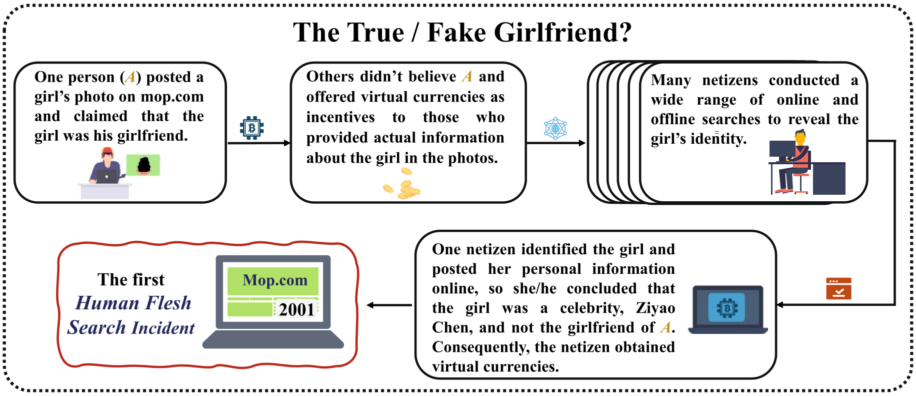


Fig. 5 The first HFS incident: A starting point in CPSS

(CMOs) (Wang 2004b, 2004d). As shown in Fig. 5, the Ziyao Chen Incident, happened in 2001, was the first time that HFS attracted wide attention and therefore raised critical questions on moral ethics and human rights. Afterward, HFS spread to multiple areas of the world and finally evolved to the concept of crowd-sourcing (Wang 2009; Wang et al. 2016b). During this process, Wang and others wrote two books on HFS (Feng 2012; Zhang 2012; Wang 2011), but they remain unpublished because of some non-academic reasons. Within these two books, one provides a comprehensive summary of relevant work conducted over the past decade, while the other delves into a detailed presentation of the research on HFS. Moreover, there are some published materials on this subject (Wang 2010a; Wang et al. 2010; Zhang et al. 2012).

In Wang's opinion, Wei Zhao should be considered the originator and biggest promoter of CPS (Zhao and Abdelzaher 2018; Zhao 2019), who was previously employed at the National Science Foundation (NSF) of the United States of America. In the early 2000s, Wang and Zhao discussed their respective ideas, where Wang called for "CSPS for knowledge automation (KA)" and Zhao advocated "CPS for Knowledge discovery (KD)". About 2006, Zhao organized a series of workshops and then initiated NSF's program on "CPS for KD", which makes CPS a worldwide research interest and a significant field today. Meanwhile in 2007, when the Chinese Academy of Sciences (CAS) planned to develop a strategic roadmap for "Science and Technology to 2050", Wang et al. collectively contributed to the promotion of CSPS. The roadmap project has completed 18 books, with three of them embodying the concept of CSPS (Strategic Research Group for National and Public Security Technology 2011; Li 2011; Wang et al. 2012). Later in 2010, Wang renamed CSPS to CPSS (Wang 2010a). At the workshop on discussing new directions for information and automation technologies, held by the National Natural Science Foundation of China (NSFC) in 2011, Wang raised the issue of CPSS, and there were also proposals for CPHS and Human CPS (HCPS). However, some researchers considered that "social" was a broader term than "human", and Wang's proposal was not accepted. But in 2019, HCPS was reintroduced and promoted in China (Zhou et al. 2019; Liu and Wang 2020). Overall, the authors consider that CPSS, CPHS, and HCPS are different terms that represent the same research directions.

Throughout the entire history of development, a comprehensive framework of CPSS has been developed and applied to various domains, such as transportation, healthcare, manufacturing, and energy. Also, related activities have been supported by international organizations, including the International Federation of Automatic Control (IFAC), the Association for Computing Machinery (ACM), IEEE Systems, Man, Cybernetics Society (IEEE SMC), IEEE Intelligent Transportation Systems Society (IEEE ITSS), and IEEE Council on Radio-Frequency Identification (IEEE CRFID). Furthermore, relevant professional research institutes consist of the State Key Laboratory for Management and Control of Complex Systems, Chinese Academy of Sciences (SKL-MCCS, CAS), National University of Defense Technology (NUDT), Qingdao Academy of Intelligent Industries (QAII), with each contributing its unique insights to the CPSS research.

3 Parallel Intelligence: From Digital Twins in CPS to ACP in CPSS

When facing complex social systems, the current paradigm of “Digital twins in CPS” shows its deficiency and requires more effective strategies. To meet these challenges, Parallel Intelligence (PI) is proposed to play pivotal roles in bridging the modeling gap between model and reality, further facilitating the “6S”-based (safe, secure, sustainable, sensitive, service, smart) (Wang et al. 2023d; Li et al. 2023c; Chen et al. 2023a) complex systems. In this section, both the fundamental framework and technological implementation of PI are highlighted, and more details are provided in the following sections.

3.1 The Fundamental Framework of Parallel Intelligence

Compared with digital twins and CPS, one obvious feature of PI lies in the consideration of social factors. Originated from Karl Popper’s theory of reality (Wang 2022a), CPSS effectively considers the impacts that social factors will have on complex systems (Lu et al. 2022), where “C” denotes the virtual system in artificial worlds, “P” contains matters and objects in physical worlds, and “S” involves the complicated spiritual activities in mental worlds. Under this framework, CPSS will develop the governance mode with more parallelism, transparency, intelligence, and ubiquity. Meanwhile, with the fast development of foundation models and other advanced technologies, conventional computer-based smart machines have transcended their roles as pure tools for human task completion, and permeated into various fields of human production and lives, assisting in tasks spanning from perception to decision-making and reasoning (Zhang et al. 2021). Throughout the historical progression of “IT” (as depicted in Fig. 6), human beings are now stepping into a new era, where an information ecosystem that integrates cyberspace and physical space brings a profound influence on human cognition and actions. To deal with the “intelligence asymmetry” in the 3rd axial age (Wang 2017), “intelligent technology” emerges as the third epoch of “IT”, where the resource asymmetry and information asymmetry in “Old IT (industrial technology)” and “Past IT (information technology)” can be addressed.

Different from CPS, CPSS not only can integrate social factors but also will strengthen interactions among physical systems and cyber systems. Based on the tripartite elements (“C”, “P”, “S”), CPSS is regarded as the basic infrastructure to coordinate and regulate the complex factors in PI, therefore advancing AI towards hybrid intelligence. Consequently, how to introduce smart agents to integrate social signals, establish professional knowledge networks, perceive interconnected organizations, and finally realize intelligent management and control of complex systems becomes a critical issue. Meanwhile, the extraction, analysis, and application of knowledge that embeds within numerous physical and social

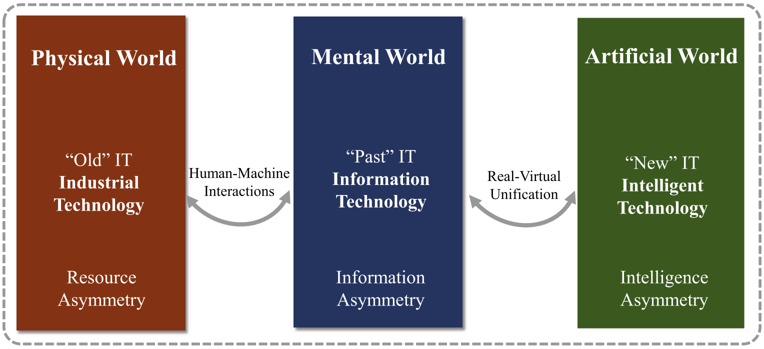


Fig. 6 The "new IT" in the 3rd axial age: Intelligent technology

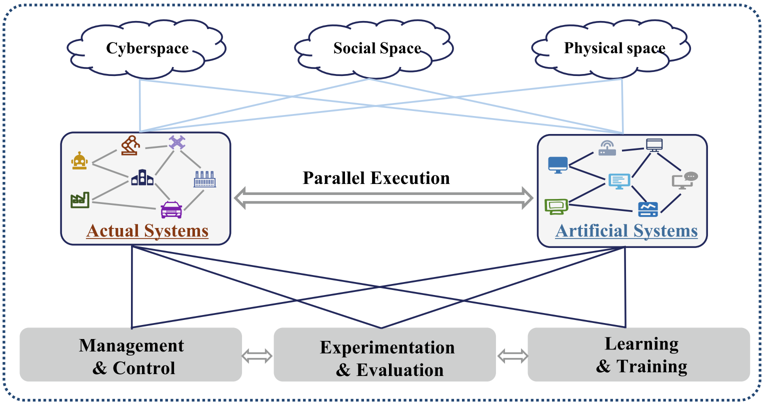


Fig. 7 The fundamental framework of PI

entities in CPSS require the management of vast amounts of data and information, which surpasses the processing capabilities of humans and indicates that KA (Wang et al. 2023k) will be instrumental in the deployment of CPSS applications.

In the era driven by data intelligence, knowledge is conceived as a series of instructions or rules that can inform and shape the actions of humans and machines. With knowledge being the controlled object, KA can complete the cyclic process of knowledge generation, acquisition, application, and re-creation. Nevertheless, since KA is a newly proposed theory, one of the most difficult issues lies in how to transform the conventional characteristics of uncertainty, diversity, and complexity (UDC) in complex systems to agility, focus, and convergence (AFC) in intelligent systems (Wang et al. 2023d). To meet this, KA is embedded into the ACP-based framework of PI.

Grounded in ACP and CPSS, Fig. 7 demonstrates the basic framework of PI, in which actual systems and the corresponding artificial systems are connected by various modes and objectives. ACP is utilized to model the complex "soft" parts of intelligent systems and handle practical issues through quantitative and real-time computing techniques. The "A" in ACP refers to one or multiple artificial systems that can be considered as a generalized knowledge model of actual systems. For "computational experiments", behaviors of actual systems in different situations will be predicted and evaluated, which will provide more insightful guidance for decision-making. And "parallel execution" is responsible for facilitating the interaction between artificial and actual systems. Finally, the efficient management and control of complex systems will be realized through the joint work of closed-loop feedback, real-virtual interactions, and parallel execution, where PI is generated and propagated. Additionally, there are three interconnected modes: management & control, experiment & evaluation, and learning & training, whose division of labor is listed as follows:

- Management & control: In this mode, the relationship between actual and artificial systems can be regarded as digital twins, where artificial systems are required to replicate physical behaviors with high accuracy. Also, the two kinds of systems should be connected in real time to promote efficient communications. The operation differences among them can then be employed to optimize system parameters and modify control feedback.
- Experiment & evaluation: During this process, multiple computational experiments will be conducted in artificial systems to predict and evaluate behaviors of actual systems under various situations, thereby providing timely guidance for some undesired or unanticipated situations.
- Learning & training: Under this setting, artificial systems mainly serve as data centers that are capable of acquiring operation processes and training biological workers. Hence, whether artificial systems have accurately modeled actual systems becomes less significant, and this virtual system can be considered as one alternative to actual systems.

In summary, based on the "small data" collected in actual systems, ACP can first generate "big data" through computational experiments, and then leverage the obtained "big data" to realize "deep intelligence" (Zhao et al. 2023), greatly overcoming the limitations of traditional approaches and enabling "emergence" and "convergence" to be in the unity of opposites (Wang 2022a; Yang et al. 2023).

3.2 Technological Implementations of Parallel Intelligence

Based on ACP, PI is a novel paradigm of AI that can develop intelligent mechanisms to acquire, create, and support parallel systems (Wang 2020a; Yang et al. 2023). Theoretically, three steps are integrated to realize the scope of PI, which are concluded as: 1) constructing artificial systems; 2) conducting computational experiments; and 3) implementing parallel execution. Through the interactions among artificial and actual systems, actual systems will approach artificial systems with higher accuracy, thereby handling the existing UDC challenges and realizing the AFC management and control of complex systems (as shown in Fig. 8). More detailed technological implementations of PI are provided next.

3.2.1 The Construction of Artificial Systems

Supported by softwares, artificial systems are interpreted as the digital avatar of actual systems in cyberspace, which can provide trustworthy experimental platforms for subsequent actions and promote better decision-making for complex social systems. Instead of mechanically digitizing actual systems, artificial systems emphasize the integration of social knowledge and relationships (Yang et al. 2019) to effectively capture the collective interactions between humans and environments.

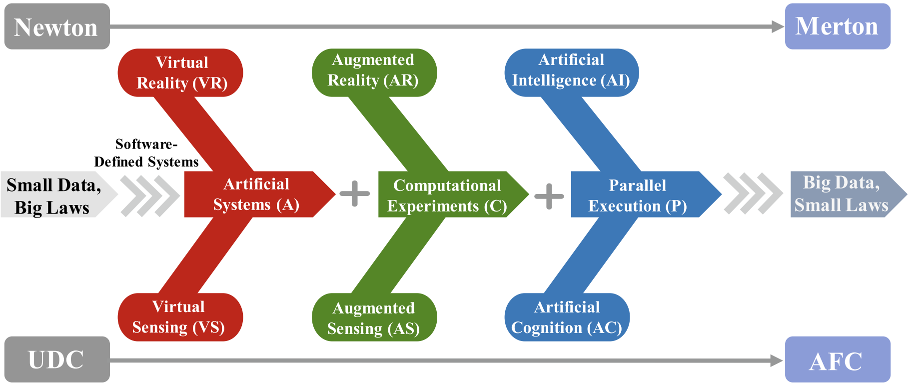


Fig. 8 Parallel intelligence in CPSS: From UDC to AFC

For actual systems in physical space, the construction of artificial systems can address the existing limitations of uncontrollability and non-repeatability (Tian et al. 2020). With the introduction of intelligent techniques like knowledge representation, different artificial systems with diverse objectives will be developed in cyberspace. And each virtual system represents a possible solution to real-world issues. Furthermore, with the confines between entities and relationships in physical space, more than one artificial system can be developed to offer diversified experimental settings, thereby providing solid foundations for predicting and analyzing the behaviors of actual systems. Meanwhile, with the continuous evolution of advanced technologies, scenarios engineering (Li et al. 2022, 2023e) has replaced the previous feature engineering and become the state-of-the-art technique for constructing artificial systems.

3.2.2 Computational Experiments in the Cyberspace

To enhance real-virtual interactions in parallel execution, comprehensive experiments and evaluations should be conducted in cyberspace, where the vast number of generated actual data is employed as the training and test data. However, the virtual experiments are usually constrained by various factors, such as challenges in active testing, evaluation difficulties, and limitations imposed by subjective and uncontrollable disturbances in physical space, which hinder the broader applications of computational results in actual systems.

Fortunately, computational experiments in parallel systems can serve as powerful tools for handling the above issues. As depicted in Fig. 9, since artificial systems can offer abundant possibilities and widen experimental boundaries, the introduced mechanism is able to reconstruct and provide controllable experiments for different digital settings. For the design of computational experiments, the adopted rule is "*Fischer three principles*" (Wu and Hamada 2021) that refers to replication, randomization, and blocking. Specifically, each computational experiment can represent a distinct artificial system with given optimization objectives and control rules, and each output corresponds to a potential evolutionary path of physical systems. It can be observed that in situations with enough computing power, computational experiments can effectively utilize actual data and enhance the computational performance of artificial systems, as well as offer ample opportunities to identify

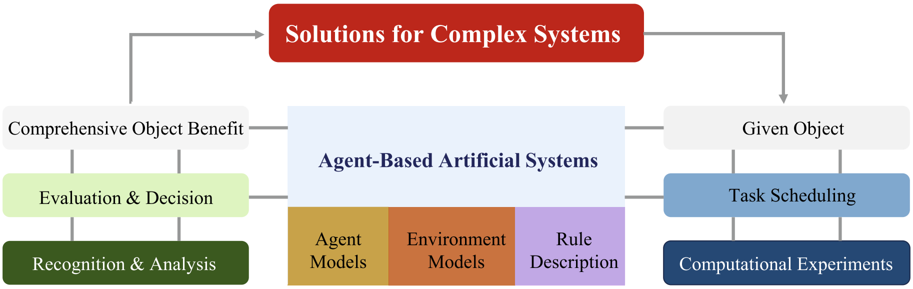


Fig. 9 Solutions for complex systems: Computational experiments

optimal strategies of some predefined conditions. All of these will help promote the prescriptive intelligence in parallel execution.

3.2.3 Parallel Execution for Closed-Loop Optimization

Based on the above two procedures, the next problem that needs to be considered is how to bridge the gap between artificial systems and actual systems, therefore facilitating the closed-loop optimization of parallel systems. Hence, parallel execution is employed as an innovative mechanism to facilitate the management and control of actual systems, where the comparison, evaluation, and interactions between artificial systems and actual systems will be performed. Then, the optimal solutions generated by computational experiments are applied to assist the decision-making and control of actual systems. During this process, the behavioral differences between artificial and actual systems not only play a pivotal role in adjusting their operation state but also provide significant feedback information for modifying and upgrading the parameters of artificial systems. In addition, the current state of actual systems can be utilized as the initial condition of some artificial systems, which will finally build a new artificial system and develop the closed-loop feedback for parallel systems. That's to say, besides supporting intelligent decision-making in actual systems, parallel execution is also well-prepared for future changes in complicated environments.

3.2.4 Other Enabling Techniques

Besides providing a comprehensive solution for the management and control of complex systems, spanning from data collection and construction of artificial systems to computational experiments and closed-loop feedback, PI also presents some supporting technologies. Among them, parallel perception, parallel learning, and parallel blockchain are briefly introduced in this subsection, whose details are listed as follows.

- ***Parallel Perception***: For the physical space, real data is crucial in establishing artificial systems, which indicates that data collection is an inseparable process. To this end, parallel perception (Wang et al. 2017c; Liu et al. 2023c) is employed to optimize artificial systems and enhance better perception of challenging environments through both virtual data and real-world data.
- ***Parallel Learning***: Upon collecting data, learning and training for some specific scenarios and optimization objectives become necessary. To meet this challenge, parallel

learning (Li et al. 2017; Miao et al. 2023a) is utilized as a novel theoretical framework of data analysis, which originates from the combination of parallel systems and machine learning. This framework fully considers the different characteristics of both actual and artificial data and explores the potential of parallel systems. Moreover, with the aim to predict, control, and monitor the decision-making of complex systems in PI, parallel control, a novel feedback strategy, is also introduced to facilitate the algorithmic analysis of physical processes and enable the efficient evaluation of specific policies, thereby enhancing the performance of parallel systems.

- ***Parallel Testing***: Following the management and control of complex systems, it is crucial to conduct suitable tests and evaluations to obtain the system's iterative direction and develop integrated closed-loop feedback. Parallel testing (Li et al. 2018, 2020) is an intelligent "human-in-the-loop" model that can fully integrate the advantages of human experts and computers. With the assistance of expert knowledge, it enables the system to accomplish self-upgrading and generate explicit task definitions and solutions. Also, virtual scenarios are used to broaden artificial testing data, thereby guaranteeing the accurate and efficient operation of system testing and evaluation.
- ***Parallel Blockchain***: Throughout the whole process of managing and controlling complex systems, certain technologies are required to ensure the security of operational data, thereby reaching the consensus of solid competitive ecology. With the advantages of decentralization, tamper resistance, and programmability, blockchain is introduced to ensure the fair and secure operations of parallel systems. To maximize the performance of this encrypted technique, parallel blockchain (Wang et al. 2018b, 2019b) presents artificial blockchain as a "computational laboratory", where extensive offline trial-and-error experiments will be conducted to generate strategies that are adaptable to varying conditions in the actual blockchain. Furthermore, to facilitate win-win cooperation among organizations and ensure the security and immutability of transactions among multiple parties, DAOs (Decentralized autonomous organizations and operations) (Li et al. 2023b; Miao et al. 2023b; Wang et al. 2023g) are also introduced to enable distributed cooperation and decision-making in transactions.

4 Parallel-Intelligence enabled Industry 5.0

Within the past few decades, the continuous evolution of advanced AI technologies has brought considerable opportunities for industry, therefore enabling a substantial leap in the digitalization and intelligence of industry. However, the existing industrial paradigm, Industry 4.0 (Bécue et al. 2021), is constructed through ICT (Information and Communication Technologies) and CPS, which is struggling to meet the increasingly complex demands of humans. Under this situation, the need to develop a novel human-oriented industrial paradigm becomes urgent.

Since the 1990s, Wang has been dedicated to the research of industrial applications. He initiated the discussion on the "Fifth Industrial Revolution" based on CSPS in 1999 (Wang 1999) and redefined it as Industry 5.0 in 2014 (Wang et al. 2023i). After decades of iteration and accumulation, a mature theory of PI-enabled Industry 5.0 has been established and applied in various fields, such as Transportation 5.0, Education 5.0, Healthcare 5.0, Manufacturing 5.0, and Energy 5.0, forming an integrated and comprehensive "X5.0" (Wang 2015b) scheme and promoting significant advancements and innovations. In terms of

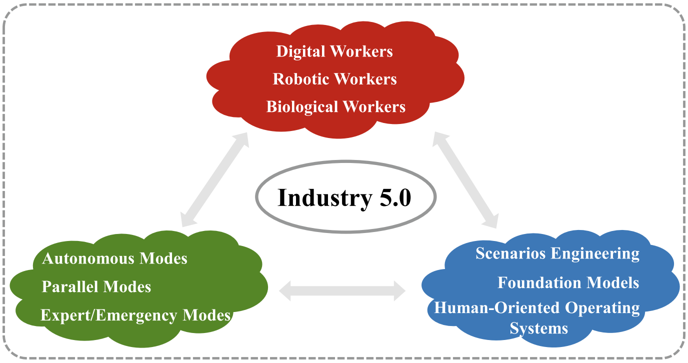


Fig. 10 The key elements in Industry 5.0

theoretical underpinnings, Industry 5.0 is primarily composed of three pillars (as depicted in Fig. 10), which are briefly outlined as follows:

- Three kinds of basic infrastructures. To achieve the desired goal of Industry 5.0, some enabling technical infrastructures are indispensable. The first employed technique is scenarios engineering, which enables the construction of artificial systems that are more reliable and trustworthy through Intelligence & Index (I &I), Calibration & Certification (C &C), and Verification & Validation (V &V). Then, the powerful foundation models (Wang et al. 2022a, 2023f), referred to a platform for conducting computational experiments, are utilized to analyze and predict the behavior of artificial systems and actual systems. Furthermore, to benefit and improve the welfare of humans, human-oriented operating systems (HOOS) (Wang et al. 2023a) are introduced to facilitate the experience of related workers.
- Three kinds of workers. Within the framework of Industry 5.0, digital workers, robotic workers, and biological workers (Wang et al. 2023e) collectively form a novel human-in-the-loop paradigm. Among them, biological workers stand for the top authority and hold holistic control of the complex system. Serving as the virtual avatar in cyberspace, digital workers are responsible for communicating and processing difficult issues. While robotic workers are actual executing agents in physical space, where the delivered orders are received and executed.
- Three kinds of operation modes. The development of advanced technologies has accelerated the appearance of novel operating mechanisms. For the era of Industry 5.0, autonomous modes (AM), parallel modes (PM), and expert/emergency modes (EM) (Wang et al. 2024b) will collaboratively work to lower economic costs and improve operation efficiency. During AM, related agents can operate with predefined control orders and strategies. However, when some undefined or undesired occasions occur, PM will be triggered and professional experts at "clouds" will work with digital and robotic workers. If the issue still persists, EM will then be activated and those professional experts will be delivered to the physical site to handle the difficult problems.

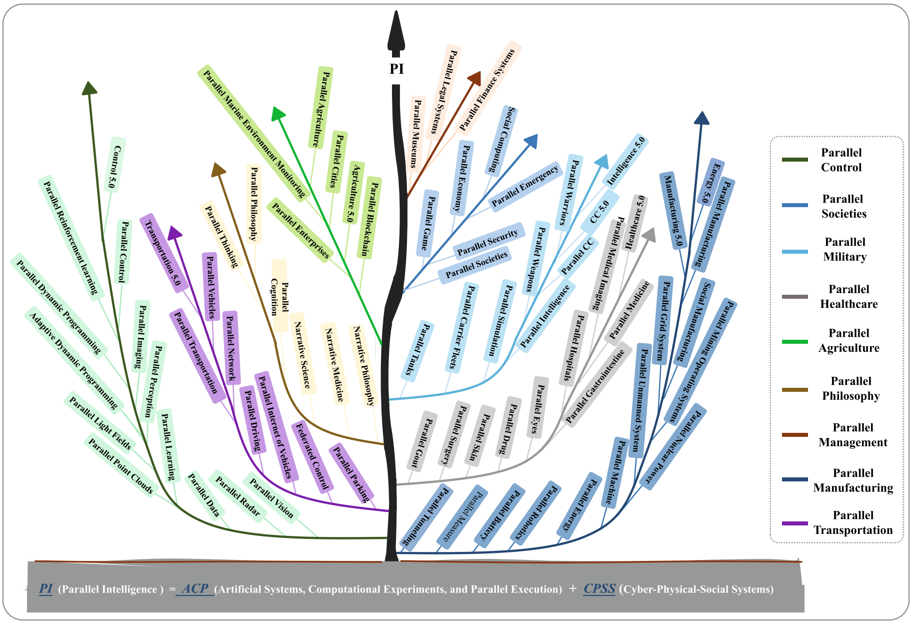


Fig. 11 The applications of PI

5 Case Studies

As shown in Fig. 11, to facilitate the transformation from CPS to CPSS and realize the intelligent and digital upgrades across various domains, PI has been successfully applied to diverse fields, including parallel transportation, parallel healthcare, parallel control, parallel manufacturing, and parallel agriculture. This section will provide a detailed introduction to their main contents, whose details are listed as follows.

5.1 Parallel Transportation

Transportation systems are of paramount importance to the national economy and the well-being of the populace, serving as the lifelines of economic development and the foundation of societal functioning. However, urbanization has exacerbated challenges such as traffic congestion, safety incidents, environmental pollution, and energy consumption, posing significant issues for urban management and resident life quality. To address these issues, Intelligent Transportation Systems (ITS) have been introduced by leveraging informatization to enhance the efficiency and level of traffic management. Nevertheless, the ITS has predominantly focused on traffic informatization and physical systems, therefore neglecting the influence of social systems.

Within this context, Parallel Transportation Systems (PTS) (as indicated in Fig. 12) have emerged as an innovative approach to intelligent traffic management and control (Wang 2010b). Rooted in ACP and CPSS, PTS can first construct software-defined artificial transportation systems, and then conduct computational experiments for analysis,

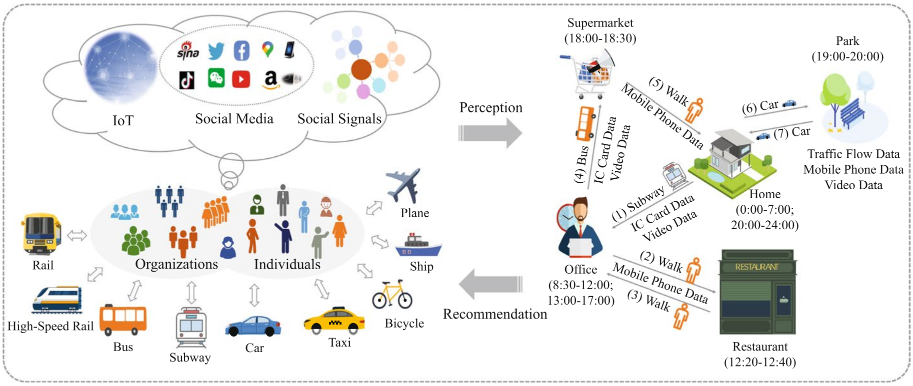


Fig. 12 The parallel transportation systems in CPSS

prediction, evaluation, and optimization of complex issues. Finally, through parallel execution, the management and control of actual traffic systems can be achieved, which will greatly facilitate the realization of PTS (Lv et al. 2018; Zhu et al. 2019; Wang et al. 2023b). The core components of PTS encompass both actual and artificial transportation systems, along with three operational modes: management & control, experimentation & assessment, and learning & training. The virtual-real interactions and closed-loop feedback between actual and artificial transportation systems serve as a mechanism for managing and controlling the traffic systems, driving the entire transportation system towards preset or emergent objectives.

In terms of applications, PTS has been implemented and validated in various cities and scenarios. For instance, in the traffic signal control project in Taicang, Jiangsu, China, the system has significantly improved the local traffic condition and increased the average vehicle speed (Lv et al. 2019a). The Qingdao Parallel Traffic Control System, as the first municipal road traffic parallel control system, has realized interactive operation and evolution between artificial and actual traffic systems, effectively enhancing traffic quality and reducing investment costs for road construction (Zhu et al. 2016; Lv et al. 2019a). Additionally, during the Guangzhou Asian Games in 2010, the system was utilized for public transportation management, which ensured efficient traffic operations throughout the event (Xiong et al. 2012; Lv et al. 2019a). Furthermore, several platforms have been constructed during the development of PTS. Under TransVerse (Transportation Metaverse), DeCAST (Zhao et al. 2022b) operates on DAOs and integrates with artificial transportation systems (ATS) through virtual-real interactions. TransWorld, an integral simulation software for ATS modeling, employs agent-based techniques for behavioral traffic simulation. DynaCAS (Zhang et al. 2008) performs computational experiments for traffic optimization, while aDAPTS (Wang 2005) utilizes mobile agents for decentralized traffic control. Supported by TransChain, TransCloud, and TransMedia, the iTOP platform orchestrates these components to form a cohesive system for intelligent transportation advancement. Recently, in TengYun (Zhao et al. 2022a), a transportation foundation model has been designed and developed with parallel learning and federated intelligence for TransVerse.

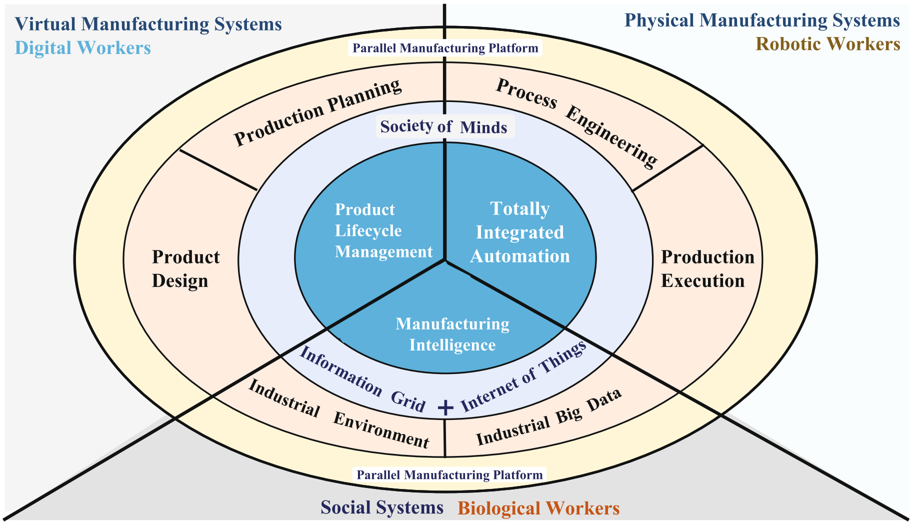


Fig. 13 The basic framework of parallel manufacturing

5.2 Parallel Manufacturing

As the cornerstone of numerous industries, manufacturing holds significant importance in the adoption of cutting-edge technologies like digital twins and the Internet of Things (IoT). This significance becomes particularly evident with the increasing demands for personalized intelligent products, making human wisdom and skills necessary and indispensable in the future industry. However, this issue goes beyond the ability of Manufacturing 4.0, where the main focus lies in attaining complete digitalization and automation in factories without human involvement. As shown in Fig. 13, to deal with this issue, parallel manufacturing and Manufacturing 5.0 (Wang et al. 2018a; Yang et al. 2022a, 2022b; Yang et al. 2024; Wang et al. 2024c) are introduced with the characteristics of human–machine integration, knowledge-action emergence, and real-virtual convergence. This parallel mechanism emphasizes the utilization of organizational technologies such as blockchain (Yuan and Wang 2018), smart contracts (Wang et al. 2018d), and DAOs (Li et al. 2023d) to alleviate the constraints of time and space, thereby integrating and coordinating various human-included resources. Grounded in PI (Wang et al. 2022c), foundation models are incorporated to support the construction of digital workers with computational rationality. Within parallel manufacturing, three types of workers are introduced: biological workers for social systems, robotic workers for physical manufacturing systems, and digital workers for virtual manufacturing systems. These workers can interact and collaborate with each other to autonomously perform intellectual and physical tasks like demand analysis, product design, production planning, process engineering, and execution.

Also, the sustained operation of parallel manufacturing hinges upon the joint support provided by parallel machines (Bai et al. 2019) (e.g., parallel unmanned systems (Chen et al. 2018) and parallel robotics (Bai et al. 2017) and parallel energy (Deng et al. 2015) [e.g. MetaGrid (Li et al. 2021), parallel nuclear power (Hou et al. 2019), and parallel battery (Wang and Jiang 2021)]), and one of its essential raw materials

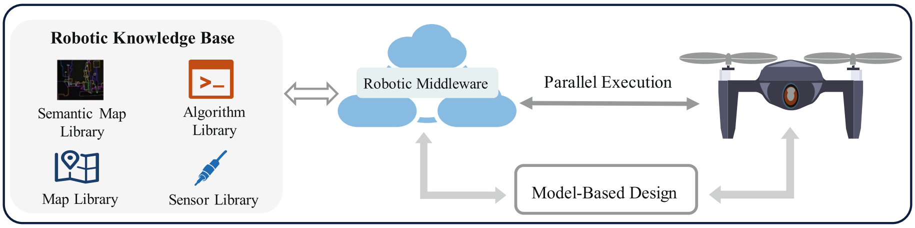


Fig. 14 The architecture of parallel machines

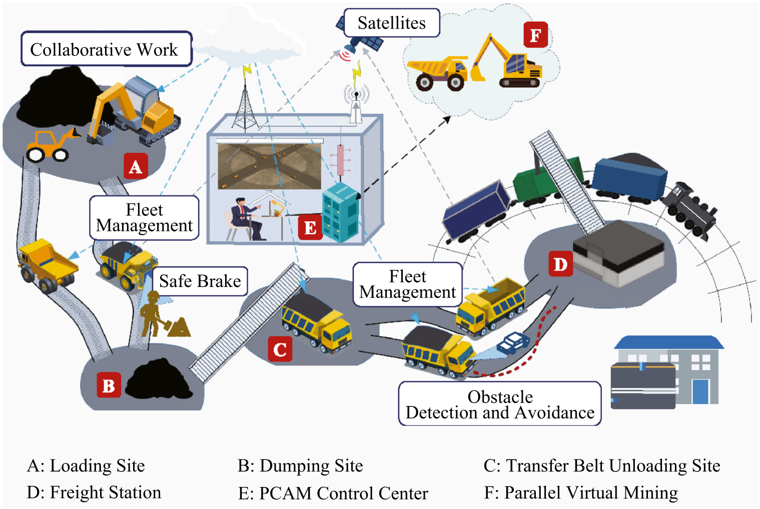


Fig. 15 The technological process of parallel mining

need to be supplied by parallel mining (Chen et al. 2023b) and parallel tunneling (Yang et al. 2021a). Parallel machines (see Fig. 14) are regarded as software-defined virtual machines (also known as knowledge machines), which can augment the conventional machine's system architecture with virtual control, virtual execution, and virtual loops within the extended loop. Its goal is to liberate humanity from tedious physical labor, and even undertake tasks that may be difficult or hazardous for humans to accomplish. Parallel energy synergistically operates artificial virtual systems with socio-technical systems through sufficient interactions and massive computing to advance the coordinated development of multi-energy intelligence. As depicted in Fig. 15, parallel mining, or Mining 5.0, builds a virtual mining system parallel to the actual mining system, where the feasibility of task execution strategies in various scenarios are tested and evaluated to guide the efficient operation of single-vehicle systems, multi-vehicle systems, and vehicle-road cooperative systems. It has been successfully applied in the Baorixile open-pit mine and verified to reduce human involvement, mitigate safety risks, and enhance operational efficiency. Recently, the first mining foundation model, YUKON, was released to propel intelligent mining into the new era of AI, marking that the intelligence level of the mining industry has reached a new milestone.

5.3 Parallel Healthcare

To address the issue of traditional medical methods that heavily rely on physician experience, strained doctor-patient relationships, and insufficient medical sample volumes (Lv et al. 2022; Fan et al. 2021), parallel healthcare (Wang 2021b, 2023c) is proposed to systematically study medical-related problems through PI. It aims to generate medical "big data" from medical "small data" and extract medical "knowledge", thus advancing medicine towards scientific, humanistic, and socially intelligent healthcare. In terms of medical images, parallel medical image (Wang et al. 2021a) can integrate parallel learning, parallel data, and expertise to provide a viable framework for interpretability in small-sample medical imaging analysis.

For healthcare, the transition from "professional division of labor" to "human–machine division of labor", and then to "virtual-real division of labor" is an inevitable path for the development of intelligent healthcare. Within the framework of healthcare, hospitals are significant complex systems that comprise various medical elements such as doctors, patients, and medical equipment. Parallel hospital provides feasible solutions on how to effectively manage hospitals and realize the transformation of the division of labor among medical staffs. As shown in Fig. 16, parallel hospital (Wang 2021a; Wang et al. 2021b) digitalizes and parallelizes the hospital's infrastructure and participants by introducing digital doctors and robotic doctors, providing patients with reliable, trustworthy, and efficient medical services. Among them, digital doctors act as virtual assistants, who are capable of planning and evaluating patients' medical treatment plans through computational experiments and directing robotic doctors to complete related tasks. Biological doctors are responsible for the overall supervision of the medical process and possess the highest priority in modifying the decisions of digital doctors, as well as interrupting and changing the behavior of robots. For specific methods and diseases, some typical cases of parallel healthcare, such as parallel surgery (Wang et al. 2017b), parallel skin (Wang et al. 2019a), parallel gout (Wang et al. 2017a), parallel eye (Wang et al. 2018e), and parallel gastrointestine (Zhang et al. 2019), have been proposed to overcome the issue of varying skill levels among medical staffs, where the optimal diagnostic and treatment plans are selected by

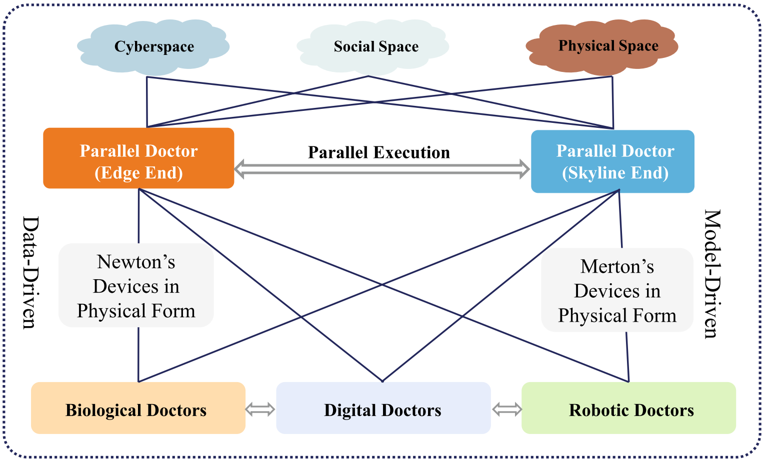


Fig. 16 The CPSS-based parallel hospital system

considering the differences among patients. In the future, human–machine interfaces that can transmit tactile information across time and space (Luo et al. 2024) will be one of the most potential topics in healthcare.

5.4 Parallel Control

Based on PI, parallel control, parallel sensing, parallel learning, and parallel testing constitute the theoretical pillars that support the intelligent perception, modeling, control, and testing of complex systems.

Parallel control provides new insights for addressing complex nonlinear dynamic control and optimization problems through PI (Wei et al. 2020; Lu et al. 2024; Wang 2023b). As depicted in Fig. 17, it firstly constructs artificial systems for complex physical systems; then conducts computational experiments for control strategy analysis; and finally achieves virtual-real interactions among artificial and actual systems by parallel execution. Based on this mechanism, parallel control is capable of facilitating the convergence between artificial and actual systems. Moreover, self-learning optimal control has pioneered the theoretical analysis of parallel control, laying a solid foundation for the subsequent research and wide applications (Wei et al. 2022).

With descriptive sensing, predictive sensing, and prescriptive sensing (Liu et al. 2022b) serving as the key parts, parallel sensing emerges as a novel theoretical framework for designing next-generation intelligent sensors (Shen et al. 2022b; Liu et al. 2023a). Among them, descriptive sensing focuses on building high-fidelity digital sensing systems in cyberspace, which can not only enable virtual data generation in offline mode but also handle real-time data processing for online emergency situations; predictive sensing leverages computational experiments conducted in cyberspace to enhance perceptual performance and monitor the operation of sensors; prescriptive sensing provides professional guidance for physical sensors through the generated “deep intelligence”. Finally, they jointly establish an integrated closed-loop control between actual and artificial sensing systems. To facilitate further systematic studies, the experimental platform named DAWN (Digital Artificial World for Natural) (Liu et al. 2023c) is developed. As illustrated in Fig. 18,

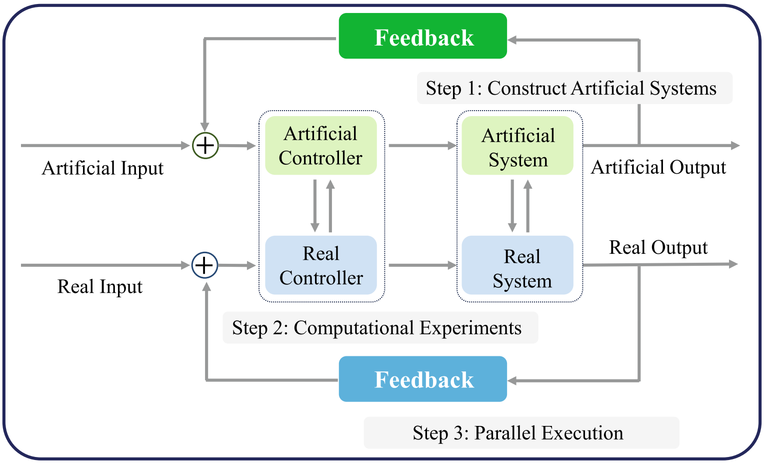


Fig. 17 The basic framework of parallel control

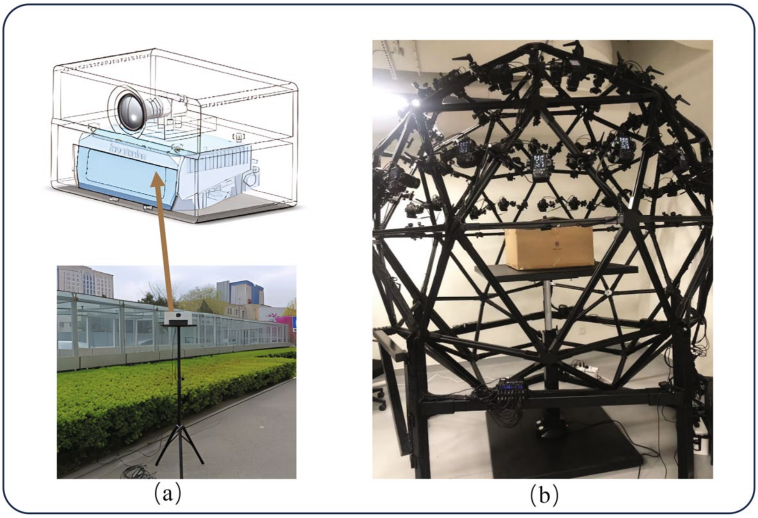


Fig. 18 **a** The hardware prototype of parallel LiDARs. **b** Parallel light fields

DAWN mainly supports two projects: parallel LiDARs and parallel light fields. Between them, parallel LiDARs represent a new generation of intelligent LiDAR sensors that integrate physical, digital, and social spaces (Liu et al. 2022a, 2022c, 2023b, 2024), while parallel light fields emphasize constructing more realistic artificial scenarios (Shen et al. 2022a, 2024).

In response to the difficulties in low efficiency and strategy selection of machine learning, parallel learning (Li et al. 2017) has developed a novel machine learning framework, where the key structure involves a cyclic interaction among data, knowledge, and actions. Figure 19 depicts the technological process of parallel learning. Firstly, a plethora of "new data" will be generated through the original "small data" in physical systems and software-defined artificial systems. Then, "small data" and "new data" are integrated to obtain "big data", paving the way for better machine learning models and parameter optimization. During the model learning phase, the knowledge for solving complex system tasks is obtained through descriptive, predictive, and prescriptive subsystems. Afterwards, the acquired knowledge is applied to guide physical behaviors and generate new data, which serves as the basis for knowledge updating and ensures iterative learning. Finally, parallel learning enables continuous iterative optimization to specific objectives by fusing data, knowledge, and actions into closed-loop optimization systems, thereby increasing the intelligence level of complex systems.

For complex systems in physical space, the adopted industrial products are usually required to conduct extensive validation and testing to ensure their reliability. However, traditional testing methods are facing significant challenges in terms of robustness and efficiency, where high costs in time, labor, and economy hinder the advancement of testing processes. Therefore, parallel testing (Li et al. 2019) introduces the "human-in-the-loop" testing mechanism and incorporates adversarial learning to get rid of the heavy reliance on human experts' prior knowledge and experience. Also, machine gaming can autonomously explore and generate new testing tasks as well as configure task scenarios and data, thus conducting comprehensive and efficient testing verification of both systems and products.

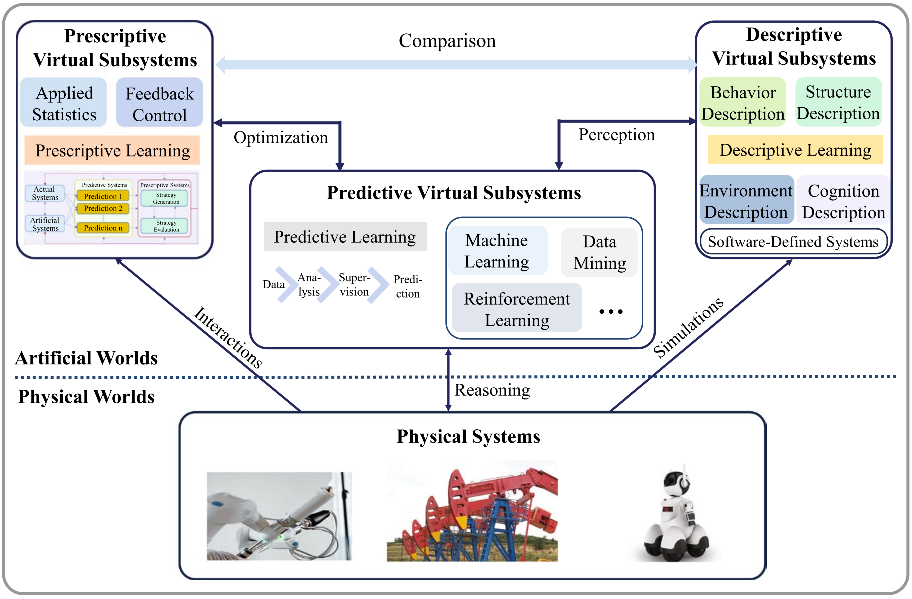


Fig. 19 The ACP-based parallel learning

The parallel testing has been utilized in iVFC (Intelligent Vehicle Future Challenge) and provided significant support for this international competition.

5.5 Parallel Societies

As the digitalization of resources in social institutions becomes more widespread, a vast amount of socio-economic information is dynamically presented in real time to decision-makers, researchers, and even the general public. This information, characterized by its wide impact and rapid dissemination, requires a timely and effective process to ensure that decisions are made with immediacy and comprehensiveness. However, such issues cannot be fully and accurately predicted or analyzed due to their social and engineering complexity, making computational theories and methodological systems indispensable in addressing these challenges of complex socio-economic systems.

Correspondingly, how to innovate social service management through various new information technologies has become a significant question that concerns national prosperity, development, and social stability and security (Wang et al. 2007). As shown in Fig. 20, the ACP-based parallel societies have addressed the issue of social services and resource planning posed by dynamic network groups. This parallel mechanism can facilitate virtual-real interactions between artificial and actual social systems, and formalize, compute, as well as visualize relevant knowledge and experience from both physical and mental worlds. Through parallel execution, predictive reasoning, inductive learning, and closed-loop feedback will be guaranteed and realized, thereby fulfilling the goal of more flexible, focused, and convergent social management.

Meanwhile, with computers as laboratories for socio-economic systems, parallel economic systems (Wang 2020b) are introduced to apply parallel theories for studying

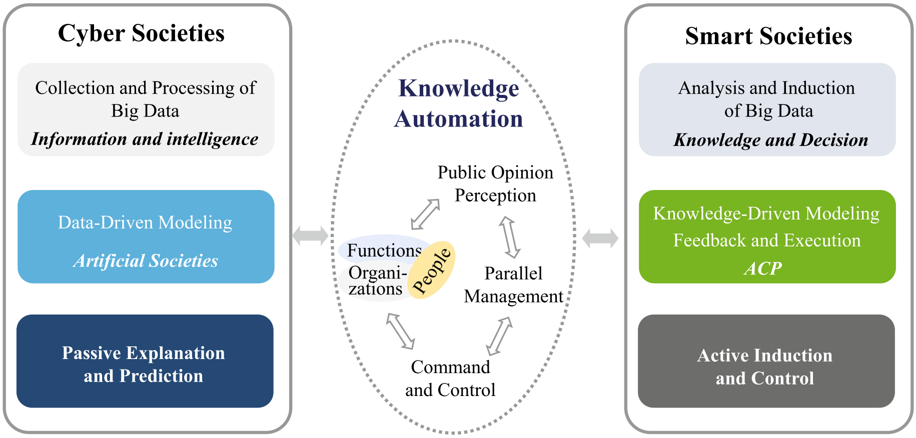


Fig. 20 The infrastructure of parallel societies

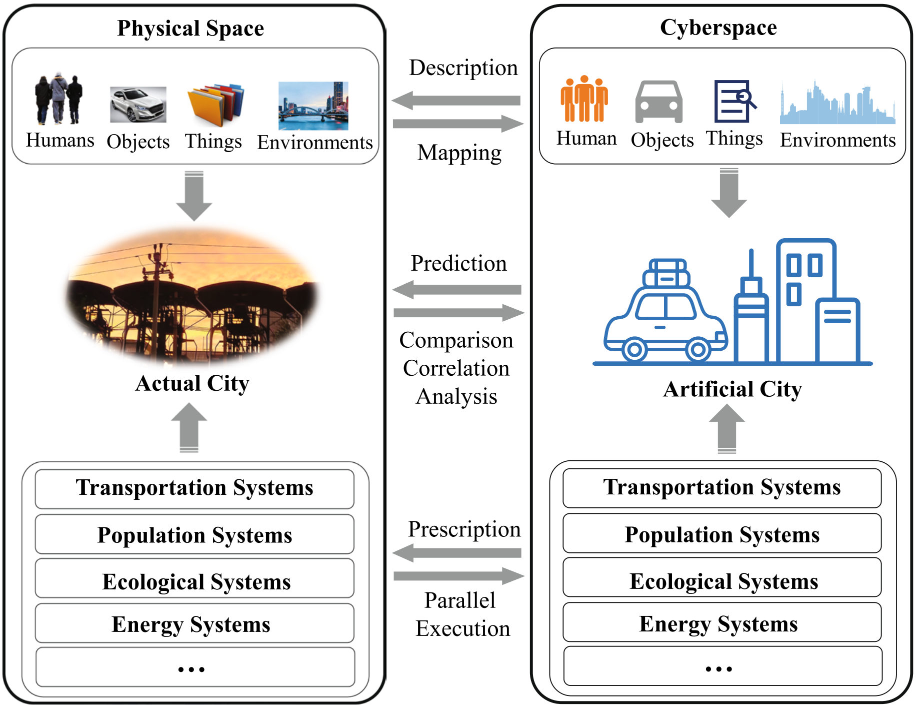


Fig. 21 Parallel city characterized by virtual-real interactions

complex systems into the research of socio-economic issues. By integrating experimental economic methods with economic computational experiments, a computational research theory and system is developed through PI, where CPSS has triggered an explosive growth in data scale and increased the degree of data complexity (Chen et al. 2021; Yu et al. 2021). Correspondingly, the obtained big data that contains abundant social signals and governmental information will be utilized to effectively guide and control the physical society, thereby fostering the emergence of a novel social management industry in the future (Wang et al. 2015).

City, as a prototypical socio-ecological system, is another vital social field that consists of humans, infrastructures, social relations, and complex environments (Han et al. 2021a; Zhao et al. 2022c; Han et al. 2021b; Yang et al. 2021b). Within the realms of the parallel city (Lv et al. 2019b) (Fig. 21) and parallel societies (Wang et al. 2020), every entity, including individuals, devices, and macro systems, will possess its digital counterpart that coexists or operates in parallel with its physical entities. Both parallel city and parallel societies can integrate these digital representations to simulate the operational processes of urban or social environments through strategic planning. This allows for the selection of optimal solutions to complete specific tasks of cities or societies, such as the construction of urban infrastructure, and the management and control of civic activities.

5.6 Parallel Agriculture

Generally, the ecosystem consists of the physical ecosystem, artificial ecosystem, and social ecosystem, where the artificial ecosystem can also be interpreted as a digital ecosystem/information ecosystem/knowledge ecosystem (Wang and Wang 2020). Among them, agriculture is an integral component of ecological systems and crucial for national security. However, due to factors such as external disturbance, market circumstances, and national policies, agricultural production exhibits strong uncertainty and complexity. The natural environment exerts a profound influence on plants, shaping their growth and development. Human management interferes with the natural environment and shapes the success and sustainability of agricultural practices. Therefore, a parallel system of agriculture consists of the components of plants, environments, and management, as in Fig. 22. Compared to Agriculture 4.0 which focuses on the adoption of big data, IoT, and cloud computing, parallel agriculture (Kang et al. 2023, 2018), or Agriculture 5.0, is expected to take into account the social dimension, giving the scientific meaning to AgriVerse (Wang et al. 2022b).

While currently, most AI applications in agriculture are on phenotyping, which is to obtain the morphological or physiological states of the crop, for AgriVerse, a key role of AI approaches is to serve the decision-making (Wang et al. 2022b) in smart agriculture, such as for the planning of planting schedules, autonomous environment control of greenhouses, etc. Since nowadays the quality of food is of high priority because of pollution and

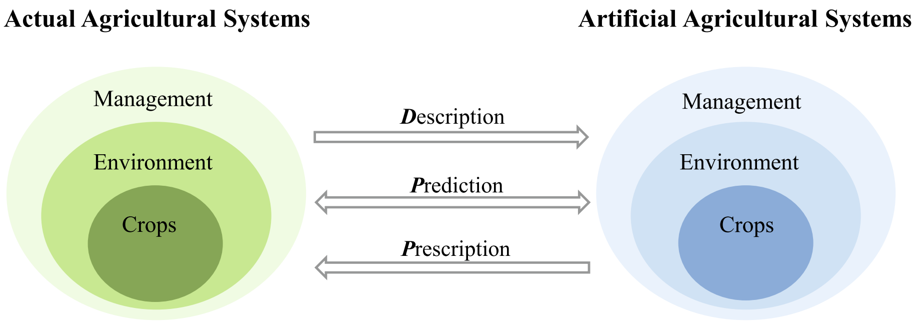


Fig. 22 The systematic design of parallel agriculture

chemical agricultural inputs, trust is a scarce resource among agricultural stakeholders. For this reason, DAOs are identified as a key technology to support Global Food Security and Sustainability (Wang et al. 2022b, 2023j).

In building the artificial systems of agriculture, the description of crops and their interaction with the environment is a key component. In the past two decades, we have developed the GreenLab plant growth model that computes the two basic processes of plant development and growth (Wang et al. 2024a). The model parameters can be estimated inversely from the organ-level phenotypic data, which is an ideal feature for building parallel plants (Wang et al. 2024a), or digital twins of plants (Kang et al. 2012). In the context of agricultural applications, the internal behavior of plants, i.e., the organ formation, the biomass partitioning, and yield formation, is of high importance aside from the visual output (Kang and Wang 2017), which paves the way for training, control, and experiments (Wang et al. 2022b).

With superior characteristics like decentralization, immutability, and transparency, blockchain (Yuan and Wang 2016) is therefore introduced as a novel encrypted technology to store and analyze big data and social signals for artificial ecosystems. However, the traditional blockchain shows its deficiency in terms of uncertainty, diversity, and complexity, necessitating powerful evaluation, optimization, and innovation solutions. Under this situation, one promising plan is the ACP-based parallel blockchain (Wang et al. 2018b), which can construct more than one artificial blockchain system and conduct experiments for specific blockchain systems. In addition, this parallel framework enables the optimization without negative impacts of direct implementation on physical blockchain systems. Meanwhile, through virtual-real interactions and closed-loop feedback between artificial and actual blockchain systems, parallel blockchain can test the feasibility of technologies and search for optimal strategies, providing significant support for better practical applications.

5.7 Parallel Management

Management can be interpreted as the science of deploying resources to attain specified objectives, where humans are one key element that must be considered. However, human subjectivity and irrationality usually conflict with the basic requirements of scientific principles, making "management" difficult to be accurately and clearly defined. Meanwhile, with the rapid social progress and updates in advanced technologies, related enabling techniques have become increasingly complex, and greatly increased the difficulty level of management. Hence, in an era full of AI breakthroughs, how to transform management science, innovate management technologies, and promote management modes toward a more sustainable direction becomes an urgent issue. To answer this question, parallel management (Wang 2022c) is introduced to provide new insights. With the integration of intelligent technologies like virtual-real interactions, parallel management aims to enable knowledge works measurable and guide quantified social actions in a human-centered and complex manner, thereafter establishing a trustworthy and reliable smart management ecology through DAOs.

Enterprises serve as the micro-units of the national economy and are the driving forces behind management progress. However, traditional enterprises face multiple challenges in their operational processes. On one hand, they lack comprehensive and accurate methods for acquiring and analyzing big data from their environments; on the other hand, they struggle to promptly integrate and adjust existing data, resources, and workflows, leading to the neglect of human and societal factors' impact on the business. The complexity of personnel

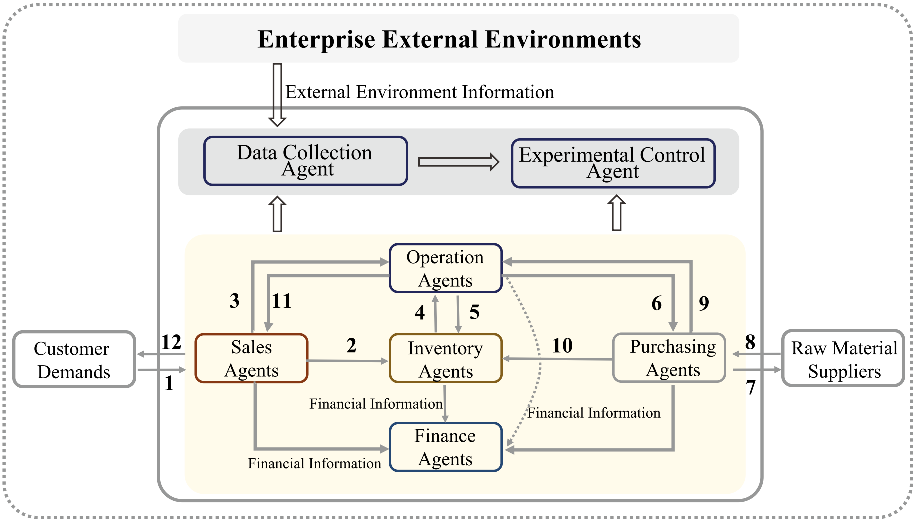


Fig. 23 The basic operational workflow of a parallel enterprise

and relational networks, the subjectivity of management processes, and the dynamic nature of external environments are calling for new management forms in enterprises.

Based on PI, parallel enterprise (as depicted in Fig. 23) can model the enterprise's procurement, inventory, production, sales, after-sales, and finance processes (Qin et al. 2017) through technologies like multi-agent systems. Also, it utilizes data collection and decision-making technologies to simulate the entire operational process of business. Through computational experiments, it quantitatively analyzes the impact of changes in different scenarios on the operational costs of the enterprise. By utilizing parallel execution to rapidly update and iterate management strategies, the integration of virtual-real interactions within parallel enterprises is realized, driving the continuous improvement in the quality of business operations.

5.8 Parallel Military

The advent of parallel military has marked a significant shift in the command & control (C2) paradigm, stressing the integration of both cyberspace and physical space to enhance operational capabilities. The notion of Command & Control 5.0 (CC 5.0), introduced by Wang (2012b), encapsulates the core idea of a parallel military, where virtual and actual interactions are seamlessly intertwined. This integration is underpinned by ACP and CPSS to serve as the foundational theories and technologies for intelligent military forces and organizations. Meanwhile, the essence of CC 5.0 (Wang 2015a) lies in the agility, focus, and convergence of military operations, transcending traditional C2 to a spectrum of intelligent functions. These functions extend beyond mere command and control to include sophisticated analysis, timely decision-making, and predictive analytics, which are crucial for managing the complexity and uncertainty inherent in modern warfare.

The integration of CPSS in military operations further facilitates real-time feedback mechanisms and enables the closed-loop system that is responsive to the dynamic nature of battlefields. This paradigm shift is also reflective of broader technological trends, such as the

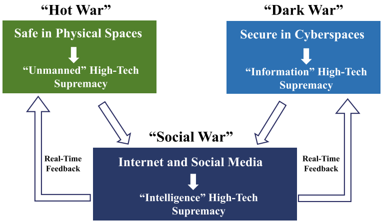


Fig. 24 CPSS-based parallel military systems

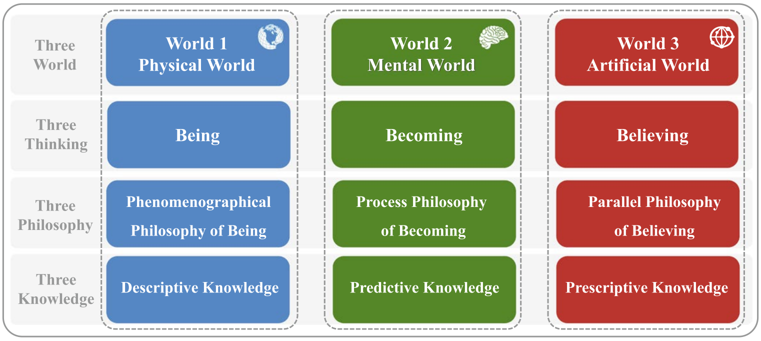
IoT (Thakur et al. 2023), cloud computing (Ullah et al. 2022), and big data analytics (Himeur et al. 2023), which are redefining how military strategies are formulated and executed.

Figure 24 presents the conceptual framework of the parallel military for cross-domain combat operations in CPSS, illustrating the integration of physical, cyber, and social worlds into a cohesive strategic approach. The figure encapsulates the "new trilogy" of warfare, which includes "hot war", "dark war", and "social war", highlighting the interconnectivity and real-time feedback mechanisms that are pivotal in contemporary conflict scenarios. In "hot war", the focus is on direct military engagements where physical force is applied. The "dark war" involves stealth and intelligence operations, which are usually conducted in the digital realm of cyberspace. The "social war" represents the role of public opinions and media influence, which can sway the perception of conflicts and affect strategic outcomes. The framework proposed in Fig. 24 underscores that a unified CC structure can orchestrate complex military operations across multiple domains. It promotes a paradigm shift from traditional and rigid approaches to a more integrated and adaptive model, where the lines between physical and artificial operations are blurred, and social dynamics are integrated to strategic decision-making. The synchronized planning and execution across cyberspace and physical space is particularly important in the context of modern warfare, where cyber-attacks and information operations can be as decisive as kinetic military actions. Finally, both the "intelligence" and "defense" capabilities of military applications can be developed and strengthened through PI.

5.9 Parallel Philosophy

The launch of ChatGPT in 2023 has opened a new era of intelligent technologies. It swiftly garnered widespread attention and propelled the development of intelligent technology far ahead of information technology. Meanwhile, industrial technology also remains the foundation of the real economy. And the coexistence of three ITs is bound to be the norm in the future society and is deeply rooted in the philosophical foundation of Karl Popper's theory of reality. Building upon this theory, Wang has proposed a novel scientific philosophical concept called parallel philosophy for the evolving intelligent technology (Wang 2020b). It promotes the transition from existing process philosophy towards parallel philosophy, achieving a shift from the concepts of *Being* and *Becoming* to *Believing*.

As illustrated in Fig. 25, parallel philosophy establishes a comprehensive theoretical framework that contains descriptive, predictive, and prescriptive knowledge, laying a solid foundation for the development of intelligent technology (Wang 2021c). Parallel thinking and parallel cognition are the core of parallel philosophy. Parallel thinking requires individuals to offer different viewpoints on the same issue, thereby preventing the negative impact



Three World	World 1 Physical World	World 2 Mental World	World 3 Artificial World
Three Thinking	Being	Becoming	Believing
Three Philosophy	Phenomenographical Philosophy of Being	Process Philosophy of Becoming	Parallel Philosophy of Believing
Three Knowledge	Descriptive Knowledge	Predictive Knowledge	Prescriptive Knowledge

Fig. 25 Parallel philosophy: Being, becoming, and believing

of adversarial thinking. Based on parallel thinking, various intelligent methods are applied to CPSS and collectively constitute parallel cognition, which provides new approaches for addressing complex social issues.

6 The Goal of Parallel Industry and Parallel Societies

The history of human development indicates that the advancement and evolution of most pioneering AI techniques are aiming at improving industrial efficiency and promoting digitalization. Indeed, these advanced technologies have not only enhanced industrial productivity but also brought great convenience to human lives. However, these technologies overlook the unique and important roles that humans play, resulting in the neglect or underestimation of human factors in both industrial and social production and leading to certain limitations. Under this circumstance, parallel industry and parallel societies are supposed to provide effective solutions. By projecting PI into traditional industrial and social systems, parallel industries and parallel societies will emphasize the collaborative intelligence between humans and AI technologies, while encouraging human involvement in the decision-making processes, thereby facilitating more intelligent and human-in-the-loop developments.

In addition, one should note that integrating the highly uncertain and inexplicable social factor into the system design will raise significant ethical and legal issues (Ge et al. 2023; Ortega-Bolaños et al. 2024), which could lead to catastrophic consequences if not addressed properly. These issues involve ensuring that the decision-making of complex systems should adhere to ethical standards and legal regulations, as well as managing the social impacts and risks that these systems may provoke. Therefore, researches on AI, e.g. brain computer interfaces (BCIs) (Livanis et al. 2024), must focus on resolving these issues to guarantee the sustainable development of PI and benefit both industries and societies.

That is, leveraging the progress in AI technologies and significant programs, such as foundation models, generative AI, digital twins, extended reality (XR), WIDE,[1] HYCON,[2] and PATH,[3] the PI-based mechanisms can provide novel thinking for mitigating human neglect in current AI frameworks, and finally construct the "6S"-based parallel ecosystems.

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[1] https://cse.lab.imtlucca.it/hybrid/wide/.

[2] https://portal.research.lu.se/sv/projects/hyconhybrid-control-taming-heterogeneity-and-complexity-of-networ/.

[3] https://www.ca-path.com/.

7 Conclusion and Future Perspective

With the ever-growing demands for better lives, AI has experienced unprecedented changes. Grounded in CPSS and ACP, this paper introduced the evolution and key concepts of PI. Firstly, the history of CPSS was discussed to illuminate its origin and developments. Then, both the fundamental framework and technological implementations of PI were highlighted. Driven by PI, the basic elements of Industry 5.0 were listed to exhibit its potential in constructing a new industrial roadmap. Additionally, applications of PI across various domains, such as transportation, healthcare, and agriculture, were outlined. All of these have verified that PI will be vital in future AI developments and advancements.

Meanwhile, a series of foundation models like ChatGPT and GPT-4 have opened a new era of technological revolution and propelled the transition from algorithmic intelligence to linguistic intelligence. During this process, plenty of cutting-edge technologies (Kaur et al. 2023) and innovative AI works, including digital assistants (Ribino 2023), metaverses (Mu et al. 2024), testbeds (Mokhtarian et al. 2024), metareasoning (Herrmann 2023), the program on“Future Road System[4]”, and the idea of “robot imagination (Zhang et al. 2024)”, are expected to play indispensable roles. Following the philosophical theory of “the DAO, the Speakable DAO, the Eternal DAO” (Wang et al. 2023c), the driving engine of future development will originate from imaginative intelligence that focuses on human creativity. As one steps into this new era, human imagination will bring in novel ideas, new solutions, and infinite possibilities, greatly accelerating technological innovation and social developments. Further, to optimize this process, both operation modes and social governance should be redefined to be more flexible and intelligent. And that’s how the world can move towards “TRUE DAO (TAO)” (Li et al. 2023a) and usher in the era full of opportunities.

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Data availability Not applicable.

Declarations

Conflict of interest The authors have no Conflict of interest to declare that are relevant to the content of this article.

Ethical approval Not applicable.

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