Perspective

The DAO to MetaControl for MetaSystems in Metaverses: The System of Parallel Control Systems for Knowledge Automation and Control Intelligence in CPSS

Fei-Yue Wang, *Fellow, IEEE*

Briefing**:** An investigation and outline of MetaControl and DeControl in Metaverses for control intelligence and knowledge automation are presented. Prescriptive control with prescriptive knowledge and parallel philosophy is proposed as the starting point for the new control philosophy and technology, especially for computational control of metasystems in cyber-physical-social systems. We argue that circular causality, the generalized feedback mechanism for complex and purposive systems, should be adapted as the fundamental principle for control and management of metasystems with metacomplexity in metaverses. Particularly, an interdisciplinary approach is suggested for MetaControl and DeControl as a new form of intelligent control based on five control metaverses: MetaVerses, MultiVerses, InterVerses, TransVerse, and DeepVerses.

Keywords**:** MetaControl, MetaSystems, Metaverses, CPSS, DAO, DeControl, Prescriptive Control, Parallel Control, Computational Control, Knowledge Automation, Control Intelligence, Parallel Intelligence.

I. Introduction

I Would like to share a different story about the origin of metaverses, with a new vision for their future, and their potential implication and significance to the field of control intelligence and knowledge automation.

Metaverse? Virtually real or really virtual? The modern origin of metaverses starts from Norbert Wiener's "CC": The *Circular Causality* or feedback in the sense of *Teleology*, that is, feedback-controlled purpose, where "the observed outcomes of actions are taken as inputs for further action in ways that support the pursuit and maintenance of particular conditions" (see Fig. 1) [1], [2]. Initially, CC is considered as the core concept of Wiener's *Cybernetics* (see Fig. 2) [2], originally a study of "teleological mechanism" for regulatory and purposive systems in living beings and machines. Through Macy Conferences, CC motivated the creation of "MP Model" for *Artificial Neural Networks* by Warren McCulloch and Walter Pitts [3], [4] in 1943 (see Fig. 2), and contributed significantly to the establishment of modern computer architecture in 1945, the *von Neumann model* according to von Neumann himself (see Fig. 3) [3], [5]. During the World War II, through the close contact and interaction between Wiener and Claude Shannon, CC has influenced the formation of concepts and theories of *communication, cryptography, and information* [3], [6]–[12]. Near the end of the World War II, we witnessed the incarnation of personal computers, hypertext, Internet, World Wide Web, knowledge base software, and metaverses, the concept of *Memex* [13] for "memory-extender" and "automatic personal filing system" by Vannevar Bush, Wiener's colleague at MIT, and two of them had worked closely on design and construction of computing devices before and during the war [3]. After the World War II, CC and its Cybernetics went on to inspire H. S. Tsien (Xuesen Qian)'s *Engineering Cybernetics* [14] in 1954 for modern control theory and methods (see Fig. 3), Lee Yuk-Wing's *Statistical Communication Theory* (see Fig. 3) [15] for modern communication technology and systems from early 1930s to 1960s, the "*Virtual Reality*"

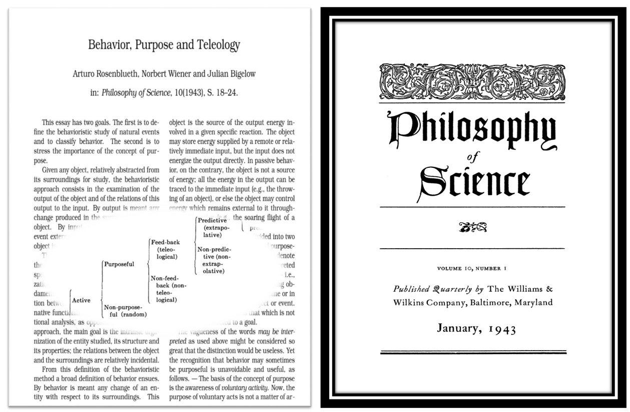

Fig. 1. Circular Causality in Teleology: Origin of Cyberspace and Metaverse.

Citation: F.-Y. Wang,"The DAO to MetaControl for MetaSystems in Metaverses: The System of Parallel Control Systems for Knowledge Automation and Control Intelligence in CPSS," *IEEE/CAA J. Autom. Sinica*, vol. 9, no. 11, pp.1899-1908, Nov. 2022.

F.-Y. Wang is with The State Key Laboratory for Management and Control of Complex Systems, Chinese Academy of Sciences, Beijing, 100190, China, and also the Macao Institute of Systems Engineering, Macau University of Science and Technology, Macao, 999078, China, (e-mail:feiyue.wang@ia.ac.cn).

Digital Object Identifier 10.1109/JAS.2022.106022

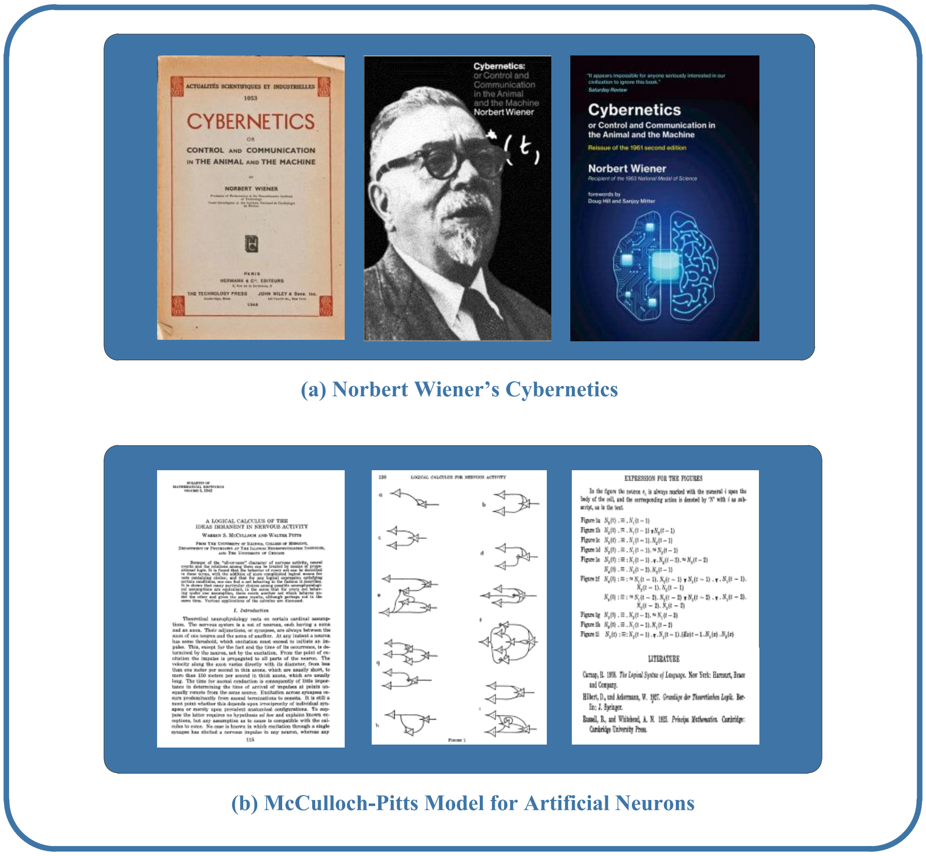

Fig. 2. Cybernetics and Neural Networks: CC's First Two Major Inspirations.

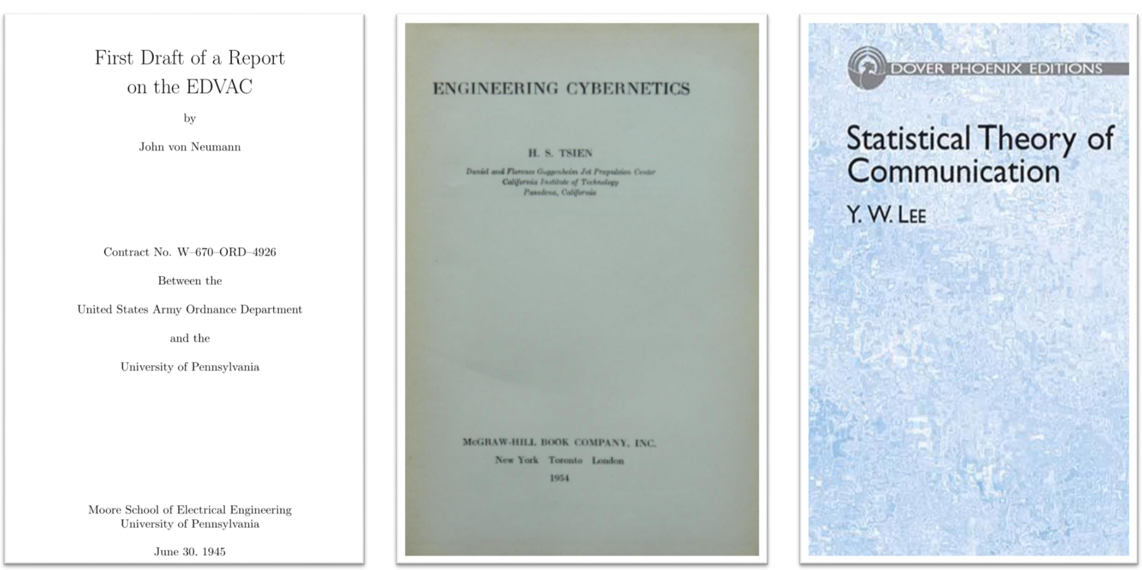

Fig. 3. The CS from CC: Computer Systems/Sciences, Control Systems/Sciences, and Communication Systems/Sciences.

Project at Wright-Patterson Air Force Base initiated in 1953 and demonstrated in 1982 in the form of VCASS (Visually Coupled Airborne Systems Simulator) [16] by "Grandfather of Virtual Reality" Thomas Furness. In 1989, Tim Berners-Lee introduced World Wide Web as a document management system at CERN and opened to the public in 1991 [17]. That same year, David Gelernter published his *Mirror Worlds* [18], technically marking the birth of metaverses as well as digital twins (see Fig. 4). Clearly, those efforts have formed the scientific and technical foundation for our dreams and visions of metaverses and their future. Especially, they have provided all CS we need for MetaControl in Metaverses: Computer Science/Systems, Communication Science/Systems, Control Science/Systems, Cognitive Science/Systems, and Cyber Space/Systems.

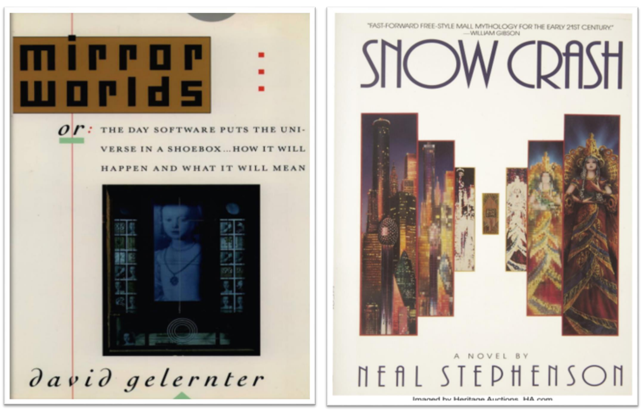

Fig. 4. From Mirror Worlds to Metaverse in Snow Crash.

In the cultural and social domains, CC has spawned the cyberculture, especially the cyberpunk that leads to the general spirit and specific term for *cyberspace*, originally "an effective buzzword" in science fictions that essentially seems evocative and meaningless with no real semantic meaning, as in Vernor Vinge's *True Names* (1981, a fully fleshed-out concept of cyberspace in spirit), and William Gibson's *Burning Chrome* (1982, where term cyberspace is officially introduced) and *Neuromancer* (1984, where cyberspace takes off and gets its popularity) (see Fig. 5). In the end, Neal Stephenson luckily receives today's highlight and most of the social credits by introducing term *Metaverse* in his fiction *Snow Crash* in 1992. To me, Cyberspace and Metaverse are the True Names for the same evocative and meaningless buzzword, Stephenson has contributed nothing technically, but he deserves a full credit for predicting, 30 years ago, today's anti-globalism sentiment in USA and fast delivery industry in China (Yes, it was actually Los Angeles in *Snow Crash*) in the first chapter of his book.

The Metaverse has become the new buzzword and new fashion of the day. We must face this phenomenon, and have our own dreams of *One Thousand and One Night* about various metaverses from the perspective of new intelligent science and technology. It will be the job of our engineers and scientists to endow metaverses with real semantic and technical meaning. I was lucky to encounter the idea of using Monte Carlo Method for conducting computational

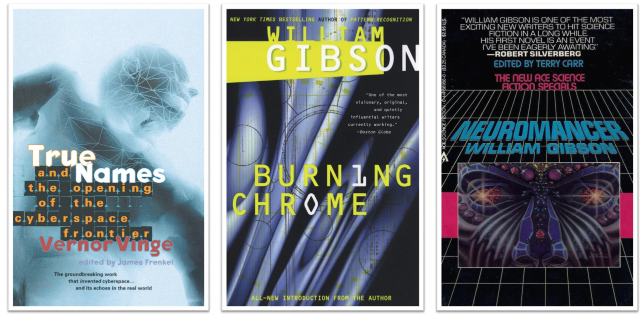

Fig. 5. Before Metaverse: From True Names, Cyberspace, to Neuromancer.

experiments for fractural and fatigue experiments of metals in 1982 and Gaussian Random Fields for describing geometrical imperfection of plates and shells in analyzing their vibrational behaviors from 1983 to 1986, when I was a researcher in mechanics, control, and robotics; then the concepts of Shadow Systems for modeling and control unmanned robotic systems in Lunar/Martian environments in 1994, when I was working on autonomous and intelligent systems for NASA projects, and Parallel Systems and Parallel Intelligence in CPSS (Cyber Physical Social Systems) in 2004 for control and management of systems complexity for complex systems [19], [20], when I started to investigate issues and methods for complexity science. Based on my own experience in research and development over the past four decades, I would like to present my own vision for the impact and implication of metaverses, parallel intelligence, mirror worlds, shadow systems, digital twins, as well as blockchain, smart contracts, Web3, DAO (Decentralized Autonomous Organizations), DeSci (Decentralized Autonomous Science Movement), and DeSoc (Decentralized Autonomous Societies) to the future development of automatic control and intelligent automation. My hope is that this work would lead to the start of a new and intensive discussion in control and automation.

II. Parallel Intelligence and Metaverses: New Philosophy

My position is simple: For the new age of intelligent industries, Intelligent Technology such as Artificial Intelligence alone is not good enough, we need a new philosophy and a paradigm shift in our thinking in order to fulfil our mission for this new age. First of all, we need to adapt in our thinking Karl Popper's Three Worlds Model of reality, i.e., our reality is consisting of three interactive worlds: World 1 for physical world, World 2 for mental world, and World 3 for artificial world. Secondly, we need to extend our philosophy of science and technology from "*Two Bs*" to "*Three Bs*": From *Being, Becoming to Believing*. As illustrated in Fig. 6 , we should believe, not ideologically but technologically, in terms of our *Descriptive Knowledge* with *Phenomenographic Philosophy* of Being around World 1, *Predictive Knowledge* and *Process Philosophy* of Becoming around World 2, *Prescriptive Knowledge* with *Parallel Philosophy* of Believing around World 3 [21]–[23] for Parallel Intelligence (see Fig. 7).

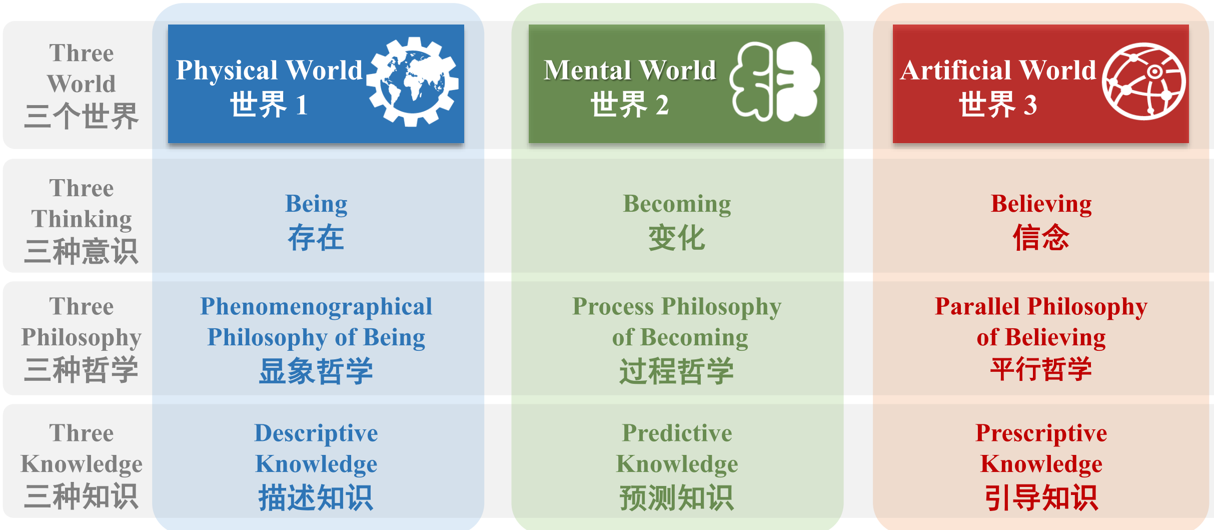

Fig. 6. The Parallel Philosophy of Being, Becoming, and Believing for Parallel Intelligence and Metaverses.

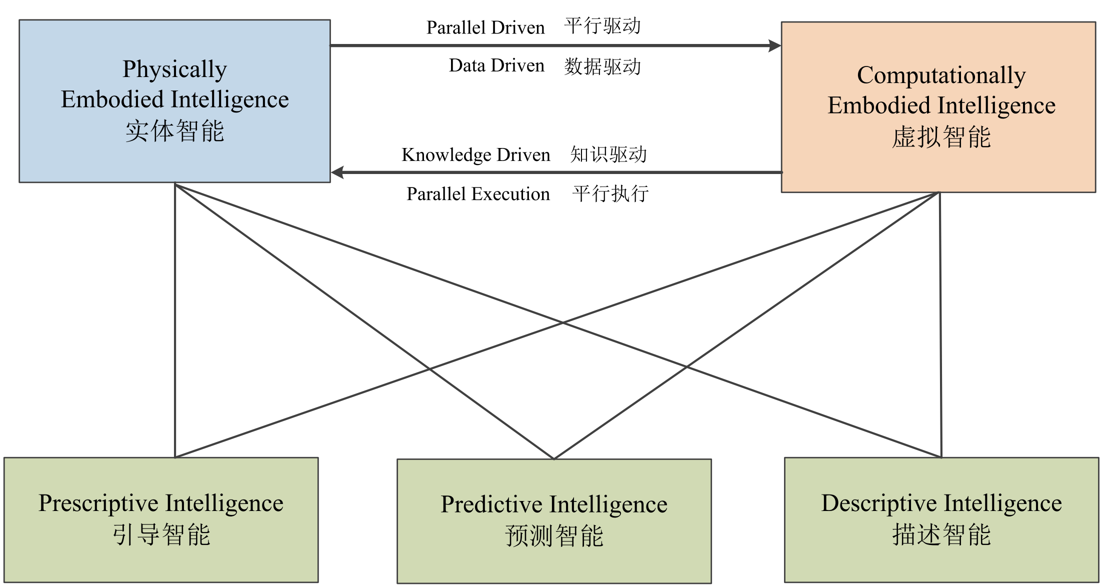

Fig. 7. Parallel Intelligence: Descriptive Intelligence, Predictive Intelligence, and Prescriptive Intelligence.

The interaction and feedback among the three worlds naturally lead to CC and CPSS for its execution, mainly emergence and convergence, in various causes, as presented in Fig. 8 . In CPSS [24], [25], the two essential concepts of complex systems and complexity science, the *emergence* and the *convergence* are able to be in the unity of opposites, for example, emerged in cyberspace while converged in physical space, or vice versa. Otherwise, without the support of the new space provided by CPSS, emergence and convergence might be in opposite and direct contradiction most of times, the main reason why most of the contemporary methods and approaches in complexity science bear few or no tangible results so far. Scientifically, metaverses are just actual and concrete attempts to implement CPSS, with the goal of enabling the closed-loop virtual-real or artificial-actual interaction and feedback, i.e., parallel control and parallel intelligence, in on-line real-time or offline causal time form, between cyber and physical spaces among the three worlds in the universe of reality, and in metaverses. With the advances in blockchain intelligence, smart contracts, DAO, DeSci, DeSoc, etc., parallel intelligence and metaverses would provide a deep and solid societal infrastructure for believing in intelligent industries and smart societies, and lead us to the "TRUE DAO" (DAO means journal or road in Chinese) for new IT, Intelligent Technology:

TRUE= ***T****rustable* + ***R****eliable* + ***U****seful* + ***E****ffective/****E****fficient*
DAO = ***D****ecentralized/****D****istributed* + ***A****utonomous/****A****utomated* + ***O****rganized/****O****rdered*
= ***D****ecentralized* ***A****utonomous* ***O****rganization*
= ***D****ecentralized* ***A****utonomous* ***O****peration*

The essence and significance of the TRUE DAO and its parallel philosophy are the establishment of scientific and technical foundation for the emergence of two new commercial commodities of mass production and mass circulation from World 3, *trust* and *attention*, and associated new tools and infrastructures for achieving a new level of productivity and efficiency and intelligence required for intelligent industries and smart societies. This has opened up a new world in the history of humankind: The Artificial World with Artificial Intelligence and New IT, Intelligent Technology, along with Information and Industrial Technology, where big data are new materials, robots and digital people are new workforce, and blockchain and smart contracts are new social norms and production relationship.

This would be a long but exciting way to go for professionals in control and automation, as well as in AI, robotics, and broad intelligent science and technology. As one might recall the belief of Herbert Simon, one of the founding fathers of AI, that attention and trust would never become commercial commodities of mass production and circulation due to the intrinsic limitation within human cognitive capacity, as bounded by George Miller's number of 7 plus or minus 2 for individual attention, and Robin Dunbar's circle of 150 plus or minus 50 for social trust. With the advance in parallel intelligence and metaverses, this would be changed, and we need to change our way of conducting research and development in control and automation accordingly.

III. DeSci for Control in CPSS: New Science

We need a new norm for conducting scientific activities in order to march safely into parallel intelligence and metaverses. We should integrate and apply three ITs effectively and in parallel, i.e., Old IT, Industrial Technology from 200 years ago mainly for developing the physical world; Past IT, Information Technology from 120 years mainly for developing the mental world, and New IT, Intelligent Technology from 60 years ago for developing the artificial world. However, the complexity involved in this process and diversified knowledge needed for its success demand a new approach for control education, research, and application, and DeSci for control and automation in CPSS might be essential for this purpose.

Traditionally, control and automation are organized and conducted around Centralized Science (CeSci) that based on centralized and hierarchical structures for fundings and operations, which are ineffective in handling the uncertainty, diversity, and complexity they are facing today, and increasingly and easily deviate from their original missions and goals. An example in control instruction: students still spend too much time on theoretical analysis of stability [26], convergence, controllability, observability, etc., of control systems over an infinite time horizon, those are good "virtual" properties to have for the old age control technology, and prerequisite for control thinking and control system design, but that are often with no chance of materialization in real applications, since no control process should be allowed for long operation without monitoring or supervision. Our current cloud/edge technology make real-time monitoring and supervision easy and economical, so we should no longer sacrifice real functionalities of control systems in order to meet their virtual performance requirements as in many of current control practices. However, my own experience indicates it is hard and sometimes even illegal to break away from the old thinking.

As illustrated in Fig. 9 , we can start from combining traditional CeSci with new DeSci to gradually break the oligarchies in control and automation, both in academics and industries or knowledge and practice, and build new platforms and networks for control science and technology that lead us from CeSci for Control, Control Science of Team Sciences (Control SciTS), Open Science for Control, to DeSci for Control Intelligence [25], [27] with the help of CPSS and its metaverses, blockchain, smart contracts, Web3, and DAO for both organizations and operations. At this point, more investigation and effort are urgently needed in this direction for revolutionizing the chain and ecology from the generation of control knowledge to the application of automation technology, and making knowledge automation, instead of physical automation as in today's industrial automation, as the new norm of intelligent industries.

IV. Parallel Control and MetaControl: New Control

There could be many approaches for implementing parallel intelligence and metaverses with DeSci and DAO for control and automation. To make it simple, here I would report my own investigation of MetaControl and its conjugate DeControl based on computational control and parallel control for decision-making and management of complex systems over the last two decades [28]–[31].

We can safely define MetaControl as a new control field that studies and applies metaverse technology to control and automation. However, the problem is that there is no agreeable definition on metaverses at this point. As for DeControl, it will be the new decentralized and distributed control technology and automation systems based on web3, blockchain, smart contracts, and DAO for both organizations and operations [32], [33]. They should be among the key technologies to make unmanned systems humanized and human systems mechanized and autonomous, as demonstrated by newly proposed federated control [34] and federated/crypto management [35]. Since the current trend of discussions appears to define metaverses as an application of web3 technology, the boundary between MetaControl and DeControl would be difficult to mark clearly. In general, MetaControl would be mainly for the purpose of convergence at the initial problem definition for control design and the final stage of control implementation, while DeControl would be mainly for the objective of emergence in the organization and coordination of people and resources, as well as in the monitoring and assessment of control performance during and after the control system construction in

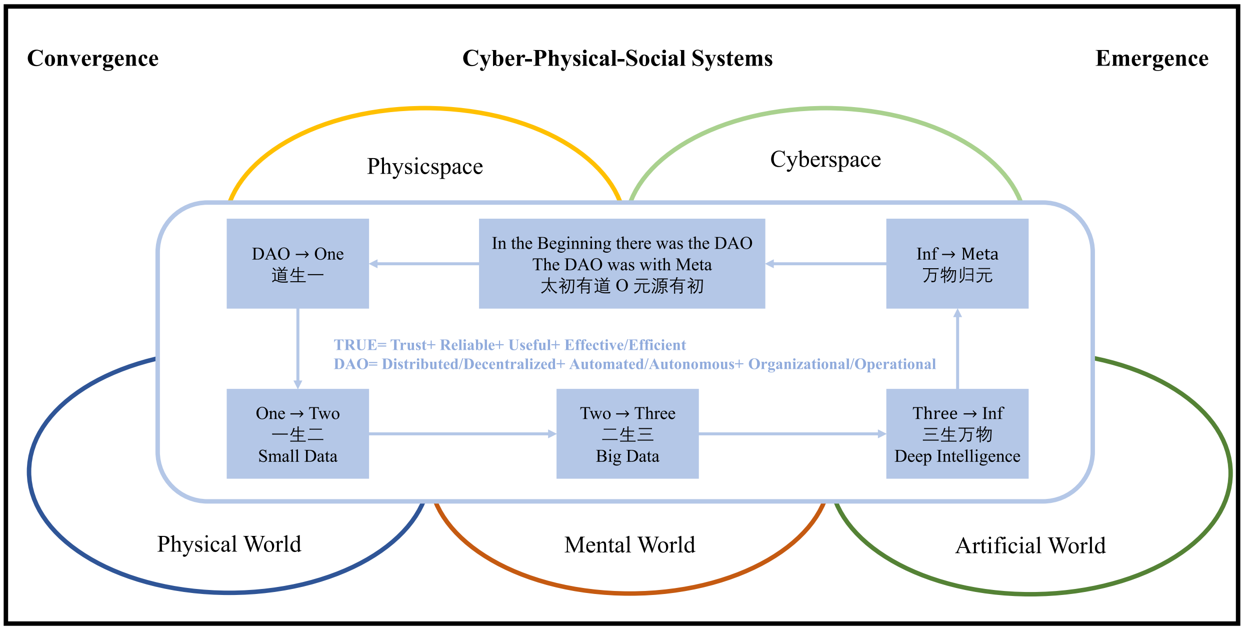

Fig. 8. CPSS and TRUE DAO for Parallel Intelligence and Metaverses.

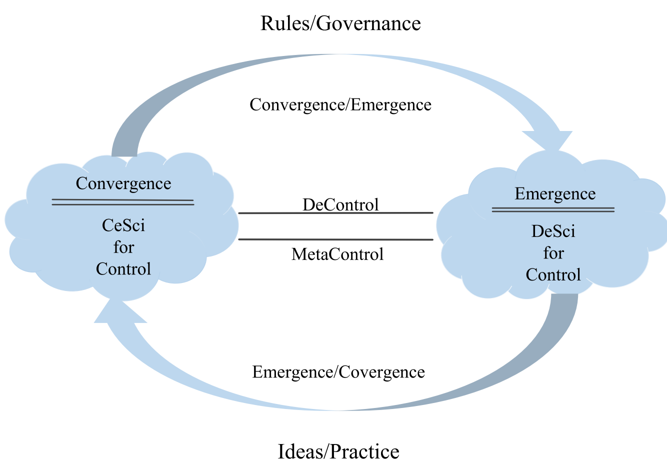

Fig. 9. From CeSci for Control to DeSci for Control Intelligence.

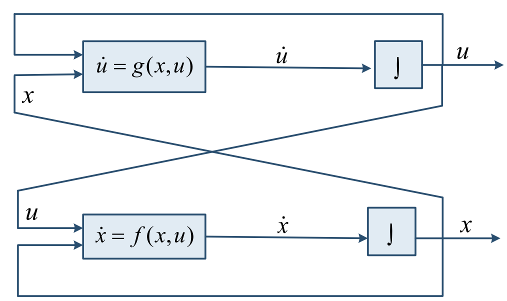

Fig. 10. Parallel Control in Metaverses.

metaverses or any real-virtual interactive environments. Based on this consideration, as CPSS for metaverses, we focus on parallel control for MetaControl and DeControl at this initial phase and address its mathematical structures in three levels of abstraction.

1) Parallel Control: Energy Oriented Optimal Control.

As specified in Fig. 10 , the state and control equations in this level can be presented as:

$$\dot{x} = f(x, u, d) \tag{1}$$

$$\dot{u} = g(u, x, r) \tag{2}$$

where x is the state vector of the systems to be controlled and u is the control vector of the controllers to be designed, while d and r are vectors for disturbances and references, respectively. Here f is the given state mapping for changes, and g is the control mapping for updating to be constructed.

The difference between the conventional control and parallel control is clear: we take the derivative of control, instead of control itself, in the framework of the parallel control system design, and control equation is differential, no longer algebraic. As the result, the systems to be controlled and the controllers to be designed are equal in forms mathematically, thus enable their separation and extra freedom in control design and implementation [29]–[31] [36]–[40]. Note that Eqs. (1-2) can be rewritten into a set of autonomous differential equations by treating state and control as the components of a united meta-vector, and the corresponding edge/cloud implementation fits naturally to the idea of MetaControl in Metaverses [36].

2) Parallel Management: Entropy Oriented Optimal Design.

As illustrated in Fig. 11 , the state and control equations in this level can be presented as:

$$\dot{N} = S(N, M, U) \tag{3}$$

$$\dot{M} = T(M, N, I) \tag{4}$$

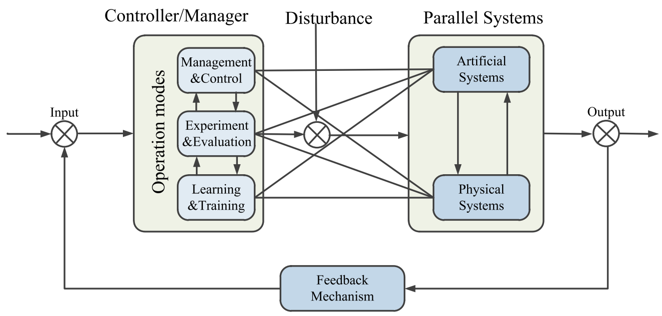

Fig. 11. Parallel Management in Metaverses.

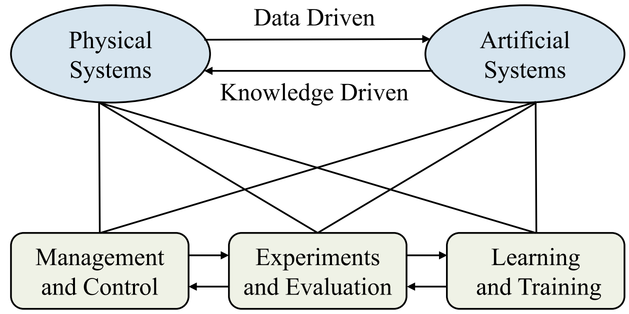

Fig. 12. Parallel Governance in Metaverses.

where N is the Newtonian descriptor of the actual systems to be constructed and managed, and M is the Mertonian descriptor of the artificial systems to be designed and implemented, while U and I are descriptors for uncertainty and instruction, respectively. Here S is the desired state mapping for transformation, and T is the management mapping for improvement to be designed. Normally, both S and T are considered to be fixed after their construction and implementation, but they are functional variables for the process of optimization.

The central issue here is optimal management through parallel management by construct S and design T. Newtonian descriptor is normally specified in the form of "Big Laws, Small Data", while Mertonian descriptor usually by "Small Laws, Big Data" [41]. Again, Eqs. (3) and (4) can be rewritten into a set of autonomous equations by treating Newtonian and Mertonian descriptors as the components of a united meta-descriptor for MetaManagement in Metaverses.

3) *Parallel Governance: Entanglement Oriented Optimal Prescription.*

As descripted in Fig. 12 , the state and control equations in this level can be presented as:

$$\dot{U} = N(U, V, D) \tag{5}$$

$$\dot{V} = M(V, U, R) \tag{6}$$

where U is the ensembler (defined as a set of variables for describing the state of an ensemble) of the Newtonian ensembles to be built and governed, and V is the ensembler of the Mertonian ensembles to be designed and implemented, while D and R are ensemblers for diversity and regulation, respectively. Here N is the desired ensemble mapping for evolution, and M is the governance mapping for sustainability to be designed. Generally, U and V reflect our estimation of potentials for Newtonian systems and values for Mertonian systems, and both N and M have to be refined after their initial construction and implementation.

The main issue here is optimal governance for parallel ecological systems, e.g., for parallel DAO, DeSci, DeSoc, by construct N and design M [42]. Similarly, Eqs. (5) and (6) can be rewritten as an autonomous differential equation by treating ensemblers as the components of a united meta-ensembler for MetaGovernance in Metaverses.

In the theory for parallel universes in quantum physics, there are four levels of parallelism [43]. Since the first level is the consequence of simple repetition due to the finite number of the quantum states in the infinite space, the remaining three levels share the similar structure as our three levels of abstraction for parallel systems. Categories and graphical neural networks, especially dynamic GNN with variable architectures, are good candidates for specifying equations in (1-6) [21], [23]. Prescriptive control, management, and governance need to be investigated and developed for those parallel systems at different levels of complexity.

V. The System of Parallel Control Systems for Knowledge Automation: New Technology

Differential equations for parallel systems alone are not enough in dealing with the complexity we are facing for complex systems in metaverses and CPSS. Discrete and event-based parallelism must be considered, and can be specified using parallel automata and schemata, as in the formal models for coordination structures of intelligent machines [44], [45],

$$PS = PS_1 || PS_2 || \cdots || PS_n. \tag{7}$$

Examples of various parallel finite state machines and Petri nets can be found in [45].

Equation based parallel systems, continuous, discrete, or event-based, provide a mechanism for abstracting and defining complex parallel processes for research, training, and education. In reality and application, we must use the System of Parallel Systems (SoPS), or the Parallel System of Parallel Systems (PSoPS), for modeling, analysis, and control as well as management, as SoS (System of Systems) for complex systems. For parallel control of complex systems or metacontrols in metaverses, we need to consider the System of Parallel Control Systems (SoPCS).

As illustrated in Fig. 13 , for most of actual control scenarios in CPSS or metaverses, the conventional sequential ordered process of modeling, analysis, and control or management would be violated due to the nature of spatio-temporal distribution, power decentralization, and autonomous behaviors. Instead, we must concurrently process various issues in systems modeling, systems analysis, and systems operation, since those activities would occur concurrently and simultaneously, simultaneous design, simultaneous implementation, and simultaneous feedback among them must be addressed, and in a distributed, decentralized, and autonomous fashion. This new

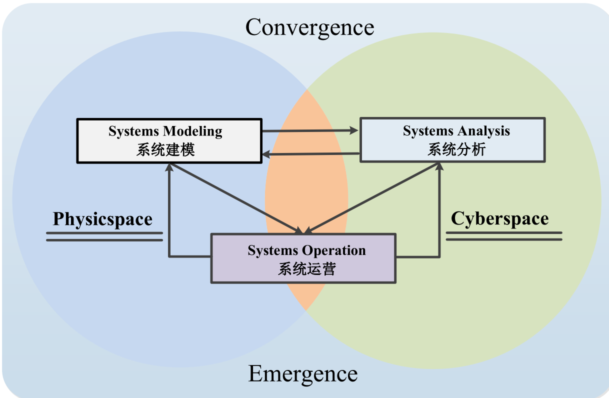

Fig. 13. MetaComplexity in MetaSystems: Sequential Operation vs Current Entanglement.

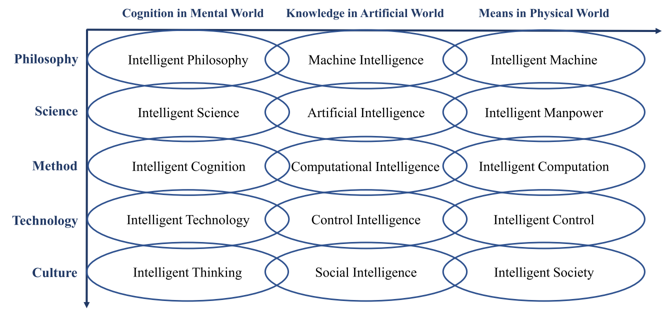

Fig. 14. The Interdisciplinary Nature of Control Intelligence and MetaComplexity.

type of phenomena would be the typical indication of future metacomplexity by metasystems.

The SoPCS approach is the only viable way to handle such metacomplexity. As in SoS, a SoPCS is the ensemble of multiple, independent parallel control systems in context as part of a larger, more complex system, a group of interacting, interrelated, interdependent or entangled components that form a complex and unified whole, particularly, in CPSS or metaverses for the purpose here.

Two recent technical advances will help us to break the traditional thinking and methods for the current SOS in systems engineering and operations research:

1) Big models or foundation models in deep learning of AI field for decision recommendation, especially federated transformers and their federations in federated ecology as proposed in the recent works [46]–[51];
2) New organizational, co-ordinational, and executional technology emerged in blockchain, smart contracts, web3, DAO, DeSci, and DeSoc, called OCE or ecological smart technology collectively [25], [27], [52]–[54].

OCE technology will provide great potential to enable SoPCS in constructing intelligent metasystems for humanized unmanned processes with human intelligence, and mechanized human operations with machine precision, the ultimate goal of metacontrol and decontrol in metaverses.

VI. Control Intelligence and Circular Causality: An Interdisciplinary Approach for MetaSystems Complexity

Our mission is control intelligence for intelligent control and knowledge automation, metacontrol, decontrol, and parallel control based on shadow systems, digital twins, artificial systems, metaverses, parallel systems, etc., are simply means or milestones for our goal along the way. I believe the first and most urgent application of metaverses is to revolutionize our control education, and make multidisciplinary, interdisciplinary, and transdisciplinary studies be the central issue and objective in our instruction for control and automation. As illustrated in Fig. 14 ., first of all, we need to redesign our undergraduate and graduate programs with new thinking, philosophy, science, method, technology, and least but not least, culture, and build our cognitive capacity, knowledge base, and means to work with the whole ecology in physical, mental, and artificial worlds.

The circular causality starts the modern cybernetic and computational intelligence 80 years, as a new way of thinking in the philosophy of science for ancient Greek teleology in terms of modern machinery. We should continue and advance, and put circular causality within the context of Karl Popper's three world model of reality, as shown in Fig. 15 , and rethink our Being, Becoming, and Believing in the simple and daily-life forms of What-IF and IF-Then, as encoding and decoding in our home base of electrical engineering.

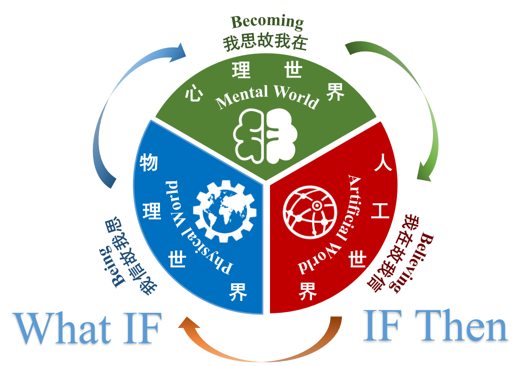

Fig. 15. Circular Causality in Popper's Three Worlds: What-IF-Then as ONE.

I would like to suggest the 5-verse approach for future control thinking and control intelligence, as presented in Fig. 16 : let us start our control problem in MetaVerse, build its artificial system in MultiVerse, conduct its computational experiments in InterVerse, and design its parallel execution in TransVerse, and finally implement metacontrol systems in DeepVerse. Through this metaprocess in metaverses, we produce big control data from small control data, and transform big control data into deep control intelligence for specific control problems [55].

VII. Conclusion

We need an open mind and new thinking for control and automation, and this article is a call of more discussion

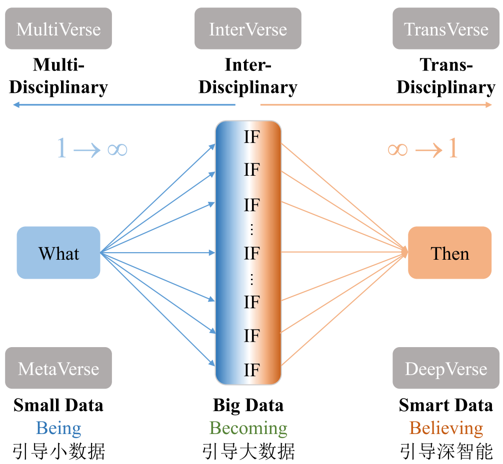

Fig. 16. The DAO to MetaControl and DeControl: MetaVerses, MultiVerses, InterVerses, TransVerses, and DeepVerses.

and deep investigation for control intelligence and knowledge automation for the coming future. For a control engineer, we have come up to what we are today by industrial automation or physical automation in the physical world, which has enhanced our physical power significantly. In order to move into a better tomorrow, we need knowledge automation in the mental and artificial world, that would enhance our mental or intellectual capacity tremendously.

Parallel intelligence in CPSS, digital twins in CPS, and metacontrol in metaverses are all potential technology for our future. We should be open to their coming, be careful to their construction, and be diligent in their research and development. As claimed by Karl Jaspers, who has coined term "The Axial Age" to signify the coming of human philosophy between 800BC to 200BC, our humankind must face the virtual and emptiness in order to survive, and "philosophy means to be on the way. Its questions are more essential than its answers, and every answer becomes a new question." Our initiative of "I&I, C&C, V&V" for scenarios engineering in intelligent control and smart systems is just an effort for such thinking [56]–[61].

Let us look into the virtual, the cyberspace, and metaverses, and be on the way or DAO to build our "6S" societies with intelligent control technology: Safe in the physical world , Secure in the mental world and cyberspace, Sustainable in the ecological world, Sensitive to our right, privacy, and preference, Service for all, and Smart in our way of living and delivering.

Acknowledgment

I would like to express my sincere thanks to my graduate students Yu Shen, Jing Yang, Xingxia Wang, and Chen Zhao, as well as to Mrs Yanfen Li, Ping Song, and Xiaolei Hu in my office for their drawing, typing and reference checking.

References

[1] A. Rosenblueth, N. Wiener, and J. Bigelow, "Behavior, purpose and teleology," *Philosophy of Science*, vol. 10, no. 1, pp. 18–24, 1943.

[2] N. Wiener, *Cybernetics or control and communication in the animal and the machine*. Technology Press, 1948.

[3] M. B. Marcus, "Dark hero of the information age: In search of Norbert Wiener, the father of cybernetics," 2006.

[4] W. S. McCulloch and W. Pitts, "A logical calculus of the ideas immanent in nervous activity," *The Bulletin of Mathematical Biophysics*, vol. 5, no. 4, pp. 115–133, 1943.

[5] J. Von Neumann, "First draft of a report on the EDVAC," *IEEE Annals of the History of Computing*, vol. 15, no. 4, pp. 27–75, 1993.

[6] N. Wiener, "The extrapolation, interpolation, and smoothing of stationary time series with engineering applications," US Office of Scientific Research and Development, College Park, Maryland, Tech. Rep., 1942.

[7] C. E. Shannon, "A mathematical theory of cryptography," *Mathematical Theory of Cryptography*, 1945.

[8] C. E. Shannon, "A mathematical theory of communication," *The Bell System Technical Journal*, vol. 27, no. 3, pp. 379–423, 1948.

[9] C. E. Shannon, "Communication theory of secrecy systems," *The Bell System Technical Journal*, vol. 28, no. 4, pp. 656–715, 1949.

[10] C. E. Shannon and W. Weaver, *The mathematical theory of communication*. University of Illinois Press, 1949.

[11] N. Wiener, *Extrapolation, interpolation, and smoothing of stationary time series: With engineering applications*. MIT Press, 1949.

[12] J. F. Coales and S. J. Kahne, "The "yellow peril" and after," *IEEE Control Systems Magazine*, vol. 34, no. 1, pp. 65–69, 2014.

[13] V. Bush, "As we may think," *The Atlantic Monthly*, vol. 176, no. 1, pp. 101–108, 1945.

[14] H. S. Tsien (X. Qian), *Engineering cybernetics*. McGraw-Hill, 1954.

[15] Y.-W. Lee, *Statistical communication theory*. John Wiley, New York, 1960.

[16] D. F. Kocian, "A visually-coupled airborne systems simulator (VCASS)-an approach to visual simulation," Aerospace Medical Research Lab, Wright-Patterson AFB, Ohio, Tech. Rep., 1977.

[17] T. Berners-Lee, "Information management: A proposal," Tech. Rep., 1989. [Online]. Available: https://www.w3.org/History/1989/proposal.html

[18] D. Gelernter, *Mirror Worlds: Or the day software puts the universe in a shoebox... How it will happen and what it will mean*. Oxford University Press, 1991.

[19] F.-Y. Wang, "Parallel intelligence: Belief and prescription for edge emergence and cloud convergence in CPSS," *IEEE Transactions on Computational Social Systems*, vol. 7, no. 5, pp. 1105–1110, 2020.

[20] F.-Y. Wang, "Parallel intelligence in metaverses: Welcome to Hanoi!" *IEEE Intelligent Systems*, vol. 37, no. 1, pp. 16–20, 2022.

[21] F.-Y. Wang, "Parallel philosophy and intelligent science: From Leibniz's monad to blockchain's DAO," *Pattern Recognition and Artificial Intelligence*, vol. 33, no. 12, pp. 1055–1065, 2020.

[22] F.-Y. Wang, "Parallel philosophy: Origin and goal of intelligent industries and smart economics," *Bulletin of Chinese Academy of Sciences*, vol. 36, no. 3, pp. 308–318, 2021.

[23] F.-Y. Wang, "Parallel philosophy and intelligent technology: Dual equations and testing systems for parallel industries and smart societies," *Chinese Journal of Intelligent Science and Technology*, vol. 3, no. 3, pp. 245–255, 2021.

[24] F.-Y. Wang, "The emergence of intelligent enterprises: From CPS to CPSS," *IEEE Intelligent Systems*, vol. 25, no. 4, pp. 85–88, 2010.

[25] S. Hamburg *et al.*, "Call to join the decentralized science movement," *Nature*, vol. 600, no. 7888, pp. 221–221, 2021.

[26] X. Huang and J. Dong, "Learning-based switched reliable control of Cyber-Physical Systems with intermittent communication faults," *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 3, pp. 711–724, 2020.

[27] F.-Y. Wang, W. Ding, X. Wang, J. Garibaldi, S. Teng, R. Imre, and C. Olaverri-Monreal, "The DAO to DeSci: AI for free, fair, and responsibility sensitive sciences," *IEEE Intelligent Systems*, vol. 37, no. 2, pp. 16–22, 2022.

[28] F.-Y. Wang, "CAST Lab: A cyber-social-physical approach for traffic control and transportation management," Intelligent Control and Systems Engineering Center in Chinese Academy of Sciences, Tech. Rep., 1999. [Online]. Available: http://www.sklmccs.ia.ac.cn/1999reports.html

[29] F.-Y. Wang, "Parallel system methods for management and control of complex systems," *Control and Decision*, vol. 19, no. 5, pp. 485–489, 2004.

[30] F.-Y. Wang, "Artificial societies, computational experiments and parallel systems: A discussion on computational theory of complex social-economic systems," *Complex Systems and Complexity Science*, vol. 1, no. 4, pp. 25–35, 2004.

[31] F.-Y. Wang, "The DAO to DeEco and DeSoc with DeSci in Metaverses: CPSS-Based Parallel Economics with Parallel Intelligence," *Journal Intelligent Science and Technology*, vol. 1, no. 1, pp. 3–13, 2021.
[32] M. M. Hassan, G. Fortino, L. T. Yang, H. Jiang, K.-K. R. Choo, J. J. Zhang, and F.-Y. Wang, "Guest editorial for special issue on blockchain for Internet-of-Things and Cyber-Physical Systems," *IEEE/CAA Journal of Automatica Sinica*, vol. 8, no. 12, pp. 1867–1867, 2021.
[33] B. B. Gupta, K.-C. Li, V. C. Leung, K. E. Psannis, S. Yamaguchi *et al.*, "Blockchain-assisted secure fine-grained searchable encryption for a cloud-based healthcare cyber-physical system," *IEEE/CAA Journal of Automatica Sinica*, vol. 8, no. 12, pp. 1877–1890, 2021.
[34] F.-Y. Wang, J. Zhu, R. Qin, X. Wang, and B. Hu, "Federated control: Toward information security and rights protection," *IEEE Transactions on Computational Social Systems*, vol. 8, no. 4, pp. 793–798, 2021.
[35] J. Li, G. Wang, X. Wang, J. Li, Y. Yuan, and F.-Y. Wang, "Crypto management: A novel organizational management model based on blockchain," *Chinese Journal of Intelligent Science and Technology*, vol. 4, no. 2, pp. 145–156.
[36] F.-Y. Wang, "Parallel control and digital twins: Control theory revisited and reshaped," *Chinese Journal of Intelligent Science and Technology*, vol. 2, no. 3, pp. 293–300, 2020.
[37] Q. Wei, H. Li, and F.-Y. Wang, "Parallel control for continuous-time linear systems: A case study," *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 4, pp. 919–928, 2020.
[38] J. Lu, Q. Wei, and F.-Y. Wang, "Parallel control for optimal tracking via adaptive dynamic programming," *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 6, pp. 1662–1674, 2020.
[39] Q. Wei, F.-Y. Wang, D. Liu, and X. Yang, "Finite-approximation-error-based discrete-time iterative adaptive dynamic programming," *IEEE Transactions on Cybernetics*, vol. 44, no. 12, pp. 2820–2833, 2014.
[40] J. Lu, Q. Wei, Y. Liu, T. Zhou, and F.-Y. Wang, "Event-triggered optimal parallel tracking control for discrete-time nonlinear systems," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2021.
[41] F.-Y. Wang, "A framework for social signal processing and analysis: From social sensing networks to computational dialectical analytics," *Science China*, vol. 43, no. 12, pp. 1598–1611, 2013.
[42] F.-Y. Wang, "Parallel management: The DAO to smart ecological technology for complexity management intelligence," *Acta Automatica Sinica*, vol. 48, no. 11, pp. 2655–2665, 2022.
[43] F.-Y. Wang and G. N. Saridis, "A coordination theory for intelligent machines," *Automatica*, vol. 26, no. 5, pp. 833–844, 1990.
[44] M. Tegmark, "Parallel universes," *Scientific American*, vol. 288, no. 5, pp. 40–51, 2003.
[45] F.-Y. Wang, "Formulation of parallel discrete event dynamical systems: Equations and applications," QAII, Tech. Rep., 2020.
[46] Y. Tian, Y. Wang, J. Wang, X. Wang, and F.-Y. Wang, "Key problems and progress of vision transformers: The state of the art and prospects," *Acta Automatica Sinica*, vol. 48, no. 4, pp. 957–979, 2022.
[47] Y. Tian, J. Wang, Y. Wang, C. Zhao, F. Yao, and X. Wang, "Federated vehicular transformers and their federations: Privacy-preserving computing and cooperation for autonomous driving," *IEEE Transactions on Intelligent Vehicles*, 2022.
[48] F.-Y. Wang, Y. Wang, Y. Chen, Y. Tian, H. Qi, X. Wang, W. Zhang, J. Zhang, and Y. Yuan, "Federated ecology: From federated data to federated intelligence," *Chinese Journal of Intelligent Science and Technology*, vol. 2, no. 4, pp. 305–311, 2020.
[49] C. Zhao, Y. Lv, J. Jin, Y. Tian, J. Wang, and F.-Y. Wang, "DeCAST in TransVerse for parallel ITS and smart cities: Three decades and beyond," *IEEE Intelligent Transportation Systems Magazine*, 2022.
[50] Y. Zhao, H. Gao, S. Wang, and F.-Y. Wang, "A novel approach for traffic signal control: A recommendation perspective," *IEEE Intelligent Transportation Systems Magazine*, vol. 9, no. 3, pp. 127–135, 2017.
[51] J. Jin, D. Rong, Y. Pang, F. Zhu, H. Guo, X. Ma, and F.-Y. Wang, "PRECOM: A parallel recommendation engine for control, operations, and management on congested urban traffic networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 7, pp. 7332–7342, 2022.
[52] F.-Y. Wang, "The DAO to federated intelligence and decentralized autonomous federation of intelligent systems (DeFiS): From cognitive intelligence to ecological smartness," *International Journal of Intelligent Control and Systems*, vol. 1, no. 4, pp. 1–5, 2021.
[53] W. Ding, S. Wang, J. Li, Y. Yuan, L. Ouyang, and F.-Y. Wang, "Decentralized autonomous organizations: The state of the art analysis framework and future trends," *Chinese Journal of Intelligent Science and Technology*, vol. 1, no. 2, pp. 202–213, 2019.
[54] S. Wang, W. Ding, J. Li, Y. Yuan, L. Ouyang, and F.-Y. Wang, "Decentralized autonomous organizations: Concept, model, and applications," *IEEE Transactions on Computational Social Systems*, vol. 6, no. 5, pp. 870–878, 2019.
[55] F.-Y. Wang, "Intelligent control in 50 years: From K. S. Fu's vision to G. N. Saridis' inspiration." *Acta Automatica Sinica*, vol. 47, no. 10, pp. 2301–2320, 2021.
[56] F.-Y. Wang, "The engineering of intelligence: DAO to I&I, C&C, and V&V for intelligent systems," *International Journal of Intelligent Control and Systems*, vol. 1, no. 3, pp. 1–5, 2021.
[57] X. Li, P. Ye, Z. Liu, L. Cao, and F.-Y. Wang, "From features engineering to scenarios engineering for trustworthy AI: I&I, C&C, and V&V," *IEEE Intelligent Systems*, vol. 37, no. 4, pp. 18–26, 2022.
[58] D. Zhang, G. Feng, Y. Shi, and D. Srinivasan, "Physical safety and cyber security analysis of multi-agent systems: A survey of recent advances," *IEEE/CAA Journal of Automatica Sinica*, vol. 8, no. 2, pp. 319–333, 2021.
[59] F.-Y. Wang, "Metavehicles in the metaverse: Moving to a new phase for intelligent vehicles and smart mobility," *IEEE Transactions on Intelligent Vehicles*, vol. 7, no. 1, pp. 1–5, 2022.
[60] G. Franzè, D. Famularo, W. Lucia, and F. Tedesco, "A resilient control strategy for Cyber-Physical Systems subject to denial of service attacks: A leader-follower set-theoretic approach," *IEEE/CAA Journal of Automatica Sinica*, vol. 7, no. 5, pp. 1204–1214, 2020.
[61] D. Cao, X. Wang, L. Li, C. Lv, X. Na, Y. Xing, X. Li, Y. Li, Y. Chen, and F.-Y. Wang, "Future directions of intelligent vehicles: Potentials, possibilities, and perspectives," *IEEE Transactions on Intelligent Vehicles*, vol. 7, no. 1, pp. 7–10, 2022.

Fei-Yue Wang (S'87–M'89–SM'94–F'03) received his Ph.D. degree in computer and systems engineering from the Rensselaer Polytechnic Institute, Troy, NY, USA, in 1990. He joined The University of Arizona in 1990 and became a Professor and the Director of the Robotics and Automation Laboratory and the Program in Advanced Research for Complex Systems. In 1999, he founded the Intelligent Control and Systems Engineering Center at the Institute of Automation, Chinese Academy of Sciences (CAS), Beijing, China, under the support of the Outstanding Chinese Talents Program from the State Planning Council, and in 2002, was appointed as the Director of the Key Laboratory of Complex Systems and Intelligence Science, CAS, and Vice President of Institute of Automation, CAS in 2006. He found CAS Center for Social Computing and Parallel Management in 2008, and became the State Specially Appointed Expert and the Founding Director of the State Key Laboratory for Management and Control of Complex Systems in 2011.

His current research focuses on methods and applications for parallel intelligence, social computing, and knowledge automation. He is a Fellow of INCOSE, IFAC, ASME, and AAAS. In 2007, he received the National Prize in Natural Sciences of China, numerous best papers awards from IEEE Transactions, and became an Outstanding Scientist of ACM for his work in intelligent control and social computing. He received the IEEE ITS Outstanding Application and Research Awards in 2009, 2011, and 2015, respectively, the IEEE SMC Norbert Wiener Award in 2014, and became the IFAC Pavel J. Nowacki Distinguished Lecturer in 2021.

Since 1997, he has been serving as the General or Program Chair of over 30 IEEE, INFORMS, IFAC, ACM, and ASME conferences. He was the President of the IEEE ITS Society from 2005 to 2007, the IEEE Council of RFID from 2019 to 2021, the Chinese Association for Science and Technology, USA, in 2005, the American Zhu Kezhen Education Foundation from 2007 to 2008, the Vice President of the ACM China Council from 2010 to 2011, the Vice President and the Secretary General of the Chinese Association of Automation from 2008 to 2018, the Vice President of IEEE Systems, Man, and Cybernetics Society from 2019 to 2021. He was the Founding Editor-in-Chief (EiC) of the International Journal of Intelligent Control and Systems from 1995 to 2000, IEEE ITS Magazine from 2006 to 2007, IEEE/CAA JOURNAL OF AUTOMATICA SINICA from 2014-2017, China's Journal of Command and Control from 2015-2021, and China's Journal of Intelligent Science and Technology from 2019 to 2021. He was the EiC of the IEEE Intelligent Systems from 2009 to 2012, IEEE TRANSACTIONS on Intelligent Transportation Systems from 2009 to 2016, IEEE TRANSACTIONS ON COMPUTATIONAL Social Systems from 2017 to 2020. Currently, he is the President of CAA's Supervision Council, and the EiC of IEEE Trans. on Intelligent Vehicles.