Perspective

New Control Paradigm for Industry 5.0: From Big Models to Foundation Control and Management

By Fei-Yue Wang, *Fellow, IEEE*

DO we need a fundamental change in our professional culture and knowledge foundation for control and automation? If so, what are necessary and critical steps we must take to ensure such a change would take place effectively and efficiently, or more general, smoothly and sustainably?

This question has started circulating in my mind two decades ago right after my first two decades of research and development in automation, robotics, intelligent control, and artificial intelligence. By the end of the 20th century, the effort of achieving the initial goal of intelligent control for complex systems, such as intelligent robotic systems and smart human-machine interaction, as envisioned by its pioneers, such as K. S. Fu [1] and G. N. Saridis [2], had seemed run into and stopped by an invisible wall, as witnessed by the fact that the well-known flagship academic gathering in the field, the annual IEEE International Symposium on Intelligent Control (IEEE ISIC), was losing steam after a decade's rapid rising since 1985 [3]. For those of you interested, related historical reviews and future perspectives can be found in [3]–[5].

The rapid rising of AI during the last decade, especially the recent progress made in deep learning technology, as demonstrated by AlphaGo and ChatGPT [6], [7], has suggested that control and automation do need a fundamental change in their professional culture and knowledge foundation, and I am glad that at IEEE/CAA Journal of Automatica Sinica, a leading effort for such change has been launched intensively since last year [8]–[19], and similar initiatives were also started by other IEEE Transactions and publications [20]–[26]. IEEE/CAA JAS's recent call for papers on a special issue in Industry 5.0 [27] and its article on steps towards Industry 5.0 are renewed calls for a paradigm shift in control and automation [28].

An entry point for such shift is to move directly from big models or foundation models in cyber physical systems (CPS) to foundation control, foundation management, and foundation governance in cyber physical social systems (CPSS), all for the purpose of knowledge automation for decision intelligence in complex systems. Why and how? Let's revisit the history and reconsider the future with the help of Norbert Wiener's circular causality [29].

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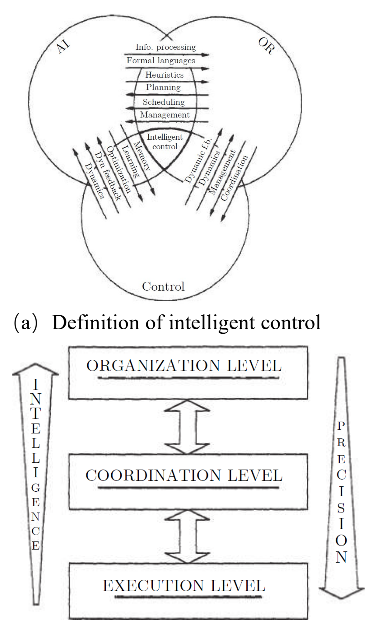
The Motivation of Intelligent Control

K. S. Fu coined term "Intelligent Control" and defined it as the interaction of Artificial Intelligence and Automatic Control in 1971 [1]. It should be noted that, before him, J. M. Mendel had introduced term "Artificial Intelligence Control" with a proposed content and direction that were almost identical to these of Learning Control [1]–[3]. Fu considered Intelligent Control as a natural extension of Learning Control as new AI method and technology were incorporated and applied into automation, and the ultimate goal of his Intelligent Control should be control like humans, but replace biological humans with robotic humans in automated processes [1], [3]. However, he envisioned an "algorithm of algorithms" approach for Intelligent Control.



(a) Definition of intelligent control

(b) Framework for intelligent control

Fig. 1. G. N. Saridis' Inspirational "Three Rings, Three Boxes" for Intelligent Control.

After Fu left for research and development in patterns recognition and machine intelligence, his colleague G. N. Saridis led an interdisciplinary effort and opened up a new journey of "system of systems" for Intelligent Control in a hierarchically structured organizational approach along with a complicated decision process, as illustrated by Fig.1 [2]. Under his effort and leadership, this emerging new field took off in the late 1970s and undergone a rapid growth in the middle 1980s, especially after the creation of IEEE Technical Committee on Intelligent Control and IEEE Workshop on Intelligent Control 1985, which became the annual IEEE International Symposium on Intelligent Control since 1987.

However, due to the historic limitations in thinking and computing, the proposed procedure and architecture for algorithms and systems by both Fu and Saridis were not powerful enough to support a long term sustainable development of Intelligent Control. My own attempt in early 1990s on shadow systems for data generation in intelligent control based on a world model constructed according to Karl Popper's foundation model of the reality, or the big reality model, i.e., the physical world for world 1, the mental world for world 2, the artificial world for world 3, did not attracted much attention [30]. By the end of 1990s, the grand vision of Intelligent Control Systems seemed losing its initial lust and the new effort of using artificial neural networks, as well as fuzzy logic and genetic algorithms, so called computational intelligence approach for Intelligent control started to gain the momentum and popularity, and became mainstream research since.

The Vision of Parallel Control

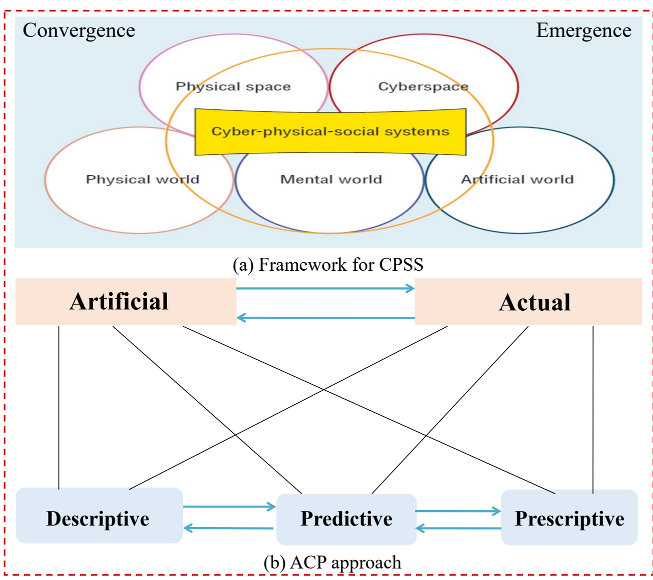


Fig. 2. Fei-Yue Wang's "Five Rings, Five Boxes" Approach for Parallel Control and Parallel Intelligence.

The journey to Parallel Control was primarily motivated by the lack of data and the high cost, and in many cases no scientific means to conduct actual or physical experiments for verifying or validating governing mechanisms or intelligent control of complex systems. The key to parallel control as well as parallel intelligence is the idea of computational experiments beyond conventional computer simulations, which had been originated from my graduate research in 1982 on experiments for metal imperfection and fatigue in fracture mechanics. This idea was further extended in the late 1980s and the early 1990s to the purpose of generating training data for and building knowledge structures into neural networks by fuzzy reasoning using words, heuristics, and deep modular neuro-fuzzy subnetworks [31]–[33]. Together with the concept of shadow systems, this led naturally to the road of ACP-based parallel control in CPSS for management and control of complex systems in the beginning of the 21st century [34], see Fig. 2 for its basic framework and decision structure.

As pointed out in [8], parallel control and parallel intelligence are linked with Generative Artificial Intelligence intrinsically and naturally, and provide an analytical approach for conducting MetaControl for intelligent control in metaverses and DeMetaControl for intelligent control in decentralized autonomous metaverses based on the new feedback mechanism of circular causality and foundation or big models, which can be summarized mathematically in the following and illustrated briefly in Figs.3-5, at a three-level abstraction.

$$\dot{x} = f(x,u,d)$$
$$\dot{u} = g(u,x,r)$$

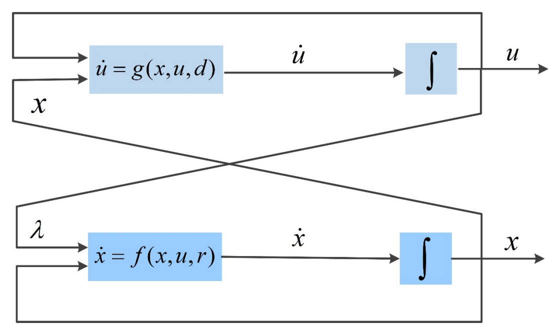


Fig. 3. Parallel Control: Energy Oriented Optimal Control.

$$\dot{N} = S(N,M,U)$$
$$\dot{M} = T(M,N,I)$$

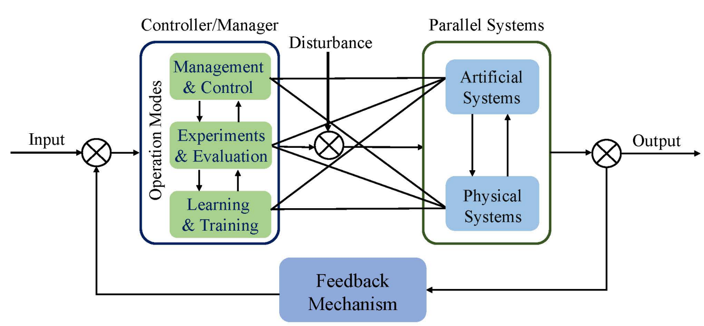


Fig. 4. Parallel Management: Entropy Oriented Optimal Design.

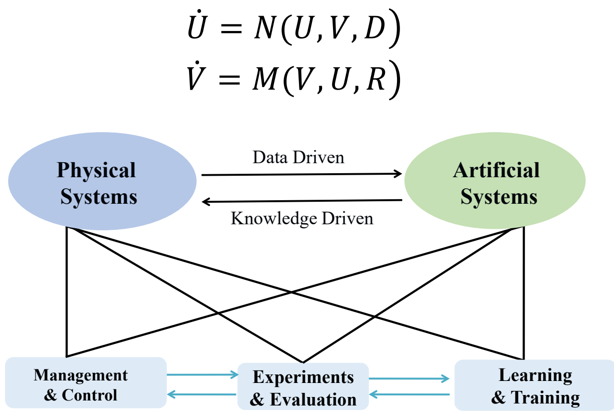


Fig. 5. Parallel Governance: Entanglement Oriented Optimal Prescription.

The tremendous success of AlphaGo and ChatGPT has greatly enhanced the enthusiasm and energy for advanced works in parallel control and parallel intelligence with easily accessible technological supports, and made the parallel philosophy of living and the technology of digital humans for parallel systems an emerging reality for widespread applications in engineering and social services, which will be addressed briefly in the next section.

The Goal of Foundation Control

I believe that it is time for the next phase of parallel control, to fundation control, foundation management, and foundation governance: implementing K. S. Fu's original vision for intelligent control, but not control liking humans by replacing humans with robots, instead, we would achieve intelligent control as human-like control by augmenting biological humans with both robotical and digital humans, and empowering them with parallel foundation models and updated G. N. Saridis' OCE technologies with Blockchain Intelligence, Smart Contracts, and Decentralized Autonomous Organizations and Operations [4], [28], [35], not just hierarchical structures and distributed AI. The goal and process of Foundation Control, Management, and Governance can be stated shortly as:

- ***Three Worlds, Three Philosophies.*** Science and technology alone are not good enough for the new age, we need a new thinking and new philosophy. For this, we can start by adding the third B into the current 2B Western philosophies, i.e., from Being, Becoming, to Believing, and forming the new parallel philosophy through interacting and paralleling three Bs in the three worlds, along with circular consequences of the circular casualty by three categories of knowledge, Descriptive, Predictive, and Prescriptive. Our task is to make this philosophical thinking into a technological reality for foundation control, management, and governance, based on Blockchain, smart contracts, DAO, and DeSci.
- ***Three Worlds, Three Humans.*** For the future workforce, we need to develop a parallel population of parallel humans by interacting three types of humans, biological with less than 5%, robotical with less than 15%, and digital with more than 80%. In other words, a biological human would direct 3 robotical and 16 digital ones to ensure the future is still humanity-centric, with an expected increase of 96000% in effectiveness and efficiency for our sustainability.
- ***Three Worlds, Three Modes.*** We all go through our each day by Morning (AM), Afternoon (PM), and Evening (EM). A future day in our life and work would be AM for autonomous modes, for more than 80% of our time or about 20 hours of a day, in which we enjoy our life and let the world move autonomously; PM for parallel modes, for less than 15% of our time or about 3 hours of a day, in which we must interact with the world remotely through clouds or telematical operations; and finally EM for expert/emergency modes, for less than 5% of our time or about 1 hour of a day, in which biological humans must be sent through a fast delivery fashion into the field to handle special situations beyond the capacities of foundation models, robotical and digital humans alone. Three types of emerging intelligent technologies are coming to our help, namely, application specific foundation models, scenarios engineering, and humans oriented operating systems.

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