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Cyber-Physical-Social Systems for Command and Control

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A cyber-physical-social system regards human factors as a part of a system instead of placing them outside the system boundary.[1] Such systems consist of not only cyberspace and physical space, but also human knowledge, mental capabilities, and sociocultural elements. Information from cyberspace interacts with physical and mental spaces in the real world, as well as the artificial space mapping different facets of the real world. A CPSS carries out parallel execution, self-synchronization, and influences in the physical, information, cognitive, and social domains.

These four domains are also the key elements in military command and control systems. In terms of fusing physical, information, cognitive, and social domains, CPSSs provide a new way to transform command and control organizations. To a degree, the nimbleness of a command and control organization stems from the fusion of its internal essential components, especially the human factors involved. Thus, CPSSs provide an ideal paradigm for designing and constructing command and control organizations.

With this article, we provide a preliminary account of the operational process of command and control based on the CPSS and a self-synchronization mechanism. The CPSS we propose for command and control incorporates the essential characteristics of operational mechanism and connects the physical network, cyberspace, mental space, and social network.

CPSS for Command and Control

The application of information technology has changed command and control organizations, flattened their structures, and formed more dynamic and complex interactions.[2,3] Such organizations have become organic entities, including sensor, enabler, communication, and social networks composed of human beings. The components are closely linked, enabling information collection, situation awareness, planning and decision making, and action execution within a loop. With the support of AI, a command and control organization is able to model its own conduct. This kind of technology can substitute traditional processing and planning routines, thereby leading to human-centricity and synchronicity.[4] Coordination between physical systems and human individuals can be done via networks and organizational intelligence, inclusive of simultaneous decision making, multimodal consultation, and self-adaptive construction and reconstruction of organizational structure.

The study of network-centric warfare shows that an efficient military organization must be robust, resilient, responsive, flexible, innovative, and adaptive.[5] These attributes form the basis of self-synchronic military operations conducted by a command and control organization.[6] To effectively carry out command and control, the main challenge lies in the organic integration of multidomains—that is, the physical systems in the physical domain, cyber networks in the information domain, mental elements in the cognitive domain, and social networks in the social domain. Thus, the concepts behind CPSS raise interesting research issues such as how to create more effective command and control organizations and improve the control chain from human mentality to physical systems.

The CPSS for command and control is the integration of relevant functions from physical

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systems, information sharing, thinking and decision process, command and control, and coordination, all falling into the four domains (see Figure 1). Such an integrated system reorganizes the traditional military organization structure and procedures to achieve the dynamic synchronization of the entire command and control organization. To achieve self-synchronization of military operations, these systems do not control every individual action; rather they encourage the coordination of organization intelligence as well as integrated cognition and decision making in guiding organizational behavior. In this sense, an individual or regional organization ascends to a systematic multidomain organization.

Self-synchronization includes four aspects:

- vertical self-synchronization throughout the physical, information, cognitive, and social domains;
- horizontal self-synchronization in each domain;
- self-synchronization of structures and programs; and
- self-synchronization of the real world and virtual world for parallel execution.

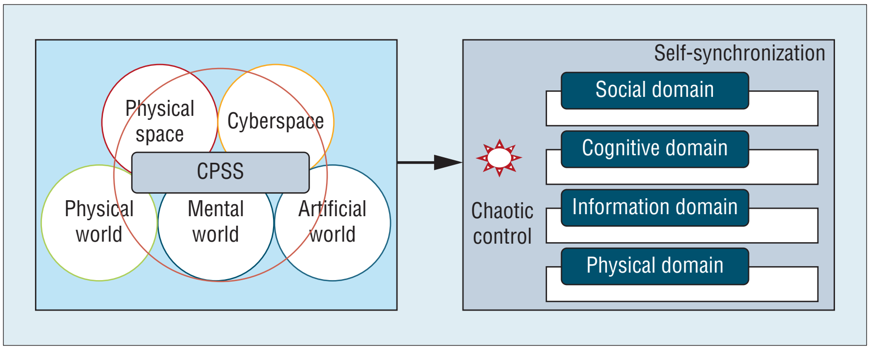

Figure 1. The CPSS command and control domain. By reorganizing traditional military organization structure and procedures, we can achieve dynamic self-synchronization of the entire command and control organization.

Transregional and transdomain self-synchronization leads to the complexity and emergence of system operations. Because there are trade-offs between response time and decision quality, chaotic control might be the key to balance them under critical situations.[7] In addition, the organizational structure and corresponding actions could be synchronized to achieve optimal effectiveness.

Operational Mechanism

To achieve self-synchronization of a command and control organization, we need to establish a chaotic control mechanism for the CPSS (see Figure 2). The inputs are military missions such as events or tasks. The CPSS will automatically integrate an organization's essential elements in the four domains, assign physical resources, set up sensor networks and enabler networks, construct the command and control relationships in the social network, and organize and share relevant information as needed. The chaotic system's output is the complete operational system—the entire command and control organization as a CPSS.

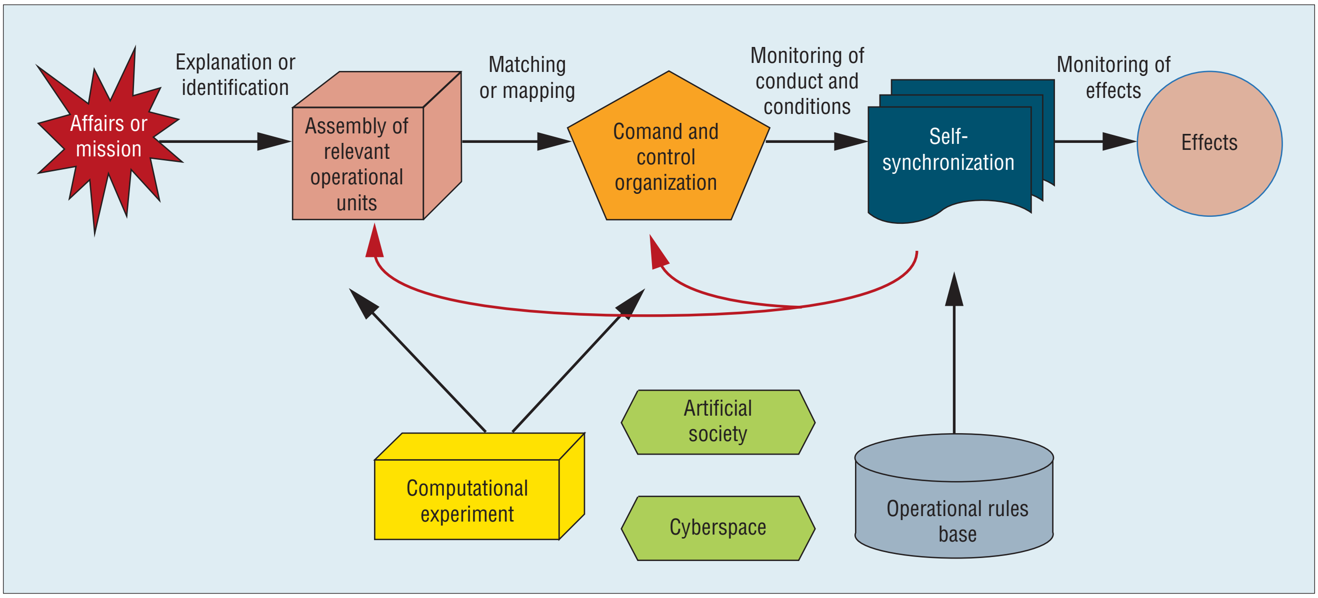

Figure 2. Operational mechanism of self-synchronization. The inputs are military missions such as events or tasks.

In the operational process, a distributed command and control organization is both self-organizing and self-adaptive in accordance with changes in the battlefield. Instead of pursuing an absolutely central control of the organization behavior, a chaotic control mechanism focuses on the harmony of a system of systems. The mechanism of self-synchronization can be further detailed as the following: identification of missions, operational planning, comprehensive integration of operational units and operational elements by the distributed network, and the quick construction of a cyberphysical organization's missions through distributed organizational intelligence.

During operation, a CPSS can monitor and adjust structures and relationships within itself in a timely manner. Operational considerations include examining how tasks are assigned to systems or humans, collaboration and coordination between operational units, command and control relationships between humans (and physical systems), and interactions in information sharing and communication. The operational rule base provides the common knowledge shared within a command and control organization to ensure consistent military conduct.

The self-synchronizing process of a command and control organization includes five steps:

1. Explain operational orders or identify missions and affairs in distributed environments. Explain orders by making their intentions clear, including the resolution of mission objectives and the construction of mission models. Understand the situation by determining a common operational picture.
2. Cluster the operational units according to the need of the mission disposition, integrate relevant operational units, and aggregate resources for the formation of the command and control cyberphysical organization. These resources consist of physical systems and humans in the physical domain.
3. Construct a complete command and control cyberphysical organization on the basis of the aggregated resources. This includes the plans and strategies for executing missions in the cognitive domain; the command control, collaboration, and coordination relationship between the operational units in the social domain; and the relationship between information sharing and communication in the information domain. The CPSS's structure must match the course of actions dictated in plans.
4. Get self-synchronization of the CPSS ready for processing missions and affairs. Within the CPSS's framework, the assessment of affairs and situations originated from the cognitive domain results in changes in the distribution of the operational units, the relationship of command and control, and communication and information sharing. Every entity could select adaptive rules within the common rule base using a Semantic Web service in accordance with their respective roles. The decisive node could play war games or explore possible results via computational experiments.
5. Perform parallel execution of self-synchronization and surveillance of after-action effects. After achieving the expected results, the already formed operational system is terminated after mission completion. If the desired results are not achieved, synchronization of the command and control cyberphysical organization will be adjusted according to the feedback information.

During the synchronization process on the battlefield, an open-loop feedback mechanism is in place. When accidents such as loss of operational units occur, an adaptive CPSS could be resilient. When mismatching between structure and function of the CPSS occurs and the mission reaches a particular limit, the CPSS must adjust. Although it might be necessary to recluster new operational units for a new CPSS, it is possible that only structural adjustments the CPSS are needed to adapt to the new demands. Determining the limiting conditions and cost estimates for the CPSS's changes and restructuring are key points in establishing chaotic feedback mechanisms.

A Framework for Self-Synchronization

Within system theory, self-synchronization of a CPSS is both a self-organizing and self-adapting process. The end effect is the collective emergence of a CPSS's component actions. To guarantee a CPSS's validity, accuracy, and rationality, the interaction mechanism must be carefully designed. Figure 3 presents a framework to realize self-synchronization mechanism in the CPSS for command and control.

This CPSS is made up of physical network, cyberspace, cognitive network, organizational network, and artificial societies. The physical network includes sensor, enabler, and communication networks, closing the sensor-to-shoot cycle. Cyberspace supplies space for computing, storage, information processing, and sharing services, especially situation awareness and decision-support services directly for command and control. The cognitive network is a Semantic

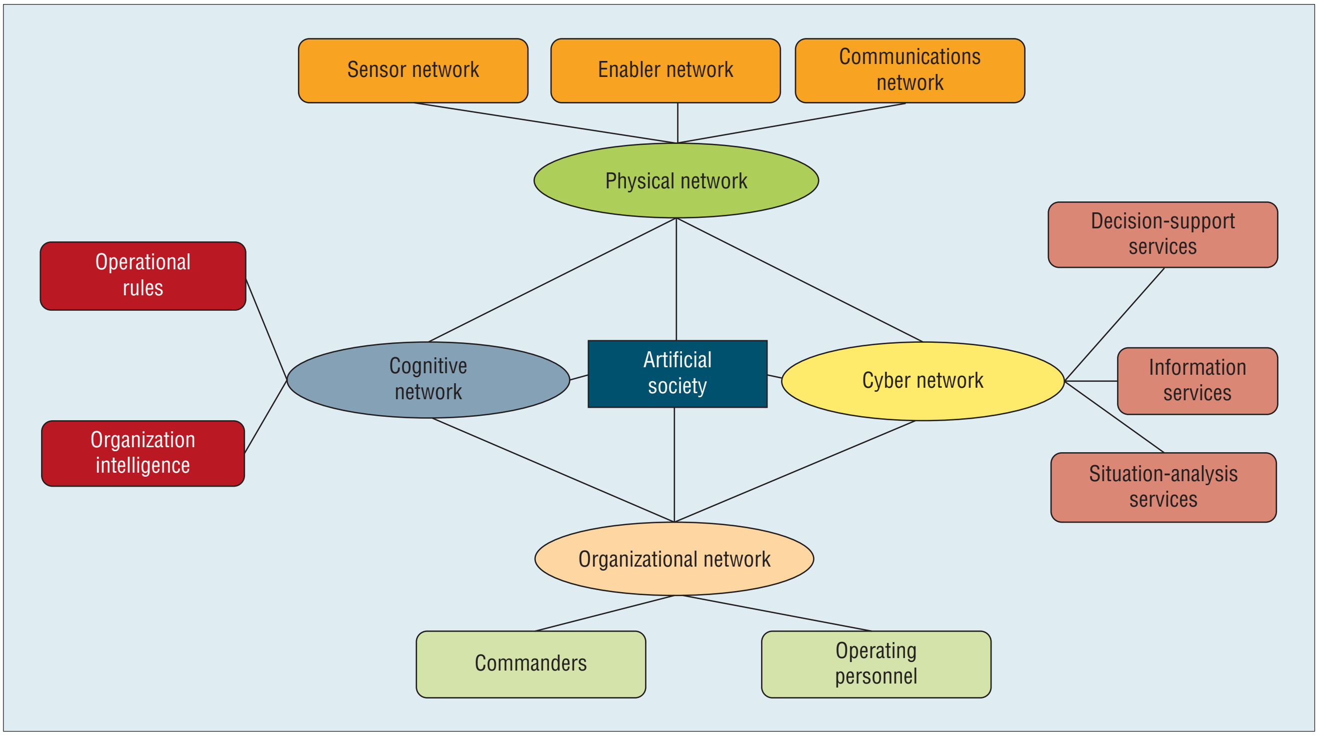

Figure 3. A framework for command and control self-synchronization.

Web based distributed knowledge management system, with the goal of managing, evolving, and utilizing operational rules and organization intelligence. The organizational network is a social network consisting of commanders and the operating personnel that play a key role in the command and control relationship.

According to "artificial societies + computing experiments + parallel control,"[8,9] artificial societies are introduced as a virtual world mapping of the physical network, cyberspace, cognitive network, and organizational network in the real world, as well as multiple future virtual worlds for exploration of possible scenarios. The physical network, cyberspace, cognitive network, and organizational network are integrated and overlapping. For instance, although the sensor network reports the targets' information, the information is then transferred by the communication network.

With the help of information services and situation analysis services, command and control teams, organized as a social network to match the mission, receive a common operational picture of the battlefield. They can then define objectives and prioritize the effort matrix by recommending and evaluating courses of actions using scenario exploration, computational experiments, and war games. These explorations are supported by the artificial society, rule bases, and decision-support services. Finally, the CPSS will instruct and activate the enabler network to shoot. The CPSS maintains synchronization with the real world as well as self-synchronization of the human and physical system.

The proposed framework couples humans and physical systems in an observe, orient, decide, and act (OODA) loop. Human beings are included in the CPSS, not outside the system boundaries. It also emphasizes human-system integration in command and control. Human observation, orientation, decision, and action are supported by systems, and the systems make supplementary decisions and perform routine work according to the organizational intelligence of human beings.

We also designed such systems to accept the inherent uncertainty and complexity of a command and control organization, understanding the emergence of the CPSS, estimating multiple possible trends for events, and exploring the expected state of operations by chaotic control instead of precise control. The current real-world state could be observed by humans and sensor networks and fed to artificial societies as state variables.

Through computational experiments and scenario exploration, the framework can examine multiple courses of actions and the possible results of the respective courses of actions. It can also explore the sensibility of scenario variables in a computational experiment, control the dimensions of scenario variables, and overcome "the dimensional disaster."

We also feel it is important to model the causality, interconnection, and cross-impact of the real world using artificial societies, computational experiments, and operational rules. The goal is to interpret how and why the world will change.

To incrementally increase organization intelligence, the CPSS framework might make use of the Semantic Web, adding concepts, properties, axioms, and rules, and enabling humans and systems to learning from one another.

Lastly, the CPSS can make decisions and take actions with or without a human in the loop. Supported by artificial societies, computational experiments and operational rules, the CPSS can automatically guide enabler resources and other resources toward various executions under time pressure.

Prospects

The widespread application of information technology in the command and control field has enabled systems integrated with command, control, communications, computers, intelligence, surveillance, and reconnaissance. However, this integration focuses on the integration of a system of systems. It is more about the physical systems than humans, more about matter than the mental elements of command and control, and more about the measure of effectiveness than the quality of the command and control organization, such as robustness and adaptability.

We believe that the next step for integration is to source more advanced intelligent technologies and realize the self-organization of sensor, enabler, communication, and command and control resources when confronted with battlefield changes. Further integration should accommodate commander observation, orientation, decision making, and action in the system loop to promptly estimate future trends in real time. The CPSS introduces a new paradigm for integrating command and control through physical, information, cognitive, and social domains. In the future, further refinement of the CPSS for command and control calls for the advancement of interdisciplinary theory in both human and computational studies. ■

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