Satellite-UAV Networks for 6G Control: A Sensing-Communication-Computing-Control Closed Loop Perspective

Chengleyang Lei, Xinran Fang, Wei Feng, Yunfei Chen, Ming Xiao, Ning Ge, and Shiwen Mao

Abstract

The future sixth-generation (6G) networks are envisioned to support machines and robots besides human beings. In order to efficiently support machines and robots working in remote and post-disaster areas, satellites and autonomous aerial vehicles (AAV, also known as UAV) can be utilized. In this article, we investigate how satellite-UAV networks can serve robots for their control tasks. We introduce the typical use cases of the satellite-UAV networks for control and outline the relevant challenges. The control process usually involves sensing, communication, computing, and control components, which forms a sensing-communication-computing-control (**SC**^{3}) closed loop. In analogy with the reflex arc structure of humans, we reveal the indivisibility of the **SC**^{3} closed loops and propose a closed-loop-oriented system design framework. Within this framework, we take the closed-loop control performance as the design target, and highlight the holistic consideration of sensing, communication, computing, and control components in the **SC**^{3} closed loop. Furthermore, we discuss the extended **SC**^{3} closed loop with multiple sensors and robots to decompose complex control systems. A case study is provided to show the performance gain of the proposed closed-loop-oriented system design. Finally, we outline open issues in designing more efficient satellite-UAV networks for control.

Introduction

With the development of robotics and automation, more and more automatic machines and robots have been deployed in scenarios such as emergency response and industrial automation. This extends the service scope of future sixth-generation (6G) networks to machines and robots beyond human beings [1]. As terrestrial infrastructures are usually unavailable in remote or post-disaster areas, non-terrestrial networks consisting of satellites and autonomous aerial vehicles (AAV, also known as UAV) can be utilized to assist the control tasks of robots [2].

The robots rely on closed-loop control to execute tasks in complex and dynamic environments [3]. In the task execution process, the sensors collect information from the environment, and then computing units analyze sensing data and compute proper commands to control the robots. This forms a closed loop involving sensing, communication, computing, and control parts, referred to as a sensing-communication-computing-control (**SC**^{3}) closed loop [4]. The **SC**^{3} closed loop integrates sensing, computation, and control through communication networks, which can be regarded as a special type of cyber-physical systems (CPSs) [5].

Although there have been many works on CPSs, there are still challenges for current networks to support CPSs in remote areas due to the limited system resources. The traditional communication system design considers different communication links as separate units, and focuses on improving communication link metrics. For example, the key performance metrics of the fifth-generation (5G) networks [6], including peak data rate, user experienced data rate, latency, etc, were proposed from the link-oriented perspective. However, the communication links for robot control are closely coupled in the **SC**^{3} closed loops. The link-oriented communication system designs rely on abundant resources to meet the communication performance requirements for each individual link, neglecting the interactions among links within an **SC**^{3} closed loop, as well as the coupling between the communication and other components of the **SC**^{3} closed loop. While this method may be applicable in scenarios with sufficient communication resources, it is not feasible for resource-limited satellite-UAV networks as it fails to maximize the overall performance of **SC**^{3} closed loops.

Motivated by above issues, in this article, we propose a closed-loop-oriented system design framework, to improve the overall closed-loop performance of the **SC**^{3} closed loops supported by the satellite-UAV networks. The main contributions of this article are summarized as follows:

- We provide typical use cases of the satellite-UAV networks for control. The main challenges for the satellite-UAV networks to support control tasks are discussed.
- We emphasize the indivisibility of the **SC**^{3} closed loop and propose a closed-loop-oriented framework to design CPSs in remote

Digital Object Identifier: 10.1109/MNET.2025.3551343
Date of Current Version: 15 July 2025
Date of Publication: 14 February 2025

Chengleyang Lei, Xinran Fang, Wei Feng (corresponding author), and Ning Ge are with the Department of Electronic Engineering, State Key Laboratory of Space Network and Communications, Tsinghua University, Beijing 100084, China; Yunfei Chen is with the Department of Engineering, University of Durham, DH1 3LE Durham, U.K.; Ming Xiao is with the Department of Information Science and Engineering, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, 114 28 Stockholm, Sweden; Shiwen Mao is with the Department of Electrical and Computer Engineering, Auburn University, Auburn, AL 36849 USA.

areas, where the closed-loop performance is the design focus, and the heterogeneous components are unified based on the information entropy. In addition, we discuss the decomposition of a complex system with multiple extended **SC**^{3} closed loop structures.

- We provide a case study on the resource allocation among multiple **SC**^{3} closed loops. Simulation results show that the proposed closed-loop-oriented system design framework can improve the control performance.
- We discuss the open issues and future directions of the satellite-UAV networks for control.

Use Cases of Satellite-UAV Networks for Control

The satellite-UAV networks are envisioned to support machines and robots in wide areas such as maritime areas and polar regions. Due to the limited individual ability of the robots, the UAVs need to be equipped with a device integrating sensing, communication, and computing functionalities to assist these robots. As a center of the task-related information, this device can be referred to as an edge information hub (EIH) [7]. We show a systematic view of the satellite-UAV networks for control in Fig. 1. It can be seen that the satellite-UAV networks are like the arm-hand structures of humans [8]. Specifically, the hand-like UAVs rely on the EIHs to provide flexible edge capabilities such as sensing, computing and communication to support multiple **SC**^{3} closed loops, and the arm-like satellite beams can support and guide the UAVs, providing backhaul to the powerful cloud center. The typical use cases of such networks are listed as follows.

Disaster Response

After disasters, rescue robots can replace humans to execute essential tasks in dangerous environments, including life detection, firefighting, transportation, and hazardous material management. However, terrestrial communication infrastructures may be destroyed during disasters. In order to enable the swift response to disasters, flexible UAVs can be deployed rapidly to establish emergency networks with satellites. In such cases, UAVs can be equipped with sensory devices such as cameras to obtain comprehensive situational information, with communication devices to enable information exchanges and with computational devices to analyze sensor data and determine control commands for robots. Due to the limited payload of UAVs, the orchestration of the sensing, communication, and computing resources becomes important to improve the rescue efficiency.

In order to enable the swift response to disasters, flexible UAVs can be deployed rapidly to establish emergency networks with satellites.

Remote Industrial Applications

In the context of remote industrial operations, such as mining or offshore oil extraction, machines and robots can supplant humans in harsh conditions, so as to improve the production efficiency. Constrained by the geographical environments, it is hard to deploy fiber optics and terrestrial base stations there. Therefore, satellites and UAVs can be utilized as communication infrastructures to support information exchanges among industrial sensors and actuators. In addition, UAVs can be leveraged to monitor the operational sites and detect abnormal conditions, improving the security of industrial systems [9]. In such scenarios, the satellite-UAV networks are envisioned to integrate the edge computing capabilities for lower latency and higher security [10].

Scientific Expedition

In extreme environments like the polar regions, deserts, and deep space, robots can perform scientific expedition tasks such as sampling, detection, and monitoring, enhancing the operational efficiency and personnel safety [1]. Due to the lack of fiber optics and terrestrial base stations therein, satellite-UAV networks emerge

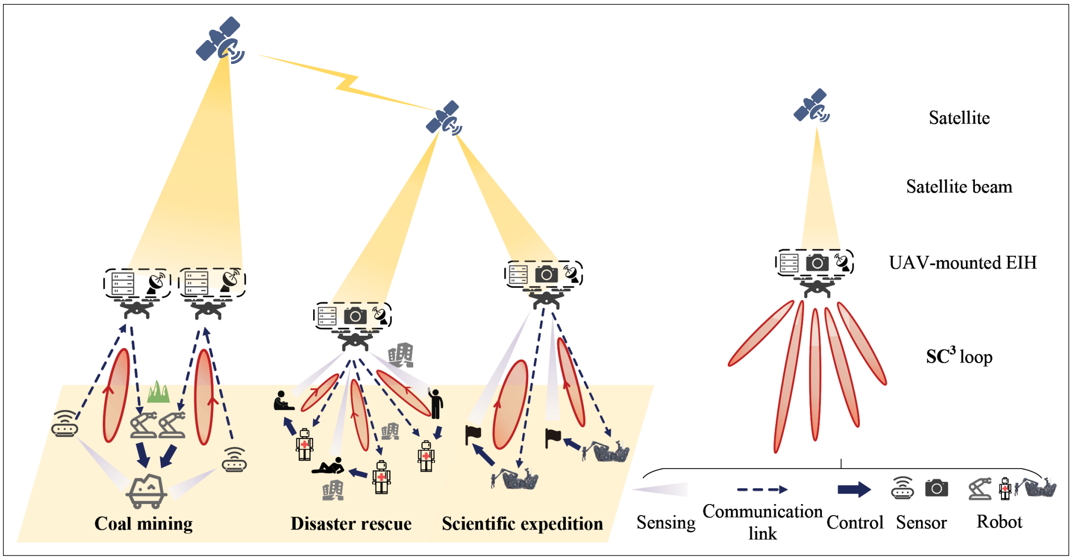

FIGURE 1. A systematic view of the satellite-UAV networks for control.

The satellite-UAV networks for control exhibit several common characteristics across various applications, posing unique challenges for system design.

as alternative communication infrastructures, enabling the backhaul of the field information and collected data, as well as real-time teleoperation capability for remote control center to schedule robots. In addition, UAVs can be equipped with sensory and computing devices to help the robots to obtain global information and analyze the collected data, improving the efficiency of scientific expedition. To address the challenging environmental conditions in extreme regions, the satellite-UAV networks should ensure reliability to maintain robust communication.

Challenges of Satellite-UAV Networks for Control

The satellite-UAV networks for control exhibit several common characteristics across various applications, posing unique challenges for system design. Constrained by the harsh conditions, the terrestrial infrastructures are usually unavailable. Therefore, the system resources are limited compared with the traditional communication networks for industrial control. In addition, the remote environments are usually complex and dynamic, requiring robots to rely on external sensing and computing devices to acquire and analyze global information. These characteristics render the traditional communication system design methods for industrial control unsuitable for the considered scenarios. For example, ultra-reliable low-latency communications (URLLC) rely on abundant resources to achieve low latency for control. In resource-limited satellite-UAV networks, supporting URLLC across all communication links is challenging, and efficient resource utilization becomes essential. In the following, we outline the main challenges in the designs of satellite-UAV networks for control.

Diverse Requirements of Control Tasks

In the control process, the varying task types and machine categories impose diverse requirements for satellite-UAV networks. Specifically, industrial robots have short control cycles for real-time operations, thereby requiring low-latency communication. The reconnaissance UAVs require networks with high bandwidth to capture real-time sensing data from the field. In addition, when serving rescue robots in post-disaster areas, networks are required to have rapid deployment capabilities to enable timely emergency response, and robustness to handle potential secondary disasters and extreme environmental conditions. Moreover, considering the limited capabilities of individual machines and robots, the networks are expected to integrate edge sensing and computing functionalities, so as to support the control tasks more efficiently.

Capability Limitation of Satellite-UAV Networks

The satellite-UAV networks have inherent capability limitations. On the one hand, the long propagation distances of satellite links cause high latency and low data rates of the satellite communication. On the other hand, constrained by the payload of UAVs, the onboard resources and flight duration are both limited, significantly limiting UAVs' service capabilities.

Therefore, it is necessary to optimize the use of the limited resources in satellite-UAV networks, including the power, the bandwidth, the computing capability, and the service time, so as to satisfy the diverse network demands of machines and robots.

Complexity of the Control Systems

In the control systems, there are usually various nodes including sensors, robots, and computing units. These nodes need communication for information exchange, facilitating interactions that form a complex network topology. This topology is typically irregular, influenced by the task demands, node functionalities, and communication coverage. Moreover, during the task process, nodes may enter or leave the network, resulting in a constantly dynamic system structure. The irregular topology and high dynamics of the systems pose significant challenges in system analysis, especially the large-scale systems.

Thinking From the Reflex Arc of Humans

The diverse task requirements, limited resources, and high complexity of the systems pose challenges to the satellite-UAV networks for control. To handle these challenges, we propose a novel systematic perspective based on the **SC**^{3} closed loop, inspired by a similar structure in human bodies. We use a firefighting scenario as an example to illustrate the process of the **SC**^{3} closed loop. As shown in Fig. 2(a), the sensor monitors the field conditions and then transmits the acquired data, including optical and infrared thermal images, to the computing unit through communication link. The computing unit then analyzes the sensing data to identify the location and extent of the fire, accordingly generating appropriate commands that specify the direction and rate of fire extinguishing agent discharge. Next, the commands are transmitted to the robots, which execute the required actions. Through this closed-loop process, the sensing, communication, computing, and control components cooperate to optimize the actions of robots to adapt to the real-time fire conditions. Coincidentally, a similar structure exists in the human body to assist the activities of humans, that is the reflex arc [11]. A typical reflex arc contains a receptor, an afferent nerve fiber, a nerve center, an efferent nerve fiber, and an effector, as shown in Fig. 2(b). During the reflex process, the receptor detects the external stimuli and generates electrical signals. These signals are then transmitted to the central nerve center via the afferent nerve fiber. Next, the nerve center processes the signals, generates the commands, and transmits them to the effectors via the efferent nerve fibers. Finally, the effector produces the response. It can be seen that the **SC**^{3} closed loop in the robotic system and the reflex arc in the human body are similar in both the components and the working process.

In the biological context, the reflex arc is regarded as the foundational structure for reflexive activity [11], enabling humans to respond to external stimuli promptly. Correspondingly,

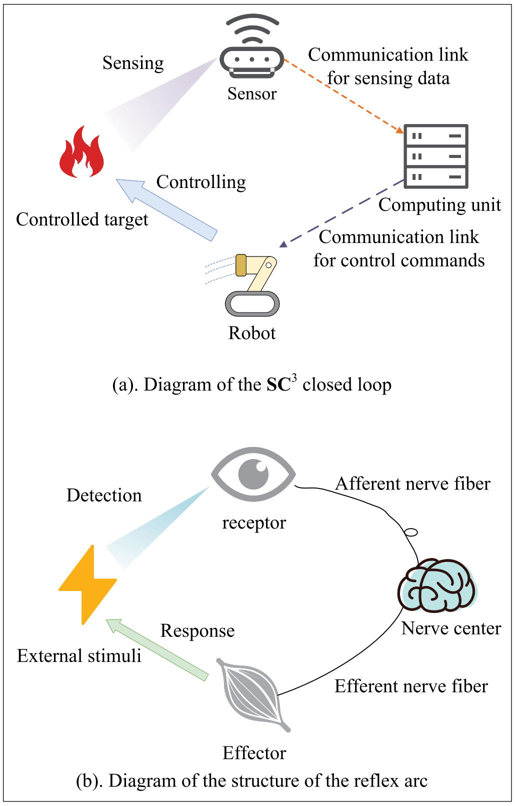

FIGURE 2. A comparison between a) the **SC**^{3} closed loop and b) reflect arc.

the **SC**^{3} closed loop should be considered as the fundamental unit of the robot control process. Both the system design and the resource allocation should be conducted considering the whole loop, rather than traditional communication links. In addition, in the reflex arc, different components collaborate to participate in reflexive activities. Abnormalities in any component will lead to diminished or augmented reflex responses, resulting in diseases known as hyperreflexia or hyporeflexia. Similarly, the different components of an **SC**^{3} closed loop cooperate closely to execute a task. The effective completion of the tasks relies on the coordination among the sensing, communication, computing, and control components. Therefore, the **SC**^{3} closed loop should be considered as an indivisible unit. The communication component, an important part in the **SC**^{3} closed loop, should be analyzed by accounting for the parameters from other components.

In conclusion, through learning from the reflex arc, we emphasize the indivisibility of the **SC**^{3} closed loop, and take it as a fundamental unit in the control systems. In the next section, we propose a closed-loop-oriented system design framework that focuses on the **SC**^{3} closed loop, so as to enhance the control performance of the systems.

Closed-Loop-Oriented System Design

The main idea of the closed-loop-oriented framework is to focus on the **SC**^{3} closed loops in the system design. However, the diversity of the tasks and the heterogeneity of the sensing, communication, computing, and control components pose challenges when analyzing the **SC**^{3} closed loops and designing the systems. To this end, we summarize the key features of the proposed closed-loop-oriented system design framework as follows.

> The effective completion of the tasks relies on the coordination among the sensing, communication, computing, and control components.

From Communication Metrics to Closed-Loop Metrics

In traditional communication system design, the objective is typically link-level communication metrics, such as the throughput or latency. However, in the control system, the utility of the tasks is the focus, not individual communication metrics. Communication requirements can vary significantly depending on the task types and the control parameters of the systems. For example, the minimal data rate to stabilize a control system is related to the state matrix of the control system [12]. However, traditional system design usually uses general communication provisions for a wide range of tasks, such as the 1 ms latency requirement for URLLC in 5G [6]. This approach cannot be adapted to the specific requirements of tasks, resulting in the inefficient utilization of resources. To this end, instead of relying on general communication metric requirements, it is more efficient to use the closed-loop control metrics for the design. This methodology integrates task characteristics into the system design, thereby directly enhancing the efficiency of control tasks and improving the utilization of constrained resources in satellite-UAV networks. Specifically, it is necessary to establish the relationship between the overall performance of an **SC**^{3} closed loop and the performance of its internal components. Based on this, the system design, such as the resource allocation, can be conducted to improve the overall closed-loop performance. Currently, the influence of the communication on the robot control has been studied in some works [13].

Holistic Design: Unifying Sensing, Communication, Computing, and Control Based on Information Entropy

In the control process, the sensing, communication, computing, and control components collaborate to accomplish tasks. There exist complex interactions among these four heterogeneous components. Due to the bucket effect in the **SC**^{3} closed loops, the capabilities of the four components should be aligned at the task level. Therefore, in order to utilize resources effectively, it is necessary to holistically consider the parameters of each component in system design. However, the heterogeneity of these components makes it difficult to analyze their joint influence on the overall closed-loop performance. To unify the four heterogeneous components within the **SC**^{3} closed loops, information plays a pivotal role. Specifically, the sensing, communication, computing, and control processes involve the acquisition, processing, transmission, and utilization of information, respectively. Therefore, information entropy can be utilized to establish a framework to describe the four components. For example, the sensing capability can be measured by the entropy of its

Designs	Integrated Components				Main objective
	Sensing	Communication	Computing	Control	
Integrated sensing and communication	Yes	Yes	No	No	Resolution, Cramér-Rao bound, communication data rate, etc
Mobile edge computing	No	Yes	Yes	No	Latency, data throughput, energy consumption, etc
Over-the-air computation	No	Yes	Yes	No	Computation error, federated learning performance, etc
Networked control system	Yes	No	Yes	Yes	System stability, control cost, age of information, etc
Proposed framework	Yes	Yes	Yes	Yes	Closed-loop performance

TABLE 1. Comparison of the proposed framework with existing related designs in integration of sensing, communication, computing, and control.

collected information, and the computing process can be regarded as the process of extracting useful entropy. A preliminary result on the relationship between the control performance and the transmitted entropy has been presented in [14].

Comparison With Other Related Methods

We compare the main features of our proposed framework with other related designs in Table 1. It can be seen that several technologies have considered components of **SC**^{3} closed loops. For example, the integrated sensing and communication technology combines sensing and communication functions into a unified system, and the works about mobile edge computing deploy the computing devices at the edge of networks to reduce the computing latency. However, most of them only focus on local parts of the **SC**^{3} closed loops, without a comprehensive consideration of **SC**^{3} closed loops. In addition, existing methods mainly focus on the metrics of the local parts, such as the sensing or communication metrics. On the contrary, in our proposed method, the core ideas are to jointly take the four components of **SC**^{3} closed loops into consideration, and take the overall closed-loop metric as the main objective of the system design. It is worth noting that the proposed framework is not a replacement of these methods, but an addition, as it is valuable for the framework to integrate local parts of **SC**^{3} closed loops.

Decomposition of Complex Systems for Control Tasks: A Structural Perspective

In practical applications, multiple reflex-arc-like **SC**^{3} closed loops exist to perform complicated control tasks. This forms a nervous-system-like control system. In order to analyze such a complex system, we draw significant inspiration from material structures. Specifically, in nature, there are various complex materials with varied properties. The basic units of these materials are molecules, which arise from different structures formed by atoms through chemical bonds. The unique structures determine the properties of the materials, enabling them to be utilized in various applications. Similarly, in complex control systems, the **SC**^{3} closed loops are the basic units, with networks bonding the units such as sensors and robots into different structures. The diverse structures of the **SC**^{3} closed loops make them flexible to meet complex and diverse task requirements. A complex control system can be decomposed into multiple **SC**^{3} closed loops with different structures. In the following, we analyze the basic structures of the **SC**^{3} closed loops.

Considering progressively complex structures, we show a pyramid-like illustration of different **SC**^{3} closed loop structures in Fig. 3. Fig. 3(a) shows a simple structure of an **SC**^{3} closed loop that contains one sensor, one computing unit, and one robot. This is the minimum structure of the **SC**^{3} closed loop. Investigating this structure is beneficial for clarifying the interactions among the sensing, communication, computing, and control components. However, the limited capabilities of individual devices make it difficult for such a simple structure to satisfy the task demands. This entails the collaboration of multiple devices, leading to more complex structures of the **SC**^{3} closed loops. In Fig. 3(b), we show three structures of the **SC**^{3} closed loops with two sensors, two computing units, and two robots, respectively. Such structures require the cooperation of multiple devices of the same type, so as to compensate for the insufficiency of a certain capability. By studying these three structures, the mechanisms of cooperative sensing, distributed computing and robot cooperation can be clarified. Based on these structures, we show an **SC**^{3} closed loop that contains multiple sensors, computing units, and robots in Fig. 3(c). We refer to an **SC**^{3} closed loop as an (M, N, K) structure when there are M sensors, N computing units, and K robots within the loop to accomplish a task. The (M, N, K) structure is a general structure of the **SC**^{3} closed loops, as a basic unit of the complex systems. All of the structures shown in Fig. 3(a) and Fig. 3(b) can be considered as special cases of the (M, N, K) structure, e.g., the **SC**^{3} closed loop in Fig. 3(a) corresponds to a (1, 1, 1) structure. Investigating the basic (M, N, K) structures can be helpful for gaining better insight into the overall system. Specifically, we provide an illustration of control system with complex topology in Fig. 3(d). The complex control system is non-linear composition of multiple basic units, i.e., (M, N, K) structures. It can be seen from the figure that the local parts of this complex system can be regarded as the above basic structures. A potential approach to designing and analyze such systems is based on the system entropy. By focusing on reducing system entropy, we can uncover pathways for the dynamical system decomposition and the iterative system design methods.

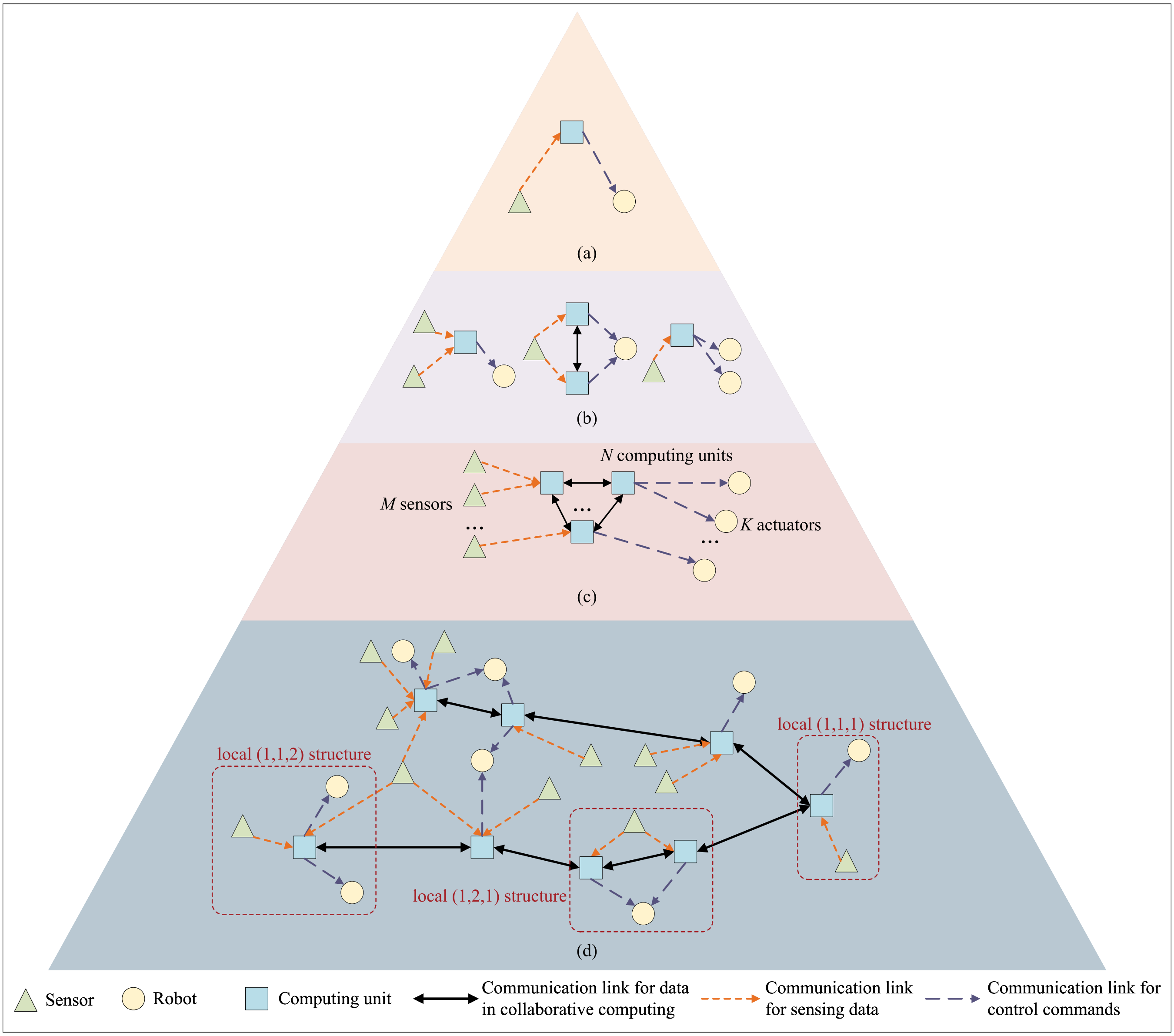

FIGURE 3. Diagrams of different **SC**^{3} closed loop structures and a complex system containing multiple **SC**^{3} closed loops. a) (1, 1, 1) structure of an **SC**^{3} closed loop. b) (2, 1, 1), (1, 2, 1), and (1, 1, 2) structures of **SC**^{3} closed loops. c) (*M*, *N*, *K*) structure of an **SC**^{3} closed loop. d) Complex system for control.

A Case Study

In this section, a case study is provided to evaluate the proposed closed-loop-oriented system design framework [7].

The case study considers a satellite-UAV network serving multiple robots for control tasks. The UAV is equipped with an EIH integrating with a remote sensor, a computing unit, and a communication module. Due to the limited computing capability of the EIH, some of the sensing data will be offloaded to the cloud server via the satellite for further processing. The detailed computing and offloading process of the sensing data is shown in Fig. 4. Specifically, the sensing data is split into three parts: the first part is completely transmitted to the cloud for processing through satellites, the second part is pre-processed on the EIH to extract semantic features and then sent to the cloud for further processing, and the third part is completely processed on the local computing unit of EIH. Under the closed-loop-oriented design framework described in the previous section, the optimization of data offloading and multi-domain resource allocation among the **SC**^{3} closed loops is investigated. Specifically, the closed-loop control performance is measured by the linear quadratic regulator (LQR) cost [14]. The LQR cost is a widely used performance metric in control systems, defined as the weighted sum of a quadratic function of the system state and control input, and its formulation can be seen in [14]. The LQR cost function penalizes deviations of the system state from the desired reference and the magnitude of control input, effectively balancing system state deviation and control energy consumption. The LQR cost provides a simple form to evaluate the control performance, and the relationship between the LQR cost and communication capability has been investigated in [14].

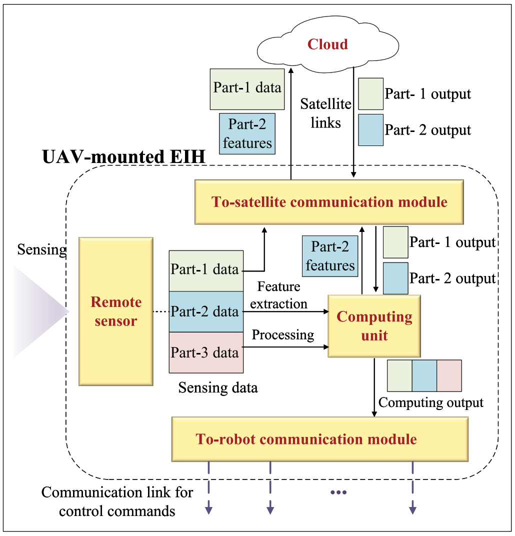

FIGURE 4. Illustration of the computing and offloading process in the case study.

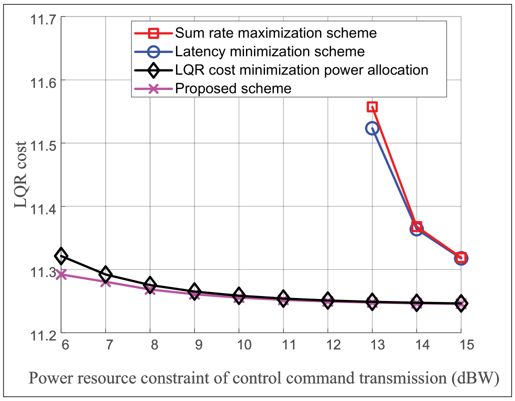

FIGURE 5. The LQR cost achieved with different schemes.

In the case study, the sum LQR cost of the **SC**^{3} closed loops is minimized by jointly optimizing the sensing data partition, the computing capability of the computing unit, the satellite-backhaul rate, and the transmit power resource of the control command transmission.

The simulation parameters of this case study are provided as follows [7]. The system consists of 5 robots to perform control tasks, and they are randomly distributed in a circular area with a radius of 5000 m. The UAV is located in the center of the circle, and the height of the UAV is set as 100 m. We utilize a realistic channel model considering both the line-of-sight (LoS) and non-line-of-sight (nLoS) elements [15]. And the path loss parameters of LoS and nLoS elements are set as 0.1 and 20 corresponding to suburban scenarios [15]. The channel noise variance is -110 dBm, and the bandwidth of each channel is 5 kHz. The satellite-backhaul rate constraint is set as 50 Mbps, and the propagation delay of the satellite link is 5 ms. For the computing parameters, the maximal CPU frequency of the computing unit is 5 GHz, and the data size of sensing data in each **SC**^{3} closed loop per control cycle is 300 kilobits.

In Fig. 5, we evaluate the proposed closed-loop-oriented system design method by showing the LQR cost achieved with different schemes. We take the traditional communication-oriented resource allocation strategies as benchmarks, including the latency minimization scheme and sum rate maximization scheme. In addition, the control-oriented power allocation scheme [4] is also compared, where sum LQR cost is minimized by optimizing power allocation, with computing capability and satellite-backhaul rate allocated equally. As shown in Fig. 5, the proposed scheme achieves the lowest LQR cost among these schemes, demonstrating its superiority. The performance gap decreases as the available power increases, indicating that the proposed scheme is more effective in resource-limited remote areas. In addition, the two communication-oriented schemes yield significantly higher LQR costs than the two control-oriented schemes, indicating that the optimization objective should be the closed-loop performance, instead of communication performance.

Open Research Issues

SC^3 Integrated Information Theory

The information theory, computer science, and control theory have developed in their respective domains. However, the application of these theories in CPSs is limited due to the tight coupling of the different components within the **SC**^{3} closed loops. This necessitates the development of a novel theoretical framework that can integrate the components of **SC**^{3} closed loops. As information plays a pivotal role in the **SC**^{3} closed loops, developing a novel **SC**^{3} integrated information theory that extends the traditional Shannon information theory and characterizes the relationship between information and the closed-loop performance is an important direction for future research.

Security

The transmission environments of the satellite-UAV networks are more open than the terrestrial networks due to fewer scatterers in the UAV links and longer distance of satellite links. Therefore, the networks are susceptible to adverse security threats, such as eavesdropping and cyber attacks. The cyber-security in satellite-UAV networks for control is crucial for safeguarding the confidentiality of industrial secrets and ensuring the smooth execution of critical control tasks. To this end, corresponding security technologies such as encryption and physical layer security measures should be adopted. In such cases, the trade-off between the security performance and control performance should be further investigated.

Dynamic SC^3 Closed Loop Design

Practical control systems are dynamic in nature, as nodes (sensors, computing units, and robots) may join or leave the systems due to task scheduling, node failures, or variations in communication channels. This results in frequent changes of the system topology and structure, posing new challenges in maintaining the stability and functional integrity of the **SC**^{3} closed loops. Consequently, the dynamic nature of **SC**^{3} closed-loop structures necessitates a more efficient system design framework that includes the dynamic task assignments and resource orchestration mechanism.

Conclusion

In this article, we have investigated satellite-UAV networks that assist robots for control tasks. We have provided typical use cases of the satellite-UAV networks for control and analyzed the challenges of the system design. Considering the role as fundamental unit of the **SC**^{3} closed loops in the control process, we have proposed a closed-loop-oriented system design framework, where the main focus is the closed-loop metric. The structural decomposition of complex system based on the **SC**^{3} closed loops has been discussed. We have provided a case study to show the superiority of the closed-loop-oriented framework. Finally, we have discussed the open issues in the satellite-UAV networks for control as the future research directions.

Acknowledgment

The work of Chengleyang Lei, Xinran Fang, Wei Feng, and Ning Ge was supported in part by the National Natural Science Foundation of China under Grant 62425110 and Grant U22A2002, in part by the National Key Research and Development Program of China under Grant 2020YFA0711301, in part by the Suzhou Science and Technology Project, and in part by FAW Jiefang Automotive Company Ltd. The work of Ming Xiao was supported in part by the European Commission, in part by Horizon Europe, in part by the MSCA Project, in part by the Secured and Intelligent Massive Machine-to-Machine Communication for 6G (SCION), and in part by the Autonomous Vehicular Edge Computing and Networking for Intelligent Transportation (ASCENT).

References

[1] X. Fang et al., "Control-oriented deep space communications for unmanned space exploration," *IEEE Trans. Wireless Commun.*, vol. 23, no. 10, pp. 14466–14481, Oct. 2024.

[2] W. Feng et al., "Radio map-based cognitive satellite-UAV networks towards 6G on-demand coverage," *IEEE Trans. Cognit. Commun. Netw.*, vol. 10, no. 3, pp. 1075–1089, Jun. 2024.

[3] G. F. Franklin, J. D. Powell, and A. Emami-Naein, *Feedback Control of Dynamic Systems*, 6th ed., Englewood Cliffs, NJ, USA: Prentice-Hall, 2009.

[4] C. Lei et al., "Control-oriented power allocation for integrated satellite-UAV networks," *IEEE Wireless Commun. Lett.*, vol. 12, no. 5, pp. 883–887, May 2023.

[5] W. Duo, M. Zhou, and A. Abusorrah, "A survey of cyber attacks on cyber physical systems: Recent advances and challenges," *IEEE/CAA J. Autom. Sinica*, vol. 9, no. 5, pp. 784–800, May 2022.

[6] *IMT Vision-Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond*, document ITU-R M.2083-0, Sep. 2015.

[7] C. Lei et al., "Edge information hub: Orchestrating satellites, UAVs, MEC, sensing and communications for 6G closed-loop controls," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 1, pp. 5–20, Jan. 2025.

[8] W. Feng et al., "Structured satellite-UAV-terrestrial networks for 6G Internet of Things," *IEEE Netw.*, vol. 38, no. 4, pp. 48–54, Jul. 2024.

[9] S. Lee, S. Lee, and H. Kim, "Differential security barriers for virtual emotion detection in maritime transportation stations with cooperative mobile robots and UAVs," *IEEE Trans. Intell. Transp. Syst.*, vol. 24, no. 2, pp. 2461–2471, Feb. 2023.

[10] J. Jin et al., "Cloud-fog automation: Vision, enabling technologies, and future research directions," *IEEE Trans. Ind. Informat.*, vol. 20, no. 2, pp. 1039–1054, Feb. 2024.

[11] P. Brodal, *The Central Nervous System*. New York, NY, USA: Oxford Univ. Press, 2010.

[12] G. N. Nair et al., "Feedback control under data rate constraints: An overview," *Proc. IEEE*, vol. 95, no. 1, pp. 108–137, Jan. 2007.

[13] H. Lv et al., "Impacts of wireless on robot control: The network hardware-in-the-loop simulation framework and real-life comparisons," *IEEE Trans. Ind. Informat.*, vol. 19, no. 9, pp. 9255–9265, Sep. 2023.

[14] V. Kostina and B. Hassibi, "Rate-cost tradeoffs in control," *IEEE Trans. Autom. Control*, vol. 64, no. 11, pp. 4525–4540, Nov. 2019.

[15] A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal LAP altitude for maximum coverage," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 569–572, Dec. 2014.

Biographies

Chengleyang Lei (lcly21@mails.tsinghua.edu.cn) received the B.S. degree from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2021, where he is currently pursuing the Ph.D. degree. His research interests include communication and control integration, coordinated satellite-UAV-terrestrial networks, and future 6G technologies.

Xinran Fang (fxr20@mails.tsinghua.edu.cn) received the B.S. degree from the School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing, China, in 2020. She is currently pursuing the Ph.D. degree with the Department of Electronic Engineering, Tsinghua University, Beijing. Her research interests include integrated space-air-ground networks, communication and control co-design, and task-oriented communication.

Wei Feng (Senior Member, IEEE) (fengwei@tsinghua.edu.cn) received the B.S. and Ph.D. degrees from the Department of Electronic Engineering, Tsinghua University, Beijing, China, in 2005 and 2010, respectively. He is currently a Professor with the Department of Electronic Engineering, Tsinghua University. His research interests include maritime communications and coordinated satellite-UAV-terrestrial networks.

Yunfei Chen (Senior Member, IEEE) (yunfei.chen@durham.ac.uk) received the B.E. and M.E. degrees in electronics engineering from Shanghai Jiaotong University, Shanghai, China, in 1998 and 2001, respectively, and the Ph.D. degree from the University of Alberta in 2006. He is currently a Professor with the Department of Engineering, University of Durham, U.K. His research interests include wireless communications, performance analysis, and joint radar communications designs.

Ming Xiao (Senior Member, IEEE) (mingx@kth.se) received the Ph.D. degree from the Chalmers University of Technology, Sweden, in November 2007. Since November 2007, he has been with the Department of Information Science and Engineering, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Sweden, where he is currently a Professor. He received the IEEE Vehicular Technology Society Best Magazine Paper Award 2023. He was an Editor of IEEE Transactions on Communications from 2012 to 2017 and has been an Editor of IEEE Transactions on Wireless Communications since 2018. He has been an Area Editor of IEEE Open Journal of the Communication Society since 2019.

Ning Ge (Member, IEEE) (gening@tsinghua.edu.cn) received the B.S. and Ph.D. degrees from Tsinghua University, Beijing, China, in 1993 and 1997, respectively. He is currently a Professor with the Department of Electronic Engineering, Tsinghua University. His research interests include ASIC design, short-range wireless communication, and satellite communications.

Shiwen Mao (Fellow, IEEE) (smao@ieee.org) received the Ph.D. degree in electrical and computer engineering from Polytechnic University, Brooklyn, NY, USA. He is currently a Professor, a Earle C. Williams Eminent Scholar, and the Director of the Wireless Engineering Research and Education Center, Auburn University. His research interests include wireless networks and multimedia communications.