SCIENCE CHINA
Information Sciences

• PERSPECTIVE •

October 2024, Vol. 67, Iss. 10, 206201:1–206201:3
https://doi.org/10.1007/s11432-023-4156-5

Cloud-based control systems: towards the control architecture in cloud computing era

Yuanqing XIA[1,2]

[1]*School of Automation, Beijing Institute of Technology, Beijing* 100081*, China;*
[2]*Zhongyuan University of Technology, Zhengzhou* 450007*, China*

Received 24 December 2023/Revised 17 May 2024/Accepted 7 August 2024/Published online 24 September 2024

Era of cloud computing. After Google introduced the concept of "cloud computing", this paradigm experienced rapid growth and found widespread applications across various industries, establishing itself as one of the most favored business and technological modes. According to the definition provided by the National Institute of Standards and Technology in the United States [1], "cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources". This mode, evolved and integrated from grid computing and distributed computing, functions like a utility, offering business access on a pay-as-you-go basis, tailored to resource needs. Consequently, the emergence of cloud computing has brought a transformative impact on the landscape of computing.

Leveraging its service-oriented characteristics, cloud computing facilitates seamless expansion into diverse industries, fostering cross-sector collaboration and cost-effectiveness. For instance, automotive companies such as BYD, NIO, XPeng, and Great Wall Motor have enthusiastically established intelligent computing centers, covering areas such as intelligent connected vehicles (ICVs), autonomous driving, new energy, security, and experimental prototyping. Meanwhile, various regions such as Beijing, Guangdong, and Chongqing, are constructing industrial Internet big data centers, to meet users' demands for data-driven decision-making, management, and innovation. These intelligent computing centers and big data centers serve as the physical embodiments of cloud computing in the real world.

Concept of cloud-based control systems (CCSs). The development and applications of cloud computing have given rise to a series of emerging industries, such as ICVs, unmanned aerial vehicle (UAV) logistics, and intelligent manufacturing. These industries bring new transformations and challenges for control systems, as they generate massive amounts of data that traditional control architecture cannot adequately process. Control, as the core element in these industrial scenarios, directly dictates the levels of efficiency, performance, and stability. However, traditional networked control systems (NCSs) lack the capacity to process vast amounts of data, suffer from computational insufficiency, and struggle to meet real-time and high-quality demands. Therefore, the research on the integration of cloud computing and control systems holds profound theoretical and practical significance.

In 2012, the concept of cloud-based control systems (CCSs) was proposed [2], incorporating cloud computing into the traditional control systems. This innovation involved aggregating sensor data in the cloud, enabling online system identification and modeling, and performing tasks such as planning, scheduling, control, and decision-making processes of complex systems in the cloud. In recent years, CCSs have shown promising progress in method design, theoretical research, and industrial applications [3]. With the development and popularization of cloud computing, CCSs will be the control architecture in the future.

Promising directions of CCSs. Now, we introduce six promising directions of CCSs as follows.

(1) Data-driven cloud control. The improvement of computational ability brought by cloud computing allows for the integration of more complex controlled plants and more devices into control systems. For these plants and devices, the precise mathematical models are often challenging to establish, due to the process complexity and involvement of numerous variables. Simultaneously, in such scenarios, we can use the sensing technologies to measure system states or outputs, containing valuable information. Then, leveraging the computational prowess of cloud computing, we can harness the vast data, analyze the characteristics of the plants and devices, and establish the relationship from historical data to control inputs. Therefore, data-driven cloud control can be realized, holding significant importance for model-free control challenges in cloud environments, such as large-scale multi-agent systems, ICVs platoon control with unknown faults, and model-varying control problems.

(2) Model predictive cloud control. The task domain in modern scenarios is expansive, characterized by significant challenges posed by environmental disturbances and heightened internal model uncertainties within systems. This complexity requires advanced control algorithms to address the demands of complex systems with multiple constraints and diverse optimization objectives. In a cloud environment, if the precise model can be established and utilized as prior knowledge, model predictive control (MPC) is also an ideal strategy. MPC is a model-based optimal control strategy that determines the future control signals for a system, by

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Email: xia_yuanqing@bit.edu.cn

optimizing a performance metric describing system behavior, while ensuring the satisfaction of constraints. Hence, MPC has advantages such as foresight, robustness, and the ability to handle complex constraints. On the other hand, MPC imposes high computational cost requirements, which can be met by CCSs that offer ample computational resources. Therefore, model predictive cloud control, as the integration of MPC and CCSs, can effectively meet the requirements of the mentioned challenges.

(3) Workflow-based CCSs. When deploying data-driven control, MPC, and other algorithms in the cloud, how to efficiently utilize cloud computing resources for enhancing computational efficiency becomes a crucial challenge. If the controller is simply deployed on a cloud server, it still resembles closely to the research approach of NCSs, without considering the structural features and advantages specific to cloud computing. Cloud computing is a network-based computing model that enables users to access and share configurable computing resources, such as networks, servers, storage, and application services, on-demand, without the need to understand or manage the underlying infrastructure. From the structure aspect, it abstracts and consolidates multiple physical computers distributed across different locations into a shared virtual cloud resource pool, encapsulating them into new logical computers as needed. Therefore, cloud computing allows users to launch multiple virtual machines or containers in the resource pool to accomplish complex tasks. In practical applications such as genetic computation and seismic wave analysis, with complex structures, large datasets, and high-performance requirements, they are often modeled as cloud workflows with Directed Acyclic Graph structure. Inspired by this, control missions are considered as a specific type of computational workload, that can be restructured into the form of cloud workflow. This approach improves the utilization of cloud computing resources and leverages the computational advantages. Consequently, workflow-based CCSs are proposed [4], employing distributed numerical algorithms and distributed optimization to establish the cloud workflows of advanced control algorithms.

(4) Cloud-network-edge-end collaborative control. For complex, large-scale, and widely distributed systems, leveraging cloud resources is necessary to obtain sufficient computing power, enhance real-time computation, and improve the capability for global information processing. While methods like workflow-based CCS can enhance computing efficiency, the extent of improvement is not limitless. Additionally, cloud computing is not a hard real-time system and cannot guarantee strict real-time computation. Furthermore, introducing cloud computing into control systems introduces unavoidable communication delays. The contingencies for occasional failures of cloud platforms must also be considered. On the other hand, with the rapid development of edge computing technology, computing capabilities are extending to edge systems. In the long term, relying solely on cloud platforms would result in resource mismatch. Therefore, the cloud-network-edge-end collaborative control is required. For instance, the cloud performs high-level decision-making tasks, the edge handles small-scale planning tasks, and the terminal executes control based on planning signals. Depending on the scenarios, the cloud-edge-terminal collaborative control can be simplified to cloud-edge collaborative control. For example, when a cloud controller runs, the computing process introduces intrinsic disturbances and uncertainties. Thus, it is necessary to study the reliable collaborative scheme with an edge disturbance observer. The above layers are interconnected via networks to achieve overall collaborative control.

(5) Security and privacy protection. In CCSs, the physical space of the controlled system is connected to the information space, thereby inheriting the security and privacy concerns that are inherent to cloud computing. For the security issue, common threats include denial of service (DoS) and replay attacks. For instance, the Stunet malware infiltrated Iran's nuclear enrichment facilities, accessed historical operational data, and conducted replay attacks to deceive control systems. In CCSs, security threats in the information space become more severe. As for the privacy issue, the cloud platform poses a primary risk. Even if cloud service providers comply with privacy regulations, they still have an interest in the data value and the capability to access user data. To address these issues, researches are needed on security-resilient control and privacy-preserving control based on techniques such as differential privacy and homomorphic encryption (HE) in CCSs. However, both two algorithms introduce computational disturbances, so it is important to estimate the bound of disturbance and design the disturbance-rejection control laws. Specifically, the computation of HE is slow. Thus, the designs and analyses of cloud control laws from the perspective of numerical computation and optimization are also significant.

(6) Service-oriented cloud control platform. The domain of CCSs is not only a theoretical issue but also holds strong practical applicability and value. For theoretical algorithms, their implementation is dependent on a suitable cloud control platform. Simultaneously, a cloud control platform that aligns with industry ecosystems and exhibits excellent scalability and portability is of significant importance for advancing engineering practices. With the development and widespread adoption of cloud-native principles, container technology has supplanted virtual machines as the mainstream infrastructure in Internet production environments. For example, to conduct the control tasks with workflow structure, a containerized cloud control platform is designed and implemented in [4]. Furthermore, this platform has been extended to the cloud-edge environment [5]. Based on its advantages of high flexibility, strong reusability, and less resource consumption, container technology has gained prominence. Concurrently, container technology is making inroads into control domains. The cloud control platform, implemented with a cloud-native ecosystem, allows cloud controllers to be encapsulated as services, invoked on demand, realizing control as a service (CaaS).

In addition, resource scheduling, theoretical stability analysis, and the integration of computation, communication, and control in CCSs are also important directions.

Next generation: so-called dynamic cloud and its CCSs. With the advancement of technologies and the development of various industries, whether in civil fields such as aviation, oceanography, fisheries, petroleum, environmental monitoring, or in defense and military areas such as reconnaissance, target strike, and communication relay, the traditional single-movement-body platforms struggle to meet the multidimensional and all-element mission requirements. The cross-domain multi-movement-body system is an organic entity composed of distinctly functional bodies operating in different spatial domains. The cross-domain interconnection and collaborative cooperation among space, air, and ground multi-movement-body systems help reduce the functional redundancy of heterogeneous platforms, fully

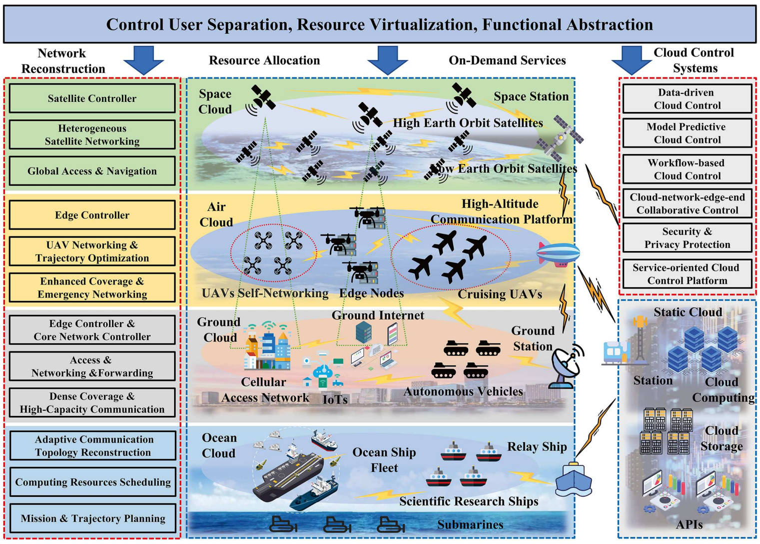

Figure 1 (Color online) Space-air-ground-ocean cross-domain collaborative system.

leverage the system robustness and complementary capabilities, and achieve the integrated utilization of various units.

Due to these requirements from the control aspect, cloud computing may evolve into a dynamic cloud called by the author [6], combined with the cross-domain collaborative control systems based on multiple clouds. Research on the so-called dynamic cloud and its CCSs is poised to play a crucial role, possibly serving as one of the architectures for the next generation of cloud computing and control systems. Meanwhile, the introduction of CCSs also provides a new perspective for addressing the emerging space-air-ground-ocean issues. As shown in Figure 1, in the space-air-ground-ocean cross-domain collaborative system, the space cloud, air cloud, ground cloud, and ocean cloud could not only form individual sub-CCSs but also interconnect, intercommunicate, and interoperate through the integrated space-air-ground-ocean network. This system consists of five layers, which are the hardware, data, service, mission, and plan layers. The different dynamic clouds have enhanced the coverage, resource integration, and centralized management of cross-domain environments, which broadens the detection and perception scope, as well as the execution scenarios of cross-domain collaborative systems. There are five critical issues in dynamic cloud and its CCSs, which are cluster management of dynamic cloud topology, space-air-ground-ocean dynamic environment collaborative perception, multi-dimensional heterogeneous movement-body collaborative cloud control, cross-domain collaborative system security, and dynamic-cloud-based intelligent decision-making.

In this system, the so-called static cloud is also encompassed. Under specific conditions, the static cloud possesses the capability to manage all dynamic clouds within the system. It primarily handles tasks with high complexity requirements, leveraging functionalities such as human-machine interface, data analysis, and digital twins. Typically, the static cloud is managed by the large-scale computing centers on the ground. The dynamic clouds consist of a series of homogeneous movement-bodies, including the space cloud composed of spacecraft, the air cloud consisting of aerial vehicles, the ground cloud formed by the ground platforms such as autonomous vehicles, and the ocean cloud made up of surface and underwater vehicles. These dynamic clouds can be centrally scheduled and managed by the static cloud. The different dynamic clouds can interact with each other, and when necessary, they can obtain various service supports from the ground static cloud. In many scenarios, each dynamic cloud needs to operate independently, enabling autonomous decision and control.

Conclusion. In the era of cloud computing, CCSs emerge as an effective control solution to meet the demands of complex systems. Leveraging services such as big data, cloud computing, and cloud storage, coupled with advanced control methods, CCSs efficiently facilitate the modeling, planning, scheduling, control, and decision-making processes of complex systems. Currently, the research on CCSs is in its early stages, with numerous meaningful questions awaiting exploration. Furthermore, the integration of the so-called dynamic cloud and its CCSs with the space-air-ground-ocean cross-domain collaborative system expands the research scopes of CCSs, which will play a crucial role in both the national economy and defense sectors.

Acknowledgements This work was supported by the National Key Basic Research Program (Grant No. 2021YFC2202600).

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