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Cloud-based control systems: a systematic literature review

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ABSTRACT

Control systems and computer science are two distinct and important fields of engineering. The development of cloud computing in computer science has become an enabler for the widely used controller in control systems to migrate to the cloud and has created a new field of research in cloud-based control systems (CCS). The paper used the systematic literature review approach to obtain insight into current CCS research. The objectives include a review in areas such as the demographics, topics of the research, evaluation method, and application domain. To that end, systematic literature review (SLR) has been conducted. The study obtained 64 primary studies from 581 articles. The CCS has a distinct characteristic; despite the fact that the cloud and network dynamics system, when coupled with the controlled plant, is inherently nonlinear, research efforts have used linear models with optimal control to approach it successfully in a limited case of control objectives. Furthermore, cloud-centric and cloud-fog network architecture approaches are considered in the studies—whereas, the quantitative method mainly uses simulation and discussion. Finally, the SLR summarizes open challenges for CCS in the future.

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1. INTRODUCTION

There are several types of controllers in the industrial control systems, such as programmable logic controllers (PLC), distributed control systems (DCS), supervisory control, and data acquisition (SCADA). These controllers serve a distinct function based on computer integrated manufacturing (CIM). The CIM is often depicted as level 2 of automation-based or field-level control in the American National Standards Institute (ANSI)/international society of automation (ISA)-95 model [1]. However, recent research studies revealed a lack of development of the hardware capacity, which is a constrained device. As a result, it creates problems in the currently diversified complex industrial control requirements and increases the demand for connectivity [2].

Nowadays, industrial revolution 4.0 emerged with an intelligent factory, and several researchers introduced a cyber-physical system (CPS), an integration concept of cyber parts and physical parts with the Internet. Also, an internet of things (IoT) paradigm has been introduced to connect 'things' or 'hardware' through the internet. Additionally, the rapid development of cloud computing in providing on-demand elastic service with almost unlimited resource allocation has become a core technology in recent years [3]. More and more devices, an estimated 50 billion devices in 2020, connected to the internet recently. Thus, extensive data will be gathered and stored for further data analytics. The control systems must cope with the enormous amount of data from different data gatherers, such as radio-frequency identification readers and wireless sensor networks. In this scenario, the need for high-quality and real-time control systems will surpass the capabilities of legacy network topology since the big data in control systems will raise the network communication load and processing burden. As a solution, a new paradigm called cloud-based control systems (CCS) is being studied, combining the strengths of networked control and cloud computing technologies [4], [5].

A survey of CCS employed on intelligent and connected vehicles (ICV) is discussed in [6]. It investigated the CCS paradigm, from cloud-based application to core technology development related to ICV, in terms of the possibility as an enabler of high-level autonomous driving to improve safety and optimize traffic flow. Another review of a practical case study of CCS for smart communities is discussed in [7]. It elaborated on the foundation for India's cloud computing-based innovative community services. It showed broad implications for the future of the IoT and may be used for healthcare, energy-efficient systems, and smart cities. A literature review on cloud computing regarding elasticity, provisioning, and model classification is discussed in [8]. Finally, a comprehensive bibliometric analysis of the CCS is discussed in [9], and this paper is an extended work of the author.

The novelty of this SLR study is threefold. First, the SLR method employed the goal-question-metric approach [10] to quantify the review metric in this study and combined it with the Kitchenham method [11] to ensure the validity and repeatability of the review results. Second, the study uses the approach to obtain insight into current CCS research and its perspective on the article's demographics, current research states, evaluation method, and application domain. Third, the SLR provides insight into architecture, control algorithms, and system modeling perspectives.

The structure of the paper is as follows: section 2 outlines the research method, and section 3 offers result analysis and discussion. Next, the specific findings from the study that aided us in identifying pertinent research issues for future research are detailed in section 4. Finally, section 5 summarizes the survey's conclusions.

2. RESEARCH METHOD

The goal of the SLR based on the goal-question-metric approach is as: i) purpose: understand and clusterize, ii) issue: perspective of cloud-based control system, iii) object: ingredient of cloud-based control system and iv) viewpoint: researcher standpoint.

The SLR is conducted based on the guideline described by Kitchenham. Research questions (RQ) are formulated to achieve the overall goal of this study as:
RQ1: how are the demographics state of research?
RQ2: what topics are mainly discussed in the CCS research?
RQ3: what types of assessments are used to evaluate the proposed method?
RQ4: what kind of application domain has been considered?

The RQ1 objective is to provide a general demographics overview of the current state-of-the-art research in the CCS field. Importantly, it provides insight into diachronic productivity, author network, and the community interested in CCS. The RQ2 is formulated to identify the scope of studies related to the CCS field, especially cloud architecture, control strategy, and network, which are the essential ingredients of the CCS framework. The RQ3 gives insight into the proposed method evaluation technique to show its effectiveness. Finally, the RQ4 provides information on the application domain considered in the obtained articles.

The SLR method steps start with database source selection, as shown in Figure 1. We selected SCOPUS, ScienceDirect, IEEE Xplore, and ACM Digital Library databases. Then the second step is to establish a keywords string based on the RQs. The string contains keywords, such as "cloud-based control", "algorithm", "system", "architecture", "controller" combined as a search string to look-up up the related articles in the selected databases. Finally, articles sources selection is started manually to establish the combination of the strings. It is done by selecting a related paper that discusses the CCS domain in terms of cloud architecture, control strategy, or network, which is published in high-impact journals or received high citations per year, such as [12]–[15]. Then, a quasi-gold standard method [16] is used to start pilot searches on SCOPUS, IEEE Xplore, and ScienceDirect databases. The suggested method consists of a collection of previously published research and related quasi-sensitivity to the search process for measuring search performance. The obtained keywords from the method were then applied to the article title and abstract with the following search string: (("cloud-based control" OR "cloud control") AND ("algorithm" OR "system" OR "architecture" OR "controller")). The mentioned search string is a refined version to obtain the selected articles and a minimal number of the remaining articles.

In step three, we used the refined search string for an automatic search in all selected databases and set up inclusion criteria to get the SLR's final list of articles. In the auto search criteria, we only selected publication years from 2012, when the CCS paradigm was introduced by Xia [17], to 2022 and research published in journals or proceedings. As a result, there were 581 articles collected. The study set up three inclusion criteria (IC) as follows, IC1 discussed or mentioned cloud-based control systems in terms of algorithm, system, architecture, and controller in the title, abstract, and keywords of the article; IC2 article that is primary study, accessible, and written in English; IC3 merge and remove the duplicate article. For example, if the article is found in proceedings and journals, then we remove the article from proceedings. If the article is found in two databases, then we remove the article from the database with fewer citations. The exclude criteria is the negation of the inclusion criteria written above. Finally, the list of articles for the SLR consists of 64 references after inclusion criteria were applied. Table 1 shows the total articles based on database sources.

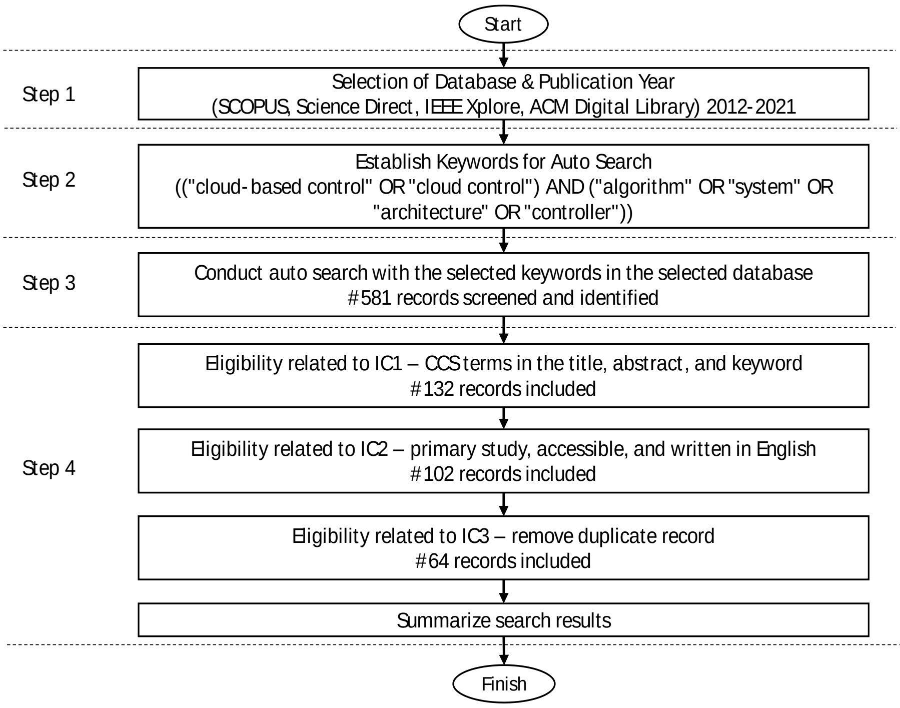


Figure 1. SLR steps used in the study

Table 1. Total articles based on database sources

No	Database sources		Auto-search	IC1	IC2	IC3
1	SCOPUS		170	65	39	39
2	ScienceDirect		235	20	17	11
3	IEEE Xplore		118	44	44	13
4	ACM Digital Library		58	3	2	1
		Total	581	132	102	64

Next, we defined quantitative metrics that will be used to answer the research questions, as shown in Table 2. The result and analysis of these quantitative metrics are explained in the next section. Herewith, we also describe briefly explain the different metrics (M). M01, M02, and M03 provide information on the published articles from 2012 to 2021, cited per year, and how the co-authorship network developed and its influence. M04 provides information on the venue of the article publication and insight into which academic community is interested in the field. Additionally, M05 provides information on the main research topic: cloud architecture, control algorithm, network, or other elements that can emerge from the result analysis. Cloud architecture scope means the proposed method in cloud computing and information systems. Control algorithm scope means the proposed method in control theory and system modeling. M06 provides information on the clusterized perspective of the control algorithm and architecture-related topics, such as i) cloud, network, and plant uncertainties, ii) control strategy and structure, iii) privacy, security and encryption, and iv) self-learning and data-driven modeling. M07 provides information on the system model used to calculate the required control action. M08 provides information on the controller type and objective used in the articles, specifically on the topic of the control algorithm. M09 provides information on the assessment method used to verify the proposed novelty: discussion, experiment with use-case, or simulation. Finally, M10 provides information on the application domain or practical use case used in the articles to support the effectiveness of the proposed method.

Table 2. Quantitative metrics

ID	Field metric	Usage	ID	Field metric	Usage
M01	Diachronic productivity	RQ1	M07	System modeling	RQ2
M02	Citations per year	RQ1	M08	Control algorithm and objective	RQ2
M03	Author network	RQ1	M09	Assessment	RQ3
M04	Publication venue	RQ1	M10	Application domain	RQ4
M05	Engineering perspective	RQ2			
M06	Control and architecture perspective	RQ2			

3. RESULTS AND DISCUSSION

3.1. Answering RQ1: articles demographics

Figure 2 shows the diachronic productivity of primary studies per year by journal and proceedings (metric M01). It is observed that 84.38% of articles were published in the last five years, although the CCS paradigm was introduced in 2012, with articles spanning nine years. Furthermore, it showed that the CCS field is gaining interest, although there was a slight decline in publications in 2021 due to the COVID-19 pandemic. Several articles have claimed that significant elements of CCS, such as big data processing capability [14], [18], [19], leverage control performance with low cost [20], [21], control-as-a-service flexibility [12], [22]–[24]. Additionally, the obtained research articles are clusterized by the number of citations received per year (metric M02), as shown in Table 3. It can be concluded that the influential research topic discussed on matters are cloud architecture, control algorithms, and network security correlated with the basic ingredients of the CCS paradigm.

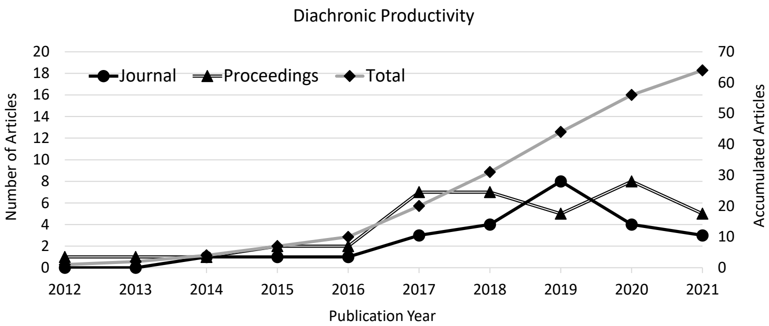


Figure 2. M01: Diachronic productivity of CCS

Table 3. M02: articles with a minimum of 10 citations received per year

Topic	Reference	Citation/year
Cloud architecture for flexible service	[12]	15.00
System stability and data processing	[25]	14.00
Secured control algorithm	[26]	13.00
Data-driven control algorithm	[27]	11.00
Cloud architecture and control algorithm	[14]	10.14

Next, VOSviewer [28] generates the co-authorship network and observes the relationship between the author and the most influential author, as shown in Figure 3. There are 180 authors within the selected 64 articles, and the largest set of a connected network consists of 41 authors (metric M03). It can be observed that the author of the three most cited articles in metric M02 is also in the author network of metric M03 and their influence on other 38 authors [14], [26], [29]. This largest set of the author-connected network was separated into 6 clusters representing the individual publication cluster in which the author's name was mentioned. The circle size represents the total number of publications for each author. For example, cluster 1 (yellow color) consists of authors name Xia, Y.; Ali, Y.; Hammad, A.; Zhan, Y.; Ma, L.; Vasilakos, A.V.

published [30]–[32]. Xia, Y. has the biggest circle size due to his contribution with other authors in different clusters too, which are: (1) Xia, Y.; Ma, L. collaborated with Gao, R. from cluster 3 (dark blue color) in [33], (2) Xia, Y. also collaborated with authors from cluster 2 (light blue color) in [34], (3) Xia, Y. also collaborated with Yan, C.; Li, Y. from cluster 4 (green color) in [35], [36], (4) Xia, Y. also collaborated with authors in cluster 6 (purple color) in [21], [26], [37], [38].

Lastly, it can be observed that the publication venues (metric M04) were scattered over different venues, as shown in Table 4. The quantitative metric of publication venue is separated into two parts: proceeding venue and journal venues, and it has a total of 39 articles and 25 articles, respectively. IFAC has published articles in the proceeding venues, followed by CCC, CDC, and CAC. Each venue published three articles; CPS published two articles, while the other 21 articles were published in the 21 conference venues. Three IEEE journals each published two articles in the journal venues, and one ScienceDirect journal published 1 article, while the other 17 articles were published in the 17 separate journal venues. From the respected venue's subject area or categories, it can be noticed that the control/industrial/systems engineering community is interested in exploring this ensemble domain between cloud computing in computer science and control systems.

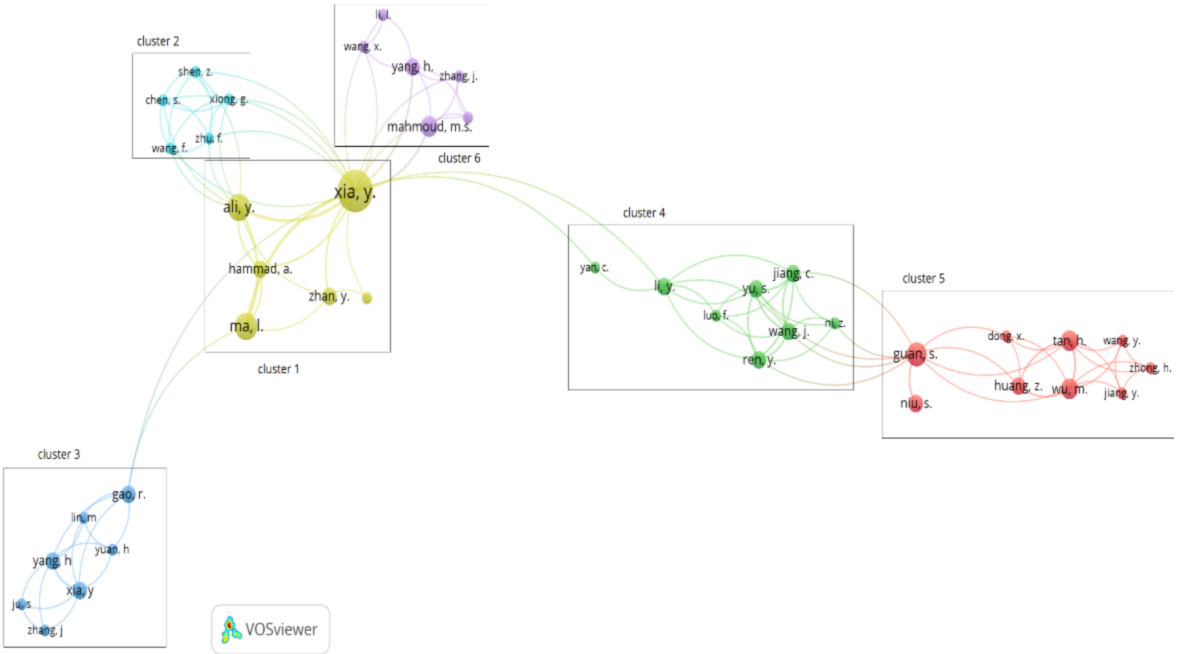


Figure 3. M03: author network

Table 4. M04: publication venues

Publication venues	Publisher	ΣArticles
Proceedings		39
IFAC (International Federation of Automatic Control)	ScienceDirect	7
CCC (Chinese Control Conference)	IEEE	3
CDC (Conference on Decision and Control)	IEEE	3
CAC (Chinese Automation Congress)	IEEE	3
CPS (Industrial Cyber-Physical Systems)	IEEE	2
21 Conference Venues		1
Journals		25
IEEE Access	IEEE	2
IEEE Transactions on Industrial Informatics	IEEE	2
IEEE Transactions on Systems, Man, and Cybernetics: Systems	IEEE	2
Robotics and Computer-Integrated Manufacturing	ScienceDirect	2
17 Journal Venues		1

3.2. Answering RQ2: states of current research

Figure 4 shows statistic results on metric to answer RQ2. First, M05 is observed in Figure 4(a) that the control algorithm leads the research topic in CCS with 29 articles. Then, it consists of [13], [18], [22],

[26], [27], [31], [33], [34], [36]–[56]. Then, followed by cloud architecture with 14 articles [12], [19], [20], [23], [24], [57]–[65]. After that, it is followed by an integrated approach to cloud architecture and control algorithm with 16 articles [5], [14], [17], [21], [25], [30], [35], [66]–[74].

Meanwhile, three articles studied network communication. First, in the data transfer mechanism, it has been shown that the general transmission control protocol (TCP)/user datagram protocol (UDP)/Websocket protocol is unsuitable, considering the average round trip time (RTT) is slower than the control cycle time, and additional mechanisms need to be considered [75]. Then, The identification of challenges related to a communication protocol, gateway and network address translation (NAT) setup, data forwarding rules, and network time delay in the initial phase of CCS implementation [32]. Lastly, an experiment with a use-case on network response between two cloud-center on different continents showed that distance between a controlled plant and cloud center is essential due to network latency [15].

Specifically, one article discussed the ontology of cloud-based control systems to integrate control-over-the-cloud with cyber-physical systems (CPS) and internet of things (IoT). The proposed method consists of three components: core components, data manager, event and context manager to create a control-as-a-service (CaaS) model, and feasibility is shown with use case application in supply chain temperature control [76]. Moreover, one article proposed a virtual environment to emulate CCS with use-case in cyber attack and response [77]. Notably, a cloud virtual-environment to emulate CCS is also an important field of research because it accelerates the speed of CCS research to get better implementation results.

It can be observed that the motivation to apply [control algorithm] and [integrated cloud architecture with control algorithm] may be an interesting topic to investigate further since 45 out of 64 articles discussed it. Figure 4(b)-(d) shows an overview of metrics M06-M08. As can be shown in Figure 4(b), from the control perspective (metric M06), it is divided into 4 clusters of sub-topics. Furthermore, it is notable that the topics of [control strategy & structure] and [privacy, security, and encryption] received the most interest, with 15 articles discussing the topic, respectively. Then followed by [cloud, network, & plant uncertainties] with eight articles, and [self-learning & data-driven modeling] with seven articles. Therefore, the definitions for each cluster are as follows: i) the control strategy and structure included the article that proposed a control algorithm and cloud structure for system performance; ii) the privacy, security, and encryption included the article that proposed a control algorithm considering cyber attack threat in the network; iii) the cloud network, and plant uncertainties included the article that proposed a control algorithm considering network congestion and controlled plant uncertainties, such as time-delay, data-packet loss, and latency; and iv) the self-learning and data-driven modeling included the article that proposed specific system model that is derived from the system's input and output data in order to create adaptable control action depending on the environment dynamics.

Figure 4(c) shows system modeling (metric M07); it is clusterized into three categories of a system model: white-box or analytical model, black-box or data-driven model, and hybrid model. Most articles used the white-box model with 38 articles and the black-box model with seven articles. Within the white-box model, 22 articles used a linear time-invariant model with state-space representation, and 16 articles used a linear time-variant model considering time delay in the derivation of the model. Meanwhile, within the black-box model, it is notable that the general linear regression model is commonly used by four articles [33], [44], [52], [68]. Then one article was used to support the vector regression model [69], 1 article used AnYa fuzzy rule-based model [41], and 1 article used a custom black-box model [18].

Control algorithm objectives are clustered into three categories: disturbance rejection, optimization, and regulatory. Disturbance rejection works to correct deviation from the given trajectory caused by unknown disturbances or uncertainties. Optimization deals with finding a control action that optimizes an objective function with input, output, or state constraints. Regulatory calculates control action for setpoint tracking to improve system performance. Figure 4(d) shows the control algorithm type and objective (M08). It is notable that optimal control, including model predictive control (MPC) and linear quadratic regulator (LQR) or Gaussian (LQG), are commonly used in the CCS derivation and can be found in 34 articles. Followed by proportional, integral, derivative (PID) control found in 5 articles, rule-based control found in 4 articles, and robust control found in 2 articles. Finally, optimization (16 articles) and regulatory (11 articles) control objectives are found evenly distributed in the [optimal control, MPC, and LQR/LQG] algorithm.

Figure 5 shows correlation results between metrics to answer RQ2. Figure 5(a) shows the correlation between metric M06 and metric M07. Figure 5(b) shows the correlation between metrics M06 and M08. Notably, in eight articles, M06–cloud, network and plant uncertainties used the M07; white-box linear time-variant model. It can also be observed that all articles also used an optimal control algorithm correlated with metric M08. The authors [13], [56], [74] use LQR/LQG control algorithm with an optimization approach. Optimal control uses an optimization approach to optimize cloud allocation scheduling [35]. Optimal control and MPC as an offloading strategy to calculate control parameters in the cloud and then update it to local control under 'cloud-fog control system architecture' are proposed in [30], [46]. It offers a solution to the latency problem and de-coupling nonlinearities between plant and network to simplify the problem. A state estimator or observer has been introduced in the proposed method to estimate the system's state and mitigate network delay or noises [35], [68], [74].

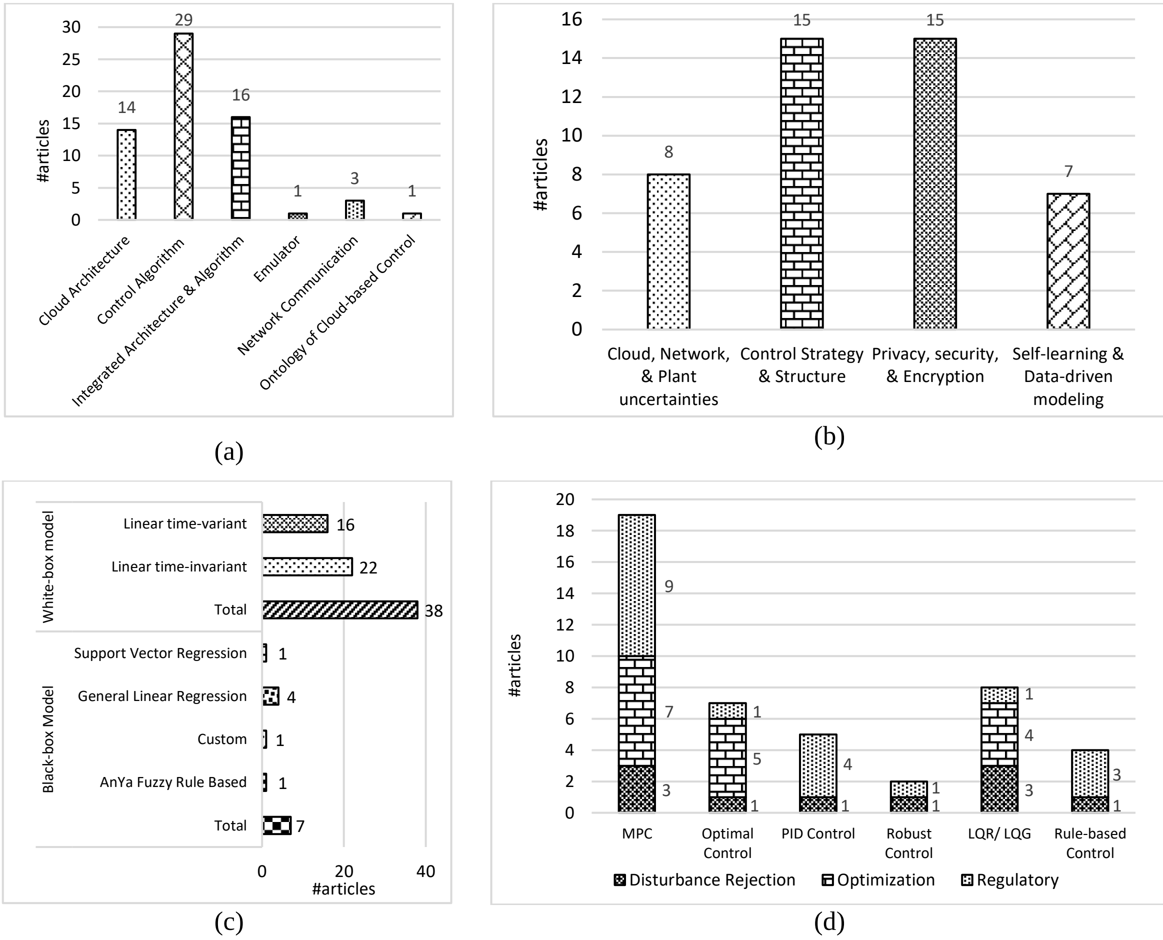
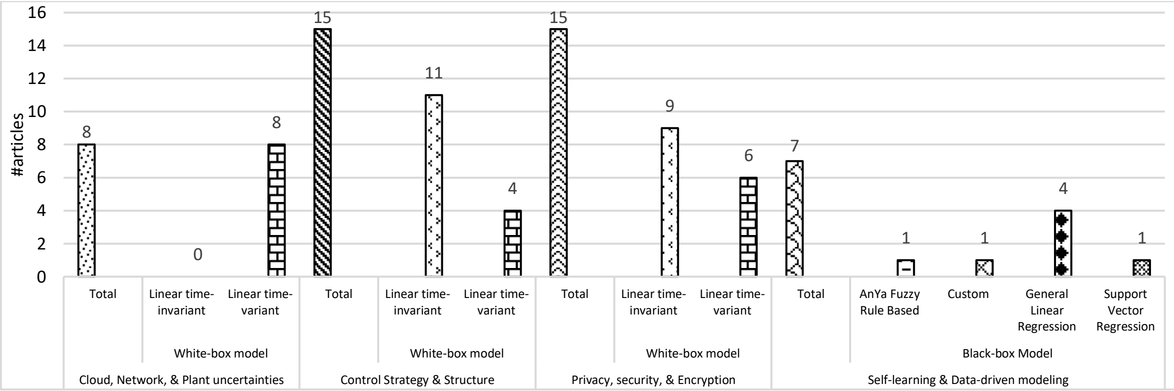


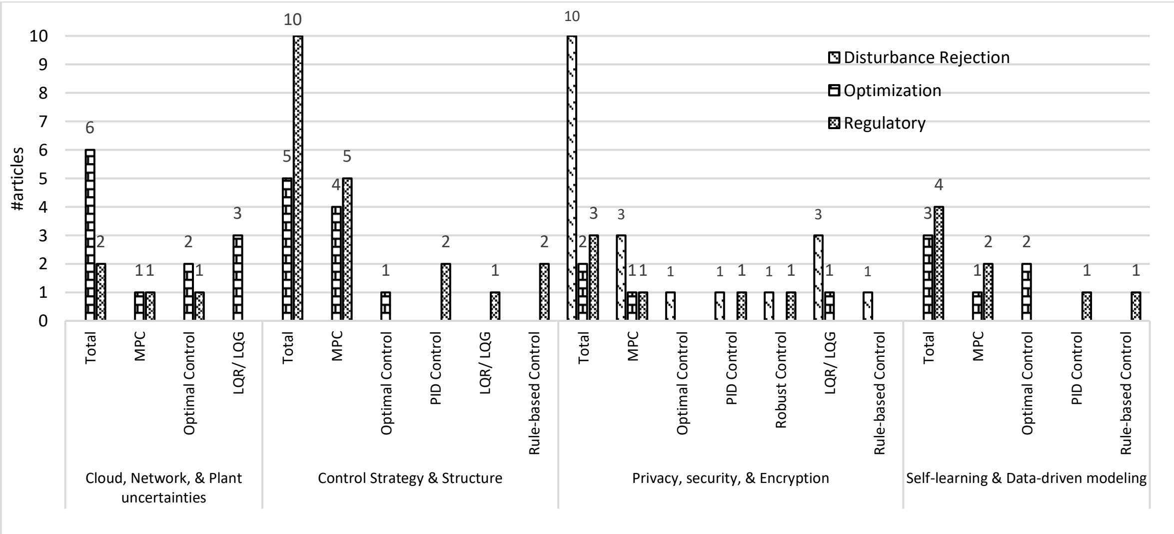
Figure 4. Statistic results on metric to answer RQ2 (a) M05: engineering perspective, (b) M06: control and architecture perspective, (c) M07: system modelling, and (d) M08: control algorithm type and objective

Meanwhile, it is notable that M06 control strategy and structure used M07–white-box linear time-invariant model in 11 articles and a linear time-variant model in 4 articles. Regulatory and optimization objectives with MPC control algorithms are commonly used in correlation with metric M08. System performance in regulatory-based with offloading strategy was discussed in [27], [40], [42], [51]. Rule-based control with fuzzy integrated with PID control structure was proposed by [25], [53] for control in an elevator building and unmanned aerial vehicles (UAV) systems. Mahmoud and Xia [21] proposed an architecture of control strategy that considers convergence between the sampling period, network congestion, and system performance.

Moreover, it can be observed that M06–privacy, security, and encryption used M07–white-box linear time-invariant and linear time-variant models evenly distributedly. The disturbance rejection control objective in the control algorithm is mainly considered in correlation with metric M08. Cyber attacks from the network can be considered a disturbance to the controlled system. MPC control algorithm in the cloud with redundancy in local control and use of switching mechanism if no optimized solution is found in the system under distributed denial of system (DDoS) attack [31]. DoS attack in [26], [36] and advanced persistent threat in [38] as a type of Stackelberg game is proposed to design a robust control system. On the other hand, the encryption method for preventing data breaches has also been considered with the Pailier encryption [54]. The alternating direct method of multipliers method is proposed by [50]. The proximal gradient method was used by [49] to calculate the control algorithm without decrypting the data.



(a)



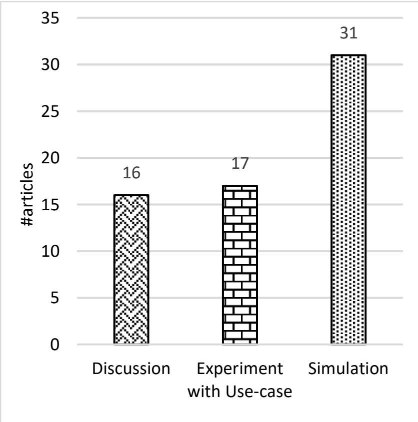
(b)

Figure 5. Correlation results between metrics to answer RQ2 (a) M06: control perspective–M07: system modelling and (b) M06: control perspective–M08: control algorithm type and objective

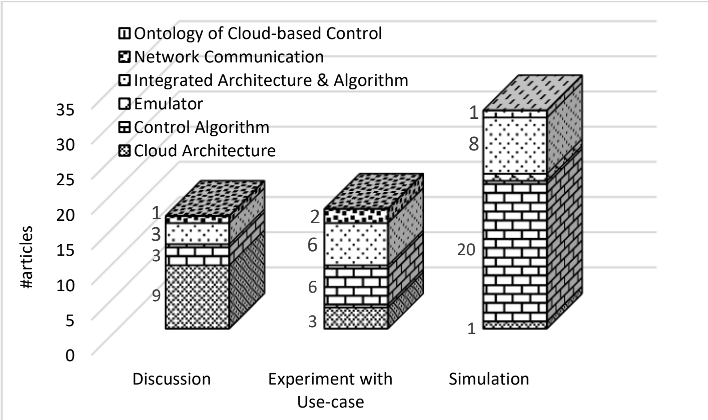
Lastly, it is notable that M06; self-learning and data-driven modeling used the M07–black box model and the general linear regression method is commonly used. Regarding metric M08, optimal control and MPC are mostly used control algorithms. Although this sub-topic received less research interest, deriving a control algorithm with a black-box model is one of the best approaches to realizing CCS. It is well known that the network and cloud system consist of unmodeled dynamics and uncertainties. If we add this up with plant nonlinearities, it creates a complex model that compromises the accuracy of the white-box linear or nonlinear model in processing the system's state [33], [68], [69]. The general linear regression model used input-output data of the heating, ventilation, and air-conditioning (HVAC)-controlled plant to calculate optimal control with particle swarm optimization (PSO) proposed by [52]. The same model in [33], [68] used the MPC algorithm to provide accurate real-time control and reduce the effects of network delay or data loss. Support vector regression model with deep learning method and employed MPC algorithm to accurately predict traffic network and congestion [69].

3.3. Answering RQ3: assessment method on the proposed model

Figure 6 shows statistic results on metric to answer RQ3. As the CCS domain is still in its early stage, it is notable from the assessment method (metric M09) used in the literature primarily by simulation that can be found in 31 articles and discussion with formal mathematical modeling and analysis in 16 articles. Although this is an expected outcome, it is also a formal realization in the CCS domain from control theory or system community, especially in mathematical modeling. On the other hand, there are also attempts to realize the effectiveness of the proposed method using an experiment with a use-case found in 17 articles, as shown in Figure 6(a). Figure 6(b) shows the correlation between metrics M05 and M09. It can be observed that articles with control algorithm topics used the simulation to assess their proposed method evaluation. The simulation assessment shows the effectiveness of the proposed control algorithm compared to previous research with time-series response over a given simulation time. On the other hand, articles on cloud architecture used discussion with formal analysis to show the proposed framework.



(a)

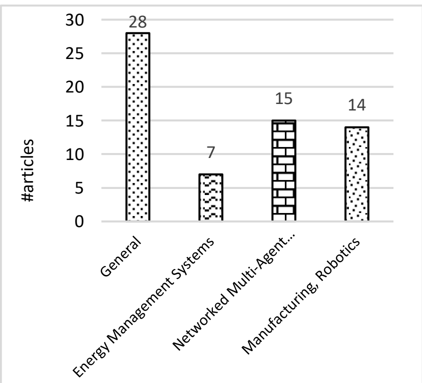


(b)

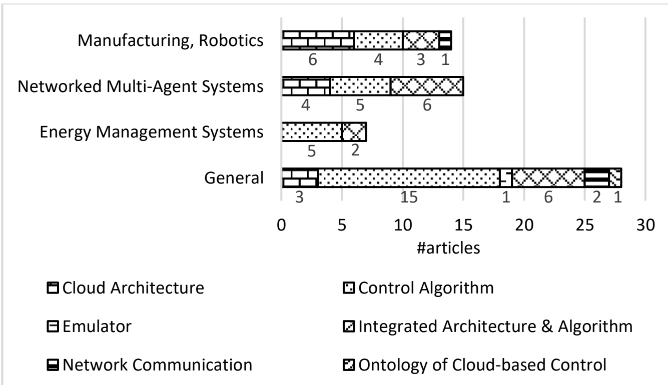
Figure 6. Statistic results on metric to answer RQ3 (a) M09: assessment method and M05: engineering perspective – M09: assessment method

3.4. Answering RQ4: type of application domain

Figure 7 shows statistic results on metric to answer RQ4. Figure 7(a) shows the selected article's application domain (metric M10). Notably, 28 articles used a general system, and these articles did not specifically discuss the application domain. Then, 15 articles discussed networked multi-agent systems (NMAS) in the application domain, such as UAV, traffic networks, and flow. Then it is followed by 14 articles that discuss manufacturing, robotics in the application domain, such as discrete manufacturing, robot control, and machine tool. Finally, seven articles discuss energy management systems (EMS), such as HVAC, heat pumps, building elevators, and solar electrical generation. based on the correlation between metric M05 and metric M10, it is notable that articles with topics of [control algorithm] and [integrated architecture & control algorithm] mostly used the general approach of the application domain, as shown in Figure 7(b). On the other hand, there is a balance in topics [control algorithm], [integrated architecture & control algorithm], and [cloud architecture] for articles that discuss the specific application domain, such as [manufacturing, robotics] and [NMAS]. Hence, it is important to have a combined approach between cloud architecture and control algorithm to implement the proposed method appropriately.



(a)



(b)

Figure 7. Statistic results on metric to answer RQ4 (a) M10: application domain and (b) M05: engineering perspective–M10: application domain

3.5. Challenges for future research

An overview of several challenges found during data analysis and answering the research questions is presented. Finally, it is clusterized in particular perspective challenges for control engineers, network and cloud engineers, and others interested in studying the CCS domain. The challenges for future research are clusterized into 4 clusters, such as i) emulator, ii) cloud architectures, networks and ontology, iii) system models, and iv) controllers.

3.5.1. Emulator

Notably, only one article proposed this topic [77]. In contrast, it is well known that a simulation environment is an indispensable tool for helping researchers evaluate the effectiveness of one's proposed method. Especially an emulator that can perform simulation for the CCS domain, including plant, network, and cloud dynamics systems. For example, it is essential to evaluate disturbance rejection and how the system performs with the proposed method in case of a cyber attack. Furthermore, there is much interest in designing virtual testbeds in cloud computing fields [78], [79] for cloud resource allocation and control of the cloud. However, the research topic is still wide open for an emulator in CCS or control-over-the-cloud domain.

3.5.2. Cloud architectures, networks and ontology

The review result shows that the distance between the cloud center and the controlled plant is an essential dependent variable due to network latency. In the controlled plant, where sampling time is critical, the author suggests bringing the cloud near the plant. Hence it is the best approach to employ fog or edge computing architecture. Currently, fog or edge computing is a hot topic in the IoT domain; this includes classification problems in selecting a wide variety of technology for network transport protocol, security encryption, and management. The cloud offers elasticity and flexibility regarding its virtualization or containerization function with unlimited resource allocation so that complex calculations of the control algorithm can be realized. However, cloud and network are hard-coupling dynamics systems, creating a challenge in realizing CCS. Open questions include: What is the sufficient cloud architecture condition to realize flexible control-as-a-service (CaaS)? How do we classify and process complex traffic data efficiently? How to integrate with the plant's legacy architecture? What is the best approach for selecting network protocol?

3.5.3. System models

The review results indicate that most derivations of the control algorithm employed simple linear time-invariant or linear time-variant models, excluding the self-learning and data-driven modeling sub-topic. The challenging aspect of the linear model is its inaccuracy when the system is subject to nonlinearity or uncertain behavior of disturbances. With the 'cloud-fog' approach, the simple linear model is still considered as it operates in the local control where the control object is the plant itself. However, it needs a new modeling approach with the 'cloud-centric' approach as the control object includes the network's dynamic. It is well known that the network and cloud system consist of unmodeled dynamics and uncertainties. Data-driven modeling, where identification of the model is based on input-output, offers an advantage compared to the white-box simple linear model. Currently, it receives less research interest, but it would be interesting to investigate such models with better accuracy. A neural-network model approach with a deep learning method to train the model is one of the candidates, as it inherently has a nonlinear neuron network. However, they are complex to build and require a sufficient background in computer science.

3.5.4. Controllers

Most articles selected optimal control, including MPC and LQR/LQG, with several control strategies and architecture depending on the control objective. Concretizing the control architecture in the real-case implementation remains an open problem for future research; the current quantitative method to show the control method's effectiveness mainly employs a simulation approach with a numerical example. From the security perspective, an approach to calculating control action with the data remaining in an encrypted state offers an intuitive solution to the system's cyber security. However, the solution is computationally heavy. Open questions include: Are the currently proposed method scalable to real-case problems? What control strategy offers the best approach in the 'cloud-centric' and the 'cloud-fog' approaches? What is the possibility of an artificial intelligence approach offering a novel model and control (especially MPC) integration as it works better at predictive analytics?

4. CONCLUSION

This study presented the findings of a thorough evaluation with a systematic literature review to offer a perspective on the CCS domain. The study's findings indicate that CCS research is still in the early stage of development. While the number of research is still limited, it has seen an exponential increase in research interest over the past five years. Additionally, it has been discovered that Xia Y. is the most prolific author with the most extensive co-authorship network. Also, the control/industrial/systems engineering community is interested in exploring this ensemble domain between cloud computing in computer science and control systems. Notably, five top-cited articles discussed topics as follows: cloud architecture flexibility, control stability, secured control algorithm, and data-driven control system.

The engineering perspectives are clusterized into six categories. cloud architecture, control algorithm, and integrated cloud architecture with control algorithm are the most discussed topics. This finding is in line with the five top-cited topics. The assessment method is still commonly used in simulation and discussion with formal modeling and analysis. However, several studies showed potential implementation in NMAS, manufacturing, and EMS. A more detailed study of the control algorithm is clustered into i) cloud, network and plant uncertainties; ii) control strategy and architecture; iii) privacy, security and encryption; iv) data-driven and self-learning modeling. From a modeling perspective, most studies employed a linear time-variant or linear time-invariant model, which is a white-box approach to modeling. Although it is well known that the network and cloud system consists of unmodeled nonlinear dynamics and uncertainties, using a linear model raises the question of how well it will perform in a real-world application. Several authors have started employing data-driven and self-learning modeling and have shown a promising approach. From a security perspective, an intuitive way to secure the system using direct calculation of encrypted data in the control algorithm has a computationally heavy drawback. From an architecture perspective, the 'cloud-fog' approach solves the latency problem and de-coupling nonlinearities between plant and network to simplify the problem. A novel 'cloud-centric' approach is preferable as it removes the redundancy of constrained devices in fog computing. In the control perspective, optimal control (including MPC and LQR/LQG) shows controller guarantees to three objectives: disturbance rejection, regulation, and optimization.

In conclusion, the CCS domain is an ensemble of two disciplines: cloud computing in computer science and control systems. Historically, these disciplines have operated in distinct fields. Nevertheless, advancement in cloud computing offers benefits in the area lacking control system development. Furthermore, progress in these CCS fields requires an open mind toward each discipline. Therefore, this systematic literature review result offers perspective to the researcher that hopefully will catalyze more study and investigation in this challenging area. The literature review's objective is ensured by following a thorough systematic approach. However, the extent of this literature review is limited to the following subjects. First, it is acknowledged that there is a possibility that primary studies missed out by limiting the automatic search to the four selected databases, and the logical combination of keywords selection, respectively. Then the inclusion criteria, which include i) selecting only English-written articles, and ii) selecting only journals and proceedings articles, might cause missing primary studies too.

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