Cloud-based control system: a bibliometric analysis

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ABSTRACT

Network control system (NCS) approaches for distributed closed-loop control systems have been established in industrial control. However, recent advancements in cloud computing provide scalable, elastic, and low-cost networked computing capabilities over the internet, which can be utilized as an extension of NCS, in this term, cloud-based control systems (CCS) with a potential replacement of the controller. The main objective of this research is to use bibliometric analysis to obtain insight into diachronic productivity, the significant effect of the published information on the research network, and research trends based on term co-occurrences of the CCS domain. The literature study employs the PRISMA method to construct necessary inclusion criteria such as keywords, databases, publication year, accessibility, and primary article, then Publish or Perish is used to generate RIS formatted file for network analysis of co-authorship and term co-occurrence with VOSviewer. The results showed that Yuanqing Xia was the most prolific author in terms of the total published article and total citations received, China was the country with the highest publication output, and Elsevier was the publisher with the most significant impact factor. CCS emerged in 2012, and current research trends include control system architecture, controller, algorithm, stability, and approach on intelligent manufacturing.

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1. INTRODUCTION

Since industrial revolution 3.0 (IR3.0) started in the middle of the 1970s, there has been an exponentially increasing number of factory automation based on computer integrated manufacturing (CIM) [1]. The main idea of CIM was to divide the various manufacturing tasks into separate layers of hierarchies, often represented as automation based on the conventional American National Standards Institute / International Society of Automation (ANSI/ISA-95) model [2]. Level 3 and level 4 layers of the ANSI/ISA-95 model composes mainly of software application that contains production management and business management modules. Currently, much research in the area has focused on adopting these layers in the cloud [3]–[5]. Hence, it leaves the Level 2 layer of a control system still maintaining the status quo.

Traditional control systems, such as the integrated control system (ICS), distributed control system (DCS), fieldbus control system (FCS), and networked control system (NCS), each have their own set of benefits and applications. However, they all share high construction, operation, and maintenance costs and the inflexibility of control algorithm replacement [6]–[8]. Throughout the automation revolution, these traditional control systems have been the critical ingredient of industrial control, where its primary function has been to command low-level regulatory feedback control loops. Despite significant recent advancements in automation technology, driven by the industry 4.0 paradigm and its hyperconnected environment, it has yet to see a modernized version that addresses an industry 4.0-oriented control system [9], [10].

The recent development of information and communication technology (ICT) and its integration with industrial automation systems (IAS) in the manufacturing industry have brought about significant changes in manufacturing modes, production processes, industrial equipment, ecosystem, and existing industrial control technologies are facing a new challenge. In recent years, cloud computing has introduced new concepts to industrial control. Cloud computing, multiprocessing, distributed computing, and distributed systems provide scalable, elastic, and low-cost networked computing capabilities over the internet [11], [12].

Many works in the industrial control domain use NCS approaches for distributed closed-loop control systems [6], [7], and references therein. Moreover, it enabled the development of networked control systems via remote control for large internet applications. In this term, cloud-based control systems (CCS) are seen as an extension of NCS employing internet-of-things (IoT) methodologies [13]. CCS contains two components: a) a cyber-physical system (CPS) and b) a CPS control system, as shown in Figure 1. It is clear to say that CCS is built on the concept of control-as-a-service (CaaS), which means that control algorithms can be scheduled as resources and executed in the cloud [14], [15]. The CCS can significantly reduce the cost and time of building the required control system in the manufacturing production process due to the virtualization of the controller and the reduction of hardware and related labor costs, and it can flexibly select the control algorithm in the cloud controller according to the controlled plants to achieve control objectives [16]. Thus, controller hardware (HW) which is the brain of the control system, can be replaced by employing CCS as one of the disruptive technology in the industry 4.0 revolution.

The characteristics of cloud computing provide a dynamic and flexible infrastructure as CaaS utilization. However, some issues must be addressed, such as cyber security, reliability, availability, computing performance, and robustness to high uncertainty. These issues cast doubt on cloud computing, posing a challenge for CCS design [16]–[18]. It can be addressed in two approaches. First, design novel dynamic resource management strategies, security protection strategies, and cloud infrastructure improvement strategies from the cloud computing perspective, namely control-of-the-cloud, the trend of research direction [19], [20], and references therein. Second, design the control algorithm with sufficient robustness to account for the impact of uncertainty, taking into account a variety of uncertainties (cloud computing, network transmission), thereby improving the performance of the CCS, namely control-over-the-cloud [17], and references therein. However, control-over-the-cloud currently has less research in the area.

This study first published a systematic literature review concerning bibliometric analysis in the CCS domain. The primary goal of this study is to use CCS regarding control-over-the-cloud as a research object to do a bibliometric analysis of papers published in the Scopus and Google Scholar databases in terms of research development in the field. These databases were chosen over the Web of Science (WoS) database due to the coverage of the more extensive database. However, these databases were not refined, and an additional refinement process is needed. We use the PRISMA [21] method to set up a systematic protocol for retrieving and measuring the researched paper. The Publish or Perish software [22] retrieves the researched papers from the databases to be analyzed. Lastly, VOSviewer software [23] for the network visualization is used following the result to enable comprehensive results on author network and keyword co-occurrences. The following research questions (RQs) served as a guideline for our research:

- RQ1: how did the publications on CCS develop?
- RQ2: which countries, publishers, and institutions have focused most on CCS?
- RQ3: which authors actively published on the subject and have the most cited publication?
- RQ4: what are the most influential citation nodes in the network map?

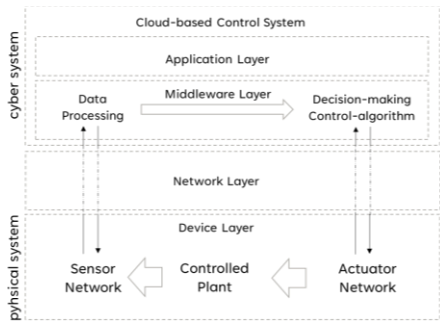


Figure 1. Cyber-physical system and cloud-based control system [13]

The inclusion criteria (ICs) structure considers literature between 1995 and 2022, using good keywords and filtering related primarily accessible articles; 55 peer-reviewed journal and proceeding papers are selected to analyze and derive the answer for the above RQs. It can be concluded from the bibliometric analysis that CCS is a new research domain that occurred in 2012 as an extension of the NCS domain. We observed that 58.19% of the total 55 articles collected had just been published from 2018. From the context of the article's author, Yuanqing Xia published the most articles and had the most substantial influence on the author network regarding CCS. China, Germany, and Saudi Arabia are the three countries with significant contributions, 54.55%, 12.73%, and 12.73%, respectively. Independent clusters of the author's collaboration were observed in the network because CCS is a new research domain. We have better insight in network visualization on co-authorship based on the author as a unit and trend of the research direction based on terms co-occurrence of the CCS domain growing research interest recently concerning control system architecture, controller, algorithm, stability, and approach of term, respectively.

The following section 2 describes the paper's review method. Then in section 3, we discussed the findings and comments on the bibliometric analysis to answer the research questions and accomplish the intended goals. The study's limitations and suggested prospective research direction are also discussed in this section. Finally, the concluding remark in section 4 is explained based on the findings.

2. METHOD

This study refers to the guidelines explained in [24] to conduct the systematic literature review. First, we set up the protocol to be used for the review, which includes: a) RQs, b) ICs, and c) eligible articles to be used in the analysis. The research conducted in March 2022 set up five RQs as a guideline for bibliometric analysis. In order to derive the answer for the RQs, we used several ICs and exclusion criteria to obtain eligible final researched papers to analyze. Exclusion criteria are the opposite of ICs, and these ICs are mentioned:

- IC1: english-written articles in journal or proceedings.
- IC2: articles published between 1995 to 2022.
- IC3: collections from SCOPUS database and Google Scholar database.
- IC4: use of keywords "cloud control system" or "cloud control systems" or "cloud-based control systems" or "cloud-based control systems."
- IC5: merge two database records and remove the duplicate article.
- IC6: filtering of the related article to IC4.
- IC7: selecting accessible and primary articles.

We retrieved the final researched paper by applying all the ICs. We obtained 65 records from the Scopus database and 101 records from the Google Scholar database regarding IC1 – IC4 criteria in the identification step. In the next step, we downloaded the obtained articles in text format with all the information given, and then it was merged and verified to remove 14 duplicate records concerning IC5 criteria. After that, the screening process excluded 83 unrelated records according to IC6 criteria. In the last step, IC1, IC6, and IC7 criteria were applied to the 69 eligible records as a final check, and we excluded 14 records. Hence, 55 records were included in the bibliometric analysis, and the articles consist of the following references: [6], [13], [17], [18], [25]–[74]. We also did a refinement process in the RIS formatted file to include and update the author's name (AU), keywords (KW), and abstracts (AB) that are not correctly mentioned or incompletely written in the database due to the data are not refined as the ones of data in the WoS database. Following that result, the bibliometric analysis was conducted according to the RQs mentioned, and we will discuss the results in the next section.

3. RESULTS AND DISCUSSION

3.1. Bibliometric analysis results

As previously stated, 55 researched articles authored by 136 researchers from 54 affiliations in 17 countries were discovered. As a result, fundamental bibliometric indicators such as year of publication, publishers, most prolific authors, journals, institutions, and nations are shown, as well as the network between descriptors and terms co-occurrence can be presented consecutively. Figure 2 depicts the distribution of literature from the first publication of the article in 2012 to 2022. The pattern seems to point to a steady increase in the number of articles released, albeit there was a decrease seen in 2021 due to pandemic COVID-19, and the year 2022 is not counted as a full year yet. We can observe that even though IC2 defined search articles were published between 1995 to 2022, the first article had just been published in 2012. It is also worth noting that the last five years, 2018 and 2022, account for 58.18% of the overall scientific output. This rise reflects the growing interest in the CCS research domain.

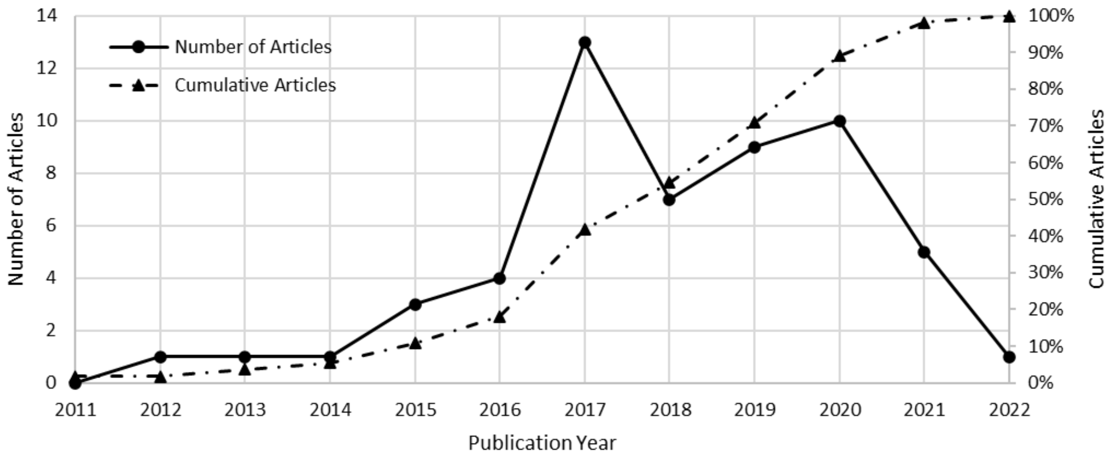


Figure 2. Diachronic productivity of CCS

One hundred thirty-six authors contributed to publishing at least one paper on the topic studied. Among them were certain scholars with a high level of output in the area, such as Yuanqing Xia, who published 14 articles; M.S. Mahmoud, who published six articles; and six authors, who published a minimum of 3 articles. Table 1 lists these authors and their contribution percentage, number of citations, and affiliation's origin. Furthermore, we can also observe that Yuanqing Xia is highly influenced in the CCS domain as his publications were cited 355 times, followed by M.S. Mahmoud with a total citation of 121. On the other hand, there were 9 authors with two published articles and 120 authors with one published article.

Table 2 lists the affiliations with the most publications in the fields of CCS. There were 54 affiliations counted, but only six stood out in terms of scientific output, with more than two publications (48 institutions had one publication, respectively). Beijing Institute of Technology took the top position with 13 publications, followed by King Fahd University of Petroleum and Minerals with six publications, and the University of Auckland with five publications.

A study of affiliation's country concerning the number of publications was conducted to identify which region was more interested. The nations with the most publications (≥ 5 articles) are shown in Table 3. China (30 articles), Germany (7 articles), Saudi Arabia (7 articles), and New Zealand (5 articles) were the nations with the most considerable number of affiliations who have published articles in the CCS domain. We can see that the issue is becoming a topic of interest in nations where one or two articles have been published and that development on this topic will grow.

Table 1. Prolific authors (≥ 3 articles) with contributions, citations, and affiliations

Author	Σ Articles	% Contributions	Σ Citations	Affiliation
Yuanqing Xia	14	10.29%	355	Beijing Institute of Technology
M.S. Mahmoud	6	4.41%	121	King Fahd University of Petroleum and Minerals
Armin Lechler	4	2.94%	64	University of Sttutgart
Liang Ma	4	2.94%	24	Beijing Institute of Technology
Xun W. Xu	4	2.94%	42	University of Auckland
Yasir Ali	4	2.94%	22	Chinese Academy of Sciences
Shouping Guan	3	2.21%	6	Northeastern University, Shenyang
9 authors	2	-	-	-
120 authors	1	-	-	-

Table 2. Prolific affiliations (≥ 2 articles) with contributions and citations

Affiliations	Σ Articles	% Contributions	Σ Citations
Beijing Institute of Technology	13	24.07%	284
King Fahd University of Petroleum and Minerals	6	11.11%	121
University of Auckland	5	9.26%	44
University of Sttutgart	4	7.41%	64
Tsinghua University	4	7.41%	18
Northeastern University, Shenyang	3	5.56%	6
48 Affiliations	1	-	-

Table 3. Prolific Affiliation's Country (≥ 5 articles) with contributions and citations

Affiliation's country	Σ Articles	% Contributions	Σ Citations
China	30	54.55%	409
Germany	7	12.73%	170
Saudi Arabia	7	12.73%	130
New Zealand	5	9.09%	44
2 Country Affiliations	2	-	-
11 Country Affiliations	1	-	-

Lastly, the publisher's analysis result is presented in Table 4. A total of 20 publishers were discovered to have published research in the CCS domain. IEEE, Springer, and Elsevier were the three biggest publishers with the most publications on this subject, with 22, 8, and 7 articles. On the other hand, it can be observed that Elsevier had the most significant impact factor with 31.14, followed by Springer and IEEE.

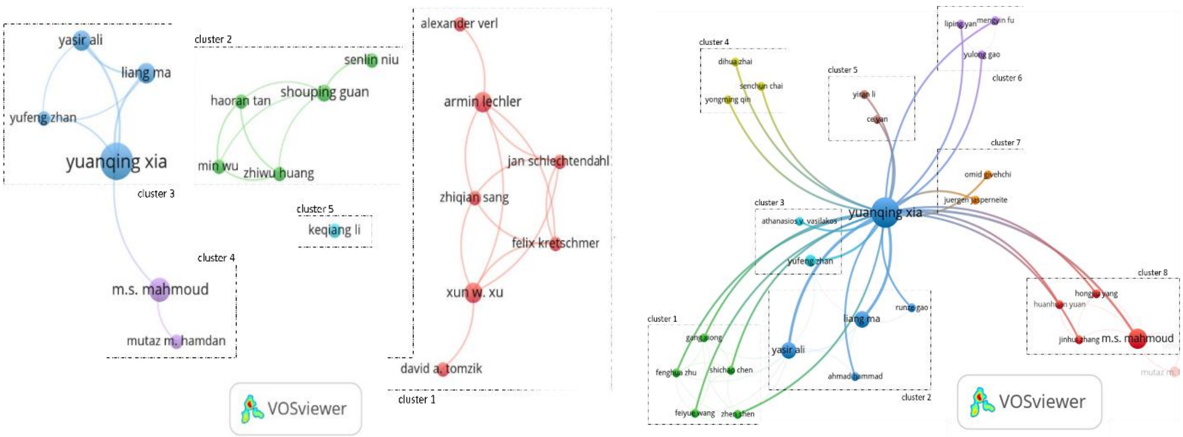
Table 4. Prolific Publishers (≥ 7 articles) with contributions, citations, and impact index

Publishers	Σ Articles	% Contributions	Σ Citations	Impact index
IEEE	22	40.74%	233	10.59
Springer	8	14.81%	235	29.38
Elsevier	7	12.96%	218	31.14
1 publisher	2	-	-	
16 publishers	1	-	-	

3.2. Network analysis results

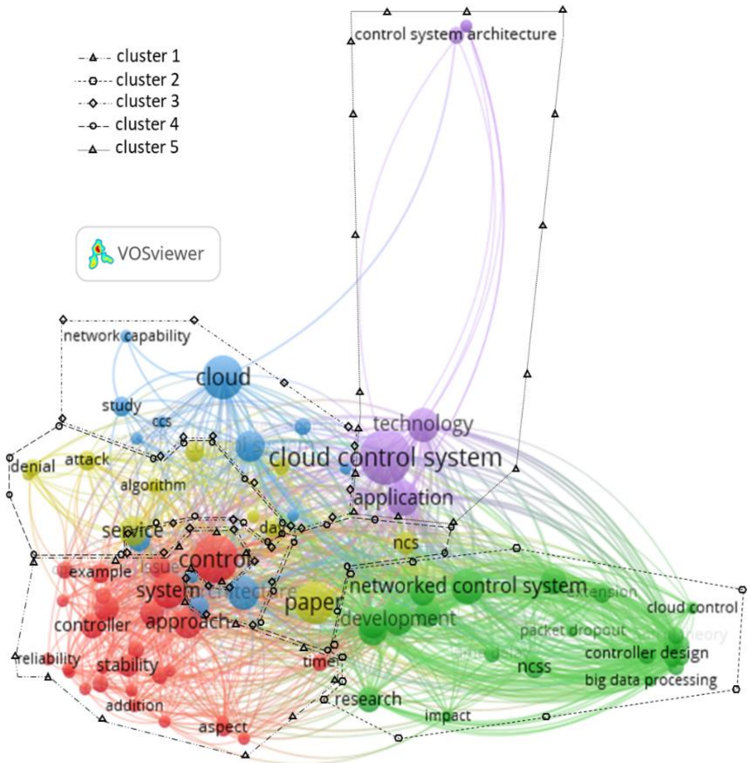
In this section, we analyzed the network of co-authorship based on the authors (as a unit of analysis) and the network of term co-occurrence with binary counting on terms mentioned in title and abstract fields. Due to un-refined data retrieved from Scopus and Google Scholar databases, we did a refinement process to the RIS formatted file to include and update the AU, KW, and AB. That is not correctly mentioned or incompletely written in the database because the data are not refined as the ones of data in the WoS database.

The co-authorship network using authors as a unit is shown in Figure 3(a) with the threshold parameter of authors with a minimum of 2 articles. With this, only 19 meet the threshold out of 136 authors. Based on the result, we found 5 clusters. The largest cluster had seven authors (cluster 1), followed by a cluster of 5 authors (cluster 2), four authors (cluster 3), 1 cluster of 2 authors (cluster 4), and 1 cluster of 1 author (cluster 5), respectively. The most significant cluster, cluster 1, consists of authors: Armin Lechler, Jan Schlechtendahl, Alexander Verl, Zhiqian Sang, Xun W. Xu, and David A. Tomzik, that comes from the University of Stuttgart (Germany) and the University of Auckland (New Zealand). Next, we observed the network of Yuanqing Xia co-authorship using the authors as a unit, as shown in Figure 3(b), with the threshold parameter of authors with a minimum of 1 article. It can be noticed that the most prolific author in the CCS domain consists of 8 clusters with 28 authors.

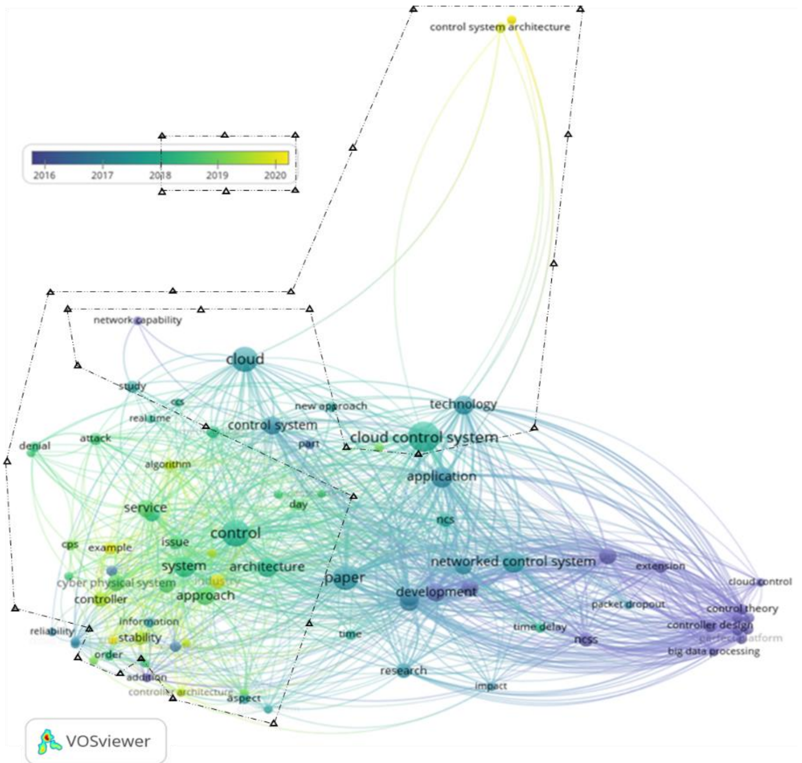


(a) (b)

Figure 3. Network of co-authorship using the authors as a unit: (a) network of overall co-authorship and (b) network of Yuanqing Xia co-authorship



(a)



(b)

Figure 4. Network of terms co-occurrence using the abstract and title fields: (a) network visualization and (b) overlay visualization

On the other hand, we can also observe network co-occurrence of terms mentioned in abstract and title fields. Since the CCS domain emerged, we selected a threshold of 2 minimum occurrences of a term, and 81 terms meet the threshold to generate the network, as shown in Figure 4. As a result, we can observe the network visualization in Figure 4(a), consisting of 5 clusters, where cluster 1, cluster 2, and cluster 5 contain 28 terms, 22 terms, 13 terms, 12 terms, and six terms, respectively. It can be noticed that the cloud control system term laid inside the smallest cluster 5 contains six terms, which are: application, cloud control system, connected vehicle, control system architecture, intelligence, and technology. Even though the cloud control system belonged to a small cluster, if we observed the network overlay visualization in Figure 4(b), it recently received growing research on control system architecture, controller, algorithm, stability, and approach term. Hence, we have better insight into network co-authorship based on the author as a unit and the trend of the research direction based on terms co-occurrence of the CCS domain.

3.3. Discussions

The paper's objective facilitates getting insight into developing research publications in the CCS domain. This topic is essential to highlight the advancement of industry 4.0 regarding cloud computing technology using IoT methodologies and its essential role as an enabler in integrating control system domain that is widely used in the industrial control application [13], [18], [31]. Furthermore, we can observe how the research was carried out throughout this period in terms of the ensemble method of cloud computing and control systems by doing this analysis. As a result, we can discuss the research questions mentioned earlier in this section.

– RQ1: how did the publications on CCS develop?

As shown in Figure 2, we can observe that even though IC2 defined search articles published between 1995 and 2022, the first article had just been published in 2012. It is also worth noting that the last five years, 2018 and 2022, account for 59.26% of the overall scientific output. The article was written by Y. Xia [31] and marked the first paper discussing the CCS domain published by IEEE. The notion of CCS came from an extension of networked control systems (NCSs) using the IoT paradigm. Simultaneously, cloud computing is rapidly evolving, providing a flexible platform for large-scale data processing, controller design, and performance evaluation based on the on-demand requirement of the client.

We also showed the development of research trend from 2012 to 2022 based on term co-occurrences as shown in Figure 4(b). Early research topics was focused on: a) network capability in regard to the communication requirement and security for CCS mentioned in [30], [47], [51], [72]; b) use cases for delivering automation tasks as cloud services to lower levels mentioned in [49], [50]; c) framework integration from the cloud to lower levels automation system [28], [62], [75]; and d) big data processing and application mentioned in [36], [45], [55]. Recent trend in research topics include: a) control system architecture [26], [56], [63], [74]; b) stability analysis [17], [43]; c) controller algorithm and security evaluation [61], [67], [76]; and d) approach on intelligent manufacturing [25], [34], [75], [77].

– RQ2: which countries, publishers, and institutions have focused most on CCS?

Beijing Institute of Technology emerged as the affiliation with the most prolific authors in this field, followed by King Fahd University of Petroleum and Minerals and the University of Auckland. It accounts for 44.44% of the contribution, and it can say that these affiliations were the most influential in the CCS field. Finally, China, Germany, and Saudi Arabia were the nations with an enormous number of affiliations who have published articles and correlated with the citation analysis. These three countries account for a total of 80.00% of the contribution.

IEEE, Springer, and Elsevier came in the first, second, and third positions of the most prolific publishers, with 68.52% of the total number of publications. IEEE, Springer, and Elsevier were the top three journals with the most documents published in both searches and analysis. In term of impact factor, Elsevier emerged at top with the highest impact factor of 31.14, and Springer in the second place even though these two publishers had smaller number of articles which are 7 articles ([33], [46]–[48], [51], [65], [68]) and 8 articles ([13], [26], [32], [34], [38], [41], [58], [63]), respectively. Hence, we can note that authors prefer to work with well-known publishers in the scientific community.

– RQ3: which authors actively published on the subject and have the most cited publication?

Yuanqing Xia is the most prolific author with a 10.29% contribution and has the most cited 355 articles. Together with M.S. Mahmoud in the second place with 4.41% contribution and 121 articles, they had written two articles in [13], [44]. They contributed to 14.7% of total articles, which shows that the CCS domain research was distributed eventually between the other 134 authors.

– RQ4: what are the most influential citation nodes in the network map?

The network of Yuanqing Xia co-authorship using the authors as a unit is shown in Figure 3(b) and is seen as the most influential citation node in the network map. Most of the authors in this network map have just published 1 article, which coincides with the previous analysis that the CCS domain has recently emerged.

The articles published by Yuanqing Xia have considerable impact factors compared to the biggest cluster 1 group consisting of Armin Lechler, Jan Schlechtendahl, Alexander Verl, Zhiqian Sang, Xun W. Xu, and David A. Tomzik, authors in Figure 3(a) network map.

3.4. Limitations

There are several limitations to this bibliometric analysis study. First, it was limited to two databases, Scopus and Google Scholar; consequently, future research should include additional datasets from other databases to further enhance the results. Second, this research performed a quantitative approach limited to presenting diachronic productivity, the significant effect of the published information on the research network, and research trends based on term co-occurrences. Therefore, future research may be done with a qualitative approach, such as but not limited to investigating the type of control system architecture employed for the specific use-case, assessing the type, performance, and limitation of the control algorithm, review of the method used in the research of CCS domain.

4. CONCLUSION

The study of the CCS domain with the bibliometric analysis presented in this study can be used as a tool for researchers to assess the current state of research development and research trend in the field. CCS are seen as an extension of NCS, employing IoT methodologies with cloud computing as a potential replacement for the traditional constrained device controller. CCS only emerged in 2012, and current research trends based on the term co-occurrence network include control system architecture, controller, algorithm, stability, and approach, respectively. The main objective of this research is to obtain insight into diachronic productivity, the significant effect of the published information on the research network, and research trends based on term co-occurrences of the CCS domain. The literature study employed the PRISMA method to construct necessary inclusion criteria such as keywords, databases, publication year, accessible and primary article and then used Publish or Perish to generate RIS formatted file for network analysis of co-authorship and term co-occurrence with VOSviewer. The results showed that Yuanqing Xia was the most prolific author in terms of the total published article and citations received, that China was the country with the highest publication output, and Elsevier was the publisher with the most significant impact factor. The current research trends include control system architecture, controller, algorithm, stability, and approach on intelligent manufacturing based-on term co-occurrence network.

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