An Exploratory Bibliometric Analysis of the Literature on Age of Information-Aware Unmanned Aerial Vehicles Aided Communication

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Overview paper

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Real-time status updates require more frequent updates with fresh information. This study investigates the applications and research potential of unmanned aerial vehicles (UAV) for achieving information freshness in time-critical applications to emphasize important aspects of this subject based on a thorough statistical analysis of current research trends. Particularly using the Scopus database, a bibliometric analysis is conducted on 122 articles written in English and published between 2018 and 2023. This analysis provides a knowledge map of past research on this subject and the journey so far, especially concerning major subjects, patterns of citations, publication activities, and the state of cooperation among contributors throughout the UAV-information freshness research history. According to the findings, applying various methods, such as deep reinforcement learning and optimization algorithms, has been evident. In contrast, energy efficiency and harvesting, trajectory planning and design, and scheduling are issues attracting researchers' interest. Finally, the study offers implications and recommendations such as fostering interdisciplinary collaboration, furthering and improving on DRL and optimization algorithms, addressing energy efficiency and harvesting, enhancing trajectory planning and design, emphasizing scheduling strategies, and bridging the gap between research and practice.

Povzetek: Opravljena je bila bibliometrična analiza 122 člankov o brezpilotnih letalnikih, objavljenih med letoma 2018 in 2023, z namenom pridobivanja osveženih informacij.

1 Introduction

The next-generation wireless networks need to handle a wider variety of services than their predecessors. They should provide communications with low latency, high reliability, and improved mobile broadband. Unmanned aerial vehicles, often known as UAVs, can offer workable solutions for next-generation networks, and they can also serve as aerial base stations (BS) for data collection and transmission [1]. UAVs have basically evolved as a form of cutting-edge technology that is relatively inexpensive, mobile, flexible, and able to communicate with terrestrial infrastructures via direct line of sight (LoS) links [2]. It has the advantages of flexible deployment and maneuverability, as well as low cost. The UAV is one of the most promising technologies and has become an interesting topic in industry and academia to drive the development of Internet of Things (IoT) applications [3, 4, 5, 6].

On the other hand, a concept known as the "Age of Information" (AoI) has been developed to determine the freshness of data, especially in real-time and (time-critical) applications [7]. Likewise, AoI has been designed and researched in numerous fields as a metric for assigning temporal values to information aging [8]. For example, the AoI is a critical metric in the data aggregation and analytics for IoT [9]. AoI is the time elapsed since generating the latest received packet at the data point; the freshness metric in status update systems [9]. Accordingly, AoI is the amount of time that has passed from the creation of information. Thus, the information generated long ago is characterized by a greater AoI, indicating that its current condition may diverge from what is expected [10]. Simply put, AoI is the measurement of the amount of time that has passed since the generation of the most recent update that was received about a process. It is an essential metric in networks such as IoT, mainly when the application requires up-to-date in-

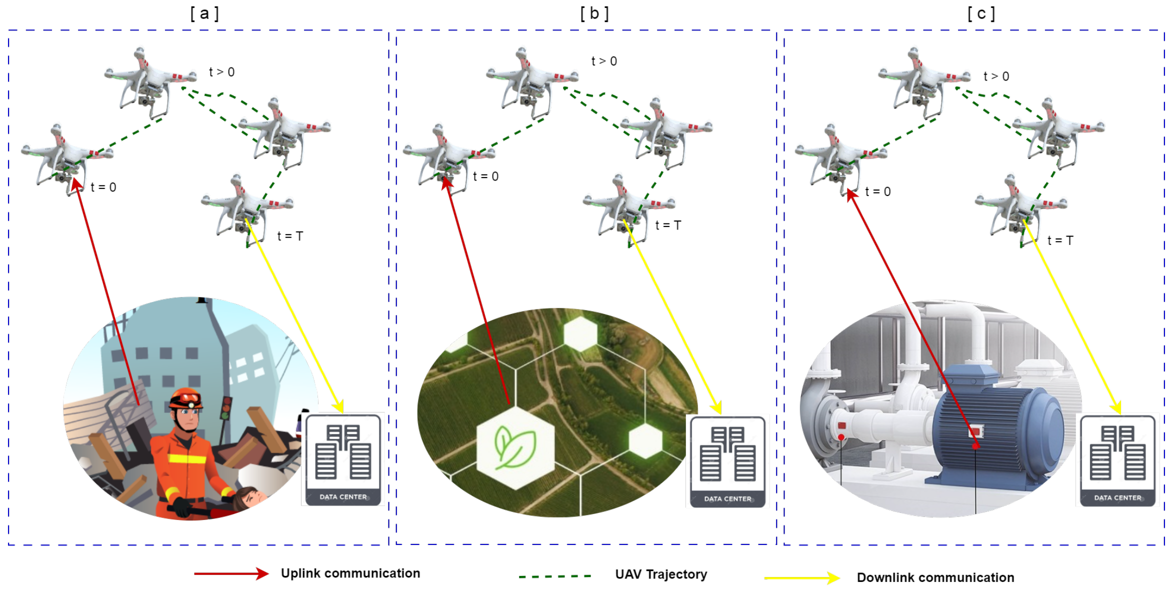

Figure 1: Illustration depicting some UAVs applications

formation [7].

Nonetheless, the evolution of UAVs has shown promise in a variety of applications of wireless communication due to the UAVs' high coverage, promising rates, and flexible installation [11]. The UAV possesses vast abilities such as high flight efficiency on fixed routes and data collection on the move [12]. When the UAV returns, the data collected by the ground fixed-point equipment while in the fixed-point cruising mode can be obtained from the multi-source sensor equipment mounted on the UAV in complex mountain environments. The data can then be stored in the data center for additional processing and analysis [12]. Additionally, when it comes to maintaining some national forest parks and keeping an eye on the area close to cities, UAV patrol has gradually replaced manual patrol as the preferred method. A typical UAV application is demonstrated in Fig. 1 [13], which shows UAV deployment in three different applications. Specifically, Fig. 1a depicts disaster or emergency applications, Fig. 1b shows UAV applications in agricultural farms to collect data from crops, and Fig. 1c represents the applications in industrial IoT.

In the applications (Fig. 1b and 1c), the sensors relay information to the BS (i.e., data center) via the UAV for transmission. The UAV flies and collects data from at least one sensor, communicates with other data points, then returns to a data center to transmit the data [14]. A UAV is deployed to collect and transmit the sensor data to the data center, especially in agriculture and industrial applications. The data collection occurs via wireless transmission medium whenever the UAV is in close vicinity to the sensor. The UAV can be equipped with a variety of sensors to gather data, including changes in speed, temperature, light, distance, chemical signals, wind, and sound. It also can detect the existence of magnetic objects. Hence, UAVs provide a platform for data collection that quickly collects information from broad perspectives. The capability of UAV camera can be used to create precise three-dimensional representations of locations or objects, especially for disaster monitoring and surveillance (see Fig. 1a). Moreover, the UAV channel exhibits several exclusive properties like shadowing, 3D deployment, high mobility, and spatial and temporal non-stationarity [15, 16]. According to [17], the UAV channel may be divided into two distinct categories: air-to-air and air-to-ground. Small to medium-sized manned aircraft and UAVs are the two forms of aerial vehicles utilized for channel measurements. Channel measurements of the former are costly, whereas channel measurements of the latter have the potential to save costs significantly [15].

Using the VOSviewer software, this study conducted a bibliometric analysis of 122 papers published in English between 2018 and 2023 and sourced from the Scopus database. The study aims to analyze bibliometric data regarding UAV and AoI. The findings offer a schematic representation of the information generated and disseminated by earlier research. It provides insights into significant subjects, citation trends, publication activities, collaboration status among contributors, and aggregated UAV research contributions in disaster management scenarios.

The remainder of this paper is structured as follows: Section 2 discusses the related reviews and rationale for conducting this work; Section 3 provides an explanation of the methodology that was applied while conducting the study; Section 4 offers a description of the results, which is covered based on keyword analysis, document sources, and citations patterns; Section 5 presents the discussion of the study, which also covers practical perspectives as well as limitations and consideration for future research. Finally, the conclusions drawn from this study is covered in Section 6.

2 Related works

Review studies combining the diverse aspects of UAV for AoI-sensitive applications are limited in the current literature [18]. However, several review efforts have been made to address potential research areas in UAV communications. For instance, the work by [19] conducted reviews on UAV path planning and 5G communications. In [20], the study performed a taxonomic review on UAVs with routing and trajectory optimization problems. In addition, the work by [21] reviewed IoT and UAV applications and communication technologies for sustainable smart farming, while [22] conducted a comprehensive review on energy sources for UAVs. Nevertheless, [23] succinctly captured various review papers related to using UAVs for data gathering in IoT applications to minimize AoI. Although the study covers a wide range of aspects related to AoI minimization, there were no bibliometric analysis-based insights giving first-hand detail on the analysis of keywords, document sources and types, most active source titles, geometric distribution of publications, most influential institutions, citations, and textual titles, which provide insights into different trendsetters and some of the statistical analysis-based trends in this field.

However, there have been various bibliometric analyses conducted on UAVs and their related applications. For instance, studies have examined UAV usage in different domains, such as UAV and forest [24], UAV in agriculture and forestry [25], UAV and precision agriculture and viticulture [26], UAV and social network [27], UAV swarms [28], UAV and crop monitoring in smallholder farms [29], drone research and scholarly output [30], UAV usage in architecture and urbanism [31], drone and blast-induced flyrock [32], UAV and wheat crop [33], UAV and cellular network [34], UAV and digitalization of public administration [35], and drone delivery systems [36]. Hence, the lack of bibliometric studies focusing on UAV and AoI justifies the need for additional research in this field. In our effort to identify existing review studies concerning UAV and AoI, Table 1 presents the few papers identified from the literature. The summary of these studies (refer to Table 1) provides important insights that justify the use of bibliometric analysis in this area.

Furthermore, Table 2 presents a critical analysis of the existing review papers combining UAV and AoI to demonstrate the rationale explaining what is missing in the current literature and how this study remedies these gaps. The study of related literature reveals that there is a lack of bibliometric studies on this subject which could help new researchers identify research clusters, as well as trends across different sub-domains. However, bibliometric analysis is a valuable approach for examining the research landscape and understanding the current state of knowledge in a specific field [38, 39, 40]. In the context of UAVs and AoI, several studies have explored different aspects of this domain [37, 23, 18], highlighting the need for a comprehensive bibliometric analysis to synthesize and analyze the existing literature. By conducting a bibliometric analysis, this study aims to address the limitations of existing reviews and provide a comprehensive overview of the research trends, influential studies, and emerging themes in the field of UAVs and AoI. This analysis will enable researchers and practitioners to identify gaps, highlight high-impact areas, and guide future investigations in this dynamic and evolving domain.

3 Methodology

The bibliometric and systematic approaches to literature review were used to draw inferences from the research and meta-data on this subject to ensure the methodology aligns with the laid-out research objectives. In this context, VOSviewer bibliometric program was adopted to analyze the bibliographic data obtained [41].

The bibliographic analysis involves the use of citations as the variable of interest. Citation analysis is a bibliometric approach based on the premise that citations can be used as indicators of activity within a scientific field [42, 43]. This means a frequently cited article is relatively more significant in the field under study [44]. The authors in [45] added that citation data could be used to identify the most influential papers, both ”locally” (within a field) and ”globally” (among the entire research community). Citation analysis facilitates the discovery of important research streams as well as attribution, access, use, management, and retrieval of scholarly content [46].

Additionally, the quantitative research methodology is adopted in this work. Several databases, such as Google Scholar, Web of Science (WoS), and Scopus, provide citation information. While Google Scholar is more inclusive, WoS and Scopus are more selective in terms of the quality of the journals they capture. Building on the research techniques and procedures used in previous bibliometric studies (see [45, 47, 48], this study adapted the concept deployed in [47]. Moreover, Scopus was selected as the primary data source for this analysis for several reasons, including credibility and peer review. It also covers most WoS papers and has a wide range of references, abstracts, and summaries under accepted practices [49].

Additionally, more than 87 million papers and 25,000 active titles are available on Scopus. The Scopus database has the most comprehensive coverage of abstract and citation databases that spans multiple disciplines. The database is a trustworthy resource for obtaining global academic knowledge and is regularly updated [47]. It is also hard to disregard the Scopus h-index tool, which determines the different category of book, author, or journal [50]. The article database search and selection was created using a five-step process [47], as shown in Fig. 2. Accordingly, this study analyzes 122 articles obtained between 2018 and 2023. The selection of the articles was applied exclusively based on the language used, English, and identifying contents related to AoI and UAV.

Table 1: Summary and focus of existing review papers

Ref	Year	Focus	Summary	Method
[37]	2018	DDDAS with an aspect of UAV and AoI	This paper provides a comprehensive review of Dynamic Data Driven Applications Systems (DDDAS), a systems design framework that integrates physical model simulations, real-time measurements, statistical methods, and computation architectures. It highlights the successes of DDDAS in various fields such as natural disaster assessment, space awareness, UAV design, and biomedical applications. The paper also discusses recent developments in DDDAS related to information management architecture, sensor design, information filtering, and computational systems.	Descriptive review
[18]	2023	UAV, AoI, WSNs, and IoT	This article provides a comprehensive review of 20 selected articles on minimizing the Age of Information (AoI) in UAV-assisted data gathering for wireless sensor networks (WSNs) and Internet of Things (IoT) applications. It explores various techniques, including machine learning and optimization methods, to optimize UAV trajectory, scheduling, and energy source acquisition, and discusses the challenges, lessons learned, and future directions in this field.	Systematic
[23]	2023	UAV, AoI, WSNs, and IoT	This article presents a systematic literature review (SLR) on age minimization in UAV-assisted data-gathering architectures for WSNs and IoT networks. The review identifies three crucial design aspects: energy management, flight trajectory, and UAV/sensor node scheduling, and discusses various issues and considerations related to these aspects, as well as future directions for optimization and system improvements.	Systematic
This study		UAV, AoI, and other paradigms.	Knowledge map concerning major subjects, patterns of citations, publication activities, and the state of cooperation among contributors throughout the UAV-information freshness research literature.	Bibliometric

Table 2: Critical analysis of existing reviews and research gap

Ref	Year	DDDAS	UAV	AoI	WSNs	IoT	Descriptive	SLR	Bibliometric
[37]	2018	✓	✓	✓			✓		
[18]	2023		✓	✓	✓	✓		✓	
[23]	2023		✓	✓	✓	✓		✓	
This study			✓	✓	✓	✓			✓

Several publications, including IEEE Internet of Things Journal, IEEE Transactions on vehicular technology, IEEE Transactions on wireless communication, and IEEE Transactions on Communications, published technical studies on UAV-assisted AoI reduction. Version 1.6.18 of the VOSviewer program is used in this study to analyze the bibliometric data. The tool is an open-source program for designing and developing bibliometric networks [41]. The bibliometric data was then processed to produce a file with the structure and format needed for network analysis. A visualization map was developed based on the bibliometric data obtained from Scopus to gain a better and more insightful understanding of the bibliometric findings related to the study themes.

The program is integrated with a text-mining feature, making it attractive to researchers. Given this, a large corpus of scholarly literature has made use of the software to build co-occurrence visualization maps related to the subjects studied [47, 48]. Hence, the research methodology was divided mainly into three stages: (1) gathering and assessing the relevant materials, (2) analyzing the bibliographic data, and (3) Extracting information based on the main keywords identified in previous stages. The initial step involved studying the collected papers using the following procedure: the Scopus database was searched, quantitative analysis was performed, additional searches focusing on disaster applications were conducted, and data-gathering methods were developed. Fig. 2 shows the method used for gathering data; these steps were done to guarantee accuracy.

In the first stage, academic literature publications from the Scopus database were examined in order to highlight

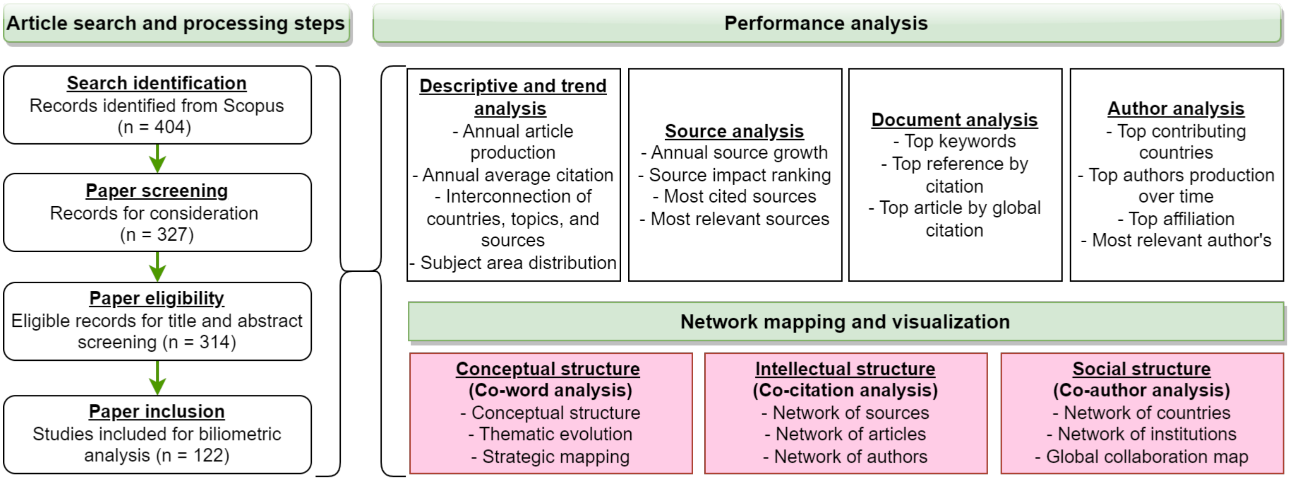

Figure 2: Research Methodology and Design of Paper Selection and Performance Analysis

and classify the primary research trends in the area. At this point, there were no limitations on the range of the publication period. The final articles were selected after conducting title and abstract reading, and the range between 2018 and 2023 was finalized, which is the range of 122 articles. To find pertinent results, a search employing combinations of two strings was carried out, and the result was utilized according to the purpose of each stage under the data collection and processing phase, as shown below.

– Search string 1: ("data freshness" OR "information freshness" OR "age of information" OR AoI) AND ("unmanned aerial vehicle" OR "UAV" OR "drone").

– Search string 2: ("data freshness" OR "information freshness" OR "age of information") AND ("unmanned aerial vehicle" OR "UAV" OR "drone").

The two-search string was designed to offer more relevant and accurate articles on the subject area. The first search string result identifies 404 papers. By critically evaluating the abstracts of the papers, it was observed that AoI is also a short form for "area of interest". In the second search string, 327 papers were identified from which 321 papers that are written in the English language were selected. Nevertheless, title and abstract reading were conducted on the 321 articles. Finally, the study included 122 for the bibliometric analysis.

4 Results

The search and selection of articles produced 122 papers related to UAV and AoI. The discussion of the results is presented in this section. The bibliometric aspect of the articles is presented. Accordingly, the study provides discussions and information regarding a quantitative study that was conducted on the selected papers. Using the keywords "Age of information" and "Unmanned aerial vehicle" identified previously, a bibliometric analysis conducted previously, this study carried out a bibliometric study according to the published data: articles keywords, article sources, and types, year of publications, publication country, authors institution, and contributions, and journal titles. Accordingly, Scopus was used to acquire the bibliographic data utilized in this study.

Table 3: Popular authors keywords

Author keywords	Frequency	Percent
Age of information	77	26.37
Unmanned aerial vehicle	63	21.58
IoT	16	5.48
Deep reinforcement learning (DRL)	19	6.51
Data collection	15	5.14
Trajectory	14	4.79
Trajectory optimization	9	3.08
Trajectory planning	9	3.08
Wireless sensor network	9	3.08
Scheduling	8	2.74
Optimization	7	2.4
Autonomous aerial vehicle	7	2.4
Task analysis	7	2.4
Energy efficiency	6	2.05
Sensors	6	2.05
Convex optimization	5	1.71
Path planning	5	1.71
Trajectory design	5	1.71
Multi-agent deep reinforcement learning	5	1.71

4.1 Keyword analysis

Utilizing the text-mining algorithm of the VOSviewer 1.6.18 [41], the study visualized the keyword information produced by various publications. Several bibliometric research has validated this approach [51, 52, 53, 48, 47]. Thus, the text-mining technique generates a map that thoroughly interprets the distance between terms as an indica-

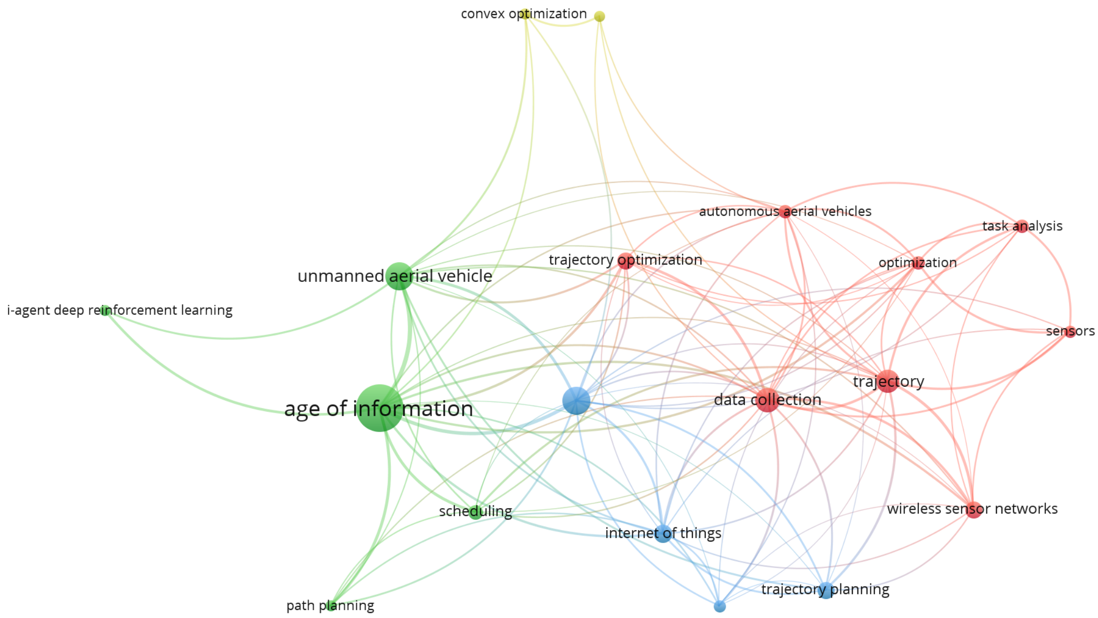

Figure 3: Map of co-occurrences of authors keywords (See Table 3 for more details).

tion of the correlation between various keywords. Accordingly, the greater the distance between two or more keywords, the greater the significance of the related terms. The co-occurrences of words in publications were analyzed to determine their interconnectedness based on a unit of analysis (author keyword) and counting method (fractional). Specifically, the network analysis of the author keywords includes only those terms that appear in the database at least five (5) times. These are presented in Table 3. This study examined the keyword occurrence carefully to ensure the accuracy of the data. 26 keywords out of 292 are deemed suitable for analysis. Then, the duplicates or keywords with synonyms (e.g., 'UAVs', 'UAV', 'Unmanned aerial vehicle' etc.) were eliminated. Moreover, the keywords that did not adequately describe anything (e.g., algorithm, analysis, etc.) were also eliminated.

Fig. 3 depicts the visualization network and map of the authors' keywords. It highlights the most used terms in the existing studies through a conceptual map to illustrate the connection between keywords used by the authors [41]. The keyword size is determined entirely by their presence in the selected articles. According to the result, the major keyword was 'Age of Information', which was used constantly throughout the study period. Similarly, the terms such as UAV, deep reinforcement learning (DRL), IoT, trajectory, data collection, optimization, wireless sensor network (WSN), and scheduling were frequently observed in the literature. Furthermore, the depiction of the keywords as well as co-occurrence (co-word estimation) demonstrates a well-known issue from the literature for AoI-aware UAV deployment. It is vital to consider color-matching of the terms 'age of information', 'DRL (the blue circle located in the center with label)', 'data collection and trajectory', and 'convex optimization'. This co-occurrence measure quantifies the strength of the interaction between the terms, particularly between UAV technology, its associated issues, and deployed methods. Accordingly, Table 3 displays the most prominent terms that have been utilized by numerous researchers in the past.

Table 4: Year of publications

Year	Frequency	Cumulative percent(N=122)
2018	2	1.64
2019	12	9.84
2020	19	15.57
2021	35	28.69
2022	53	43.44
2023	1	0.82
Total	122	100

4.2 Document source and types

The document and source types analysis shows that, within the 122 papers that were chosen as the sample, the conference papers made up 50.82% of the total, making them slightly more than the journal articles which constitute 47.54%. Moreover, when it comes to the source and origin of the papers obtained for the analysis, journal sources account for a total of 50%, slightly higher than conference

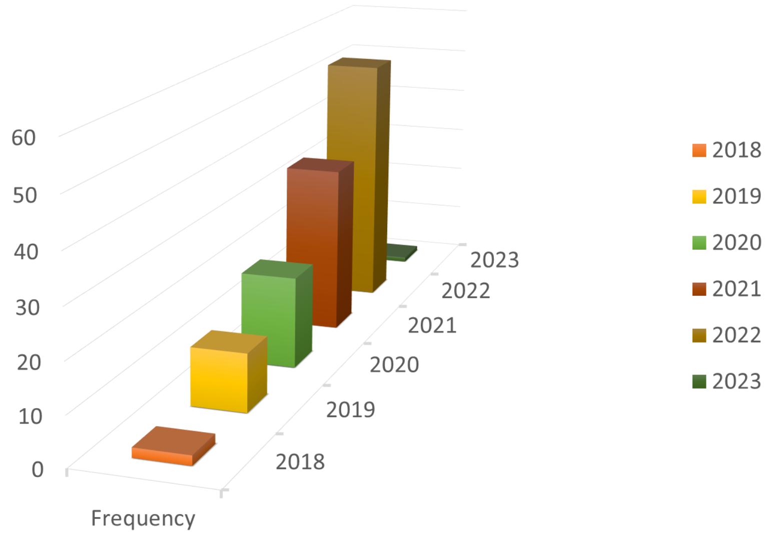

Figure 4: Document by year (See also Table 4).

Table 5: Document type and sources

Document type			Source type		
Document type	Frequency	%(N=122)	Source type	Frequency	%(N=122)
Article	58	47.54	Journals	61	50
Conference paper	62	50.82	Conference proceedings	58	47.54
Conference review	0	0	Lecture notes	2	1.64
Book chapter	1	0.82	Book	1	0.82
Editorial	1	0.82	Trade publications	0	0

proceedings sources (47.54%). Table 5 presents the number of all the different types of papers considered for this study, such as lecture notes, book chapters, and editorials.

4.3 Publications years of the published studies

The progression of published studies relating to the topic can be seen in Fig. 4, which covers the years 2018 through 2023. The study observes a slow but steady rise in the number of publications on AoI-aware UAV deployment. There were only two publications in 2018. The publications started to emerge more in 2019, which saw the fewest number and subsequently led to a surge in the number of publications between 2021 and 2022. This suggests that scholars are becoming increasingly interested in UAVs and AoI. Table 4 contains a comprehensive overview of the years in which research studies were published. The result reveals that 2022 has the highest number of publications. By observing this graph, the interest in UAV and information freshness is growing which could suggest that more publications will be produced in the future.

4.4 Most active source titles

Table 6 provides a summary of the leading and most active journals that have published works connected to AoI and UAV, with at least 3 publications. The major source title is the IEEE Internet of Things journal with eleven documents. Others include IEEE Transactions on vehicular technology, IEEE transactions on wireless communication, IEEE Transactions on intelligent transportation systems, IEEE vehicular technology conference, international conference on Communications, and IEEE Journal on selected areas in communication. These source titles provide essential works that pertain to AoI and UAV, respectively. Refer to Table 6 for more details about the titles and the percentage of the document produced by these source titles.

4.5 Distribution of publications geographically

The proportion of research contributions made by each of the topmost 18 countries is outlined in Table 7. China contributes the most articles, with 64.75%, followed by the United States (US) (30.33%). This finding suggests that China is the main contributor to research concerning UAV and AoI, and the closest country is the USA. It is interesting to note that Hong Kong (12.30%), which is a special

Table 6: Most active source title with at least 3 publications

Source title	No of documents	%(N=122)	Citations	%(N=622)
IEEE internet of things journal	11	19.3	174	27.97
IEEE transactions on vehicular technology	9	15.79	181	29.1
IEEE transactions on wireless communication	6	10.53	83	13.34
IEEE transactions on intelligent transportation systems	5	8.77	38	6.11
IEEE vehicular technology conference	5	8.77	5	0.8
Proceedings- IEEE Infocom	4	7.02	34	5.47
IEEE international conference on communications	4	7.02	8	1.29
IEEE wireless communications and networking conferences (wcnc)	4	7.02	0	0
IEEE transactions on communications	3	5.26	55	8.84
IEEE journal on selected areas in communications	3	5.26	34	5.47
IEEE transactions on mobile computing	3	5.26	10	1.61

administrative region in China, is ranked third among the most productive countries. The fourth and fifth on the list are South Korea (7.38%) and Australia (6.56%), respectively. Countries such as Italy, Germany, and Singapore are located at the very bottom of the list. Together, they are responsible for less than 5% of all the publications.

Apart from China and the United States, the study does not identify additional countries commonly prone to natural disasters where UAV applications are crucial [37, 54, 12]. Countries such as Indonesia, Vietnam, Malaysia, the Philippines, and Turkey are a few examples of this category. Researches centered on AoI and UAV are more frequently found in industrialized nations. In such regions, there are a lot of research sponsors that concentrate on UAV applications to improve the efficiency of UAVs through the AoI metric.

Table 7: Top 18 countries/regions of the published articles

Country/Region	Frequency	%(N=122)	Citations
China	79	64.75	653
United States	37	30.33	661
Hong kong	15	12.3	367
South Korea	9	7.38	92
Australia	8	6.56	54
Canada	7	5.74	97
Finland	6	4.92	23
Japan	5	4.1	23
Qatar	4	3.28	148
Sweden	4	3.28	31
United kingdom	3	2.46	82
Lebanon	3	2.46	70
Luxembourg	3	2.46	20
United Arab Emirates	3	2.46	10
India	3	2.46	7
Italy	3	2.46	1
Germany	2	1.64	43
Singapore	2	1.64	3
	196	160.66	2385

4.6 Authorship

The authors who have contributed the most to AoI-aware UAV deployment are listed in Table 8. Liu J. (China) and Han Z. (United States) have the most documents, which puts the authors at the top of the table with 10 publications each. The third on the list is Zhang H. (United States) with 9 documents. Next is Poor H. V. (United States) and Zhang X. (China) in fourth and fifth with 8 documents each. Wang X. has 7 and Song I. has 6 documents. Five other authors have 5 documents each. The remaining authors were responsible for at least four documents each.

Table 8: Most productive authors (minimum document 4, citation 10)

Author's name	Documents	%(N=122)	Citations
Liu J.	10	8.2	244
Han Z.	10	8.2	86
Zhang H.	9	7.38	115
Poor H. V.	8	6.56	107
Zhang X.	8	6.56	18
Wang X.	7	5.74	218
Song I.	6	4.92	103
Bai B.	5	4.1	216
Fan P.	5	4.1	134
Letaief K. B.	5	4.1	134
Han R.	5	4.1	20
Yang Y.	5	4.1	16
Dai H.	4	3.28	180
Tong P.	4	3.28	66
Qin X.	4	3.28	45
Chen X.	4	3.28	22
Wang W.	4	3.28	15
Shen C.	4	3.28	10

According to [55], collaboration between authors from a variety of disciplines is required to improve any sector. Hence, an increase in international collaboration is required. Fig. 5 and Fig. 6 illustrate the level of collaboration that exists between academics using authors and countries as units of analysis and fractional counting methods.

Nonetheless, China, as well as the United States, are the two nations that are leading the charge in the combined efforts (refer to Fig. 6). The analysis and visualization map demonstrates a comprehensive network of joint efforts that spans all the continents. Chen X.'s works, which involved a broader collaboration with researchers from diverse countries, is the most prestigious of all of them (refer to Fig. 5).

Although [56] stated that co-authorship preferences are determined and shaped by a variety of factors, including cultural relations, geopolitical position, and language, according to the findings of this study, geopolitical proximity and shared language are two of the most important factors that signify co-authorship relationships across countries. Remarkably, there is a bigger quantity of research articles coming out from China as well as the USA. This could be a result of their interest in newer technological advancements. For example, the world-leading UAV manufacturer (DJI) is a Chinese technology company and has 76% global market share of consumer and commercial UAVs. In addition, [47] highlighted that academics working in the United States have a remarkable openness when it comes to working with peers in other countries.

4.7 Most influential institutions

The top institutions for AoI-aware UAV research are listed in Table 9, which shows that the institutions have at least 3 publications. According to the finding, each of the institutions has contributed at most 3 documents. The breakdown of the number of articles from each institution and their citation counts has been demonstrated accordingly. Remarkably, the Department of electronic engineering, Tsinghua University, Beijing China is the institution with the most citation (131), which is followed by the Department of Electronics, Peking University, Beijing China.

4.8 Citation analysis

According to [57], the impact of particular research can be measured by the extent to which other researchers have found it to be beneficial. The citation metrics of the 122 articles, which spans the years 2018 to 2023, are presented here in Table 10. The total amount of citations throughout the course of the past 5 years is 1,073, which breaks down to 178.83 citations per year and 8.8 citations per paper. Citations are supposed to illustrate the impact of a publication in relation to several other publications according to the ideas of other researchers and their research findings. Consequently, the number of citations that are used in research evaluation serves as a determining factor of the impact of the research. Accordingly, the citations are used to indicate that a publication has improved the quality of several other publications [58].

Furthermore, Table 11 identifies the study by Liu *et al.* [59] as having the highest citation count. The highly referenced article, which is titled "Age-optimal trajectory planning for UAV-assisted data collection" is currently the most cited in the list with 117 citations. This study focuses on optimizing the collection of data from ground sensor nodes using unmanned aerial vehicles (UAVs) in wireless sensor networks. The goal is to plan the UAV's trajectory to minimize the age of information (AoI) gathered from the nodes. Two types of optimal trajectories are considered: one aims to minimize the age of the oldest information collected, while the other aims to minimize the average age of information. The study shows that finding an optimal trajectory is equivalent to finding the shortest path in the sensor network. The dynamic programming method and genetic algorithm are used to find these trajectories. Simulation results validate the effectiveness of the proposed methods and demonstrate how the UAV's trajectory is influenced by the AoI metrics. Similarly, the second paper on the list is cited 113 [60], which has a slightly equal number of citations with the first article on the list [59]. Both papers were published in 2018, and are technical papers. The study observed most of the papers are cited less than 50 times, except the study by [61] which is cited 78 times, respectively.

4.9 Textual analysis

The VOSviewer is capable of recognizing and analyzing keywords, after which they will be presented in a structured format. A representation of a co-word network in the form of a map was developed using bibliographic information. It was possible to standardize the principles of involvement in relation to the keywords based on the strength of the connection between them [62]. To graphically locate and place each word on the map, the approach known as "visualization of similarities" was utilized accordingly [41]. In conclusion, the VOSviewer method provides a variety of resolution parameters to enable the detection of a wide variety of clusters.

In this study, the study focused and selected 21 keywords, which were used to measure the relative full strength of connections and co-occurrence with other keywords. The colors were applied to differentiate between three unique groups (green, blue, and red). The graphical depiction of co-words (keywords co-occurrence) is shown in Fig. 7 to Fig. 11. Particularly, the network is produced with respect to the information contained in earlier literature on AoI and UAV, as demonstrated in Fig. 7. The investigation of the terms is represented by clusters of varying colors and sizes. The VOSviewer identified three distinct clusters and assigned each one of those clusters one of three colors, based on the thematic community they were most closely associated. The size of the cluster represented by some terms shows the frequency of their occurrences in titles and abstracts of the publications [41]. Moreover, the observed distance between the cluster indicates the strength of their relationships. The number of times that both words appear together in the titles and abstracts of the various papers provided evidence for this connection. The inclusion criteria of a term to be selected must have at least ten occur-

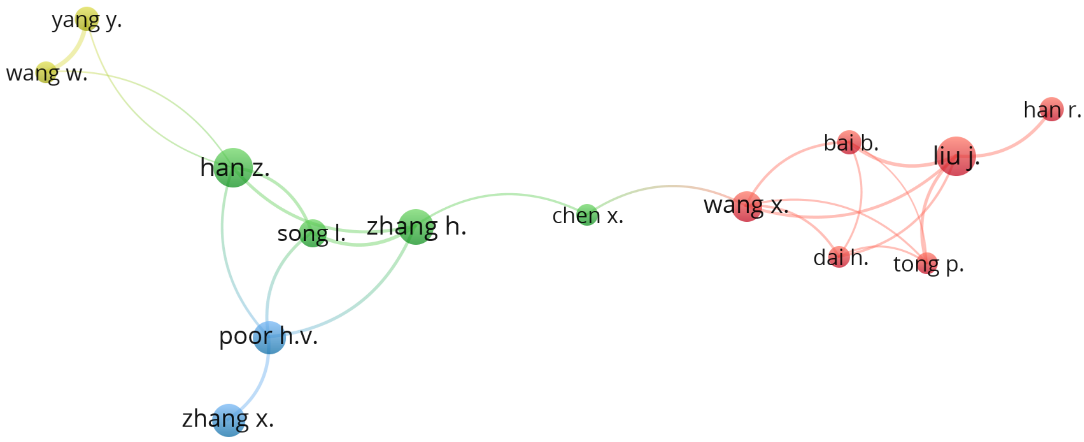

Figure 5: Map of the co-authorship based on Author unit of analysis

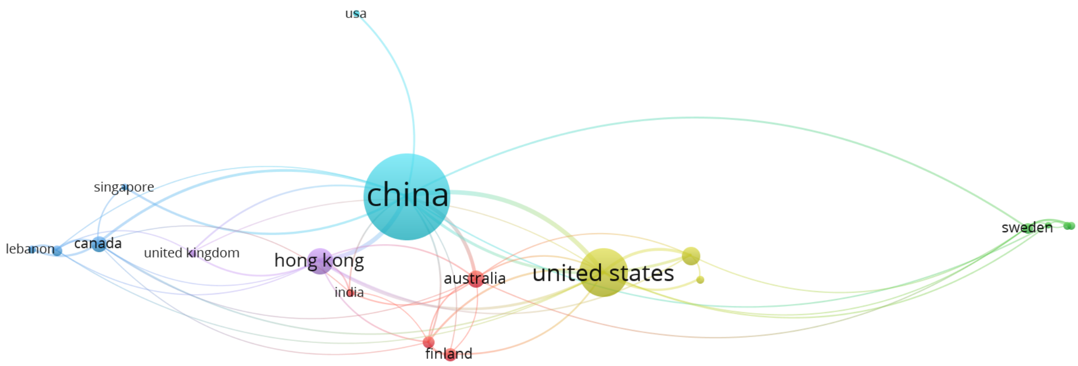

Figure 6: Map of the co-authorship based on countries unit of analysis

Table 9: Most influential institutions with a maximum of 3 publications

Institution	Frequency	%(N=122)	Citations
Lab of rail traffic control and safety, Beijing Jiaotong University, Beijing, China	3	2.46	3
Department of computer science and engineering, Kyung hee university, Seoul, South Korea	3	2.46	44
Department of electrical and computer engineering, university of Houston, Houston, Texas, united states	3	2.46	39
Department of electronic engineering, Beijing national research center for information science and technology, Tsinghua University, Beijing, China	3	2.46	131
Department of electronics, Peking University, Beijing, China	3	2.46	85
School of electrical engineering and computer science, Ningbo University, Zhejiang, China	3	2.46	65
School of electronics and communication engineering, Sun yat-sen university, Guangzhou, China	3	2.46	66
Laboratory of networking and switching technology, Beijing University of posts and telecommunications, Beijing, China	3	2.46	46

Table 10: Citations metrics

Measure	Data
Years of publications	2018—2023
Years of citations	(6) 2018—2023
Quantity of papers	122
Citations count	1073
Citation/year	178.83
Citation/paper	8.8
Citations/author	3.17
Papers/author	0.36
Authors/paper	2.78

rences for both binary and full counting. In binary counting, the occurrences attribute reflects the number of documents in which a word appears at least once, whereas the occurrences attribute in full counting displays the total number of appearances of a term across all documents [63].

Fig. 7 and Fig. 8 illustrate the co-occurrence network of terms from titles and abstracts fields based on full and binary counting, respectively, while Fig. 10 and Fig. 11 illustrate the co-occurrence network of terms from abstracts fields only; based on full and binary counting. According to the data, topics such as trajectory, data collection, AoI minimization, data freshness, average AoI, convergence, and timeliness, are frequently used in the literature. Moreover, the study has identified the usage of UAVs in disruptive technologies such as wireless sensor network (WSN), mobile edge computing (MEC), and IoT, as well as, methods such as the DRL, optimization algorithm, and Markov decision process (MDP) (see Fig. 7. Secondly, the map of title and abstract based on full counting presents more keywords associated with UAV research. Example of these keywords includes status update, transmission, application, and cellular internet (see Fig. 8).

Furthermore, effectiveness, communication, the data packet, and a few other keywords observed in Fig. 10 and Fig. 11 disclose the potential of UAV applications to improve overall data collection, accuracy, completeness, reliability, relevance, and more importantly timeliness. Improving these characteristics will help management and decision-making processes in any UAV applications scenario. As a result, both the public and private sectors should concentrate their efforts on developing their capabilities of UAVs in order to improve their data management and decision-making procedures. Consequently, the classification of the articles that were carried out through the schematization of the subtitles and a brief explanation of the intent of those studies reveals that most of the prior studies studied the concerns of the relation between UAV, information freshness, UAV trajectory, etc.

5 Discussion and matters arising

Through the bibliometric analysis of the relevant literature, this study has presented some of the most pertinent terms related to AoI in UAV-assisted wireless communication literature. It is quite obvious that the success of efficiently guaranteeing information freshness in wireless networks cannot be considered complete without a discussion of the role of UAVs especially in disaster-stricken or hard-to-reach places. The UAV is increasingly required for the delivery of fresh data in several applications. As a result, this study illustrates the key themes identified by the network visualization presented in the preceding sections (refer to Fig. 7 and Fig. 8). This study believes that UAV-aided AoI minimization can transform the network applications where data are needed in real-time, which includes emergencies and disasters, industrial IoT networks, etc. The analysis of terms relating to UAV and AoI shows different applications, concepts, and methods in the literature. One particular method, with a remarkable performance when compared with the existing benchmarks, and is evident across a number of existing studies is DRL [64, 65, 66] with few examples presented in Table 12 and 13. DRL is a prominent machine learning-based method that facilitates autonomous control of the UAV and thus has been quite resourceful in UAV trajectory planning for AoI minimization. Table 12 presents the problems and focus areas addressed by DRL in UAV and AoI research. In particular, DRL has been applied to various aspects, such as energy harvesting, real-time data collection decisions, UAV altitude scheduling policies, and AoI optimization. In Table 13, the various application of DRL methods in UAV and AoI literature are presented. This presents how existing scholars have utilized DRL to address some of the issues and problems pertinent to UAV-assisted AoI.

5.1 Technology paradigm of DRL in the use of UAV for achieving minimal AoI

The analysis of the visualization network has shown that the concept of UAV-aided information freshness has garnered significant attention in various technological paradigms, showcasing its versatility and wide applicability while accommodating different assistant technologies. One such paradigm is the utilization of reconfigurable intelligent surface (RIS), as explored by [74]. These surfaces, capable of manipulating the propagation of electromagnetic waves, offer an innovative approach to enhance information freshness in UAV systems. Additionally, the study of studying UAV-aided information freshness in IoT domain has witnessed substantial research efforts. Several studies have investigated the integration of UAVs with IoT to improve information freshness [66, 7, 9, 3, 4, 5, 6]. These works have explored various aspects to facilitate timely data collection, information transmission, and processing by leveraging the agility and mobility of UAVs.

In addition, WSN have also been an area of focus in the context of UAV-aided communication for achieving information freshness. The studies by [61, 103] have investigated the integration of UAVs with WSNs to improve the freshness of information. By deploying UAVs as mo-

Table 11: Most influential papers (highly cited; Min-20 citation)

S/N	Authors	Title	Year	Citation	citation per year
1	Liu J., Wang X., Bai B., Dai H.	Age-optimal trajectory planning for UAV-assisted data collection	2018	117	23.4
2	Abd-Elmagid M.A., Dhillon H.S.	Average peak age-of-information minimization in UAV-assisted IoT networks	2018	113	28.25
3	Abd-Elmagid M.A., Ferdowsi A., Dhillon H.S., Saad W.	Deep reinforcement learning for minimizing age-of-information in UAV-assisted networks	2019	48	12
4	Jia Z., Qin X., Wang Z., Liu B.	Age-based path planning and data acquisition in UAV-Assisted IoT networks	2019	29	7.25
5	Tong P., Liu J., Wang X., Bai B., Dai H.	UAV-Enabled age-optimal data collection in wireless sensor networks	2019	29	7.25
6	Li W., Wang L., Fei A.	Minimizing Packet Expiration Loss with Path Planning in UAV-Assisted Data Sensing	2019	27	6.75
7	Tripathi V., Talak R., Modiano E.	Age Optimal Information Gathering and Dissemination on Graphs	2019	26	6.5
8	Zhou C., He H., Yang P., Lyu F., Wu W., Cheng N., Shen X.	Deep RL-based Trajectory Planning for AoI Minimization in UAV-assisted IoT	2019	24	6
9	Wan S., Lu J., Fan P., Letaief K.B.	Toward Big Data Processing in IoT: Path Planning and Resource Management of UAV Base Stations in Mobile-Edge Computing System	2020	46	15.33
10	Hu J., Zhang H., Song L., Schober R., Poor H.V.	Cooperative Internet of UAVs: Distributed Trajectory Design by Multi-Agent Deep Reinforcement Learning	2020	43	14.33
11	Yi M., Wang X., Liu J., Zhang Y., Bai B.	Deep reinforcement learning for fresh data collection in UAV-assisted IoT networks	2020	36	12
12	Zhang S., Zhang H., Han Z., Poor H.V., Song L.	Age of Information in a Cellular Internet of UAVs: Sensing and Communication Trade-Off Design	2020	35	11.67
13	Samir M., Assi C., Sharafeddine S., Ebrahimi D., Ghrayeb A.	Age of Information Aware Trajectory Planning of UAVs in Intelligent Transportation Systems: A Deep Learning Approach	2020	32	10.67
14	Hu H., Xiong K., Qu G., Ni Q., Fan P., Letaief K.B.	AoI-Minimal Trajectory Planning and Data Collection in UAV-Assisted Wireless Powered IoT Networks	2021	78	39
15	Liu J., Tong P., Wang X., Bai B., Dai H.	UAV-Aided Data Collection for Information Freshness in Wireless Sensor Networks	2021	34	17
16	Samir M., Elhattab M., Assi C., Sharafeddine S., Ghrayeb A.	Optimizing Age of Information through Aerial Reconfigurable Intelligent Surfaces: A Deep Reinforcement Learning Approach	2021	32	16
17	Abedin S.F., Munir M.S., Tran N.H., Han Z., Hong C.S.	Data Freshness and Energy-Efficient UAV Navigation Optimization: A Deep Reinforcement Learning Approach	2021	23	11.5

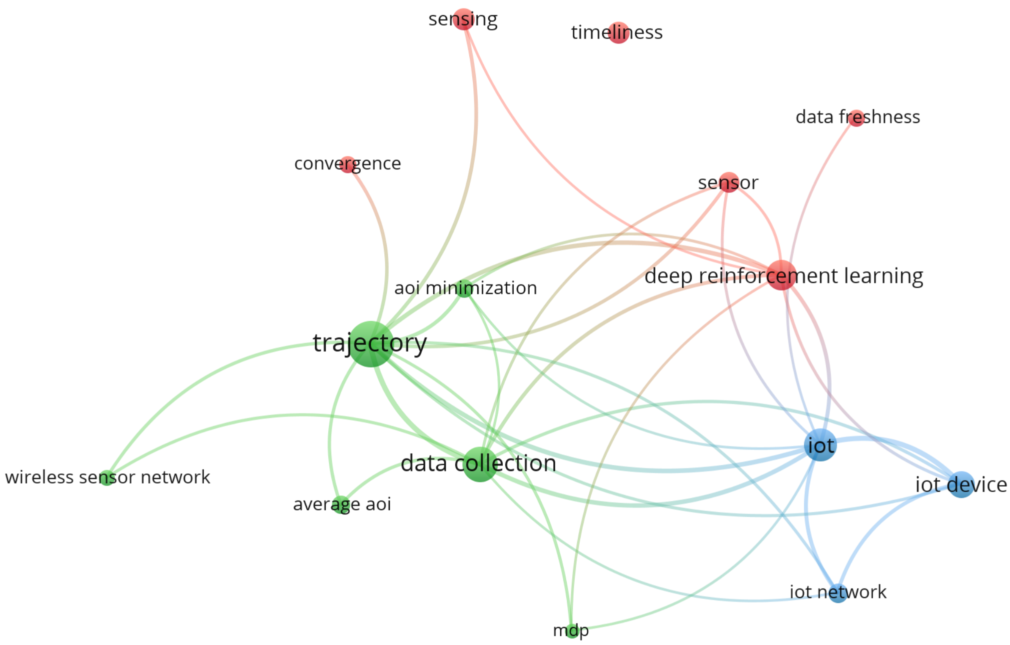

Figure 7: Map of term co-occurrence network from title and abstract based on binary counting

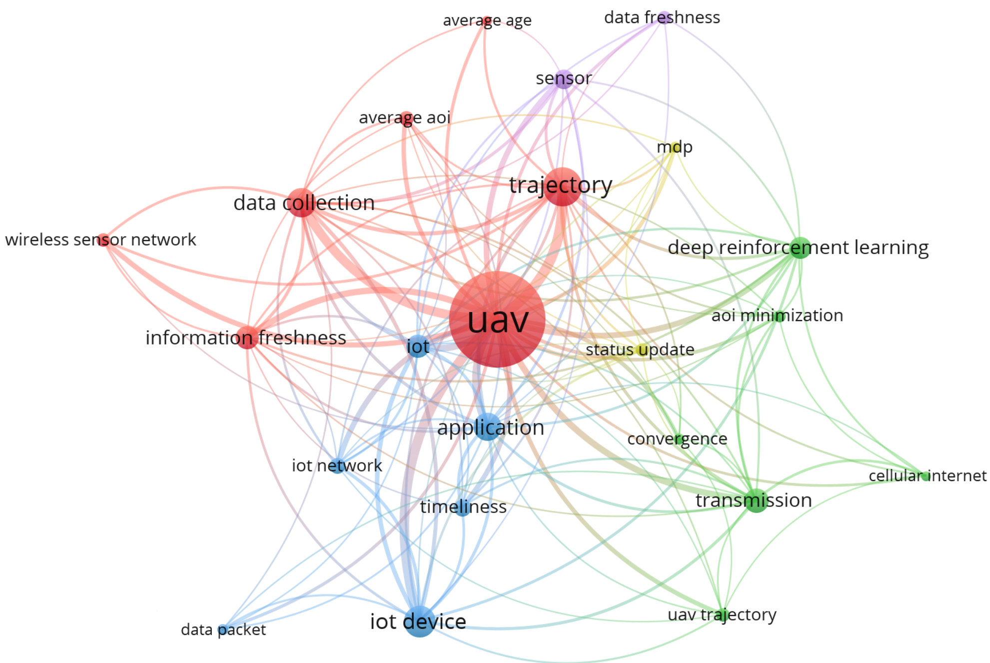

Figure 8: Map of term co-occurrence network from title and abstract based on full counting

Table 12: Problems and focus areas addressed by DRL in UAV and AoI research

Classifications	Focus areas	References
UAV energy	Energy efficiency	[67, 68, 69]
	Operation time	[70]
	Energy consumption	[71]
	Energy harvesting	[65]
	Energy transfer	[72]
UAV trajectory	Trajectory	[70, 71, 73]
	UAV altitude	[74]
	Distributed trajectory design	[75]
	Trajectory design	[76]
	Trajectory planning	[69, 77, 78, 79, 68]
	Trajectory optimization	[80, 72, 76, 81]
	Path planning	[82, 83, 84, 68]
Other focus	UAV sensing	[70]
	Sustainability	[67]
	Sampling mode	[85]
	Data collection	[70, 86, 71, 87, 69]
	Surveillance	
	Scheduling	[71, 74, 88, 73]
	Training	[71]
	Array signal processing	[89]
	Convergence	[89]
	Resource management	[89]
	Mobile relays	[82]
	UAV altitude control	[82]
	Unknown channel conditions	[82]
	Wireless power transmission or transfer	[90, 91, 92]
	Edge Caching	[93]
	Mobile crowdsensing	[94]
	Mobile data gathering centres	[95]
	UAV-to-Device communication	[96, 97]

Table 13: Aspects of DRL methods in UAV and AoI research

Classifications	Methods	References
DRL methods	Multi-Agent Deep Reinforcement Learning (MADRL)	[72, 91, 77, 98, 96, 99, 97]
	Neural combinatorial DRL	[73]
	Deep Q-network (DQN)	[89]
	Dec-POMDP	[100]
	Graph convolutional reinforcement learning	[94]
Combined with DRL	Heuristic algorithms	[89]
	Optimization	[89]
	Convex optimization	[73]
	Federated learning	[101, 99]
	Stochastic games	[98]
	Actor-critic algorithm	[99, 88]
Scheduling	Scheduling policy	[82]
	Queuing policy	[100]
	Off-Policy; On-Policy	[89]
	Proximal policy optimization (PPO)	[89, 66, 74]

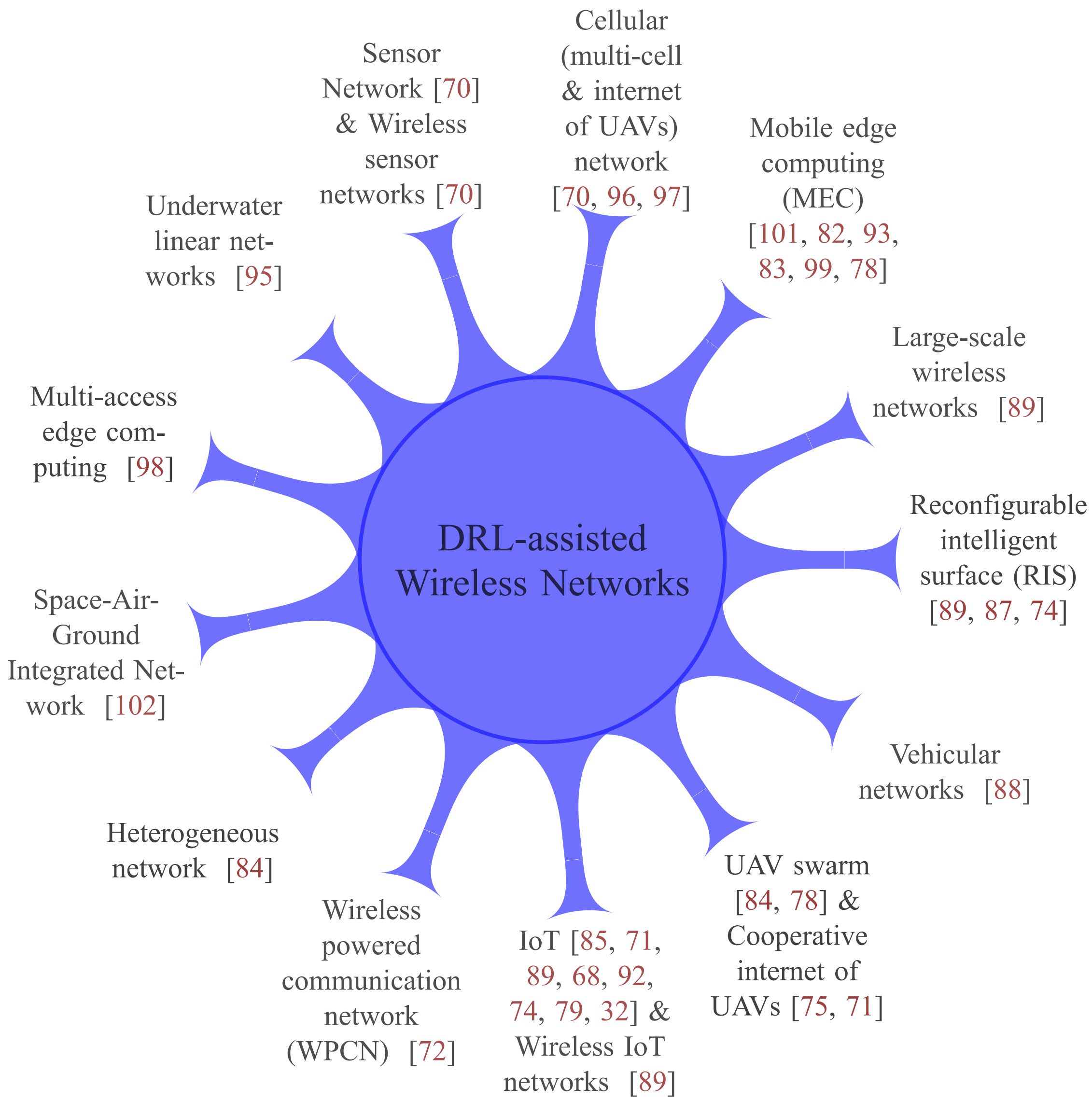

Figure 9: Examples of AoI-aware UAV-aided networks architecture where DRL applications have been applied

bile data collectors or relays, these studies have demonstrated the potential of UAV-WSN collaboration in achieving real-time data updates and minimizing information staleness. Furthermore, MEC has emerged as a promising paradigm for which UAV has been resourceful in enhancing information freshness. For instance, the integration of UAV and MEC paradigms for offloading computation tasks and reducing latency, thereby ensuring fresh and up-to-date information was considered in [104, 105]. These works highlight the potential of UAV-MEC collaboration in enabling real-time data processing and analysis. Moreover, the realm of cellular networks has also witnessed research endeavours aiming to improve information freshness with the assistance of UAVs. In [106], the integration of UAVs into cellular networks was explored, leveraging their mobility and flexibility to enhance the freshness of information.

Fig. 9 captures the key technological paradigms in the context of DRL for UAV-aided information freshness. This provides a summary of the technological domains and their interconnections, illustrating the diverse applications of UAVs in enhancing information freshness. Specifically, UAV-aided information freshness utilizing DRL has been extensively explored in various technological paradigms, including RIS, IoT, WSN, MEC, and cellular networks. The existing studies have demonstrated the potential of UAVs in ensuring up-to-date and timely information updates, offering valuable insights into the integration of UAVs with different domains to enhance information freshness in diverse applications.

5.2 Implications of the study

This study conducted bibliometric analysis and provided knowledge on the major keyword, patterns of citations, publication activities, and the state of cooperation among contributors throughout the course of the UAV-information freshness of existing research. Nevertheless, this study is not without limitations and thus provides suggestions for future studies. As a result, the study discussed the potential gap for future research, implications, and limitations.

Firstly, this study highlights themes to motivate future research as a result of investigating bibliometric data of UAVs for AoI minimization in a different range of scenarios. The examination of the bibliometric analysis showing the relative priority of various elements illustrates the importance of particular subjects to the research community. This is extremely important at the moment because the notion of the AoI metric as a measure of information freshness for UAV-aided networks is been studied mainly within the past five years, and considering the fact the technology can be used in IoT, IIoT, RIS, WSN, etc. Therefore, it is necessary to emphasize the effectiveness of studying AoI to improve data freshness for UAV applications. In this regard, the bibliometric analysis has shown to be useful because it visualizes the network of key terms about the myriad aspects of research interest that could influence academic research in various fields.

The bibliometric method, on the other hand, deviates from the way that earlier researchers reported literature studies. Few studies [107, 108, 109, 73] reported literature and evaluated some of the contributions made about AoI-aided UAV. Although a brief literature report was used to show the literature gap and justify the objectives of the existing studies in those works, the literature is not enough to present a holistic picture of the interest in AoI and UAV in various applications. In addition, narrative evaluation is both limited to a single issue of interest and may not capture a very wide scope in sufficient detail.

In addition, this study generates accurate, reliable, and enough bibliometric data for UAV and AoI. Earlier research utilized the VOSviewer for bibliometric analysis which emphasizes the value of such in-depth text analysis and its findings [45, 47, 48]. Hence, the relevance of this research is in its ability to harmonize those aspects that are more relevant for UAV and AoI in real-time applications. Furthermore, this research has other drawbacks. For example, the Scopus database is updated often, resulting in a fluctuating number of publications and citations [110]. Therefore, the accuracy of the data acquired from the Scopus database on a particular day is could be updated. Moreover, the co-word analysis (co-occurrence analysis of keywords) also has limits as certain publications may not be considered in bibliometric records. Thus, the quality of the co-occurrence analysis is dependent on the indexing method employed, over which this study has little control [111]. In light of this, it is proposed that future research utilize a unique method that blends qualitative and quantitative methods. The fundamental constraint of this study is that the evaluation of 5-plus years of research in UAVs and AoI is limited to articles published in associated publications. In addition, the choice of the keywords was also dependent on the assessment of the relevant literature and the definition of UAVs and AoI; there may be other related keywords.

This study is one of the few that analyzes the literature about UAV and AoI with bibliometric data. As a result, this adds more insight into the applications of UAV-aided AoI to enhance information freshness. Moreover, these findings demonstrate, in a nutshell, that researchers and academics should take action in order to enhance the development of algorithms and hardware that improves the use of UAV for various time-critical applications. The research community should be given enough support from research centres and universities to propagate the significance of AoI to improve information freshness. In a similar vein, sufficient support in the form of enabling legislation and financial remuneration is needed in order to improve interest in AoI, especially for practical, time-critical, real-time and emergency applications, in an efficient manner. Concerns about the information freshness should be used as a cornerstone to holistically improve techniques to improve the AoI performance of UAV-assisted wireless communication. Moreover, the findings of this study may provide important information and recommendations to policymakers, allowing them to further provide support to researchers and technical experts in developing AoI-sensitive solutions for UAV-related applications. Secondly, the scientific mapping and profiling were based on quantitative approaches, which aid in the analysis of the reports and provide a full image of the study field, showing how significant the study themes are. Therefore, the conclusions of this study provide a substantial body of evidence that can persuade researchers to take into consideration concerns that are essential for the implementation of UAV and AoI in real-time application scenarios.

5.3 Recommendations of the study

Based on the comprehensive bibliometric analysis conducted in this study, several recommendations can be made to further advance research and practice in the field of unmanned aerial vehicles -assisted wireless communication for information freshness. These recommendations are aimed at addressing important aspects that emerged from the analysis and can guide future investigations and initiatives in this area. These recommendations are discussed as follows;

– **Foster interdisciplinary collaboration:** The findings of this study highlight the multidisciplinary nature of research on UAVs and information freshness. To facilitate progress in this field, it is recommended to encourage collaboration [55] among researchers from diverse disciplines such as computer science, telecommunications, transportation, and optimization. Interdisciplinary teams can bring together complementary expertise and contribute to the development of innovative solutions for further facilitating AoI-aware UAV-aided interventions in various applications scenarios.

- **Focus on further improving on DRL and optimization algorithms:** The analysis revealed that deep reinforcement learning and optimization algorithms have been prominent methods applied in the context of UAVs and information freshness. Future research should further explore and enhance these approaches to improve real-time status updates and ensure efficient information delivery. Investigating novel algorithms and techniques can contribute to the development of more robust and reliable UAV systems.

- **Address energy efficiency and harvesting:** Energy efficiency and harvesting emerged as significant research topics in the context of UAVs and information freshness. To mitigate the limitations associated with limited onboard power and enhance the sustainability of UAV operations, it is recommended to investigate energy-efficient mechanisms and explore innovative approaches for energy harvesting or sources, such as solar, fuel cells, combustion engines, and kinetic energy, most of which can be utilized in UAV [22]. These efforts can lead to longer flight durations and increased operational capabilities.

- **Enhance trajectory planning and design:** The study identified trajectory planning and design as critical areas of interest for researchers. Future investigations should focus on developing advanced algorithms and methodologies to optimize UAV trajectories, taking into account factors such as communication constraints, environmental conditions, and real-time data availability [23, 18]. Effective trajectory planning can minimize delays, improve information freshness, and enhance overall UAV performance.

- **Emphasize scheduling strategies:** The analysis highlighted the significance of scheduling strategies in achieving information freshness (see Table 3). Researchers should explore scheduling techniques that consider time-critical applications and prioritize real-time information updates. Investigating dynamic scheduling algorithms and adaptive mechanisms can contribute to efficient resource allocation and ensure timely data delivery [64, 66].

- **Bridge the gap between research and practice:** The implications derived from this study have practical significance. To bridge the gap between research and practice, it is recommended to foster collaborations between academia, industry, and policymakers. Industry stakeholders can provide valuable insights into practical challenges and requirements, while policymakers can facilitate the adoption and integration of UAV systems for information freshness in various domains. Similarly, practical UAV deployments on the field for evaluating some of the proposed algorithms would be very promising for advancing research in this area.

By following these recommendations, researchers and practitioners can further advance UAV-aided solutions for information freshness, leading to the development of more efficient and reliable systems that cater to the demands of real-time status updates and time-critical applications.

6 Conclusion

Technology-driven various applications are continuously expanding as a new research topic. AoI in UAV-aided information transmissions have attracted increasing interest, as an evolutionary paradigm. In view of this, there is an increasing drive to increase the effectiveness and efficiency of UAV communication and control to increase information freshness in several applications. This field of study is undergoing constant evolution. As result, each step towards improving methods, algorithms, procedures, or tools can make a substantial contribution to the literature. Therefore, the purpose of this study was to explore and analyze the bibliometric data of studies relating to the use of UAVs for AoI-sensitive applications from the literature by using the VOSviewer bibliometric program. The use of bibliometric analysis revealed different primary and secondary aspects of the research that has been done in the field of UAV and AoI, via data analysis and visualizations. For instance, the most influential keywords, authors, universities, and countries were all identified. Similarly, the text analysis using VOSviewer was used to determine the co-occurrence of the terms used by previous studies. After statistically analyzing the 122 articles, the study found that optimization, MDP and DRL as significant tools, while flight trajectory, scheduling, and energy efficiency are emerging aspects of the current literature. In addition to that, the results of this study provide suggestions for enhancing research and practical application deployment in this domain.

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Appendix

Appendix A: Map of co-occurrence network from abstract

- Fig. 10: Map of term co-occurrence network from abstract based on binary counting
- Fig. 11: Map of term co-occurrence network from abstract based on full counting

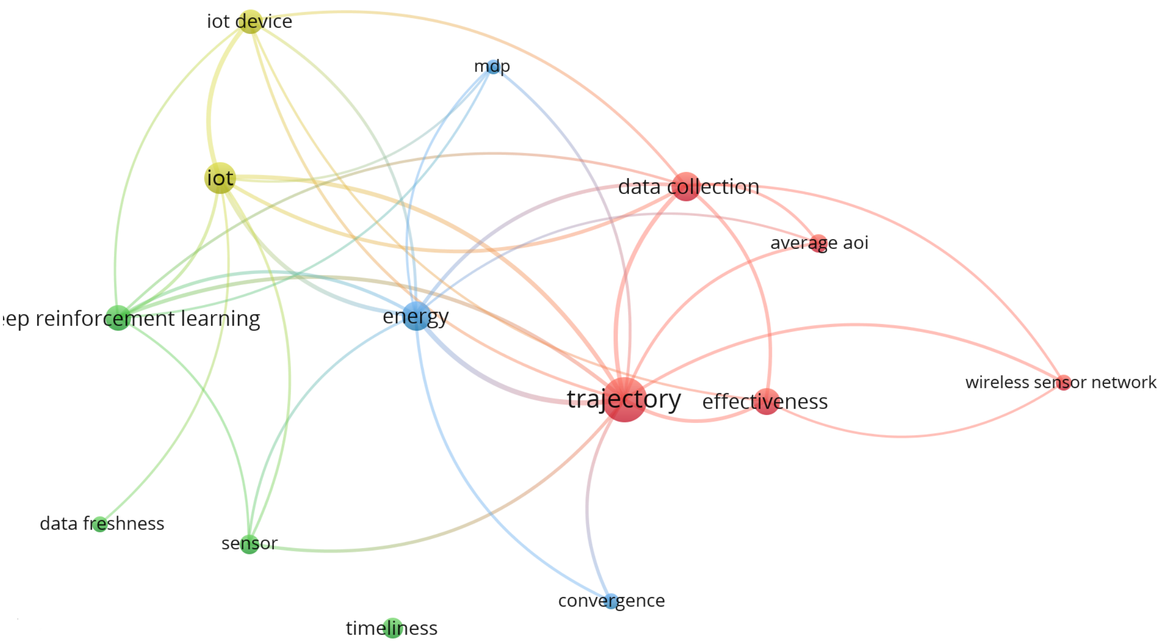

Figure 10: Map of term co-occurrence network from abstract based on binary counting

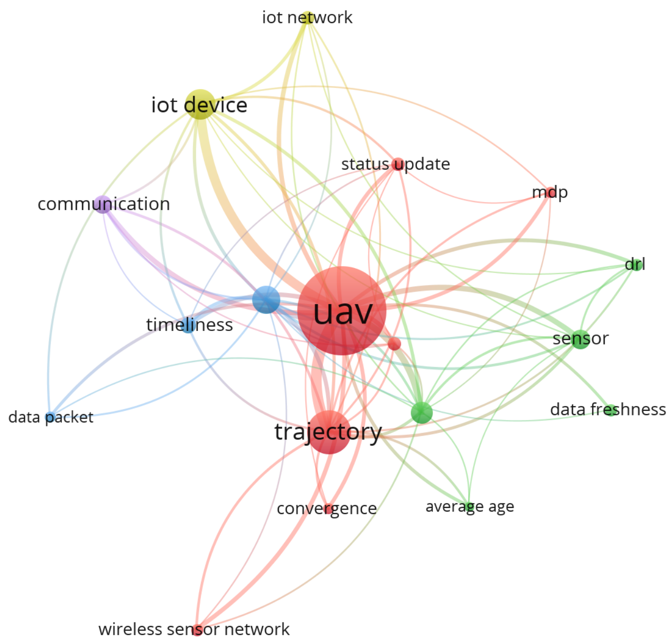

Figure 11: Map of term co-occurrence network from abstract based on full counting