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Bibliometric analysis of UAV swarms

JIANG Yangyang[1], GAO Yan[2], SONG Wenqi[2], LI Yue[2], and QUAN Quan[2,*]

1. Beihang University Library, Beijing 100191, China; 2. School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China

Abstract: Projects on unmanned aerial vehicle (UAV) swarms have been initiated in a big way in the last few years, especially from 2015 to 2016. As a result, the number of related works on UAV swarms has been on the rise, with the rate of growth dramatically accelerating since 2017. This research conducts a bibliometric analysis of robotics swarms and UAV swarms to answer the following questions: (i) Disciplines mentioned in the UAV swarms research. (ii) The future development trends and hotspots in the UAV swarms research. (iii) Tracking related outcomes in the UAV swarms research.

Keywords: unmanned aerial vehicle (UAV) swarm, bibliometric, mapping knowledge domain.

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1. Introduction

The organizational structure of many biological swarms in nature is simple, and they have group behavior. Complex tasks, such as bee colony foraging, geese migration, ant colony transportation, and fish swimming can be completed through communication and collaboration. As a result, the concept of unmanned aerial vehicle (UAV) swarms operations is proposed. They build large-scale swarms by coordinating and interacting with low-cost, distributed UAVs to execute complex tasks, including battlefield reconnaissance, regional containment, and saturation attacks [1]. Swarm warfare is the fourth type and the most advanced type in history (the first three types of conflict are melee, rallying, and mobile warfare), according to John Aquilla and David Ronfeldt's monograph [2]. The USA and Europe are key players in the field of UAV swarms, and a slew of applied research has been undertaken to meet the demands of drone swarm operations. Fig. 1 illustrates the main research projects and strategic plans of the USA and the European Union's major research initiatives and strategic plans [3−8].

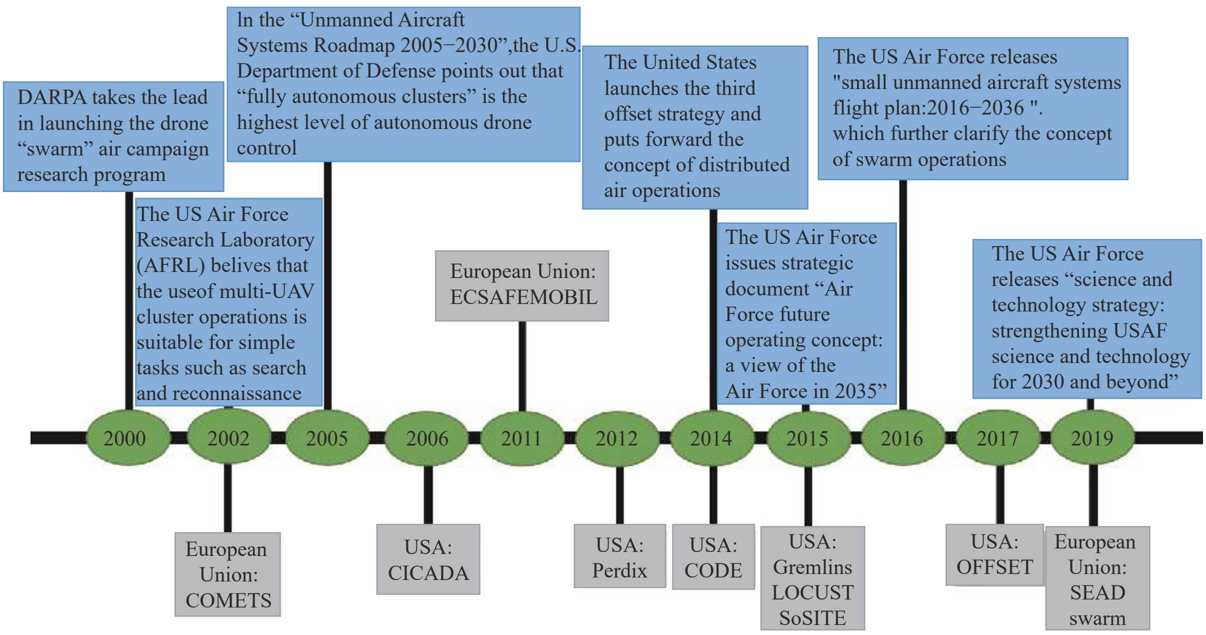

Fig. 1 Main research projects and strategic plans of the USA and European Union

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*Corresponding author.

Projects on UAV swarms are being launched more vigorously around the world as the military's demand for UAV combat effectiveness grows. They have given them enough attention as a frontier research topic in military theory and applications, a significant amount of research has been conducted in this area. Table 1 shows the major research projects and results worldwide.

Table 1 Major research projects

Country/Organization	Project	Description
USA	2006：CICADA	Close-in covert autonomous disposable aircraft
	2012：Perdix	Collective decision making, adaptive formation flying, and self-healing
	2014：CODE	Collaborative operations in denied environment system
	2015：Gremlins	Develop and demonstrate the ability to air-launch and air-recover up to drones
	2015：LOCUST	Low-cost UAV swarming technology
	2015：SoSITE	System of systems integration technology and experimentation
	2015：LCAAT	Low-cost attritable aircraft technology
	2017：OFFSET	Offensive swarm-enabled tactics
European Union	2002：COMETS	Real-time coordination and control of multiple heterogeneous UAVs
	2011：ECSAFEMOBIL	The estimation and control project of the high mobility collaborative industrial system for secure wireless
	2019：SEAD Swarm	Suppression of enemy air defenses
Russia	2019：Launched "Flock-93" combat demonstration system	"Flock-93" will be flying wings and have vertical take-off and landing capability, promising both flexibility and target range of around 95 miles
	2019：Tsentr-2019	Orlan-10 unmanned aircraft, as well as other variants of that drone with sensor and electronic warfare payloads, to locate and try to destroy critical air defense systems, command posts, communications nodes
	2020："Grom" UAV	Performing intelligence, surveillance, strike, and electronic warfare missions either on its own, as a loyal wing working together with a manned aircraft, or in a networked autonomous swarm
China	2016：67 fixed-wing UAV swarms test	It broke the previous record of 50 fixed-wing UAV clusters held by the US Navy
	2017：119 fixed-wing UAV swarms test	Dense ejection take-off, air assembly, multi-target grouping, formation encirclement, swarm operation

However, UAV swarm operations are still in their development since there is a huge gap between artificial swarm systems and biological swarms in nature. It still has a long way to go before it can be utilized in a complex application environment, and many issues must be addressed.

This study aims to present a detailed bibliometric analysis of the UAV swarms, based on the following research questions:

(i) What are the disciplines mentioned in the UAV swarms research?

(ii) What are the future development trends and hotspots in the UAV swarms research?

(iii) How to track related outcomes in the UAV swarms research?

Clarification of some basic concepts in Section 2 is done to respond to these three queries. Then, keywords are determined based on this clarification. In addition, various materials and methods are discussed. Finally, the three queries raised above are responded.

2. Some basic concept

2.1 Swarm

2.1.1 What is swarm

The concept of swarm is frequently associated with social relationships, and it encompasses two critical concepts: disorganized cluster and movement. In the real world, the most familiar swarm is the bee swarm, which flies in a disorganized cluster. With the same criteria and architecture, the flock of birds, fish, wolves, even the immune system and an economy can be taken as the swarm, respectively. In the swarm research area, various collective behaviors concentrate on more than the spatial motion [9]. Reynolds proposed the boid model to simulate the birds' behavior, using the three distributed rules to make it real. The rules can be defined as collision avoidance, velocity matching, and flock centering. In [10], Reynolds also described the variations between the distributed behavioral model and the particle system. Another famous model was proposed by Vicsek [11], which builds the model from the perspective of statistical mechanics simply without losing the essence. Cellular automata are also based on a simple mathematical model to investi gate self-organization in statistical mechanics [12]. In recent years, the physicists, Toner and Tu, examined collective behavior mathematically [13].

2.1.2 Collective behaviors

In the swarm system, rudimentary behaviors can evolve the complicated collective behavior. The collective behaviors generally include spatially-organizing behaviors, navigation behaviors, collective decision making, and other collective behaviors [14] that are described in Fig.2.

(a) Spatially-organizing behaviors (b) Navigation behaviors (c) Collective decision making

Fig. 2 Collective behaviors

(i) Spatially-organizing behaviors can be described as some agents gather to accomplish specific actions with strong spatial relationships, such as coverage, aggregation, pattern formation, chain formation, self-assembly and morphogenesis, object clustering, and assembling.

(ii) Navigation behaviors imply investigating the area collectively, such as foraging or patrolling in a coordinated state. Coordinated motion and collective transport also belong to navigation behaviors.

(iii) Collective decision making focuses on consensus achievement and task allocation, making the cluster solve the overall task in individual collaboration.

2.1.3 Swarm intelligence

The swarm will result in complex behavior if every individual performs simple actions. This scene observed in social insects is called emergent behavior. And swarm intelligence as an artificial intelligence discipline appears by imitating this swarm intelligence phenomenon. Swarm intelligence considers applying the simple rules observed in ordinary animal societies to make multi-agent systems smarter.

The pros and cons own the reasonable opinions on the controversial question of whether the swarm intelligence individual belongs to an agent, respectively. Bonabeau et al. considered swarm intelligence as the emergent collective intelligence of simple agents' groups [9]. However, the book "swarm intelligence" [15] tends to be dismissive of the relationship between swarm intelligence and the concept of agents. The book recognizes the opposite features of swarm members and agents, such as pre-rules and auto, homogeneous and heterogeneous.

2.2 Swarm robotics

2.2.1 What is swarm robotics

In [16], the author first considered distinguishing between swarm robotics and other multi-robot systems. Different works demonstrate the various definitions of swarm robotics. The following descriptions can help us find out the diversities in many concepts.

Definition 1 Swarm robotics investigate designing plenty but uncomplicated agents with a physical scale to achieve the desired effect with local interaction or perception [17]. The local interaction or perception is a small-scale, distributed information exchange or active environmental acquisition.

Definition 2 Swarm robotics is an application of swarm intelligence that utilizes local rules to create global behavior with reliability [18].

In the swarm robotic system, there are three functional requirements, namely: robustness, flexibility, and scalability. These properties appear in the nature swarm.

(i) Robustness. The swarm robotic system should be kept unaffected by multiple disturbances, especially environmental change and personal operation.

(ii) Flexibility. The individual in the system should be able to control various environments and tasks.

(iii) Scalability. The swarm should be suitable for variable scale or group size.

2.2.2 Swarm robotics vs. multi-agent

The definition of an intelligent agent is a physical or virtual entity that can perform an action on the environment with information perception, such as a robot and software program. In addition, in [19], Dautenhahn noted that agents can represent computational, mechanical, or biological entities that are relatively autonomous and interact with the environment. Furthermore, swarm robotics is restricted to only physical entities. As a result, swarm robotics must consider collision and other rules in the real world, whereas the software program does not.

2.2.3 Swarm robotics vs. multiple robots

Several features are given below to distinguish swarm robotics and multiple robots. Swarm robotics can be described as multiple robots implementing or adapting the concept of emergent behavior [18]. In addition, swarm robotic systems can be considered multi-robot systems with simple robot individuals. The individual of the swarm robot only has limited personal capabilities if the multi-robot can execute the complex task alone. For instance, the complicated search and rescue system containing aerial and ground robots may be a multiple robot system, whereas the swarm robot can only perform simple movement and primitive tasks.

2.2.4 Swarm engineering

Swarm engineering is a term introduced by Kazadi in 2000. It mainly focuses on designing predictable and controllable swarms with definite global goals and verifiable minimal conditions, which belongs to a sub-discipline of swarm robotics [20]. In 2004, Winfield first defined swarm engineering in "towards dependable swarms and a new discipline of swarm engineering" [21] to combine swarm intelligence and dependable systems. Brambilla reported that swarm engineering is applied to model the requirements, design, realize, verify, and validate, operate, and maintain a swarm system [14].

2.2.5 Swarm drones or UAVs or aerial robotics

UAV (commonly known as drones) is an aircraft or a flying object without a human pilot. UAVs or drones are subjected to a self-functioning robotics module identifying their way of traveling to the desired location or destination. There are slightly variable characterizations between UAVs and aerial robotics. Aerial robotics are based on a flying platform, with attention to physical interaction with objects and aerial vehicles, mainly with aerial robotic manipulations. Therefore, swarm drones or UAVs or aerial robotics is a type of swarm robotics that can fly.

3. Materials and methods

3.1 Bibliometric software

The mapping knowledge domain is a research approach that has emerged in the last few years, which combines bibliometrics, graphics, information technology, applied mathematics, and computer science. The mapping knowledge domain can present the structure, law, and distribution of scientific knowledge through visual means. There are a lot of software currently used for visual analysis, and each has its benefits. This study will utilize VOSviewer [22] and CiteSpace [23] software for visual drawing. VOSviewer and CiteSpace are two powerful and complementary visualization software. VOSviewer is a free bibliometric measurement mapping tool developed by Van and Waltman [24]. Its user interface is amicable, the visualization effect is good, and the drawing is exquisite. In this research, VOSviewer presents the relationship of mapping document information in a complex network, such as cooperating countries, cooperating institutions, and keywords. CiteSpace is a freely available Java application developed by Chen. CiteSpace can discover the development trend of the knowledge field by investigating the vital path of the evolution of the research topic and the turning point in the knowledge field. In this study, CiteSpace is employed to present the research progress, research directions, and research frontiers of UAV swarms over a certain period.

3.2 Search database determination criteria

The literature data used in this study mostly comes from the Science Citation Index Expanded (SCIE) database in the core collection of Web of Science. Furthermore, part of the conference information comes from the Conference Proceedings Citation Index-Science (CPCI-S) database. SCIE has always been recognized as the world's most authoritative scientific and technical literature indexing tool, which can provide the most important research results in science and technology. Institute for Scientific Information (ISI) selects journal sources through strict selection criteria and evaluation procedures and increases and decreases slightly every year so that the documents included in SCIE can fully cover the most important and influential research results in the world. In addition, SCIE also provides citation information, keywords, and references. SCIE is a multi-disciplinary comprehensive database that spans across over 100 disciplines, mainly involving agriculture, biology, and environmental sciences, engineering technology and applied sciences, medicine and life sciences, physics and chemistry, and behavioral sciences.

3.3 Data collection

UAV swarms have multiple writing methods in academic research of various disciplines. In addition, there also exist some diverse opinions on one definition. Thus, this paper does not distinguish the words "swarm" "formation" "team" and "multiple" to improve the recall rate. The search condition is set to topic search, as shown in Table 2.

Formula 1, which includes vehicle, is generally compared with Formula 2. Formula 2 concentrates on robotics and UAVs, whereas Formula 3 only focuses on drones. The time span is defined as 2000–2021, and the literature information records are searched and downloaded on March 25, 2021. After excluding invalid documents, 5 160 and 757 documents are retrieved for Formula 1 and Formula 3, respectively. The time spans are 2 000–2 021 and 2 010–2 021, respectively, for Formula 2, and the literature information records are searched and downloaded from March 25 to March 29, 2021. After excluding invalid documents, a total of 4 012 studies and 3 358 studies are retrieved, respectively.

Table 2 Basic keywords

Searching formula	Topic search
Formula 1	TS = "swarm UAV*" OR "UAV swarm" OR "swarm drone*" OR "drone swarm" OR "swarm robot*" OR "robot* swarm" OR "swarm vehicle*" OR "vehicle swarm" OR "formation UAV*" OR "UAV formation" OR "drone formation" OR "formation drone*" OR "formation robot*" OR "robot* formation" OR "formation vehicle*" OR "vehicle formation" OR "team UAV*" OR "UAV team" OR "drone team" OR "team robot*" OR "robot* team" OR "team vehicle*" OR "vehicle team" OR "multi-UAV*" OR "multi-drone*" OR "multi-robot*" OR "multi-vehicle*" OR "multiple UAV" OR "multiple drone*" OR "multiple robot*" OR "multiple vehicle*" OR "distributed UAV*" OR "distributed drone*" OR "distributed robot*" OR "distributed vehicle*" OR "collective UAV*" OR "collective robot*" OR "collective vehicle*"
Formula 2	TS = "swarm UAV*" OR "UAV swarm" OR "swarm drone*" OR "drone swarm" OR "swarm robot*" OR "robot* swarm" OR "formation UAV*" OR "UAV formation" OR "drone formation" OR "formation drone*" OR "formation robot*" OR "robot* formation" OR "team UAV*" OR "UAV team" OR "drone team" OR "team robot*" OR "robot* team" OR "multi-UAV*" OR "multi-drone*" OR "multi-robot*" OR "multiple UAV" OR "multiple drone*" OR "multiple robot*" OR "distributed UAV*" OR "distributed drone*" OR "distributed robot*"
Formula 3	TS = "Swarm UAV*" OR "UAV swarm" OR "swarm drone*" OR "drone swarm" OR "formation UAV*" OR "UAV formation" OR "drone formation" OR "formation drone*" OR "team UAV*" OR "UAV team" OR "drone team" OR "multi-UAV*" OR "multi-drone*" OR "multiple UAV" OR "multiple drone*" OR "distributed UAV*" OR "distributed drone*"

4. Bibliometric analysis

Except for Subsection 4.6–Subsection 4.8, the rest of the sections are obtained by searching Formula 2.

4.1 Tread of publication and research

All data regarding the UAV swarms are retrieved and relevant studies are searched under Formula 1—Formula 3, as shown in Table 2, respectively. Then, visual analysis is conducted on these studies. As shown in Fig. 3, compared with Formula 3, there are more related documents under Formula 1 and Formula 2, and most of the studies are under Formula 1. Overall, the number of relevant investigations on UAV swarms has been indicated an increasing trend since 2000. Furthermore, the growth rate of relevant investigations has significantly accelerated since 2017. This paper predicts that the number of relevant documents under Formula 1 will attain more than 1 000 in 2021. A lot of attention has been paid to the UAV swarms, indicating that this field will be a sustained hotspot in the future.

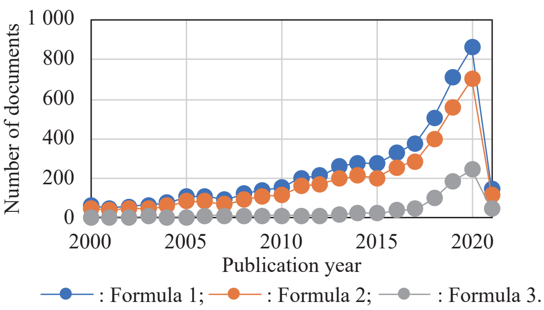

Fig. 3 Number of documents published from 2000 to 2021

As illustrated in Fig. 4, this paper uses Formula 2 to retrieve relevant works published in the USA and China since 2000 and conducts the visual analysis. From 2000 to 2016, the number of relevant works published in the USA steadily increased in general. Since 2016, the growth rate has significantly accelerated. The growth rate is the fastest, especially from 2016 to 2018.

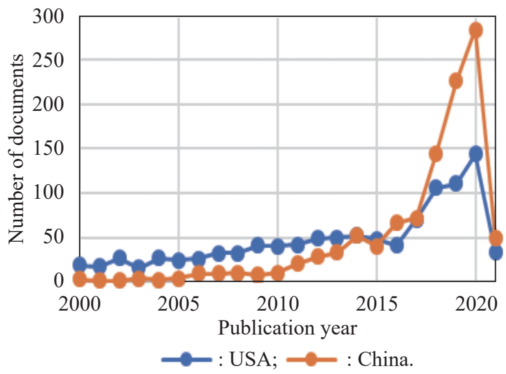

Fig. 4 Number of documents published in the USA and China

Compared with the launched projects as shown in Fig. 1, it can be concluded that the military demands have been propelling the development of UAV swarms. Before 2010, the number of works published in China was relatively less than 10. From 2010 to 2017, the number of published studies generally increased. Since 2017, the number of published works has increased significantly and attained the fastest growth rate, indicating that China has developed rapidly in the field of UAV swarms in recent years. Overall, the number of studies published in the USA is higher than that in China before 2015. Since 2016, the number of relevant studies published in China has gradually surpassed that of the USA, with a significant gap between 2019 and 2020. That is to say, the USA started early in the field of UAV swarms, whereas China has developed faster.

4.2 Countries

In recent years, the field of UAV swarms has developed rapidly. Based on the statistical analysis, more countries and regions have been involved in the research of UAV swarms, among which scholars in the USA and China have published the most papers.

As illustrated in Table 3, Portugal shows the highest citation burst with 8.74 from 2011 to 2016. The main reason is that the scholars of Portuguese cooperated with Indian scholars to publish works related to the UAV searching field in 2011, which are cited frequently [25,26]. The citation burst of the USA is only 4.72, which is lower than Portugal. However, the total number of citations in the USA is much more than that in Portugal. Furthermore, the citation burst of the USA occurred in 2010, suggesting that the USA did pioneering research in this field. The citation burst of Germany was 5.98 from 2011 to 2013 because Germany had strengthened its cooperation with the USA and other countries in those years [27,28]. The scholars in Saudi Arabia and Finland demonstrated a later burst from 2020 to 2021. The strong citation bursts of all top three countries continued until 2017, indicating that a greater number of scholars will continue to join this research field.

Table 3 TOP 9 countries with the strongest citation bursts

Countries	Strength	Begin	End
USA	4.72	2010	2010
Portugal	8.74	2011	2016
Germany	5.98	2011	2013
Spain	4.14	2013	2013
Switzerland	2.97	2014	2014
Russia	2.58	2015	2015
Brazil	4.76	2016	2017
Saudi Arabia	3.02	2020	2021
Finland	2.69	2020	2021

Table 3 shows the top 9 countries and regions that have published documents since 2010, and their citations, links, and link strength are analyzed. As observed from Table 4, China, the USA, and Spain have the highest number of documents in the past decade. Among them, the number of documents in China and the USA is greater than that in other countries. In terms of citation frequency, the USA has the highest citation frequency, followed by China, which has a much higher citation than other countries. From the perspective of total link strength between countries, the top three countries are the USA, China, and England. The link strength of the USA is slightly higher than that of China, which is significantly higher than that of other countries. Considering the number of cooperation links between countries, the USA has the most contacts with other countries, followed by China and England, indicating that the USA has the most active and inclusive attitude towards cooperation in this field.

Table 4 The most productive countries/regions

Rank	Country/region	Document	Citation	Total link strength	Link
1	China	1017	10279	393	46
2	USA	780	14237	396	50
3	Spain	212	3150	121	30
4	England	188	2700	176	35
5	Italy	182	2640	164	34
6	South Korea	182	1712	66	15
7	Canada	150	2143	131	27
8	India	139	1497	70	28
9	Germany	133	2136	121	30
10	Japan	113	1083	64	20

Fig. 5 demonstrates the national collaboration network according to VOSviewer analysis (the minimum number of country documents is 5). The size of the node represents the number of documents published by the country, and the color of the node is determined by the average appearance time of the country. The greener the color, the sooner it appears, and the yellower the color, the later it appears. The lines between countries reflect the strength of the cooperation, and the thicker the line, the stronger the cooperation. It is obvious that the number of published documents in China and the USA is significantly higher than that of other countries, and the average time of published documents in this field in the USA is earlier than that in China, indicating that the USA started earlier. Based on the average time of publication, the countries initially started studying this field include Spain, Germany, Portugal, Belgium, and other European countries, whereas China, Singapore, and other Asian countries started later.

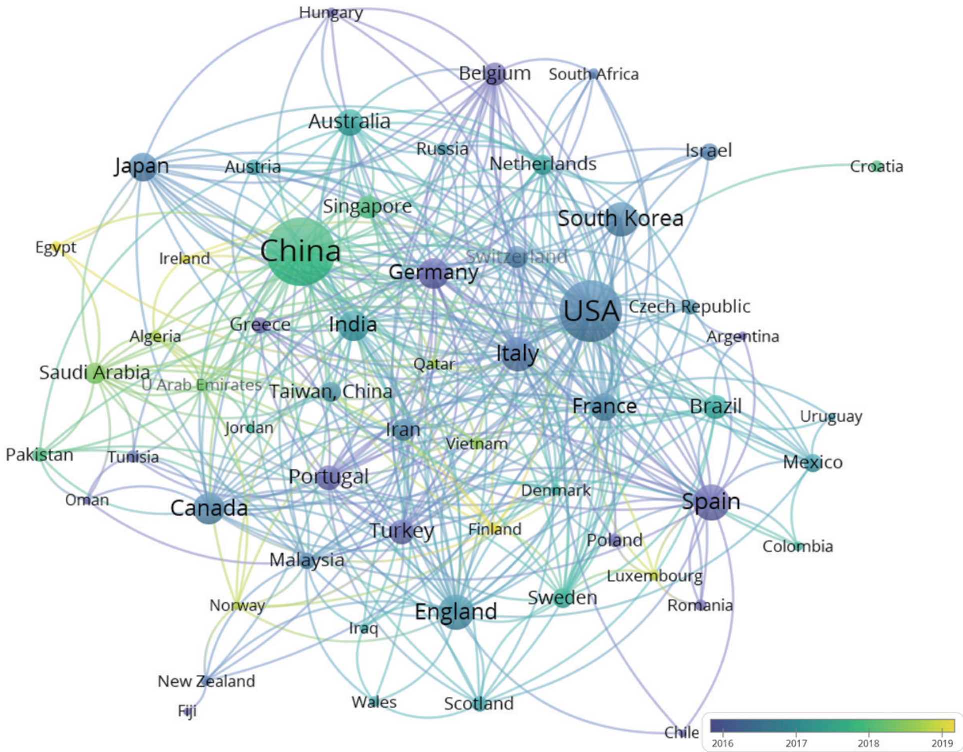

Fig. 5 Co-author analysis of countries/regions

As shown in Fig. 6, China has a positive attitude toward cooperation, and it mainly cooperates with developed countries in this field, including the USA and England, which started earlier in this field and have published more documents.

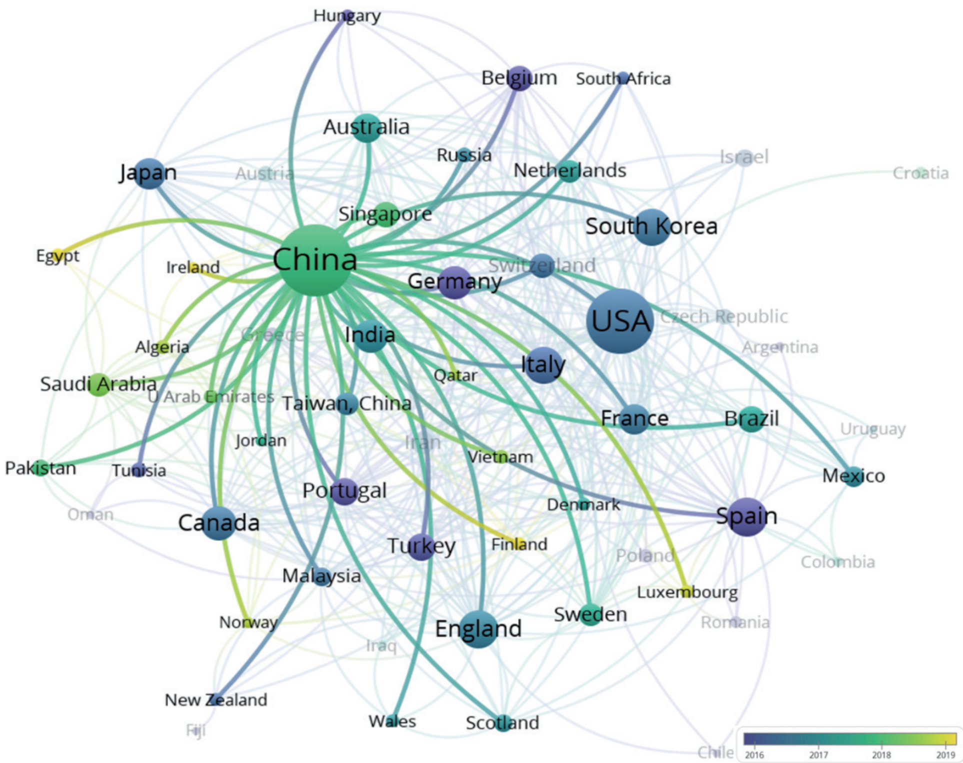

Fig. 6 Co-author analysis of countries/regions with China

As demonstrated in Fig. 7, the USA has large-scale cooperation all over the world, cooperates positively with not only many European countries, such as Spain, Germany, Portugal, and Belgium, which started research earlier in this field, but also China, England, France, and many other countries that published a large number of documents. This suggests that the USA has a very positive and inclusive attitude toward cooperation in this field.

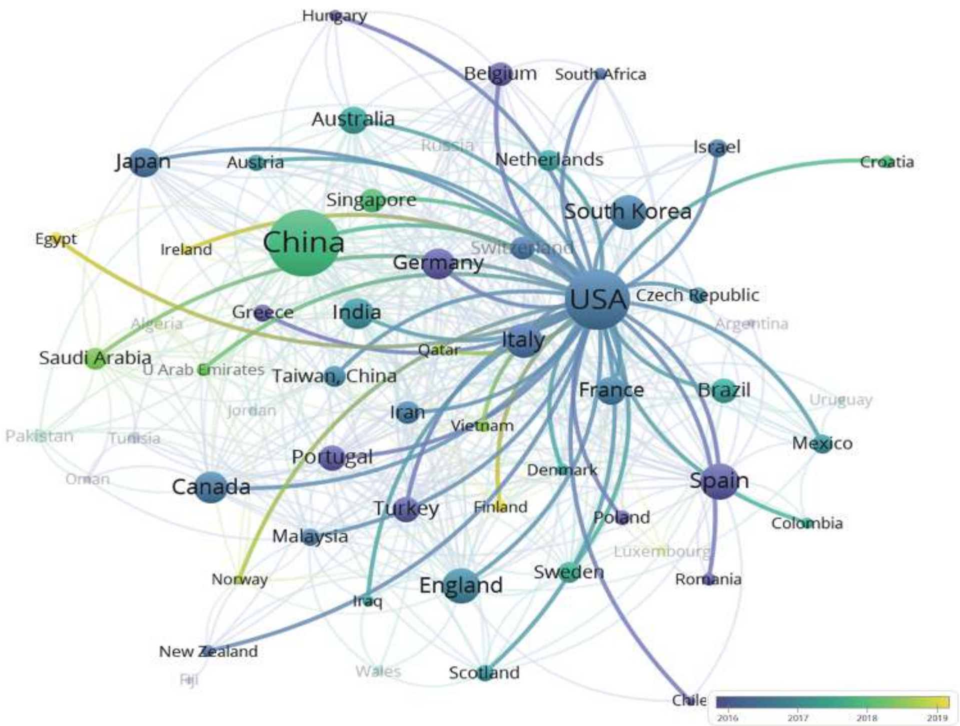

Fig. 7 Co-author analysis of countries/regions with the USA

4.3 Institutions

Table 5 counts the top 10 institutions that have published documents since 2010, and their citations, links, and link strength are analyzed. As shown in Table 5, the three institutions with the highest number of documents in the past decade are National University of Defense Technology (NUDT), Beihang University, and Massachusetts Institute of Technology (MIT). In terms of citation frequency, the top five institutions are Université Libre de Bruxelles, MIT, Carnegie Mellon University, Tsinghua University, and Beihang University, all of which are significantly higher than other countries. As shown in the top five countries with the strongest cooperation, such as MIT, Chinese Academy of Sciences, Tsinghua University, and Beihang University, the strength of cooperation connection of MIT is significantly higher than other institutions. In terms of the number of cooperation links, the top three institutions are MIT, Beihang University, and the Chinese Academy of Sciences. In general, MIT has the most active cooperative attitude and the highest cooperation strength compared with other institutions, making significant contributions to the development of this field.

Table 5 Institutions

Rank	Organization	Document	Citation	Total link strength	Link
1	NUDT	79	266	69	46
2	Beihang University	75	936	84	65
3	MIT	70	1 477	109	79
4	Northwestern Polytechnical University	63	444	69	42
5	Beijing Institute of Technology	46	468	54	42
6	Tsinghua University	45	973	91	59
7	Université Libre de Bruxelles	43	1 535	62	46
8	Carnegie Mellon University	41	1 255	54	43
9	Chinese Academy of Sciences	41	235	96	60
10	Nanyang Technological University	39	393	45	34

Fig. 8 shows the number of documents published from 2000 to 2021 by the top three institutions in Table 2 Formula 2 (the number of documents published from 2000 to 2003 is all 0), including Beihang University, MIT, and NUDT, and visual analysis is conducted on these data.

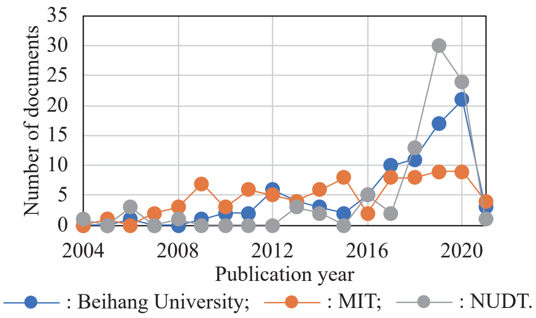

Fig. 8 Top three institutions

Overall, the number of documents published by the three institutions in this field depicts an increasing trend. Since 2006, the number of documents published by MIT in this field has shown a fluctuating growth. Compared with the two Chinese institutions, MIT in the USA started earlier and developed steadily. Before 2015, the number of documents published by Beihang University illustrated a pattern of slow and fluctuating growth in general. Since 2015, the number of documents published by Beihang University in this field has greatly increased. This paper proposes that the number of studies published by Beihang University will be more than 25 in 2021. Before 2017, the number of documents published by NUDT indicated a trend of slow and fluctuating growth. The number of documents published by NUDT in this field has increased significantly since 2017, and the growth rate is the fastest. NUDT has surpassed Beihang University and became the institution with the highest number of documents since 2018. Generally speaking, the institutions in China started later. However, they have developed rapidly, especially in recent years.

Fig. 9 shows the collaborative network of institutions (the minimum number of documents of an organization is 10). The size of nodes represents the number of published documents by these institutions. The color of nodes is determined by the average time of each key node in the year. The lines between institutions reflect the strength of the collaboration; the thicker the lines, the stronger the collaboration. It is noted that many institutions have published a large number of documents in this field, and the variation in the number of documents published is unclear.

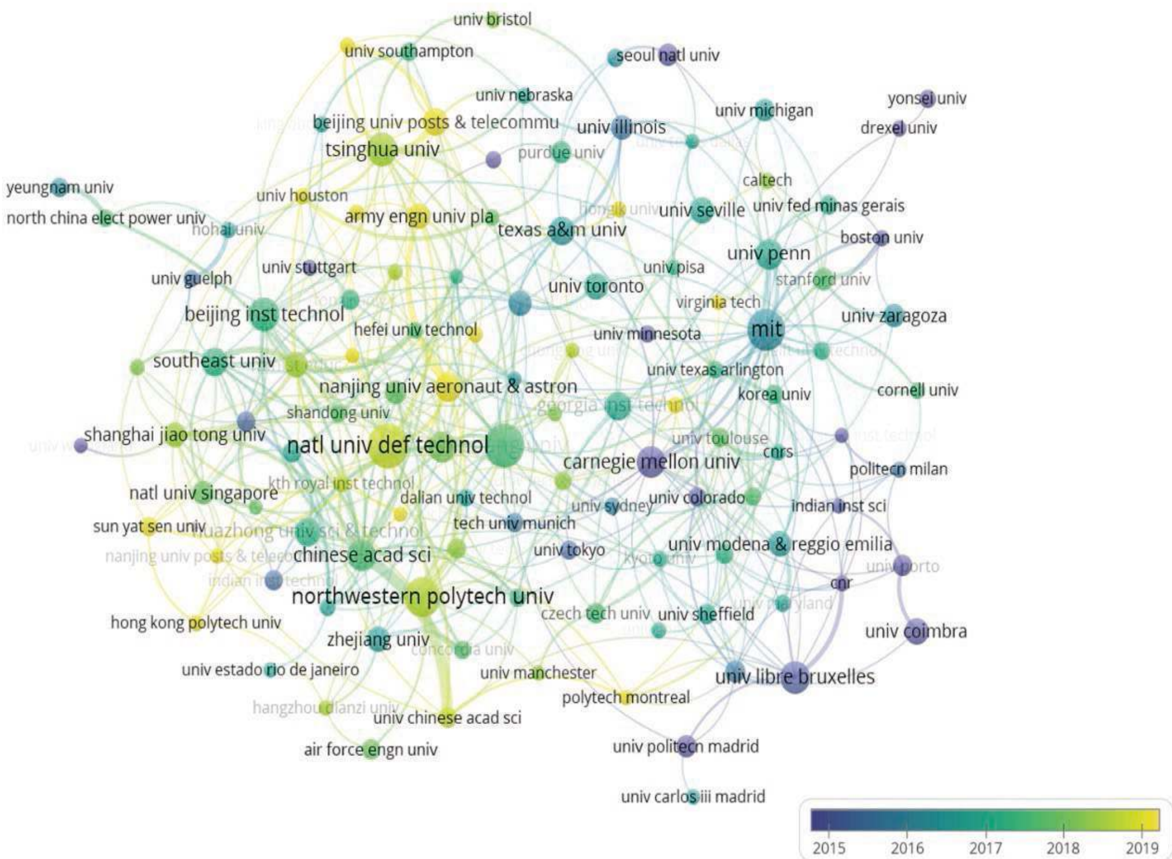

Fig. 9 Collaborative network of institutions

On the whole, institutions in the USA, Europe, and other countries and regions developed earlier and started cooperation earlier. The earliest institutions started participation in research cooperation in this field around 2015. Chinese institutions started later in the field and therefore participated in the collaboration relatively later, which started around 2018.

4.4 Research fields

Table 6 shows the top 20 research fields (the data come from the research areas classification of the SCIE database). The top three research fields are computer science, engineering, and robotics, which account for more than 60% of the records. It should be noted that the total number of documents recorded in Table 6 is 6 325 because the same document has the identification of multiple research fields.

Table 6 Research fields

Rank	Subject	Document
1	Computer science	1 420
2	Engineering	1 330
3	Robotics	1 164
4	Automation control systems	697
5	Telecommunications	440
6	Instruments instrumentation	310
7	Chemistry	194
8	Mathematics	157
9	Physics	146
10	Materials science	98
11	Operations research management science	94
12	Science technology (other topics)	90
13	Transportation	51
14	Mechanics	37
15	Psychology	27
16	Neurosciences neurology	21
17	Construction building technology	13
18	Environmental sciences ecology	12
19	Oceanography	12
20	Social sciences (other topics)	12

4.5 Journals and conferences

By the data analysis, documents on UAV swarms from 2010 to 2020 are mostly published in various journals, and the top 20 journals are listed in Table 7. The most prolific journal is IEEE Access, with 192 works, which contributes the most to research in UAV swarms. The 2020 impact factors of these journals are in the range of 0.796 to 6.725, of which Applied Soft Computing is the highest. According to the analysis of Journal Citation Reports (JCR), Q1 accounted for 35%, Q2 accounted for 35%, Q3 accounted for 15%, and Q4 accounted for 15%. By analyzing the distribution of publication sources, the core journal in this field can be discovered.

Table 7 Journals

Rank	Journal	Document	2020 impact factor	JCR partition
1	IEEE Access	192	3.367	Q2
2	IEEE Robotics and Automation Letters	157	3.741	Q2
3	Robotics and Autonomous Systems	148	3.12	Q2
4	Journal of Intelligent Robotic Systems	136	2.646	Q2
5	IET Control Theory and Applications	125	3.527	Q1
6	Autonomous Robots	115	3.0	Q2
7	Sensors	113	3.576	Q1
8	International Journal of Robotics Research	108	4.703	Q1
9	International Journal of Advanced Robotic Systems	97	1.652	Q4
10	IEEE Transactions on Robotics	76	5.567	Q1
11	Applied Sciences Basel	67	2.679	Q2
12	Robotica	63	2.088	Q3
13	Swarm Intelligence	52	2.143	Q3
14	International Journal of Robotics Automation	40	0.796	Q4
15	Advanced Robotics	34	1.699	Q4
16	IEEE Transactions on Vehicular Technology	34	5.978	Q1
17	Neurocomputing	32	5.719	Q1
18	Applied Soft Computing	29	6.725	Q1
19	International Journal of Control Automation and Systems	26	3.314	Q2
20	Intelligent Service Robotics	25	2.246	Q3

Table 8 lists the top 10 conferences that published the highest number of documents in this field. They have rendered outstanding contributions to the study of UAV swarms. The IEEE International Conference on Robotics and Automation (ICRA) and IEEE International Conference on Intelligent Robots and Systems (IROS) are the top two conferences regarding the number of documents published.

Table 8 Conferences

Rank	Conference	Document
1	IEEE International Conference on Robotics and Automation	547
2	IEEE International Conference on Intelligent Robots and Systems	319
3	Lecture Notes in Computer Science	317
4	Lecture Notes in Artificial Intelligence	274
5	Proceedings of SPIE	147
6	IEEE International Conference on Systems, Man and Cybernetics	137
7	Proceedings of the American Control Conference	126
8	Springer Tracts in Advanced Robotics	115
9	Chinese Control Conference	112
10	IEEE Conference on Decision and Control	109

4.6 Behavior distribution of swarm research

As listed in Table 9, there are 2 160 swarm-related documents found by 18 behavior-related keywords combined with Formula 2. Each behavior-related keyword corresponds to the number and proportion of all documents. It can be seen that the keyword formation has received most of the attention, with 593 documents, accounting for 27.45% of all documents. The second keyword is consensus, with 387 documents, accounting for 17.92% of all documents. These two keywords correspond to nearly half of all documents, and it is obvious that they are mainstream topics of swarm behavior.

Table 9 Behavior distribution with 18 keywords

Behavior	Total		China		USA	
	Document	Proportion/%	Document	Proportion/%	Document	Proportion/%
Formation	593	27.45	248	30.88	96	21.57
Consensus	387	17.92	215	26.77	70	15.73
Coverage	303	14.03	92	11.46	85	19.10
Exploration	272	12.59	40	4.98	62	13.93
Synchronization	141	6.53	70	8.72	27	6.07
Searching	95	4.40	47	5.85	14	3.15
Transport	87	4.03	17	2.12	23	5.17
Aggregation	70	3.24	16	1.99	6	1.35
Self-organization	70	3.24	12	1.49	16	3.60
Rendezvous	40	1.85	13	1.62	10	2.25
Pattern formation	28	1.30	8	1.00	8	1.80
Self-assembly	28	1.30	15	1.87	10	2.25
Patrol	25	1.16	6	0.75	11	2.47
Morphogenesis	16	0.74	2	0.25	7	1.57
Forage	4	0.19	2	0.25	0	0.00
Chain formation	1	0.05	0	0.00	0	0.00
Connected movement	0	0.00	0	0.00	0	0.00
Self-organized construction	0	0.00	0	0.00	0	0.00
Total	2 160	100.00	803	100.00	445	100.00

Similarly, keywords "coverage", "exploration", "synchronization" and "searching", which are also research hotspots, rank from third to sixth. Besides, this paper also puts forward comparisons between China and the USA among these 2 160 documents. It can be observed that the number of Chinese documents is 1.8 times over the number of the USA. Furthermore, from the perspective of specific keywords, Chinese authors pay more attention to formation and consensus, while American authors pay more attention to coverage and exploration.

4.7 Function distribution of swarm research

As shown in Table 10, there are 5 131 swarm-related documents found by 15 function-related keywords combined with Formula 2. It can be observed that the keyword control has received most of the attention, with 1 437 documents, accounting for 28.01% of all documents. This distribution finding is not a surprise as the swarm is highly related to control. The second keyword is communication, with 914 documents, accounting for 17.81% of all documents. The third keyword is planning, with 651 documents, accounting for 12.69% of all documents. These three keywords correspond to more than half of all documents, and it is obvious that they are mainstream topics of the swarm function. Similarly, keywords "tracking", "localization" and "navigation" rank from fourth to sixth, which are also research hotspots. Furthermore, this paper presents a comparison between China and the USA among these 5 131 documents. It can be observed that the authors in China focus more on control and tracking, whereas authors in the USA have more interest in planning and navigation.

Table 10 Function distribution with 15 keywords

Function	Document	Proportion/%	China		USA	
			Document	Proportion/%	Document	Proportion/%
Control	1437	28.01	494	32.33	331	26.95
Communication	914	17.81	307	20.09	212	17.26
Planning	651	12.69	151	9.88	195	15.88
Tracking	499	9.73	224	14.66	81	6.60
Localization	384	7.48	94	6.15	94	7.65
Navigation	339	6.61	47	3.08	75	6.11
Task allocation	244	4.76	68	4.45	66	5.37
Mapping	206	4.01	34	2.23	64	5.21
Surveillance	158	3.08	32	2.09	43	3.50
Monitoring	155	3.02	29	1.90	36	2.93
Security	87	1.70	35	2.29	15	1.22
Fault detection	23	0.45	6	0.39	3	0.24
Target detection	16	0.31	4	0.26	8	0.65
Diagnosis	15	0.29	2	0.13	4	0.33
Risk assessment	3	0.06	1	0.07	1	0.08
Total	5131	100.00	1528	100.00	1228	100.00

4.8 Development tools and region distribution of swarm research

Three keywords related to development tools, namely simulator, language, and platform, are proposed to show the trend of swarms development. As demonstrated in Fig. 10, the number of documents related to the simulator increased rapidly in 2016. From 2018 to 2020, the excessive increase in the number reveals that people emphasize the development of simulators, which also has a promoting effect on the swarm algorithm.

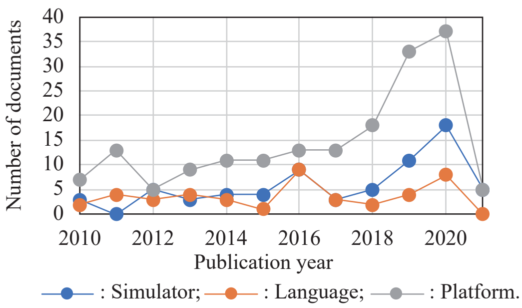

Fig. 10 Number of documents related to the simulator, language, and platform

As shown in Fig. 10, the trend of the keyword "language" is similar to the keyword "simulator," whereas the major variation is that the surge in 2016 is notable. Besides, it should be noted that the total number of documents related to language is the smallest among these three keywords. As illustrated in Fig. 10, the number of documents related to the platform has a surge in 2011 and then increased gradually from 2012 to 2017. From 2018 to 2020, there is a steep rise, showing that authors paid more attention to the development platform. And the total number of documents related to the platform is the largest among these three keywords.

For all documents related to the simulator, language, and platform, 54 countries and regions are involved. In Fig. 11, this paper presents a pie chart to compare countries with more than ten studies. It shows that China and the USA possess the most documents, followed by Spain. Canada and England are tied for the fourth place.

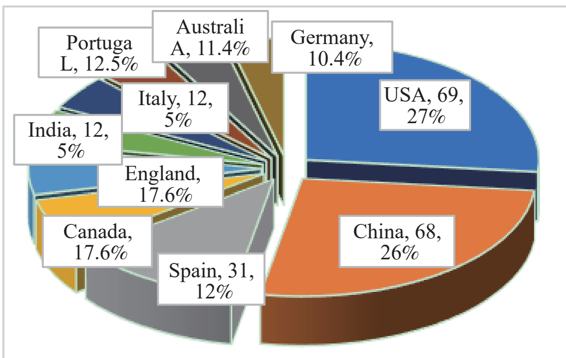

Fig. 11 Region distribution of documents related to the simulator, language, and platform

4.9 Keywords analysis of research hotspots on swarm study

In this part, this paper investigates the content by analyzing the distribution of keywords. A total of 8808 author keywords are involved in 3 358 documents, and 446 met the threshold (the minimum number of documents of a keyword is five). The keywords co-occurrence network is shown in Fig. 12, the network visualization map shows the co-occurrence relations of keywords with a timeline view.

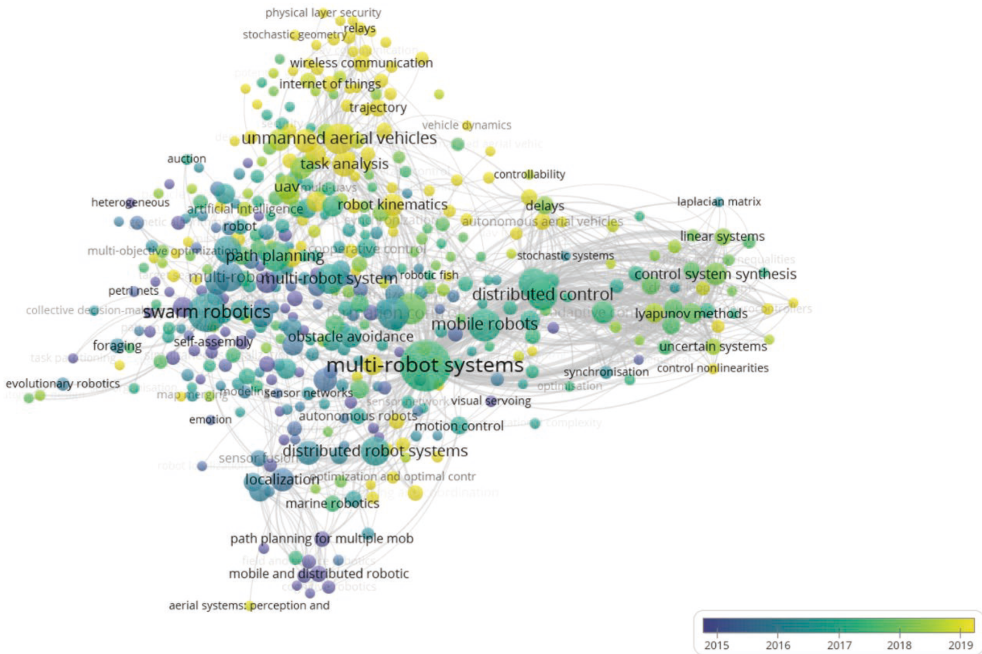

Fig. 12 Keywords co-occurrence network map with a timeline view

In linguistics, co-occurrence is an above-chance frequency of occurrence of two terms from a text corpus alongside each other in a certain order. The size of the circle indicates occurrences of keywords. The color indicates the burst time of keywords. Multi-robot system (systems), swarm robotics, mobile robots, distributed control, UAVs, and distributed robot systems are high-frequency keywords. The average publication year of UAVs is 2019, and then the other keywords are employed sequentially from 2016 to 2018 in this field. According to the statistical analysis of keywords, all keywords can be divided into four categories. Organized in chronological order, the first one is swarm robotics, whose associated keywords are multi-object optimization, genetic algorithm, self-assembly, and so on. This category is primarily concerned with the underlying biological logic of the swarm and does not examine the actual nature of the robot. The second is multi-robot system (system), and the relevant keywords are mobile robots, distributed robot systems, obstacle avoidance, motion control, etc. The robot in this category mostly refers to the unmanned ground vehicle with a single integral dynamic or a unicycle-like dynamic. The third is distributed control, whose associated keywords are Lyapunov methods, control system synthesis, linear systems, and so on. Unlike the first category of swarm robotics, this category mostly concentrates on the control principle behind the swarm behavior. The last one is UAVs, whose associated keywords are wireless communication, internet of things, trajectory, and others. Compared with other vehicles, UAVs in 3D space are more challenging to realize.

4.10 Bursts of keywords citation

Bursts of keywords citation refer to a sharp increase in the citation of a certain keyword. The detection of bursts of keyword citation is an effective analytical method to analyze the emergence of keywords with CiteSpace. This paper presents the top 30 keywords with the strongest citation bursts in Table 11. Self-organization shows the highest burst strength with 7.61. The researchers of self-organization burst in 2010 and continue to 2014, suggesting that it is a hotspot about ten years before. By the network visualization, the topics about UAV swarm, UAV, routing, topology, and sensor will be further strengthened. The data show that the UAV swarm is a hotspot, and many scholars have devoted it to this field in recent years.

Table 11 TOP 30 keywords with strongest citation bursts

Keyword	Strength	Begin	End
Self-organization	7.61	2010	2014
Self-assembly	5.43	2010	2012
Mobile and distributed robotics slam	5.03	2010	2015
Multi-robot	4.83	2010	2012
Cooperative robot	3.81	2010	2012
Field and service robotics	3.46	2010	2012
Robotics	3.37	2010	2016
Motion planning	7.23	2011	2016
Multiple robot	5.32	2011	2014
Modular robot	3.97	2011	2014
Mapping	3.67	2011	2012
Mobile robotics	3.47	2011	2014
Distributed robotics	3.45	2011	2012
Networked robot	6.06	2012	2015
Multi-robot cooperation	4.88	2012	2015
Task allocation	4.35	2012	2013
SLAM	4.03	2012	2013
Simulation	3.95	2012	2013
Communication	3.83	2013	2016
Multi-agent	3.75	2013	2015
Swarm robotics	6.34	2014	2016
Aerial robotics	3.45	2014	2018
Formation control	5.15	2015	2016
Quadrotor	4.06	2015	2017
Multiagent system	4.63	2017	2018
UAV swarm	4.18	2018	2021
UAV	7.46	2019	2021
Routing	4.1	2019	2021
Topology	3.85	2019	2021
Sensor	3.59	2019	2021

4.11 Co-citation cluster analysis

The accurate capture of citation clusters depends on whether the cluster map drawn by CiteSpace is aesthetic and reasonable. Two indexes are proposed based on the structure of the network and the sharpness of the cluster: modularity Q (MQ) and mean silhouette (MS). These two indexes provide a foundation to evaluate the effect of clustering mapping. Generally, when MQ is greater than 0.3, it implies that the cluster structure is significant. When MS is greater than 0.5, the cluster is considered reasonable [29]; hence the cluster map needs to be drawn multiple times with different thresholds until the MQ and MS attain the ideal level. As shown in Fig. 13, the swarm knowledge domain is divided into 14 clusters with MQ = 0.771 and MS = 0.921 8. The parameters of 14 clusters are listed in Table 12. Although the swarm knowledge communities are sorted by the cluster size, this paper uses the time trend of the evolution to integrate different clusters and reveal the historical track of swarm research. Therefore, the average year of 2016 is considered according to Fig. 3. It is found that, before 2016, studies are mostly with pure academic research that established a theoretical framework. Since 2016, scholars have been focusing on the practical usage of the UAV swarm because numerous key projects have provided support since 2015, as indicated in Fig. 1.

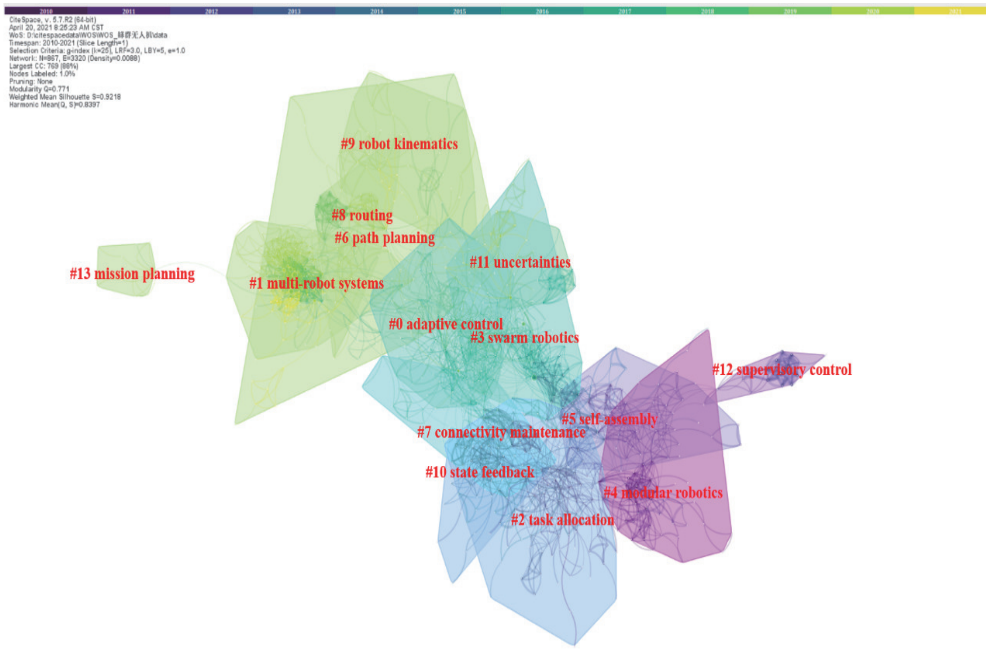

Fig. 13 Cluster visualization mapping of co-citation network about the swarm

Table 12 TOP 30 keywords with strongest citation bursts

Cluster ID	Size	Silhouette	Average/year	Cluster ID	Size	Silhouette	Average/year
#0(C0)	112	0.829	2014	#7(C7)	47	0.92	2011
#1(C1)	110	0.926	2017	#8(C8)	33	0.992	2016
#2(C2)	106	0.909	2009	#9(C9)	30	0.986	2016
#3(C3)	74	0.914	2013	#10(C10)	26	0.97	2010
#4(C4)	60	0.979	2006	#11(C11)	20	0.972	2014
#5(C5)	60	0.882	2008	#12(C12)	17	0.982	2008
#6(C6)	50	0.953	2016	#13(C13)	11	1	2017

First, this paper analyzes the clusters with the average year before 2016, as shown in Fig. 14.

C4 (modular robotics) is the earliest cluster in the research field of the swarm, which can also be regarded as the fundamental research of the swarm. This cluster forms the intellectual bases of the research fronts of the consensus algorithm, multi-robot coordination control, and others. The size of this cluster is 60, and three top-cited references are [30–32], which provide a theoretical framework for the analysis of consensus algorithms for multi-agent networked systems.

C5 (self-assembly) comprises 60 studies with the average year of 2008. This cluster forms the intellectual bases of the research fronts of bio-inspired, coordination, and optimization. The three top-cited references are [33–35].

C2 (task allocation) comprises 106 works with the average year of 2009. This cluster forms the intellectual bases of the research fronts of formation control and task assignment. The three top-cited references are [36–38]. Furthermore, representative citing studies included [39,40].

C7 (connectivity maintenance) comprises 47 investigations with the average year of 2011. This cluster forms the intellectual bases of the research fronts of metaheuristics, GPS-denied, global connectivity, and local connectivity. References [41–43] are the three top-cited works.

C3 (swarm robotics) comprises 74 works and has the average year of 2013. This cluster forms the intellectual bases of the research fronts of reinforcement, study, and learning. References [44–46] are the three most-cited works.

C0 (adaptive control) is the largest cluster in the research field of swarm with 112 works. The average year of this cluster is 2014. This cluster forms the intellectual bases of the research fronts of the adaptive cruise and Lyapunov method. References [47–49] are the three most-cited works.

Then, this paper analyzes the clusters with the average year since 2016.

C6 (path planning) comprises 50 studies with the average year of 2016. This cluster forms the intellectual bases of the research fronts of ad-hoc, semi-autonomous, and surveillance. This cluster is related closely to the practical use of the UAV swarm. References [50–52] are the three top-cited works.

C8 (routing) comprises 33 studies with the average year of 2016. This cluster forms the intellectual bases of the research fronts of metaheuristics, genetic algorithm, and swarm optimization. References [53–55] are the three top-cited works.

C1 (multi-robot systems) comprises 110 works with the average year of 2017. This cluster forms the intellectual bases of the research fronts of the communication network. The three top-cited references are [56–58].

C9, C10, C11, C12, and C13 are the smallest clusters. Each of them comprises less than 30 members which makes it unstable to interpret.

The reasons why there exist a remarkable difference around 2015 are stated as follows: Before 2016, people concentrated more on the theoretical framework of the UAV swarm research. Since 2016, in the wake of the developments in science and technology, many vital projects make scholars pay more attention to the practical usage of the UAV swarm. Therefore, with the maturity of simultaneous localization and mapping, the topics relate to the occupancy grid map attract attention, such as path planning and routing, which are also the foundations of real outdoor experiments.

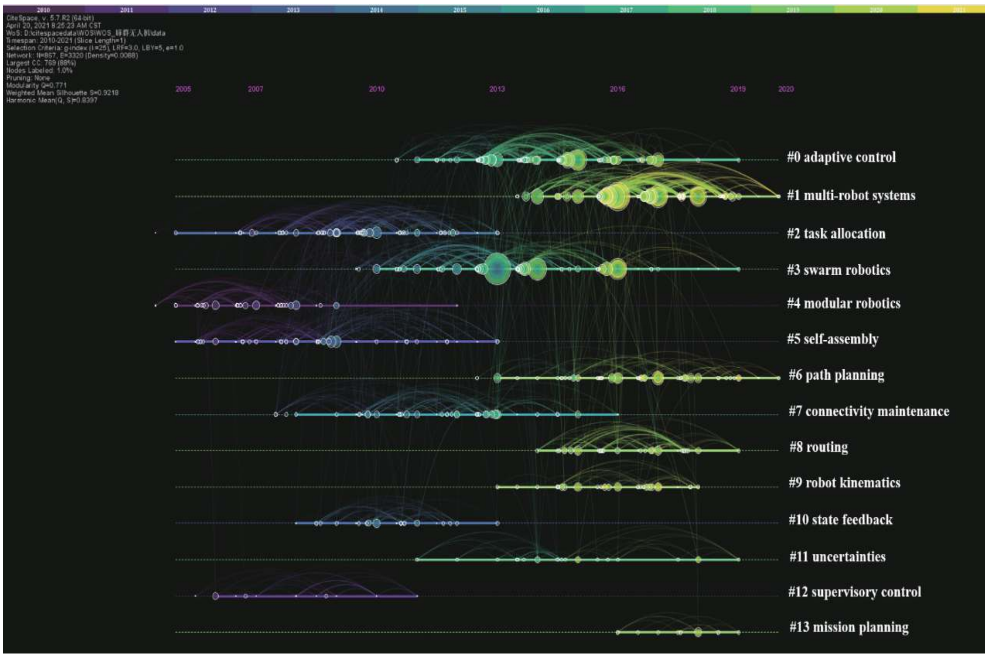

Fig. 14 Timeline visualization mapping of co-citation network about the swarm

5. Conclusions

This paper concludes by responding to the three questions raised earlier.

(i) What are the disciplines mentioned in the UAV swarms research?

UAVs research involves computer science, engineering, robotics, mathematics, physics, chemistry, and many other disciplines (Subsection 4.4). Among them, mathematics, physics, chemistry, and other basic disciplines provide an innovative and complete theoretical basis for UAV research, whereas computer science, engineering, robotics, and other applicable disciplines apply the theory to practice and are committed to achieving accurate, fast, and reliable control. In conclusion, all disciplines support each other and jointly promote the further development of UAV research.

(ii) What are the future development trends and hotspots in the UAV swarms research?

First, keywords in Subsection 4.6–Subsection 4.7 can help us to determine the trends and hotspots of swarm robotics, including UAVs. In addition, this paper reviews recent publications [45,59–66] appearing on Nature and Science, from which some latest frontier, especially on swarm robotics including UAVs can be found. To some extent, making the UAV swarm handle a task in a co-ordinated and cooperative manner is still a hurdle to some extent [59]. Besides, as stated in [59,60], the design of swarm systems cannot be completed by conventional approaches. These papers also illustrated the hypotheses, characteristics, and core challenges of semi-automatic and automatic design. Furthermore, much research focuses on collective behavior. In [61], physicists sought to investigate the essence of the living world, such as smart swarms, as active matter. The work [62] investigated the collective motion in geometrical disorder, whereas the work [63] investigated the influence of the network topology on a collective response. The work [64] proposed a novel vision-based model and a mathematical framework for collective behavior. Studies [45,65–66] focused on collective abilities, such as collective robotic construction, task sequencing, and programmable self-assembly.

Furthermore, the UAV swarm, which is a special type of swarm robotics, is the hotspot. This can be observed by the tread of publication (Subsection 4.1) and development tools (Subsection 4.8). Some of the civil applications include precision agriculture [67], infrastructure inspection and maintenance [68], and planet exploration missions [69]. Some of the military applications include that non-combat unmanned drones cooperatively accomplish information gathering and mission support actions. UAV swarms have been given much support, as indicated in Table 1, since they are useful in the military. However, UAVs also received a lot of attention in academia in recent years: i) UAV as a single keyword receives much attention (Subsection 4.9). ii) By bursts of keyword citation (Subsection 4.10), data show that UAV swarm is increasingly gaining citation in the last few years. iii) Since 2016, a cluster on path planning appears, which has a close connection to the practical use of the UAV swarm (Subsection 4.11). Finally, a higher-level swarm intelligence should be realized in the UAV swarm. That is, UAV swarms should have the ability to learn an appropriate collective behavior autonomously for a given type of challenge. The technological progress of the UAV swarm has brought a more extensive practical use.

In order to leap real-world applications more, UAV swarms are expected to be more and more robust, flexible, and scalable. So far, there have been many open challenges to face but not limited to:

i) Accurate, fast and reliable perception. To solve this, we first should figure out what is needed to be perceived, at least when performing a task, such as optical flow, target identification, visual tracking, or image understanding. Secondly, accurate, fast and reliable perception algorithms are needed to perform the lightweight calculation. On the other hand, an appropriate perception device will help to achieve such a purpose easier, such as event cameras[70] and compound eye cameras[71]. Furthermore, the mentioned perception also includes the systems' health assessment, which is also a big challenge.

ii) Accurate and robust control. As pointed out in [72], the challenge depends on the complexity of the interdependencies among the swarm vehicle dynamics, various uncertainties (including unmodeled dynamics uncertainties, environmental uncertainties, communication uncertainties, and perception uncertainties), and control methods employed. Because of these, some learning methods are utilized directly. How to make the learning fast and safe is a further challenge because the experiments are often performed at a high cost in practice.

iii) Optimal, autonomous, and resilient decision. One of the biggest challenges is to make a forward design for each UAV to drive the swarm to perform a complex task optimally, autonomously, and resiliently. It is challenging, especially because many biological swarms in nature work GPS-denied and data-link-communication-denied environment.

More open challenges can also be found in [14,59,72–74].

(iii) How to track related outcomes in the UAV swarms research?

At least three ways, namely keyword, publication, and organization, can be employed to track the related research.

i) Keyword. In addition to data collection according to basic keywords (Subsection 3.3), further retrieval can be performed by basic keyword + behavior (Subsection 4.6), basic keyword + function (Subsection 4.7), and basic keyword + tool (Subsection 4.8). More keywords can further be found in the keywords co-occurrence network map (Subsection 4.9), citation bursts (Subsection 4.10), and co-citation cluster (Subsection 4.11).

ii) Publication. The journals and conferences available can be utilized to keep track of publications (Subsection 4.5). Generally, conferences are more real-time and updated more frequently.

iii) Organization. Information can be further mined by tracking the works of an organization and the cooperation between organizations (Subsections 4.3). Some labs and groups can be further positioned to track related outcomes in the swarm UAVs.

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Biographies

JIANG Yangyang was born in 1989. She received her B.E. degree from Northeastern University, Shenyang, China, in 2011, and M.S. degree from Beihang University, Beijing, China, in 2014. She is currently a librarian at Beihang University Library. Her research interests include swarm intelligence and information science & library science.

E-mail: yangyang@buaa.edu.cn

GAO Yan was born in 1994. He received his B.S. degree in control science and engineering from Harbin Institute of Technology, Harbin, China, in 2017. He is working toward his Ph.D. degree at the School of Automation Science and Electrical Engineering, Beihang University, Beijing, China. His main research interests include UAVs swarm and quadcopter control.

E-mail: buaa_gaoyan@buaa.edu.cn

SONG Wenqi was born in 1999. She received her B.S. degree in control science and engineering from Beihang University, Beijing, China, in 2021. She is working toward her M.S. degree at the School of Automation Science and Electrical Engineering, Beihang University, Beijing, China. Her main research interests include planning and control of UAV swarms and air traffic flow.

E-mail: jnswqno1@163.com

LI Yue was born in 2000. She received her B.S. degree in control science and engineering from Beihang University, Beijing, China, in 2021. She is working toward her M.S. degree at the School of Automation Science and Electrical Engineering, Beihang University, Beijing, China. Her main research interests include reliable flight control and swarm.

E-mail: liyue9556@buaa.edu.cn

QUAN Quan was born in 1981. He received his B.S. and Ph.D. degrees in control science and engineering from Beihang University, Beijing, China, in 2004, and 2010, respectively. Since 2013, he has been an associate professor with Beihang University in control science and engineering, where he is currently with the School of Automation Science and Electrical Engineering. His research interests include reliable flight control, swarm intelligence, vision-based navigation and health evaluation.

E-mail: qq_buaa@buaa.edu.cn