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Communication Among Heterogeneous Unmanned Aerial Vehicles (UAVs): Classification, Trends, and Analysis

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ABSTRACT In the past decade, unmanned aerial vehicles (UAVs) have become a major research topic in robotics, despite their existence since 1915. UAVs can perform various activities efficiently and effectively; therefore, involving a group of UAVs in performing a certain task has become a growing research trend. Research involving multiple UAVs has been carried out in various areas such as force protection, warfare in the military, remote sensing, disaster response activities, and surveillance. While performing critical tasks, efficiency and robustness are important considerations that can be achieved by involving heterogeneous UAV teams with effective communication and coordination techniques. Communication among heterogeneous UAVs is an interesting and critical research area that needs to be thoroughly explored. In this research, an evidence-based approach is adopted to explore research carried out on multiple heterogeneous UAVs and their communication patterns while performing various activities. A mapping study research technique is employed to systematically collect, analyze, and assess the evidence available on the topic under discussion. The time period defined for this study was set from 2005 to 2019, and 46 primary studies were considered for thematic analysis. The findings show that research studies fall under the category of validation research by constructing simulations to provide a proof-of-concept implementation of the proposed solutions. The communication patterns among heterogeneous UAVs involve various components of UAV communication, networking, formation, and path planning. The application areas that were largely focused on were search, rescue, monitoring, and surveillance missions. The overall trend showed that interest in multiple heterogeneous UAV usage increases over time with a focus on UAV networks, formations, and path planning while considering communication as an implicit part of all these structures. This research has conducted an in-depth analysis of existing research on heterogeneous UAVs and provides classification and trends of various themes emerging within this research area.

INDEX TERMS Aerial robots, communication, classification, heterogeneous UAVs, mapping study, unmanned aerial vehicles (UAVs).

I. INTRODUCTION

Unmanned aerial vehicles (UAVs), also known as drones, have increasingly been employed to perform mission-critical activities worldwide over the past few decades. In earlier years, UAVs were solely used for military purposes, from world wars to cold wars, and for various surveillance missions. However, the use of UAVs for non-military activities started to emerge in 2006 when the Federal Aviation Administration (FAA) allowed the use of UAVs for commercial purposes with proper regulatory measures [1]. Initially, UAVs were operated with the support of human interaction, and later with advancements in technology, they were capable of working autonomously. In the past few years, the utilization of UAVs has increased in various military and civilian sectors, which have further encouraged the research community to conduct experiments and propose solutions. UAVs are largely used for monitoring missions such as prevention of illegal

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activities, detection of forest fires [2], surveillance and monitoring of borders [3], sensitive or isolated areas [4], and marines and pipelines [5]. In these missions and activities, multiple UAVs are used to perform tasks in coordination to overcome the limitations of a single UAV [6]. Multiple UAVs working in collaboration offer various advantages [7] which include scalability, survivability, speed, and robustness. Further, working in parallel, UAVs can increase efficiency and decrease the time required to complete a mission or task [8].

Multiple UAV teams can be homogeneous (with the same capabilities) or heterogeneous (different capabilities). Homogeneous UAVs are robust; however, they are not favorable in scenarios where different tasks with varied capabilities are involved, such as flying at different speeds, covering different surfaces, and scanning areas of different sizes [9]. In [10], an experiment was conducted to compare the performance of homogeneous UAVs with heterogeneous UAVs, and concluded that in a heterogeneous system, both slow and fast UAV swarm agents performed better than homogeneous UAVs. Heterogeneous UAVs are more robust with high speeds and a higher collision avoidance range. The heterogeneity in UAVs exploits various characteristics of different types of UAVs with different hardware, storage capacity, speed, data collection capabilities, onboard payloads, and information processing capabilities [11], [12].

Multiple heterogeneous UAVs working as teams require effective cooperation and communication with each other to complete a critical task successfully. Despite the fact that most of the research on coordination of multiple UAVs used homogeneous teams of UAVs, coordination of multiple heterogeneous UAVs still offers more benefits owing to the exploitation of various capabilities of vehicles with different sensors and mobility features [11]. In real-time coordination and control of multiple heterogeneous UAVs, various features such as different types of wireless or wired links, processors, and operating systems are used to perform crucial tasks [11]. Such heterogeneity in multiple UAVs can increase complexity and pose significant challenges. Therefore, communication among multiple heterogeneous UAVs during mission-critical activities is a significant and challenging research area that needs to be thoroughly explored.

Various studies have been conducted to discuss the different aspects of communication and collaboration among UAVs. During surveillance and monitoring missions [13], [14], the team of UAVs communicates with each other to share information and perform the assigned task efficiently and effectively. The team of UAVs must maintain a resilient communication network among themselves to avoid the loss of critical information. Such resilient communication networks require various communication techniques, including communication modes, protocols, networks, and technologies. In existing studies, research is being conducted by employing various communication techniques for heterogeneous UAVs, including decentralized peer-to-peer networks [15], delay tolerant network (DTN) architecture [16], and mobile ad hoc network (MANET) [12]. Apart from these technologies, wireless communication techniques such as Wi-Fi [17], cellular networks [18], and radio [19] are also exploited. For communication modes, one-to-one [13] and bidirectional [20] modes of communication are commonly used. Network topologies such as line [18], mesh [21], relay network [22], and IEEE wireless/protocol, that is, 802.11 [12] and MAC [23] protocols, are mostly adopted by studies. Further, for communication between heterogeneous UAVs, other communication techniques including line of sight (LOS) propagation mode [24], asynchronous transmission mode [25], wireless networks, that is, Bluetooth Low Energy (BLE) [21], and technologies, that is, ultra-wide band (UWB) [26], etc., are used.

In 2015, a survey was conducted to highlight the issues involved in UAV communication [6]. The study discussed the issues and challenges of UAV networks, including a comparative analysis of different UAV networks based on features such as mobility, topology, and energy constraints. The study also compared the features of single-and multi-UAV networks. In another study [12], a classification of UAV communication and networking architectures was discussed along with various protocols and technologies. A comprehensive study by [27] discussed the use of UAVs in wireless networks. The survey discussed UAV applications, key challenges (including techniques and tools), and fundamental open problems faced by UAV-enabled wireless networks. In the latest study by Oubbati *et al.* [28], UAV network architectures were focused on software-defined network (SDN) and network function virtualization (NFV). The study was categorized into eight main sections: classification, architectures, tools, issues, and challenges. In 2020, a study [29] on UAV assistance discussed UAV assistance applications and categorized them into nine use cases that involved UAV-UGV coordination, UAV routing, UAV data gathering, monitoring, etc. The study also discussed enabling technologies and the different challenges of the UAV assistance paradigm. All these studies discussed various aspects of research conducted on UAVs, including communication architectures, network issues, UAV-assisted systems, SDN, and NFV-based UAV networks. However, these studies have largely focused on general UAVs. They lack discussion on the challenges and opportunities associated with multiple heterogeneous UAV teams, their formations, coordination patterns, networks, and communication requirements. Only a few studies have mentioned heterogeneous networks without any detail and relevance to UAVs and their team formation.

Despite the efforts made by primary studies to address communication and coordination among multiple heterogeneous UAVs, research in this area is still emerging and is at an early stage. The studies conducted in this area lack explicit details and discussions on communication and coordination among multiple heterogeneous UAVs. Instead of considering this as the main focus of research, studies embed communication in the overall research context, which broadly involves multiple UAV path planning [30], UAV formation patterns [15], navigation, and control [17]. Path planning

mostly includes coverage path planning (CPP) by multiple UAVs, whereas UAV formation patterns include flight formation [15], coalition formation [31], and relay UAVs [32]. Further, communication patterns employed by these studies are largely ad hoc and discussed at an abstract level, which makes it difficult to assess the effectiveness of these solutions. In this research, efforts are made to conduct an in-depth analysis of research conducted on heterogeneous UAVs with a particular focus on communication and coordination patterns employed in research studies. A mapping study research technique [33] is employed to systematically evaluate the evidence available on a research topic and facilitate the identification of patterns and clusters of themes, critically analyze research techniques, identify research gaps, and derive future research trends.

The remainder of this paper is structured as follows: In Section II, the research process defined to conduct this study is explained. In Section III, the analysis and findings are presented. In Section IV, threats to validity are addressed. In Section V, a discussion and conclusion are presented. Finally, in Section VI, challenges and future directions are drawn from this research are provided.

II. RESEARCH METHOD

Evidence-based software engineering (EBSE) [34] is the concept that focuses on collecting evidence to make decisions in the area(s) of software engineering. EBSE provides techniques to systematically analyze and evaluate the evidence available on a given topic by conducting a systematic literature review (SLR), mapping study, and tertiary reviews [35]. Systematic literature reviews (SLR) [36] aimed to summarize research studies related to a specific research question in a fair and accurate way. A tertiary review [37] was conducted to analyze SLRs of secondary studies to evaluate how many SLRs have been published on a topic or phenomena, their strengths and limitations, and gaps in secondary studies where further SLRs are required. However, a mapping study (also known as scoping study) [38] is a secondary study that investigates evidence in wider research areas and provides a thorough analysis of micro-level trends within a research area by forming clusters and identifying gaps where further research is required [22]. A mapping study is a type of SLR that focuses on broader topics where little evidence is available in contrast to SLR, which is conducted on specific and narrow research topics with well-defined research questions.

In this research, a mapping study approach is employed to identify, analyze, and evaluate the evidence available on the topic of communication among heterogeneous UAVs. Since the topic is quite broad and diverse in nature, and requires careful evaluation of primary studies, the guidelines provided by Kitchenham and Charters [33] are used to structure and plan mapping study protocols. The protocol includes careful planning of the various components of the mapping study process. The process consists of five phases: setting research questions, designing a search strategy, defining selection criteria for primary studies, extracting data, and providing synthesis. Each phase of the mapping study process involves a set of activities defined by analysts in various iterations and is recorded in the form of a protocol. The details of the mapping study process are presented in FIGURE 1.

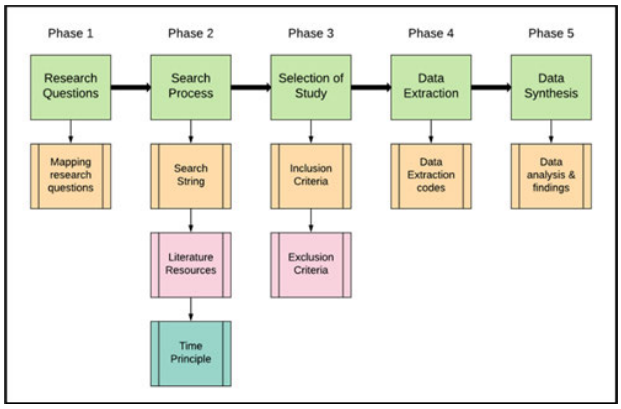

FIGURE 1. Mapping study process.

The process is initiated by defining research questions that also set the objectives of this study. In the second phase, three major activities are performed: defining the search string, selecting digital databases, and defining the time period. These activities are critical in nature, and require proper planning and extensive discussions among analysts. In the third phase, the criteria for inclusion and exclusion of primary studies were defined. Phase four involves defining data codes that facilitate the extraction of the required information from primary studies; in Phase five, data synthesis is carried out with respect to the research questions raised in phase one. In the following sections, these phases are discussed in detail.

A. PHASE 1: RESEARCH QUESTIONS

In phase 1, the research questions were designed to critically evaluate the evidence available on the topic under discussion. The research questions used in this study are as follows.

RQ1. What publication trend exists on the topic of communication among aerial robots?

RQ2. What are the publication venues used by primary studies?

RQ3. Which are the countries contributing the most to this area of research?

RQ4. How far are primary studies sponsored to conduct research in this area?

RQ5. What are the various research themes being discussed by primary studies?

RQ6. What are the domains and disciplines being focused on in primary studies?

RQ7. The classification of research techniques according to Radhakrishnan and Saripalli [24] classification.

RQ8. What are the research methods being employed by primary studies?

RQ9. What are the implementation technologies used by primary studies?

RQ10. What are the types of aerial robots used in proposed solutions?

RQ11. How various roles are defined for coordination and communication among aerial robots?

RQ12. What different types of communication techniques are being proposed by primary studies?

RQ13. How diverse communication context is being used in primary studies?

RQ14. What type of information is shared among aerial robots during their communication with each other?

RQ15. How far proposed solutions are being evaluated and discussed in primary studies?

RQ16. What are the challenges and future directions of this research?

To address these questions, a search process was designed in the second phase, as discussed below.

B. PHASE 2: SEARCH PROCESS

The search process is an important phase in mapping studies and is performed in iterations. Each iteration is followed by a rigorous discussion among analysts to address agreements/disagreements. For this study, to set the search criteria, the Population, Intervention, Comparison, Outcome (PICO) model [39], which is defined as

- **Population of Interest**: Primary studies discussing communication among heterogeneous aerial robots.
- **Intervention:** Primary studies explicitly discussed communication among heterogeneous aerial robots.
- **Comparison:** There was no alternative to compare the intervention.
- **Outcomes:** A set of primary studies relevant to research on communication among heterogeneous aerial robots

a) **Search string:** The search string is defined through an iterative search of digital databases to identify relevant studies. In this phase, analysts worked independently to perform searches using various search strings. The selected strings were compared, and conflicts were resolved through discussion. The prototyping of the search string is a key component in finding relevant studies and finalizing the search string. The use of terms such as communication and coordination created confusion, as primary studies used them sloppily. However, after careful analysis of primary studies and the way these terms were used by the research community, the final search string was constructed as: ''Communication between aerial robots OR Communication between heterogeneous robots.'' The search string was kept broad enough to access representative studies and not skip any. The use of the string ''heterogeneous aerial robot'' was not enough as in many studies the word ''heterogeneous'' was not included despite the research on heterogeneous aerial robots. Furthermore, in some studies, the term ''aerial robots'' was not used, although the study focused on aerial robots. Therefore, a broader term ''robot'' was also added in the second part of the search string. To address the threat associated with the coverage of the search space is an important factor that needs to be addressed while defining the search string.

TABLE 1. Search strings.

Initial String 1	"Communication between robots"
Initial String 2	"Communication between heterogeneous aerial robots"
Final String	"Communication between aerial robots OR Communication between heterogeneous robots"

TABLE 2. Inclusion and exclusion criteria.

Inclusion Criteria	• Primary studies must be published in Journals or Conferences. • Primary studies must contain search string in Abstract, Title, and Keywords. • Primary studies must be written in the English Language. • Primary studies containing related words such as 'UAVs', 'Aerial Robots', 'Multi-Aerial robots', 'Heterogeneous UAVs or Aerial Robots' and communication methods or techniques.
Exclusion Criteria	• Primary studies that appear in more than one database. • Primary studies with less than 5 pages. • Studies such as workshop editorials, advanced abstracts, magazines, etc. • Studies that are written in languages other than English.

b) **Time Principle:** Due to the advanced nature of the research area, the time selected for the search was set from 2005, since during this year UAVs were used for commercial purposes other than military usage. In 2005, the FAA issued guidelines for the domestic and commercial use of UAVs [40]. The complete time period used in this research was from 2005-to-2019. The search was conducted in 2020.

c) **Selection of Digital Databases:** Various electronic sources are required to search for primary studies because no single source can provide all relevant studies [41]. Therefore, to perform an exhaustive search, three digital databases were selected to collect the data. These databases include the IEEE Xplore Digital Library, Science Direct, and ACM Digital Library. These are well-reputed databases within the computer science discipline and have broad readership. Further, studies published in these databases are peer-reviewed, which facilitates the maintenance of quality in primary studies.

C. PHASE 3: SELECTION OF PRIMARY STUDIES

To select the primary studies, the final search string was applied in selected databases using their advanced search

interfaces. The studies were downloaded separately in their relevant folders, and inclusion and exclusion criteria were applied. The inclusion and exclusion criteria defined in this study are provided in TABLE 2.

- **Search:** A total of 566 studies were identified by applying a search string to all selected digital databases. Studies in which search strings appeared in titles, keywords, and abstracts were selected for screening.
- **Screening**: In this step, studies were excluded on the basis of repetition, short papers, other languages, articles, keynotes, etc.
  - **Repetition:** Studies that appeared in more than one database due to indexing were considered once, and repetition was removed. This reduced the total number from 566 to 551.
  - **Short Papers:** Studies with a length of four pages or less were excluded, reducing the dataset to 513. Thirty-eight studies were excluded at this stage.
  - **Other languages:** Papers published in languages other than English were also excluded. These studies were published in Spanish, Latin, Turkish, and Chinese languages. Seven studies were removed at this stage.
  - **Articles, Surveys, Workshops, etc.:** Publications that fall under the category of magazines, presentations, chapters, and reports were excluded. This reduced the dataset to 496 studies.
- **Eligibility:** To apply eligibility criteria, the titles, abstracts, and full texts of 496 primary studies were analyzed.
  - **Exclusion on basis of Title & Abstract:** Studies that do not have terms such as 'UAVs', 'Aerial Robots', 'Multi Aerial Robots', 'Heterogeneous UAVs/Aerial Robots' and studies with no discussion on communication were excluded. A total of 136 studies were excluded at this stage, which reduced the dataset to 360 primary studies.
  - **Full Text Analysis:** The full text of the remaining 360 primary studies was analyzed carefully to identify their relevance. During this phase, two independent analysts performed these tasks, and later results were combined, and verification was carried out by two more analysts. Conflicts were resolved through discussions among all analysts. This further reduced the dataset to 43 primary studies. Studies that did not discuss communication between multiple aerial robots or communication between heterogeneous UAVs were excluded. For example, the design architecture of a single UAV [42] was not included, as it only discussed a single UAV. Communication between swarm UAVs [43] was excluded because the swarms were mostly homogeneous UAVs. Flight formations of UAVs were also not included because flight formations only discuss the maintenance and design of UAVs. Similarly, studies that focused only on communication with ground stations [44] without discussion on communication among UAVs were excluded, which further reduced the dataset.
- The final set of 43 primary studies was included for data extraction and analysis.

D. PHASE 4: DATA EXTRACTION

The selected primary studies were examined, and data were extracted according to the codes defined in TABLE 3. The extracted data were tabulated in the spreadsheets. A unique study ID consisting of the author's name and year of publication was assigned to each primary study. During extraction and recording, notes were taken and discussions were carried out among analysts. Data were extracted in three iterations to ensure consistency and to include relevant information.

E. PHASE 5: ANALYSIS AND FINDINGS

To analyze the primary studies, "*thematic analysis*" was carried out to identify patterns in the extracted data. Thematic analysis is a method for analyzing and identifying patterns in qualitative data [46] and examines explicit and implicit meanings within the data [47]. In this study, thematic data were used to address the research questions raised in Section III of Analysis and Findings.

III. ANALYSIS AND FINDINGS

A. RQ1. PUBLICATION TREND

To identify trends in publications over the years, the studies were analyzed according to their year of publication. Studies on this topic began to emerge in 2008. In FIGURE 3, the frequency of published studies from 2008 to 2019 is shown. It was interesting to find that in 2006, the FAA issued the first commercial drone permit, and agencies started using multiple UAVs for non-military purposes such as surveillance, wildfire fighting, spraying pesticides, etc. In the following years, research activities increased, and an increased number of publications in this area were found.

The graph provides a rise and fall in the number of publications over the years. There was an initial rise in 2013 because of the UAV's popularity in public and the involvement of large companies such as Amazon, which announced in 2013 that the company was considering the use of drones as a delivery method. Further, the FAA issued a large number of drone permits in 2015 for commercial purposes, such as videography, camera shots, and other general uses. However, there was a major downfall in 2016 when UAVs were banned in many countries due to a few accidents [48]. Despite this, the popularity and research on UAVs increased again in 2018. According to the FAA Aerospace Forecast, in 2018, the U.S. and global economies saw solid growth in the drone industry, which will continue to grow in the upcoming decade [49]. A large number of studies on UAVs were found during this research; however, they fall short due to the irrelevance of the topic under discussion.

TABLE 3. Data codes for extraction.

Data Codes	Description
Study ID (Author Name, Year)	Paper id of primary study will be set by last author name with year of publication
Paper Type	Type of publication i.e., Journal or Conference
Journal /Conference	Name of the Journal, and conference
Country	Countries that are focusing more on this research
Funded Papers	Information about funding given to research published
Research method	Models, conceptual framework, case study, prototype, experiment, simulation, scenario, architecture etc. proposed by authors
Wieringa et al., [46] Classification	Proposed solution, Evaluation, Validation, Opinion, Philosophical and Personal experience papers
Research Area	Research topic of primary study and much broader than a research topic
Domain Area	Domain areas are general areas that cover all aspects of primary study areas & targeted by research.
Implementation Technology	Implementation technology includes the tools and techniques used for implementation
UAVs	Types of Aerial robots that are used
Functionality (Autonomous/ Semi-Autonomous)	Functionality of robot that is either fully autonomous or controlled by controlled unit
Capability (Heterogeneous/ Homogeneous/ Swarm)	Capabilities of robots i.e., heterogeneous, homogeneous or swarm that exists
Roles of Robots	Roles or tasks of robots that were assigned to them
Quantity of Robots	Number of robots that are used for implementation
Information Shared	Type of information shared between robots
Algorithm	Different coverage, path planning, patrolling and coordination algorithms
Communication technology & Techniques	Communication technology and techniques used for multiple robot's communication
Protocol/ topology and Bandwidth	All the protocols, bandwidth, topologies
Performance Metrics	Standards for performance evaluation

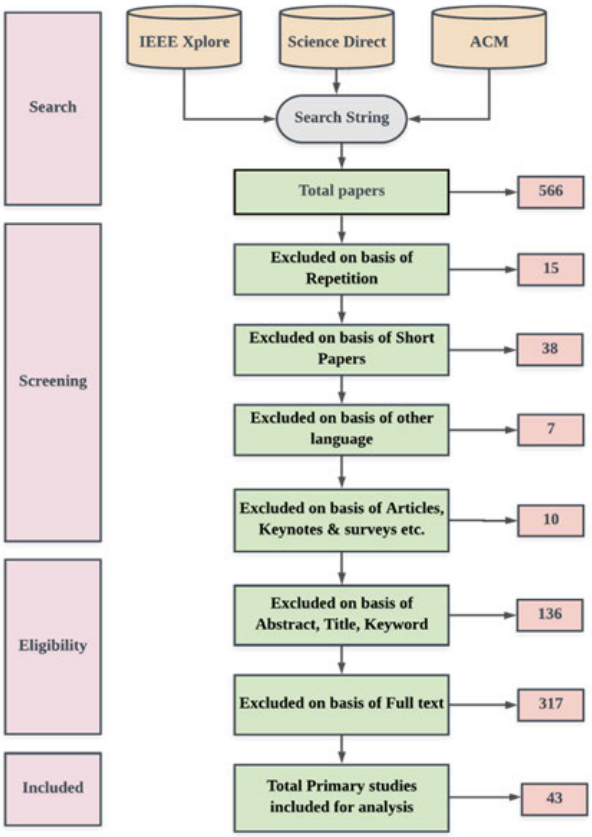

FIGURE 2. Selection of primary studies.

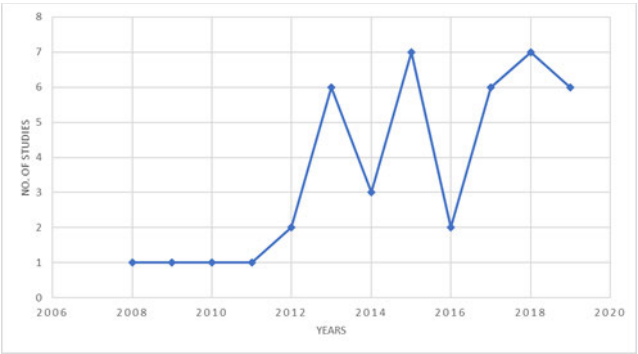

FIGURE 3. Number of publications per year.

B. RQ2. PUBLICATION VENUES

To address RQ2, the published venues of the primary studies were analyzed and recorded separately for conferences and journals. Out of forty-three publications, thirty-one were published in conferences and 12 were published in the journal. This was an interesting finding, and one reason for this was the publication time required by conferences and journals. The conferences take relatively less time, open opportunities for networking and discussion, and provide rapid publication. Further, parallel development and research on the same areas have also made researchers publish their research results through conferences and access rapid feedback. Therefore, a similar pattern was observed in the analysis of the primary studies. The details of the conferences and journals where primary studies were published are provided in TABLE 4 and TABLE 5.

In the case of conferences, the International Conference on Unmanned Aircraft Systems (ICUAS) was largely considered by primary studies. ICUAS has been considered a pioneer in organizing symposiums on UAVs over the past decade [50]. The IEEE International Conference on Robotics and Automation (ICRA) and IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) were also used to publish the research. Both are well-known conferences with a high worldwide ranking.

TABLE 4. Conferences where primary studies were published.

Conferences	Primary Studies
International Conference on Unmanned Aircraft Systems (ICUAS)	********** ***
IEEE International Conference on Robotics and Automation (ICRA)	********
IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)	******
Mediterranean Conference on Control and Automation	**
Proceedings of the IEEE/SICE International Symposium on System Integration	**
Proceedings of the Chinese Control Conference	**
American Control Conference (ACC)	**
IEEE Military Communications Conference	**
IEEE Conference on Local Computer Networks	**
IEEE International Conference on Mechatronics and Automation	**
IEEE ICC - Ad-Hoc and Sensor Networking Symposium	**
International Conference on Its Telecommunications	**

TABLE 5. Journals where primary studies were published.

Journal	Primary Studies
Journal of Intelligent and Robotic Systems	****
IEEE Access	****
IEEE Transactions on Robotics	**
Robotics and Autonomous Systems	**
IEEE Transactions on Automation Science and Engineering	**
IEEE Transactions on Vehicular Technology	**

TABLE 6. Funding bodies contributed in research.

Funding Bodies	Countries	Primary Studies
Air Force Research Laboratory	United States	[54]
Brazilian National Council for the Improvement of Higher Education (CAPES) and the Foundation for Research Support (FAP-DF)	Brazil	[15]
Engineering and Physical Sciences Research Council (EPSRC)	United Kingdom	[32]
EU-funded project	European Union (Spain)	[55]
European Commission, Ministerio de Ciencia e Innovacion of the Spanish Government	Spain	[56]
European Regional Development Fund (ERDF), Carinthian Economic Promotion Fund (KWF), and the state of Austria	Austria	[57]
H2020 AEROARMS European Union (EU) funding	European Union (Spain)	[21]
King Abdullah University of Science and Technology (KAUST)	Saudi Arabia	[17]
LOEWE Initiative of the state Hesse	Germany	[16]
MEXT Scholarship and Grants-in-Aid for Scientific Research	Japan	[23]
National Research Foundation of Korea (NRF)	Korea	[58]
National Science Foundation (NSF) and Office of Naval Research (ONR)	United States	[59]
National Science Foundation of China	China	[60] [61] [22]
The São Paulo Research Foundation (FAPESP)	Brazil	[19]
UAE National Research Foundation (NRF)	United Arab Emirates	[83]

In the case of journals, a large number of studies have been published in the Journal of Intelligent and Robotic Systems and IEEE Access. IEEE Transactions on Robotics was also considered, which is a highly cited journal in robotics according to the annual Journal Citation Report [51]. Almost all journals were from IEEE, with the exception of the Journal of Robotics and Autonomous Systems.

C. RQ3. COUNTRIES CONTRIBUTION TOWARDS RESEARCH

To address RQ3, primary studies were conducted to identify countries actively engaged in this research area. For this purpose, the affiliations of the authors were carefully analyzed. Several primary studies were conducted in the United States (US), Spain, China, the United Kingdom (UK), Singapore, Germany, Brazil, Portugal, and Turkey (FIGURE 4. Among these countries, the largest number of studies were from the US because the US spends billions of dollars on research and procurement of UAVs [52]. Other than the US, European countries such as Spain, Germany, the UK, and Portugal have also acted collectively to develop the next generation of armed UAVs and are investors in many drone projects [53]. China is another country with a large number of publications due to its research on UAVs and has become a producer and exporter of drones to other countries [52].

D. RQ4. RESEARCH FUNDING

Funding in research plays an important role as it facilitates and encourages researchers to investigate the problem in depth. Funding particularly becomes important when the area under discussion requires sensitive equipment, such as aerial robots. Therefore, it is important to identify the agencies that contribute financially to support research on this topic. The funding agencies that contributed to the research are listed in TABLE 6. These funding agencies were mostly from the USA, China, and Spain. Other countries such as the UK, Germany, Brazil, Austria, Japan, Korea, the UAE, and Saudi Arabia also contributed to support research in this area.

E. RQ5. CLASSIFICATION OF RESEARCH THEMES

A research theme shows the major ideas, subjects, and topics in which research is embedded. Research theme identification is one of the most fundamental tasks in qualitative

FIGURE 4. Countries where primary studies are conducted.

research. In this study, themes were extracted from the primary studies using thematic analyses. The themes were classified and grouped according to the most relevant concepts. This process was conducted independently by analysts, and the final iteration was carried out through mutual discussion. Fourteen themes were identified in which research on heterogeneous aerial robots was conducted and considered. The themes are presented in FIGURE 5.

An alluvial diagram was constructed to visualize the different themes and their underlying terminologies. In FIGURE 5, research themes with respect to their emergence over the years are provided. The analysis shows that the most common theme used by the research community was ''Communication'' which includes ''Communication between UAVs,'' ''Multi-robot Communication'' and ''Inter UAV Communication'' Inter UAV Communication, respectively. In addition to communication, large UAV formations were mostly used as research themes, including ''UAV relay chains,'' ''Flight Formations,'' ''Coalition Formation,'' ''MILP Formation,'' etc. Many researchers have also worked on the ''Networks'' theme which consisted of ''UAV networks,'' ''consensus-based networks,'' ''Ad hoc networks,'' etc. The ''Communication and Networks'' theme combined together was also found in studies. As communication plays an important role in patrolling and UAV warms, researchers have also used this theme in their research work. Few studies have used search, localization, control, task allocation, and collision avoidance themes, whereas communication, formations, and networks were mostly used themes for communication between heterogeneous UAVs.

F. RQ6. CLASSIFICATION OF APPLICATION AREAS

To address RQ6, application areas focused on primary studies were analyzed using the streamgraph provided in FIGURE 7. The application areas include area surveillance, search and rescue, exploration, and disaster management missions. Among these areas, area surveillance missions for monitoring and patrolling were largely focused on by primary studies by equipping UAVs with different sensors and cameras to cover large areas [13]. Other important application areas include search and rescue (SAR) missions [69] and disaster management. Both of these areas are interrelated, as search and rescue missions are usually performed in disaster management. In both missions, UAVs play an important role by providing a rapid overview of the situation. An application area, that is, the Search and Prosecution mission [82], was considered as a form of exploration mission. Further, other application areas, such as persistent monitoring [63] and coverage missions [30], were associated themes of area surveillance missions and classified in the same category. In recent years, however, the research focus has been on application areas such as denied environments [19], uncertain environments [15], and 3D environments [74], which are complex areas for multiple UAV communication.

G. RQ7. RESEARCH CLASSIFICATION ACCORDING TO WIERINGA et al. [45]

To address RQ7, primary studies were classified according to Wieringa *et al.* [45] research classification. Wieringa *et al.* classified research into six categories: validation, evaluation, opinion, solution of proposal, philosophical, and personal experience papers. The details of the classification under each category are provided in TABLE 8. After applying the classification of 43 primary studies, three main categories of research techniques were identified as validation, evaluation, and opinion studies, as shown in FIGURE 6. The majority of the primary studies came under the category of validation research. The proposed solutions were validated through experiments and simulations prototyping, etc. Among these

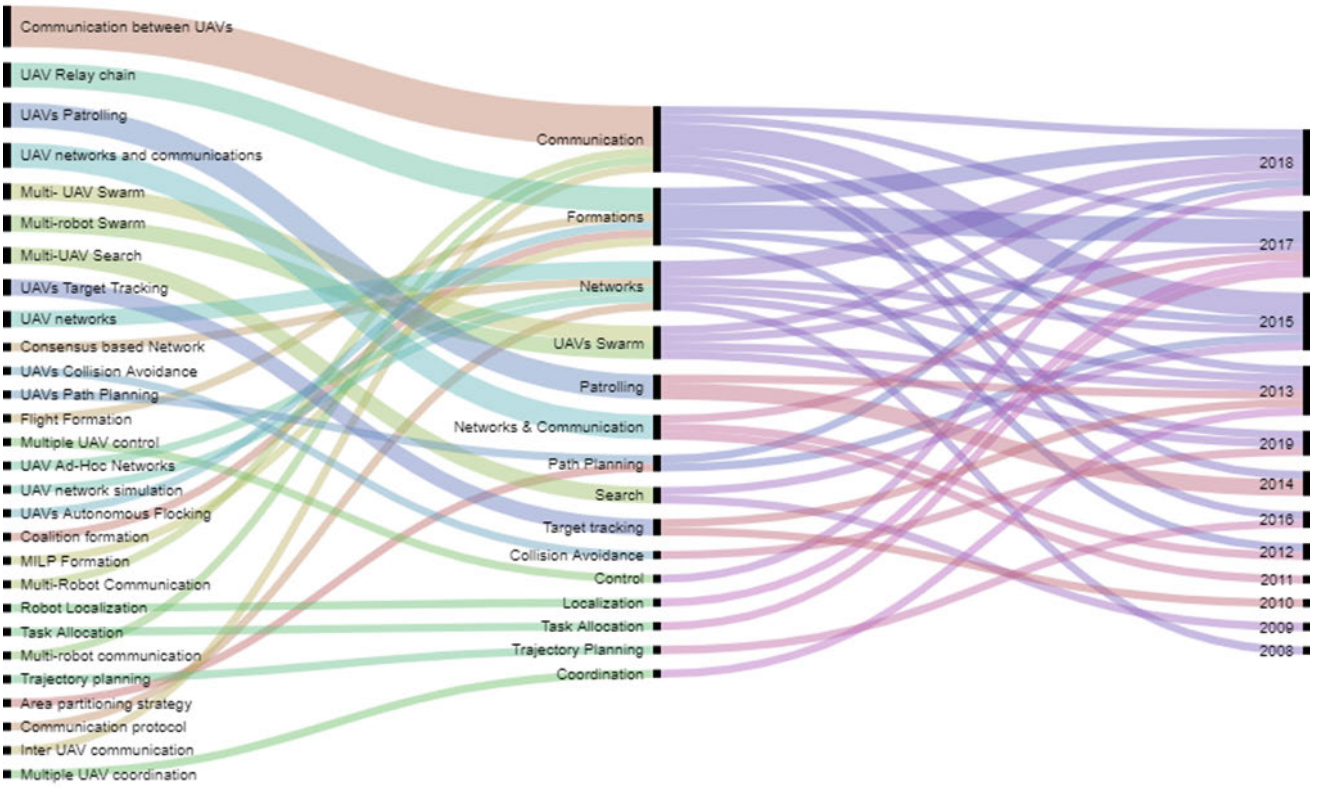

FIGURE 5. Research themes classification.

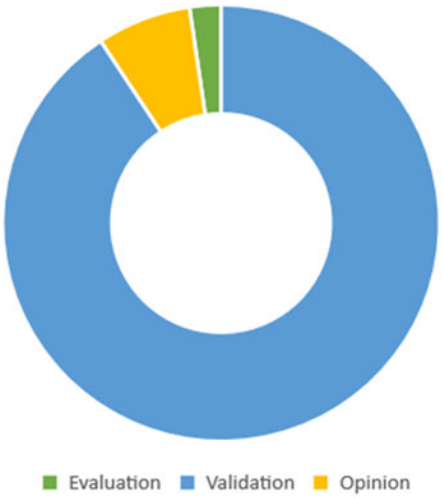

FIGURE 6. Wieringa *et al.*, [45] research classification.

validation techniques, simulations and experiments have been largely used in primary studies.

The other classification under which primary studies came was the evaluation technique, where studies used field experiments. The third category was opinion papers. Such studies do not propose new techniques, designs, or frameworks, but rather describe the author's opinion about what should be done, what's good or bad about some problems, and what are the values and preferences of that problem. Studies in this category include reviews and surveys. In [83], the author discussed the functions, services, and requirements for the networking of UAVs and different networking architectures. In [27], the opportunities and challenges of mobile networking for UAVs were discussed.

H. RQ8. RESEARCH METHODS EMPLOYED BY PRIMARY STUDIES

To address this research question, the research methods employed in the primary studies were identified and analyzed carefully. Research methods were classified according to standard classification, consisting of categories that include case studies, frameworks, experiments, prototypes, and simulations. The research method found in a large number of primary studies was simulation, as it is widely used in the field of robotics, especially in multiple robot communication. The simulation technique was discussed in 35 studies; however, there were studies that did not provide details regarding simulation, implementation tools, and results. In 13 studies, an experimental method was used that consisted of real-time demonstrations, test cases, and hardware testing. For example, a flight experiment to search an area of 40 square kilometers was conducted for cooperative search by UAVs [78]. Apart from these, framework [31]

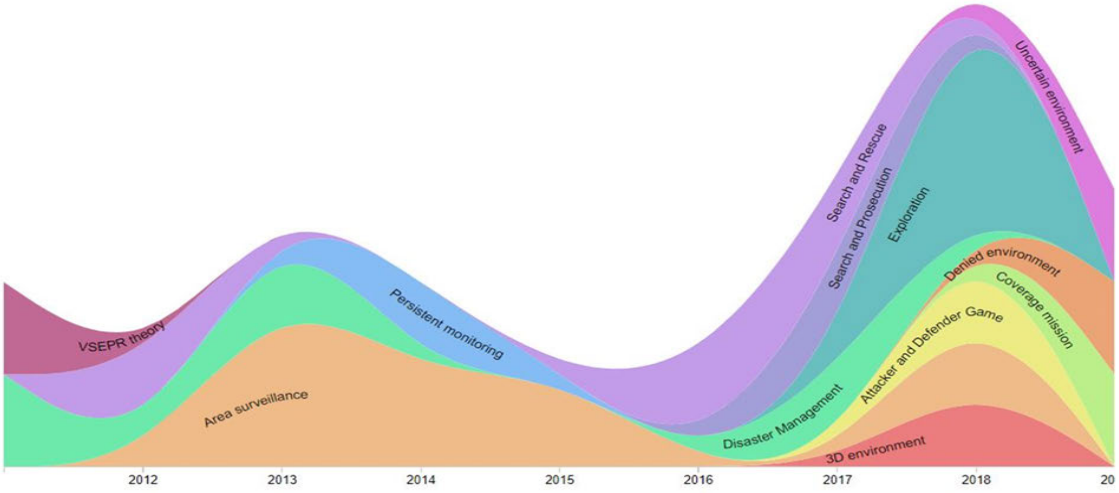

FIGURE 7. Application areas discussed by primary studies.

was proposed in 10 studies, whereas prototype [16] and case studies were also employed, but only in one study. The simulation method was mostly used in validation studies classified according to Wieringa *et al.* [45] classification in RQ7. The simulation method was also found in an opinion study by Jawhar *et al.* [12]; however, the details were not provided, whereas the author also employed a case study research method. The experimental method was used in a few validation studies, whereas a real field experiment was conducted and considered as an evaluation study [75]. The framework [31] and prototype [16] were also employed in some validation studies. In Table 9, the research method and research classification matrix are provided.

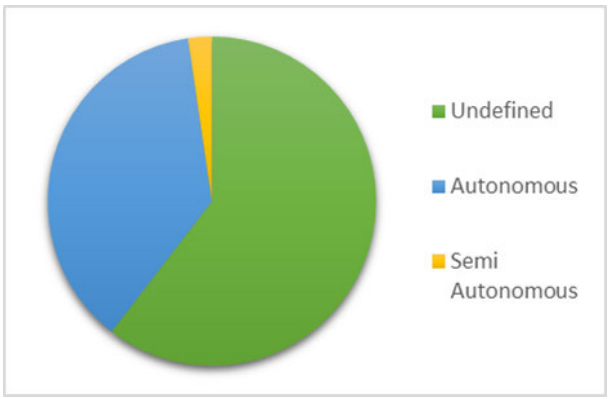

FIGURE 8. Functionality of UAVs.

I. RQ9. CONTEXT DIVERSITY

For research question 9, the research contexts were carefully investigated for all included primary studies. The context was classified and provided in TABLE 10 along with their focus in different years.

All primary studies were carefully analyzed to understand the context diversity over the years. It was found that all primary studies on communication among heterogeneous UAVs were mostly used in the path planning context because communication plays an important role in multiple UAV path planning. The studies discussed path planning strategies among multiple UAVs along with communication [54]. Networks have also been discussed in the context of a few studies. For multiple-UAV communication, effective networks among different UAVs through a wireless medium are required [84]. UAVs must be flown in formations to monitor or cover large areas. Different UAV formations, such as relay, flight, and coalition, also require UAVs to communicate with each other [85]. Different other contexts, such as coordination, trajectory planning, navigation, patrolling, task allocation, target tracking, etc., were also found in primary studies. However, some primary studies have only focused on the communication of multiple UAVs. A large number of studies in different contexts were conducted in 2018. Other contexts, such as localization, collision avoidance, task allocation, and target tracking, had limited coverage in primary studies. The research trend shows more focus on UAV formation, networking, and path planning.

J. RQ10. TYPES OF UAVs USED IN PROPOSED SOLUTIONS

For RQ10, different types of UAVs that were used in the primary studies were analyzed and are provided in Figure 9. The figure shows that most studies did not mention UAV types, particularly in studies where UAVs were also used with ground robots.

TABLE 7. Research themes classification over primary studies.

Groups Themes	Terminology	Primary Studies
Control	Multiple UAV control	[17]
Coordination	UAVs Coordination	[55]
Patrolling	Patrolling strategy	[62], [63], [64]
Path Planning	Area partitioning strategy, path planning among heterogeneous UAVs, Coverage Path planning (CPP)	[65], [54], [30]
Networks & Communication	UAV networks, wireless sensor and actor network, Communication and Networking of UAV-Based Systems, UAV Communication Networks, Connectivity of an autonomous UAV network	[66], [12], [22], [57]
Communication	Communication and coordination among heterogeneous UAVs, Data exchange between UAVs, UAV & UGV & human communication, Location information sharing in UAVs, Cooperative multirotor UAVs, Multi-robot communication, Information exchange between Aerial robots, Inter UAV communication	[54], [64], [16], [68], [20], [69], [56], [70]
Networks	UAV network simulation, UAV Ad-Hoc Networks, SUN - Stealth UAV Networks, Mobile Networking with UAVs, Communication protocol, Airborne Wireless Backbone, Consensus based Network	[18], [58], [19], [25], [23], [71], [72]
Formations	Coalition formation, Multiple Relay UAVs, Formation flight planning of UAVs, Formation flight and obstacle avoidance, Relay UAVs, Mobile relay UAVs, Multi-UAV Autonomous Flocking, MILP formulation, UAV Relay chain	[31], [73], [15], [74], [22], [32], [75], [76], [77]
Task allocation	Task assignment by UAVs	[31]
Search	Multi-UAV Exploration, Cooperative search	[59], [78]
UAV Swarm	Aerial Swarm Robotics, Multi-robot caravanning, UAV Swarms	[26], [79], [72]
Target Tracking	Cooperative Target Tracking, Targets using UAVs	[80], [24]
Trajectory planning	Trajectory planning	[81]
Localization	Localization of swarm robots	[21]
Collision Avoidance	UAVs Collision Avoidance	[60]

TABLE 8. Kitchenham and Charters [41] research classification.

Classification	Description
Validation	Validation research technique validates the solution proposal that has been proposed by someone else but not yet implemented. It includes simulation, experiments, prototyping etc.
Evaluation	Evaluation research technique consists of case study, field experiment, study, survey etc. It evaluates the problem by putting it in practice or implementation.
Opinion	Opinion papers contain the authors opinion good or bad about something.
Proposal of Solution	Proposes a novel or improved solution technique e.g., Proof of concept
Philosophical	Philosophical technique represents a new way of looking at things e.g., New conceptual framework.
Personal Experience	This technique emphasizes on author's personal experience i.e., lessons learnt. Used by practitioners and researchers about their tools experience.

TABLE 9. Research methods and classification over no. of studies.

Research Method	Research Classification		
	Evaluation	Validation	Opinion
Experiment	*	**********	---
Prototype	---	*	---
Framework	---	**********	---
Simulation	---	********** ********** ********	*
Case Study	---	---	*

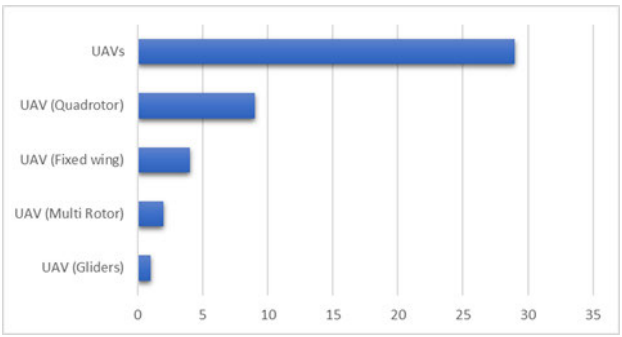

FIGURE 9. Classification of UAVs type.

A quadrotor is a type of UAV that has been found in most studies. The reasons for using quadrotors were their unique abilities of small size, easy control, and high maneuverability. They are widely used for missions such as search and rescue, emergency response, surveillance, and patrolling [86]. In addition to quadrotors, other UAV types used in studies include fixed-wing, multi-rotor, and gliders.

1) FUNCTIONALITY AND CAPABILITIES OF UAVs

The different functionality and capabilities of UAVs are also analyzed in primary studies to determine RQ10. Two types of functionalities found in studies include autonomous and semi-autonomous control, as shown in Figure 8. There were studies that did not provide any details about the autonomous status of UAVs and fell under the undefined category.

In Figure 10, the UAV's capabilities in terms of homogenous, heterogeneous, and swarm specifications are provided. Most studies did not provide explicit details of UAV capabilities. However, apart from heterogeneous UAVs, there have been studies that used both swarm and homogeneous UAVs along with heterogeneous UAVs.

K. RQ11. ROLES AMONG UAVs FOR COORDINATION AND COMMUNICATION

The roles of UAVs were identified from primary studies and are shown in Figure 11. The various roles defined in primary

TABLE 10. Classification of context considered by primary studies over years.

Contexts	Years											
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Communication				*	*	**	*	***	*	**	*	*
Coordination						***	**	***		*		*
Networks	*		*	*	*	*		**		**	**	***
Path Planning					*	**	**	****		**	**	***
Trajectory Planning		*				**		*	*	*	***	***
Navigation					*	*		*	*	***	***	*
Patrolling						*	**	*				
Task Allocation											**	
Target Tracking			*			*						
Formations					*	*		*		****	***	****
Collision Avoidance											*	*
Control						*	*				*	
Search		*						*			**	
Localization										*		

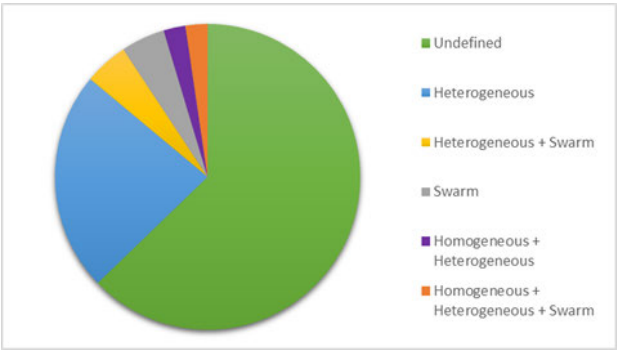

FIGURE 10. Capability of UAVs.

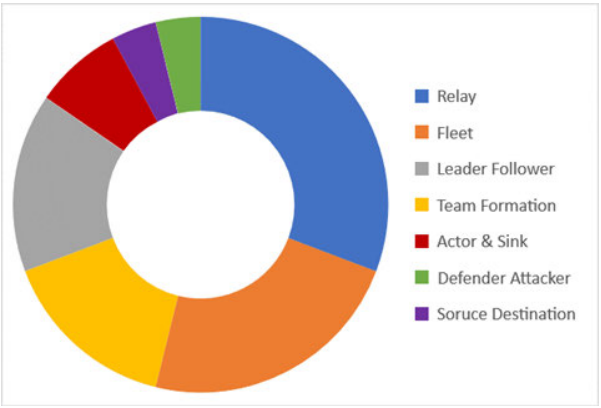

FIGURE 11. Role of UAVs.

studies include relay, fleet, leader follower, team formation, actor and sink, defender attacker, and source destination. Many studies have used relay UAVs as they are used to provide reliable communication between source and destination UAVs, especially in large areas with potential obstacles. Multiple UAVs communicate with each other using a relay chain consisting of one or more relay UAVs that pass information to the destination [24]. In addition to relay, a fleet of UAVs was also found, which consists of a large number of coordinated UAVs. In [20], a fleet of multi-rotor UAVs was used to follow a set of desired trajectories while coordinating with each other in a timely and reliable manner.

Leader follower and team formation of UAVs were also used in a few primary studies. Leader UAVs usually have different capabilities than team members. Leader-Follower is useful for controlling a swarm of UAVs, such as in [26], where a virtual leader is selected and controlled by separate dynamics, whereas the remaining swarm agents act as followers. Team formation control [31] is a generic structure of UAVs working as a team that can be leader-follower, virtual structure, coalition formation, etc. In some studies, UAVs played the role of actor sinks, defender attackers, and source destinations. In a UAV network, different numbers of UAVs are considered as sensor nodes along with larger actor UAVs and a single sink UAV as the backbone of the network with more capabilities than actor UAVs.

L. RQ12. COMMUNICATION TECHNIQUES

For RQ12, different techniques used for communication among UAVs were analyzed and classified into different categories, as shown in Figure 12. The terms used for communication were extracted in a spreadsheet, and their contexts were analyzed according to their research settings. The terms were grouped, and the relevant classifiers were

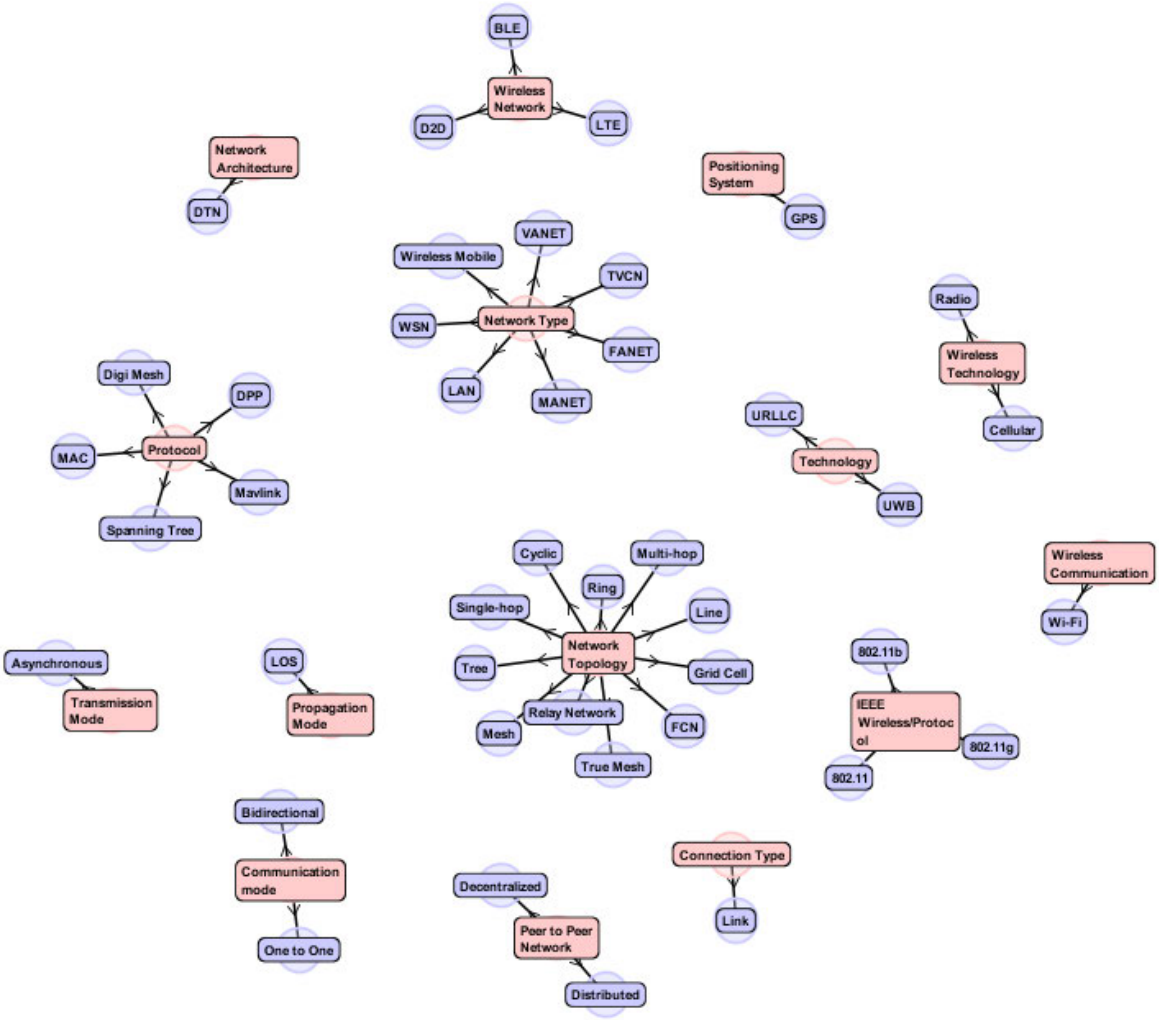

FIGURE 12. Communication techniques and strategies used in studies.

assigned. A total of 15 classifiers (called categories in TABLE 11) were defined, which included communication modes, wireless technology, peer-to-peer network, network architecture, positioning system, network topology, wireless communication, protocol, IEEE wireless/ protocol, technology, wireless network, network type, connection type, propagation mode, and transmission mode. A cluster diagram in Figure 12 was formed around the categories to provide details of the techniques used under each specific category.

The analysis shows that primary studies used both communication methods in multiple UAV systems, which included one-to-one communication and bidirectional communication. The one-to-one communication mode shows that each UAV in a system is directly connected to another UAV, whereas the bidirectional mode shows two-way communication. WIFI, cellular, and radio technologies have been used in wireless communication and wireless technologies. However, Wi-Fi was the most dominant technology used in the primary studies. In the case of network formation, peer-to-peer networks, network architecture, network topology, and network type were used in different combinations.

In the case of peer-to-peer networks, decentralized networks are considered more advantageous than centralized networks because they allow secure and reliable UAV communication without any failure [12]. Under network type, mobile ad hoc networks (MANETs) and flying ad hoc networks (FANETs) were mostly used in primary studies. Mobile ad-hoc networks (MANETs) and their variants for UAVs, and flying ad hoc networks (FANETs) are popular among the communication of UAVs. MANETs are infrastructure-free and self-organizing networks for mobile devices, whereas FANET provides communication among UAVs in 2D or 3D networks. In the latest article [87], the author presented a survey on FANET and discussed its architecture, communication, models, and other related technologies. This survey proved FANET as a future-enabling technology.

TABLE 11. Categorized communication techniques.

Categories	Communication Techniques	No. of Studies
Communication Modes	One to one, Bidirectional	8
Wireless Communication	Wi-Fi	4
Wireless Technology	Cellular, Radio	4
Peer to Peer Network	Decentralized, Distributed	4
Network Architecture	Delay Tolerant Network (DTN)	3
Positioning System (Value Added Services)	GPS	3
Network Topology	Line, Mesh, Relay Network, Grid cell, Ring, Cyclic, True Mesh, FCN, Multi-Hop, Single-Hop, Tree	18
Network Type	MANET, FANET, LAN, TVCN, VANET, WSN, Wireless Mobile	10
Connection Type	Link	2
Propagation Mode	LOS	2
Protocol	MAC, Distributed Probabilistic Protocol (DPP), Mavlink, Minimum Spanning Tree, Digi Mesh Routing	6
IEEE Wireless Protocol	802.11.0, 802.11b, 802.11g	4
Transmission Mode	Asynchronous	1
Wireless Network	BLE, D2D communication, LTE	3
Other Technology	URLLC, UWB	2

The delay tolerant network (DTN), categorized as network architecture, has been used in various studies for search and rescue (SAR) missions. The high mobility of UAV nodes in a network causes problems in rapid message delivery; therefore, DTN communication, also known as local ferry-based network (LFN), is used. DTN uses special-purpose controllable vehicles (message ferries) to transfer messages among neighboring nodes [88]. Link, mesh, and relay network topologies have been used in most studies. The mesh network allows multiple connectivities from one UAV to the other UAVs in the network and builds a network that is resilient to failure. Therefore, they are considered more effective for multiple-UAV communication [6].

In the case of protocol usage, MAC and IEEE defined protocols were used in primary studies. The IEEE 802.11.0 protocol is the most popular and provides a reliable communication range of hundreds of meters in line-of-sight communication. The analysis of communication techniques shows that they were largely used in the last few years, that is, 2017 to the present. Other communication techniques employed by primary studies include a link that is categorized as connection type, line of sight (LOS) as propagation mode, asynchronous communication as transmission mode, BLE, LTE as wireless network, UWB, and URLLC as technology.

M. RQ13. IMPLEMENTATION TECHNOLOGIES

For RQ13, all the tools and technologies used in primary studies were carefully analyzed and categorized as techniques, hardware, languages, simulation, software tools, and libraries/packages. An alluvial diagram is designed to determine how different implementation technologies are categorized over years, as shown in FIGURE 13.

Various types of software were used in primary studies to implement the proposed solutions. The most commonly used software is the MATLAB programming tool, Robot Operating System (ROS), and Simulink. MATLAB and Simulink were mostly used in primary studies for the implementation of communication among UAVs. In a study [60], MATLAB/Simulink was used to simulate multiple UAVs for a collision avoidance strategy in a communication network. ROS have also been used in primary studies to create simulations and to show interaction and control among robots. In a study [61], ROS was adopted to provide data communication middleware between the environment and the UAV simulation system.

Apart from these, other software/simulators used in primary studies include Gazebo and Software in Loop. Gazebo has been widely used by researchers in studies as it is one of the most popular and open-source multi-robot simulators. A Gazebo simulator was used along with the ROS to simulate multiple UAVs [16]. The software in loop (SITL) simulator is the simplest simulator used to test new software before using it on a real vehicle in a quick and safe manner. In [18], an SITL simulator, Ardupilot, was used to simulate a large number of UAVs.

Other than software/simulators, various techniques have been employed, including simultaneous localization and mapping (SLAM) and LIDAR sensors as hardware. LIDAR-based SLAM technology is used to construct maps and the positioning of UAVs in an unknown environment. LIDAR-based SLAM technology was employed in a study to provide navigation and obstacle detection capabilities to UAVs [75]. In terms of languages, C++ and Python were adopted for implementation [18]. Libraries such as ArUco and Open CV have also been used in some studies for implementation. The ArUco marker detection library was used in a previous study [79] for visual markers in robot localization and detection. An open CV library was utilized beside the ROS tool to stream real-time video files from the UAV to the computer [69].

N. RQ14. INFORMATION SHARED AMONG AERIAL ROBOTS

For RQ14, information shared among multiple unmanned aerial vehicles (UAVs) was analyzed. The information was extracted and classified into 15 categories, as shown in Table 12. TABLE 12 shows different information tags categorized under 15 categories in primary studies over the years.

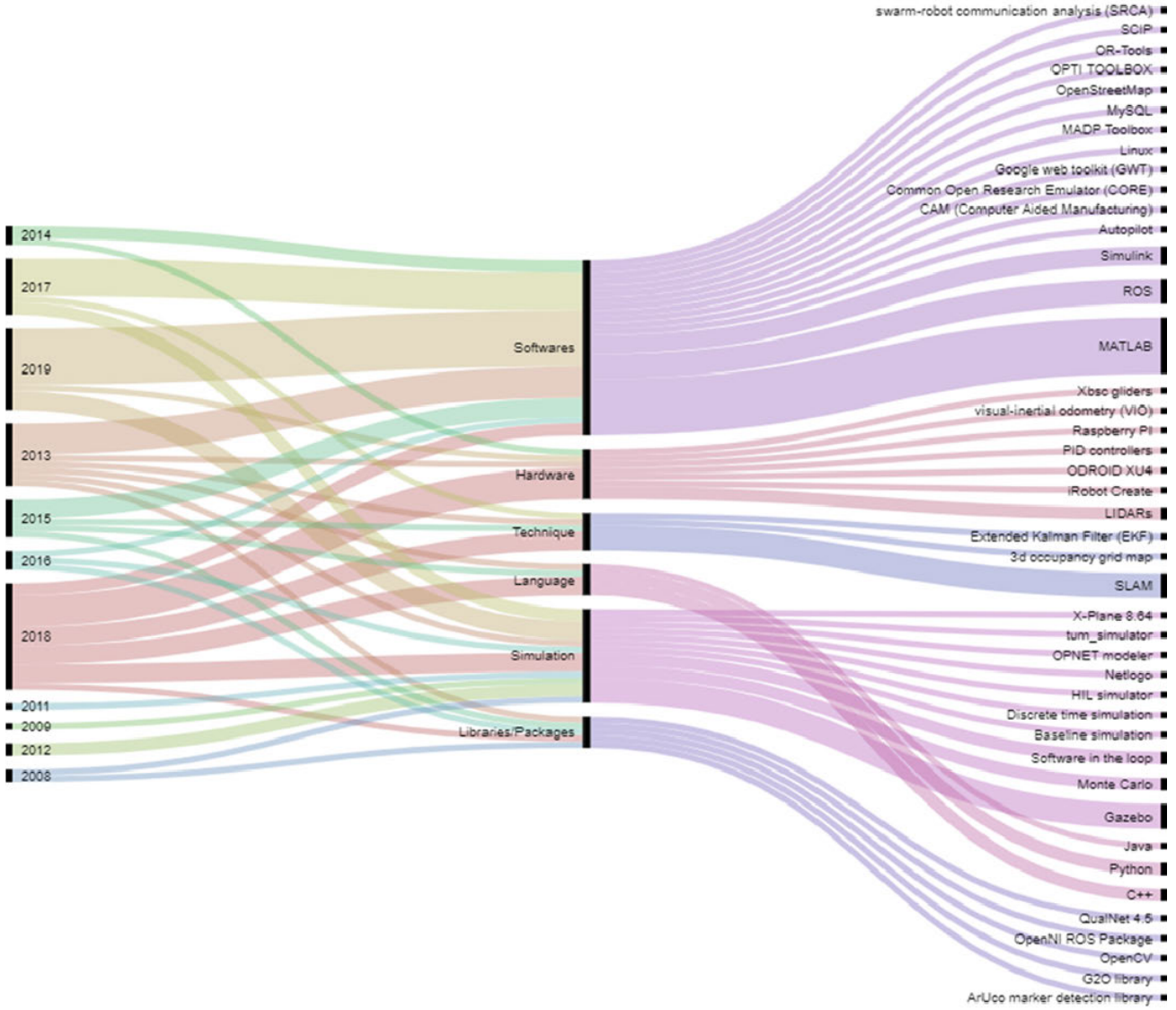

FIGURE 13. Year wise categorized implementation technologies.

The analysis shows that the information mostly communicated among UAVs was either position or location because each UAV required position and location information of other UAVs to ensure coordination among themselves. The position represents the UAV's state and grid position, whereas location information is usually about map [59], area of interest [26], and global environmental information [79]. Orientation information [21] has also been found in various studies over different years. Orientation information consists of detailed information about the angular position, attitude, or direction of UAVs, which is also required for communication. Other information shared among UAVs was categorized under target, speed, network, coverage, distance, image, resources, sensor, and quantity. Target information included information about the target, that is, the source of food/nest was a target for UAVs. The network category considered information about shared tokens that include source address, destination address, token ID, etc., used in a study [68] in 2015. In another study [23], data packets were shared between the UAVs. In 2009, for a cooperative multiple UAV system, sensor and telemetry data were shared with neighboring UAVs [89].

In [66], the study focused on actor networks in which information about the number of UAVs acting as an actor was shared between different nodes in a WSN. Table 12 shows that categories such as utility, reconnaissance, and tasks were used in limited studies. In [54], Reconnaissance information, including probabilities of intel and enemy locations, was shared between UAVs for mission planning in an uncertain environment. In a team formation [31], UAVs collect information about the utility of their neighbors to calculate their own utility for task assignment. In [63], an area was partitioned into segments and assigned to different UAVs

TABLE 12. Information categories with tags over years.

Categories	Information Tags	Years	Studies
Location	Geolocated information, Location of UAVs, Map information, Other UAVs location, Global environmental information, Current location, Search region	2012, 2013, 2015, 2018, 2019	10
Position	Position information, Thermal position, Position of UAVs, Position logs, Position of targets, GPS coordinates, odometry	2008, 2010, 2012, 2014, 2017, 2018, 2019	10
Orientation	Actual state (attitude/ energy, velocity, pitch angle, yaw angle, attitude information, direction)	2012, 2014, 2017, 2018, 2019	5
Target	Information about source of food/nest, vital information like identities of targets	2010, 2015, 2016, 2018	4
Speed	Speed	2009, 2015, 2019	3
Resources	Resources	2018, 2019	2
Coverage	Area coverage information	2013, 2014	2
Distance	Distance to other robots	2015, 2017	2
Image	Image logs, images	2014, 2017	2
Network	Token (Source address, Destination address, Token ID), Data packets	2015	2
Sensor	Telemetry and sensor data	2009, 2013	2
Quantity	Number of UAVs, Number of actor UAVs	2018, 2011	2
Reconnaissance	The probabilities of intel and enemy locations	2018	1
Utility	Utilities of neighbor UAVs	2017	1
Task	Segments assigned	2014	1

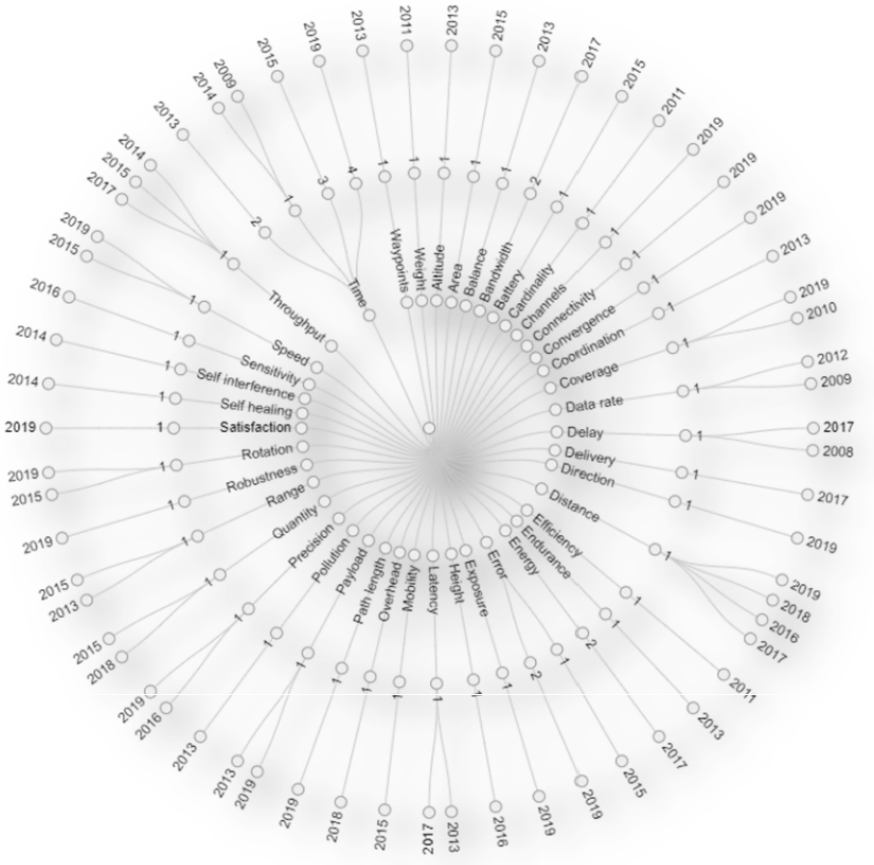

FIGURE 14. Year wise performance metrics in studies.

to cover it. To avoid collisions and to provide efficient patrolling, the information of the segments assigned to UAVs was exchanged with neighboring UAVs.

O. RQ 15. EVALUATION OF PROPOSED SOLUTIONS

To address RQ15, the solutions proposed in the primary studies were analyzed. To evaluate the proposed solutions, 'performance' was a key measure and was evaluated through various matrices. Performance metrics that were used for evaluation were provided as circular dendrograms along with no. of primary studies over the years, as shown in FIGURE 14. It was shown that "Time" was the most commonly used evaluation measure among the primary studies. Other associated terms found in the studies for time were "convergence time" and "elapsed time". In [22], convergence time was used as a performance metric to measure the performance

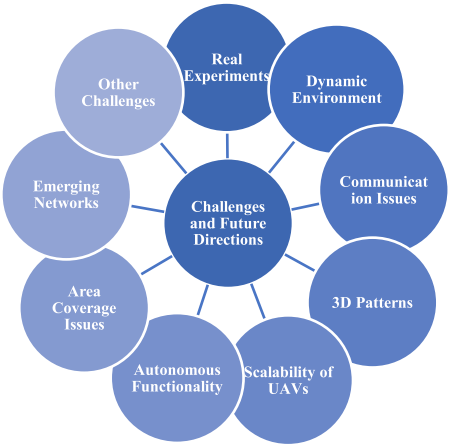

FIGURE 15. Challenges and future directions of research.

of the two algorithms proposed to deal with the topological changes of UAV networks. However, elapsed time simply measures the time of an event from its beginning to its end. In a study [64], the maximum-minimum and average elapsed times were used to compare the performance of the area division strategy and path division strategy algorithms. ''Distance'' was another measure used consecutively in recent years to calculate the distance between UAVs, orbits, obstacles, etc. Apart from these, other measures used were error, throughput, latency, payload, speed, data rate, and bandwidth.

P. RQ 16. CHALLENGES AND FUTURE DIRECTIONS

In this research question, various open challenges and associated future research directions are discussed in detail. Challenges associated with multiple heterogeneities The UAV teams are provided in FIGURE 15. To measure the effectiveness and efficiency of the proposed communication and coordination solutions among multiple heterogeneous UAV teams, real outdoor setups [17] and experiments [24] are critical. In a simulated environment, various real-time considerations and hardware features are ignored. This makes it difficult to assess the real applicability of these solutions. Similarly, conducting experiments in real environments is challenging. Real experiments are constrained by factors including availability of sophisticated hardware, skilled resources, maintenance facilities, policies or restrictions applied by governing bodies on the use of UAVs, and most importantly, availability of funds. Another challenge for heterogeneous UAV communication and coordination is the inclusion of scenarios from dynamic environments that can be created through dynamic obstacles [20] or by involving other dynamic conditions [19]. Future work focusing on dynamic environments may contribute to improved communication and coordination patterns and strategies.

Communication and coordination of heterogeneous UAVs are also affected by issues such as limited communication range [54], unreliability of wireless networks [70], routing issues [7], and ambiguous communication requirements [26]. In the future, better approaches may be proposed to address these problems or minimize their effects. Generating 3D patterns is also a challenge for heterogeneous UAV team communication. 3D patterns including 3D positioning [66], 3D antenna patterns [78], and 3D sensing [75] require real case studies and in-depth analysis, which can be carried out in future studies.

The scalability of communication networks established by heterogeneous UAV teams is critical. Scaling up the number of UAVs [59] or increasing UAV teams [79] on-demand to explore larger-scale dynamic environments is becoming a need with an increase in UAV teams in mission-critical activities. This requires dedicated research studies that can consider various cases of real-time-critical situations such as emergencies, disasters, and surveillance. Apart from scalability, autonomous decision-making [67] in multiple-UAV communication is a significant and ongoing research area. The challenge is to enable UAV teams to fulfill the required tasks autonomously [69] with human intervention. The research is still at an early age and requires a thorough assessment of the proposed solutions. Different area coverage problems, including coordination variables, one-to-one coordination [13], and area partitioning strategies [65], can be the subject of future developments in the research of heterogeneous UAV team communication. Flying ad hoc networks (FANETs) [25] and delay tolerant networks (DTNs) [16] are emerging as prominent communication technologies and can be employed in heterogeneous UAV team communication. In the future, DTN-aware control mechanisms can be developed, and various FANET issues may be solved effectively. Other challenges associated with research on heterogeneous UAV team communication include collision avoidance [80], target and task allocation issues [26], trajectory planning [81], search [78], and data gathering [12]. To reduce connectivity issues and for stable communication among UAV teams, artificial intelligence technologies [90] and other optimization techniques [31], [76] need to be explored. Research directions can also be extended to unmanned aerial and aquatic vehicle (UAAV) networks [91]. Both aerial and aquatic vehicles have similar characteristics; the main difference is the communication channel; the water makes underwater networks change the technologies. However, important features such as routing techniques, vehicle mobility, and applications of UAAV may share many similarities [91]. In this regard, NASA is already working on transforming Mars rover navigational technology for deep ocean exploration [92].

Finally, future research on heterogeneous UAV team communication and coordination can focus on developing and conducting more realistic experiments in dynamic environments using autonomous and intelligent UAVs in larger teams that can perform various tasks efficiently and effectively. Further, large dynamic environments and the inclusion of various emerging networks and communication technologies can be exploited to develop robust solutions.

IV. THREATS TO VALIDITY

A. SEARCH STRINGS

The main threats to validity are internal threats, as they do not involve human participation. The guidelines of Kitchenham and Charters [33] were used to reduce bias. The first challenge faced in the construction of the search string was not to miss any relevant studies. There is a slight possibility of including irrelevant studies because the search string was broad. However, such studies were excluded from the study selection process and by applying inclusion/exclusion criteria. Two analysts evaluated the selected studies in a peer-review manner.

B. INCLUSION AND EXCLUSION CRITERIA

The bias in the selection process of studies can be an external threat to validity. Inclusion and exclusion criteria were defined in the selection of studies according to the Kitchenham guidelines [33]. 43 studies were included in the 566 studies. Two analysts independently analyzed the studies, and conflicts were resolved through discussion.

C. SEARCH COVERAGE

Studies were considered within the time range of 2005 to 2019. The time period can be an internal threat to validity, as this study was conducted in 2020 and might miss the latest studies of the year 2020. However, an informal search showed that this threat is ignorable, as we did not miss any major studies in this area. Furthermore, the global pandemic of coronavirus that occurred in 2020 also influenced publications in this area.

D. SELECTION OF PUBLICATION SOURCES

Another threat to validity is the selection of the published sources. Three databases (Science Direct, IEEE Xplore, and ACM Digital Library) were considered because of their reputation, readership, and relevance for robotics research. No study was included through a manual search because it might have replicated the available studies.

E. ANALYSIS OF STUDIES

The data extraction process has construct validity. To extract information, two analysts analyzed the data so that any missing information could be addressed by another analyst. Further, this process involved multiple iterations; therefore, construct validity may not be considered a threat in this study.

V. DISCUSSION AND CONCLUSION

In this research, a thorough analysis was carried out on the research on communication among heterogeneous UAVs. For this purpose, different research themes, research methods, communication techniques, and implementation technologies were critically analyzed. The analysis of research themes and contexts showed that research on communication among multiple UAVs is focused on various communication techniques, UAV formations, different multi-UAV networks, and path planning strategies. In the early years, studies focused on multiple UAV communication and UAV networks; however, in later years, research was mainly focused on UAV formations and path planning strategies. These varied patterns show that the communication and coordination of heterogeneous UAVs were considered an implicit part of later research without explicit discussion on the topic.

Research themes in each primary study were further analyzed in relation to the research methods employed to understand the research strategy. As analyzed in RQ8, the most commonly used research method in primary studies was simulation. The investigation into this showed that for UAV formation, simulation and framework methods were employed, whereas simulation, experiment, case study, and prototype methods were adopted for themes that included communication and networks. Apart from these, the simulation method was widely used for the rest of the research themes.

The communication techniques employed under various themes mostly included a description of network type (i.e., MANET, VANET, FANET, FCN, DTN, WSN, TVCN, etc.), network topology (i.e., consisting of a grid cell, line, mesh, ring, multi-hop, single hop, relay network, etc.), wireless communication, wireless networks, and wireless technology. Wireless techniques, such as Wi-Fi, LTE, radio, and cellular, have been widely used to develop communication networks. The swarm UAV theme used other techniques such as URLLC and UWB in 2018, which are currently used for 5G and are considered as future wireless technology. In the literature, other latest communication techniques such as software defined networks (SDN) [93] and information centric networks (ICN) [94] were also used for UAVs; however, they were not found in primary studies because of exclusion criteria that selected studies that discussed communication among multiple heterogeneous UAVs.

The implementation technologies used under various themes showed that for communication, path planning, target tracking, and patrolling themes, the most used software tools were MATLAB, Simulink, and ROS. Under the UAV swarm theme, most hardware equipment details were provided instead of software tools. In networks and communication themes, simulation tools such as OPNET modular, Monte Carlo simulation, Software-in-loop, Baseline simulation, and X-plane 8.64, were used. Development languages such as Java, Python, and C++ were found mostly under the Communication and Networks theme. In short, different implementation technologies have been exploited by researchers; however, software and simulation tools have been widely used for the implementation of communication among heterogeneous UAVs. Therefore, the findings show that researchers used a variety of techniques, technologies, and methods for different themes, along with the diversity of themes and contexts.

In conclusion, the purpose of this research was to employ an evidence-based approach in the form of a mapping study on communication between heterogeneous UAVs. The map-

ping study was conducted according to the guidelines of Kitchenham and Charters [33] to devise a research process. Primary evidence was collected about communication techniques, implementation technologies, funding bodies, robots' roles and capabilities, research methods, research themes, domain applications, etc. from three digital libraries, that is, IEEE Xplore, ACM, and Science Direct, for the purpose of conducting mapping studies.

A systematic study selection process consisting of various phases and inclusion/exclusion criteria was developed to include and exclude primary studies. 43 studies were found to be most relevant to the research problem and were used for full analysis. Data were extracted by analyzing each study according to data extraction codes. Through the mapping study process, different sub-questions were also answered against each field and entry of data extraction form, that is, what is the trend of different types of UAVs used for communication models or what type of communication techniques are being proposed by authors. Data analysis was carried out on the extracted information to identify gaps and trends.

It was identified that communication between heterogeneous UAVs started to appear in studies after 2008. The highest number of studies on this topic was found in 2015 and 2018. Of the 43 studies, 31 were published in conferences, and 12 were published in journals. The contributions of these studies were mostly made by the USA, Spain, and China. Among these countries, the largest cluster of studies was from the United States. The majority of studies practiced the simulation research method and came under the validation research classification proposed by Wieringa *et al.* [45].

Research themes on communication among UAVs were identified and classified under main categories, such as path planning, trajectory planning, formations, control, and networking. Further, the context of each study was analyzed to identify trends over the years. Most primary studies discussed communication among heterogeneous UAVs under themes such as multi-UAV path planning, UAV formations, and networking techniques.

In terms of the types of UAVs used in primary studies, quadrotors are dominated by autonomous functionality. In addition, heterogeneous UAVs have been used in many studies. The application domains and disciplines widely targeted by primary studies include search and rescue (SAR), area surveillance, disaster management, and exploration missions. In all these application areas, the researchers used multiple heterogeneous UAVs with different roles, such as team formation, relay UAVs, leader-follower, and fleet of UAVs.

Various communication techniques employed by researchers were analyzed and classified into 15 categories: communication modes, wireless technology, peer-to-peer network, network architecture, positioning system, network topology, wireless communication, protocol, IEEE wireless / protocol, technology, wireless network, network type, connection type, propagation mode, and transmission mode. These communication techniques were further analyzed according to year of publication. Use of wireless communication technologies, such as. Wi-Fi has been found in the early years, as well as in recent years. IEEE wireless protocols have been used in different studies over different years. Communication technologies including radio wireless technology and different wireless networks, that is, D2D, LTE, Peer to Peer networks that is, Distributed and Decentralized, Network topologies that is, Relay Network, Line, Grid cell, Tree, Protocols that is, MAC, DPP, and other technologies, that is, UWB and URLLC, have been found in recent years, mostly in 2018 and 2019.

Studies have used a variety of implementation technologies that were also classified under six categories: software, libraries/packages, techniques, hardware, languages, and simulators. Information shared among multiple UAVs was also classified, and it was identified that information on position and location was largely shared among UAVs for coordination. A total of 42 parameters were identified and used in various studies. Evaluation parameters such as time and distance metrics have been used in a large number of studies.

Because the level of detail differs in each study, the analysis of techniques is a challenging task. Further, discussions on communication and coordination were limited to the description of various communication and network technologies. This made it difficult to compare the proposed solutions in the context of coordination and communication. The trend shows that research on multiple heterogeneous UAVs is evolving with a large focus on unknown environments to exploit the varied capabilities of UAVs. The coordination and communication patterns are focused on team formation and delegating various roles to different UAVs within the same team. Communication and coordination among UAVs were proposed and implemented through existing network types, topologies, protocol transmission modes, etc. However, the discussion on each level of coordination and communication was lacking in primary studies. This made it difficult to compare the solutions within the coordination and communication of the UAV team. Even evaluation parameters lack a relationship and discussion on the coordination and communication aspects of UAVs. The classifications made in this study were based on the context provided in the primary studies. The findings of this study can be used to construct a framework in which coordination and communication among heterogeneous UAVs can be analyzed through the themes, UAV types, research methods and techniques, communication technologies, and evaluation parameters. Further, the study findings highlight the importance of a detailed analysis of the proposed solutions to identify the effectiveness of coordination and communication techniques within heterogeneous UAVs. The current trend shows an increase in the use of heterogeneous UAVs for mission-critical applications, in which coordination and communication are an integral part of such teams to achieve mission success.

REFERENCES

[1] *The History of Drones (Drone History Timeline From 1849 to 2019)*. Accessed: Jul. 18, 2019. [Online]. Available: https://www.dronethusiast.com/history-of-drones/

[2] K. N. Kumar, G. Prasad, K. Rajasekar, P. Vadivelu, S. Gollakota, and S. K. Kavinprabhu, "A study on the forest fire detection using unmanned aerial vehicles," *Int. J. Mech. Prod. Eng. Res. Dev.*, vol. 8, no. 7, pp. 165–171, 2018.

[3] S. Berrahal. *(PDF) Border Surveillance Monitoring Using Quadcopter UAV-Aided Wireless Sensor Networks*. Accessed: May 8, 2020. [Online]. Available: https://www.researchgate.net/publication/318208011_Border_surveillance_monitoring_using_Quadcopter_UAV-Aided_Wireless_Sensor_Networks

[4] J. A. Gonçalves and R. Henriques, "UAV photogrammetry for topographic monitoring of coastal areas," *ISPRS J. Photogramm. Remote Sens.*, vol. 104, pp. 101–111, Jun. 2015.

[5] *Autonomous Vehicles in Support of Naval Operations*, National Academies Press, Washington, DC, USA, 2005.

[6] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1123–1152, 2nd Quart., 2016.

[7] X. Chen, J. Tang, and S. Lao, "Review of unmanned aerial vehicle swarm communication architectures and routing protocols," *Appl. Sci.*, vol. 10, no. 10, p. 3661, May 2020.

[8] U. Sahu, A. Chakole, R. Vidhate, P. S. Bandwal, A. Dube, and U. Bobde, "Fundamentals of aerial robotics & applications," *Int. J. Adv. Res. Comput. Commun. Eng.*, vol. 5, no. 4, pp. 429–432, 2016.

[9] C. Berger, M. Wzorek, J. Kvarnstrom, G. Conte, P. Doherty, and A. Eriksson, "Area coverage with heterogeneous UAVs using scan patterns," in *Proc. IEEE Int. Symp. Saf., Secur., Rescue Robot. (SSRR)*, Oct. 2016, pp. 342–349.

[10] M. Scheutz, P. Schermerhorn, and P. Bauer, "The utility of heterogeneous swarms of simple UAVs with limited sensory capacity in detection and tracking tasks," in *Proc. IEEE Swarm Intell. Symp. (SIS)*, Jun. 2005, pp. 265–272.

[11] I. A. Ollero and A. Maza, *Multiple Heterogeneous Unmanned Aerial Vehicles*, vol. 83. Mumbai, India: Star. 2012.

[12] I. Jawhar, N. Mohamed, J. Al-Jaroodi, D. P. Agrawal, and S. Zhang, "Communication and networking of UAV-based systems: Classification and associated architectures," *J. Netw. Comput. Appl.*, vol. 84, pp. 93–108, Apr. 2017.

[13] J. J. Acevedo, B. C. Arrue, I. Maza, and A. Ollero, "Distributed approach for coverage and patrolling missions with a team of heterogeneous aerial robots under communication constraints," *Int. J. Adv. Robotic Syst.*, vol. 10, no. 1, p. 28, Jan. 2013.

[14] Y. Kim and H. Bang, "Ad-hoc network for inter-vehicle communication of multiple UAVs," in *Proc. 14th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2014, pp. 840–843.

[15] B. Floriano, G. A. Borges, and H. Ferreira, "Planning for decentralized formation flight of UAV fleets in uncertain environments with dec-POMDP," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2019, pp. 563–568.

[16] L. Baumgartner, S. Kohlbrecher, J. Euler, T. Ritter, M. Stute, C. Meurisch, M. Muhlhauser, M. Hollick, O. von Stryk, and B. Freisleben, "Emergency communication in challenged environments via unmanned ground and aerial vehicles," in *Proc. IEEE Global Humanitarian Technol. Conf. (GHTC)*, Oct. 2017, pp. 1–9.

[17] M. Abdelkader, Y. Lu, H. Jaleel, and J. S. Shamma, "Distributed real time control of multiple UAVs in adversarial environment: Algorithm and flight testing results," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2018, pp. 6659–6664.

[18] S. Baidya, Z. Shaikh, and M. Levorato, "FlyNetSim: An open source synchronized UAV network simulator based on ns-3 and ardupilot," in *Proc. 21st ACM Int. Conf. Modeling, Anal. Simulation Wireless Mobile Syst.*, Oct. 2018, pp. 37–45.

[19] N. P. Borges, C. G. Ghedini, and C. H. C. Ribeiro, "SUN–Stealth UAV networks: A cooperative local model to mitigate UAVs exposure to threats," in *Proc. IEEE Int. Conf. Syst., Man Cybern. (SMC)*, Oct. 2019, pp. 4316–4323.

[20] V. Cichella, I. Kaminer, V. Dobrokhodov, E. Xargay, R. Choe, N. Hovakimyan, A. P. Aguiar, and A. M. Pascoal, "Cooperative path following of multiple multirotors over time-varying networks," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 3, pp. 945–957, Jul. 2015.

[21] P. R. Soria, A. F. Palomino, B. C. Arrue, and A. Ollero, "Bluetooth network for micro-uavs for communication network and embedded range only localization," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2017, pp. 747–752.

[22] D. Liu, J. Wang, K. Xu, Y. Xu, Y. Yang, Y. Xu, Q. Wu, and A. Anpalagan, "Task-driven relay assignment in distributed UAV communication networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 11, pp. 11003–11017, Nov. 2019.

[23] S. Say, N. Aomi, T. Ando, and S. Shimamoto, "Circularly multi-directional antenna arrays with spatial reuse based MAC for aerial sensor networks," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 2225–2230.

[24] G. S. Radhakrishnan and S. Saripalli, "Target tracking with communication constraints: An aerial perspective," in *Proc. IEEE Int. Workshop Robotic Sensors Environ.*, Oct. 2010, pp. 170–175.

[25] O. K. Sahingoz, "Mobile networking with UAVs: Opportunities and challenges," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, May 2013, pp. 933–941.

[26] S.-J. Chung, A. A. Paranjape, P. Dames, S. Shen, and V. Kumar, "A survey on aerial swarm robotics," *IEEE Trans. Robot.*, vol. 34, no. 4, pp. 837–855, Aug. 2018.

[27] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A tutorial on UAVs for wireless networks: Applications, challenges, and open problems," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2334–2360, 3rd Quart., 2019.

[28] O. S. Oubbati, M. Atiquzzaman, T. A. Ahanger, and A. Ibrahim, "Softwarization of UAV networks: A survey of applications and future trends," *IEEE Access*, vol. 8, pp. 98073–98125, 2020.

[29] B. Alzahrani, O. S. Oubbati, A. Barnawi, M. Atiquzzaman, and D. Alghazzawi, "UAV assistance paradigm: State-of-the-art in applications and challenges," *J. Netw. Comput. Appl.*, vol. 166, Sep. 2020, Art. no. 102706.

[30] D. Deng, W. Jing, Y. Fu, Z. Huang, J. Liu, and K. Shimada, "Constrained heterogeneous vehicle path planning for large-area coverage," in *Proc. IEEE Int. Conf. Intell. Robot. Syst.*, Nov. 2019, pp. 4113–4120.

[31] R. Bardhan, T. Bera, and S. Sundaram, "A decentralized game theoretic approach for team formation and task assignment by autonomous unmanned aerial vehicles," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2017, pp. 432–437.

[32] C. Luo, P. Ward, S. Cameron, G. Parr, and S. McClean, "Communication provision for a team of remotely searching UAVs: A mobile relay approach," in *Proc. IEEE Globecom Workshops*, no. 1, Dec. 2012, pp. 1544–1549.

[33] B. Kitchenham and S. Charters, *Procedures for Performing Systematic Literature Reviews in Software Engineering*. Keele, U.K.: Keele Univ. 2007.

[34] *EBSE: Welcome*. Accessed: Aug. 9, 2019. [Online]. Available: http://community.dur.ac.uk/ebse/

[35] S. Imtiaz, M. Bano, N. Ikram, and M. Niazi, "A tertiary study: Experiences of conducting systematic literature reviews in software engineering," in *Proc. 17th Int. Conf. Eval. Assessment Softw. Eng. (EASE)*, 2013, pp. 177–182.

[36] B. Kitchenham, "Evidence-based software engineering and systematic literature reviews," in *Product-Focused Software Process Improvement* (Lecture Notes in Computer Science), vol. 4034. New York, NY, USA, 2006, p. 3.

[37] A. B. Marques, R. Rodrigues, and T. Conte, "Systematic literature reviews in distributed software development: A tertiary study," in *Proc. IEEE 7th Int. Conf. Global Softw. Eng.*, Aug. 2012, pp. 134–143.

[38] B. A. Farshchian and Y. Dahl, "The role of ICT in addressing the challenges of age-related falls: A research agenda based on a systematic mapping of the literature," *Pers. Ubiquitous Comput.*, vol. 19, nos. 3–4, pp. 649–666, Jul. 2015.

[39] J. Palaskar, "Framing the research question using PICO strategy," *J. Dent. Allied Sci.*, vol. 6, no. 2, p. 55, 2017, doi: 10.4103/jdas.jdas_46_17.

[40] *Drone Laws: The History of Drone Regulations and Laws DARTdrones*. Accessed: Oct. 12, 2019. [Online]. Available: https://www.dartdrones.com/blog/drone-laws/

[41] B. Kitchenham and S. Charters, "Issue: EBSE 2007-001," Softw. Eng. Group School Comput. Sci. Math., Keele Univ., Keele, U.K., Tech. Rep. EBSE-2007-01, 2007, vol. 2, no. 3.

[42] J. Zhang, J. Yan, P. Zhang, and X. Kong, "Design and information architectures for an unmanned aerial vehicle cooperative formation tracking controller," *IEEE Access*, vol. 6, pp. 45821–45833, 2018.

[43] M. R. Brust, M. Zurad, L. Hentges, L. Gomes, G. Danoy, and P. Bouvry, "Target tracking optimization of UAV swarms based on dual-pheromone clustering," in *Proc. 3rd IEEE Int. Conf. Cybern. (CYBCONF)*, Jun. 2017, pp. 1–8.

[44] M. Fikri, A. Ashari, A. Dharmawan, and B. Alldino, "An overview of fundamental step using Wi-Fi communication for flight formation quadrotors," in *Proc. 4th Int. Conf. Sci. Technol. (ICST)*, Aug. 2018, pp. 1–5.

[45] R. Wieringa, N. Maiden, N. Mead, and C. Rolland, "Requirements engineering paper classification and evaluation criteria: A proposal and a discussion," *Requir. Eng.*, vol. 11, no. 1, pp. 102–107, Mar. 2006.

[46] V. Braun and V. Clarke, "Using thematic analysis in psychology," *Qualitative Res. Psychol.*, vol. 3, no. 2, pp. 77–101, 2006.

[47] V. Braun, V. Clarke, N. Hayfield, and G. Terry, "Thematic analysis," in *Handbook of Research Methods in Health Social Sciences*. Singapore: Springer, 2019, pp. 843–860.

[48] Justin Ford. (2018). *The History of Drones (Drone History Timeline From 1849 to 2018)*. DroneThusiast. Accessed: Jun. 10, 2019. [Online]. Available: https://www.dronethusiast.com/history-of-drones/

[49] *FAA National Forecast FY 2019-2039 Full Forecast Document and Tables*, Federal Aviation Admin., Washington, DC, USA, 2019. [Online]. Available: https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/fy2019-39_faa_aerospace_forecast.pdf

[50] L. Ding, L. Huang, S. Li, H. Gao, H. Deng, Y. Li, and G. Liu, "Definition and application of variable resistance coefficient for wheeled mobile robots on deformable terrain," *IEEE Trans. Robot.*, vol. 36, no. 3, pp. 894–909, May 2020.

[51] T. Krajna, "SCImago journal & country rank," *Polimeri*, vol. 29, no. 4, pp. 258–262, 2008.

[52] J. Walker. (2019). *Unmanned Aerial Vehicles (UAVs) Comparing the USA, Israel, and China*. www.emerj.com. Accessed: Apr. 2, 2020. [Online]. Available: https://emerj.com/ai-sector-overviews/unmanned-aerial-vehicles-uavs/

[53] *World of Drones: Who Has What: Countries Developing Armed Drones*. Accessed: Apr. 2, 2020. [Online]. Available: https://www.newamerica.org/international-security/reports/world-drones/who-has-what-countries-developing-armed-drones/

[54] S. Alqahtani, I. Riley, S. Taylor, R. Gamble, and R. Mailler, "Task allocation in uncertain environments using a QuadTree and flow network," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2018, pp. 74–83.

[55] J. Joaquin, A. Begoña, I. Maza, and A. Ollero, "Cooperative large area surveillance with a team of aerial mobile robots for long endurance missions," *J. Intell. Robotic Syst.*, vol. 70, no. 1, pp. 329–345, 2013.

[56] J. M. Diaz-Banez, E. Caraballo, M. A. Lopez, S. Bereg, I. Maza, and A. Ollero, "The synchronization problem for information exchange between aerial robots under communication constraints," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2015, pp. 4650–4655.

[57] E. Yanmaz, "Connectivity versus area coverage in unmanned aerial vehicle networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2012, pp. 719–723.

[58] N. Batsoyol and H. Lee, "Towards self-organizing UAV ad-hoc networks through collaborative sensing and deployment," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–7.

[59] K. Cesare, R. Skeele, S.-H. Yoo, Y. Zhang, and G. Hollinger, "Multi-UAV exploration with limited communication and battery," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2015, pp. 2230–2235.

[60] X. Zhu, Y. Liang, and M. Yan, "A flexible collision avoidance strategy for the formation of multiple unmanned aerial vehicles," *IEEE Access*, vol. 7, pp. 140743–140754, 2019.

[61] Y. Zhang, B. Zhang, X. Yi, and J. Zhang, "Transmitter-selection aided adaptive consensus-based data sharing for UAV swarms," *IEEE Access*, vol. 7, pp. 182217–182224, 2019.

[62] J. J. Acevedo, B. C. Arrue, J. M. Diaz-Banez, I. Ventura, I. Maza, and A. Ollero, "Decentralized strategy to ensure information propagation in area monitoring missions with a team of UAVs under limited communications," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, May 2013, pp. 565–574.

[63] J. J. Acevedo, N. R. J. Lawrance, B. C. Arrue, S. Sukkarieh, and A. Ollero, "Persistent monitoring with a team of autonomous gliders using static soaring," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2014, pp. 4842–4848.

[64] J. J. Acevedo, B. C. Arrue, I. Maza, and A. Ollero, "A decentralized algorithm for area surveillance missions using a team of aerial robots with different sensing capabilities," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2014, pp. 4735–4740.

[65] J. J. Acevedo, B. C. Arrue, I. Maza, and A. Ollero, "A distributed algorithm for area partitioning in grid-shape and vector-shape configurations with multiple aerial robots," *J. Intell. Robotic Syst.*, vol. 84, nos. 1–4, pp. 543–557, Dec. 2016.

[66] M. I. Akbas and D. Turgut, "APAWSAN: Actor positioning for aerial wireless sensor and actor networks," in *Proc. IEEE 36th Conf. Local Comput. Netw.*, Oct. 2011, pp. 563–570.

[67] A. Bahnik goleman, D. boyatzis, and R. Mckee, "Collaborative data exchange architecture," *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2013.

[68] I. Bekmezci, "Location information sharing with multi. Flying ad hoc networks—ResearchGate.pdf," in *Proc. Int. Conf. Recent Adv. Space Technol. (RAST)*, Istanbul, Turkey, 2015, pp. 669–673, doi: 10.1109/RAST35008.2015.

[69] B. Das, M. S. Couceiro, and P. A. Vargas, "MRoCS: A new multi-robot communication system based on passive action recognition," *Robot. Auto. Syst.*, vol. 82, pp. 46–60, Aug. 2016.

[70] M. Elchin, "Long-range communication framework for autonomous UAVs," Ph.D. dissertation, School Elect. Eng. Comput. Sci., Dept. Eng., Univ. Ottawa, Ottawa, ON, Canada, 2013, p. 89.

[71] A. Sivakumar, T.-S. Phang, C. K. Y. Tan, and W. K. G. Seah, "Robust airborne wireless backbone using low-cost UAVs and commodity WiFi technology," in *Proc. 8th Int. Conf. ITS Telecommun.*, Oct. 2008, pp. 373–378.

[72] Y. Hou, X. Liang, J. Zhang, Y. Li, and J. Wang, "Online route planning for cooperative area coverage search of aircraft swarm," *J. Phys., Conf. Ser.*, vol. 1187, no. 5, Apr. 2019, Art. no. 052001.

[73] J. Braga, R. P. Jain, A. P. Aguiar, and J. B. de Sousa, "Self-triggered time coordinated deployment strategy for multiple relay UAVs to work as a point-to-point communication bridge," in *Proc. Workshop Res., Educ. Develop. Unmanned Aerial Syst. (RED-UAS)*, Oct. 2017, pp. 1–6.

[74] Q. Lin, X. Wang, and Y. Wang, "Cooperative formation and obstacle avoidance algorithm for multi-UAV system in 3D environment," in *Proc. 37th Chin. Control Conf. (CCC)*, Jul. 2018, pp. 6943–6948.

[75] Y. Tang, Y. Hu, J. Cui, F. Liao, M. Lao, F. Lin, and R. S. Teo, "Vision-aided multi-UAV autonomous flocking in GPS-denied environment," *IEEE Trans. Ind. Electron.*, vol. 66, no. 1, pp. 616–626, Jan. 2019.

[76] M. Thammawichai, S. P. Baliyarasimhuni, E. C. Kerrigan, and J. B. Sousa, "Optimizing communication and computation for multi-UAV information gathering applications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 54, no. 2, pp. 601–615, Apr. 2018.

[77] M. Zhu, Y. Chen, Z. Cai, and M. Xu, "Using unmanned aerial vehicle chain to improve link capacity of two mobile nodes," in *Proc. IEEE Int. Conf. Mechatronics Autom. (ICMA)*, Aug. 2015, pp. 494–499.

[78] D. Pack, G. Dudevoir, P. Lima, and S. Gruber, "Negotiating between communication and cooperation for multiple unmanned aerial vehicles," in *Proc. MILCOM IEEE Mil. Commun. Conf.*, Oct. 2009, pp. 1–6.

[79] J. Denny, A. Giese, A. Mahadevan, A. Marfaing, R. Glockenmeier, C. Revia, S. Rodriguez, and N. M. Amato, "Multi-robot caravanning," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 5722–5729.

[80] L. Ma and N. Hovakimyan, "Cooperative target tracking in balanced circular formation: Multiple UAVs tracking a ground vehicle," in *Proc. Amer. Control Conf.*, Jun. 2013, pp. 5386–5391.

[81] H. Oh, H.-S. Shin, S. Kim, P. Ladosz, and W.-H. Chen, "Communication-aware convoy following guidance for UAVs in a complex urban environment," in *Proc. 24th Medit. Conf. Control Autom. (MED)*, Jun. 2016, pp. 1230–1235.

[82] M. Hassanalian and A. Abdelkefi, "Classifications, applications, and design challenges of drones: A review," *Progr. Aerosp. Sci.*, vol. 91, pp. 99–131, May 2017.

[83] I. Jawhar, N. Mohamed, and J. Al-Jaroodi, "UAV-based data communication in wireless sensor networks: Models and strategies," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2015, pp. 687–694.

[84] J. Li, Y. Zhou, and L. Lamont, "Communication architectures and protocols for networking unmanned aerial vehicles," in *Proc. IEEE Globecom Work. GC Wkshps*, Dec. 2013, pp. 1415–1420.

[85] C. Park, N. Cho, K. Lee, and Y. Kim, "Formation flight of multiple UAVs via onboard sensor information sharing," *Sensors*, vol. 15, no. 7, pp. 17397–17419, Jul. 2015.

[86] S. N. Ghazbi, Y. Aghli, and A. A. Akbari, "Quadrotors unmanned aerial vehicles?: A review quadrotors unmanned aerial vehicles?: A review," *Int. J. Smart Sens. Intell. Syst.*, Mar. 2017, doi: 10.21307/ijssis-2017-872.

[87] A. Srivastava and J. Prakash, "Future FANET with application and enabling techniques: Anatomization and sustainability issues," *Comput. Sci. Rev.*, vol. 39, Feb. 2021, Art. no. 100359.

[88] S. Roy, D. Tomasi, M. Conti, S. Bhusal, A. Roy, and J. Li, "Optimizing message ferry scheduling in a DTN," in *Proc. 16th ACM Int. Symp. Mobility Manage. Wireless Access (MobiWac)*, 2018, pp. 113–117.

[89] D. Pack, G. Dudevoir, P. Lima, and S. Gruber, "Negotiating between communication and cooperation for multiple unmanned aerial vehicles," in *Proc. Mil. Commun. Conf. (MILCOM)*, 2009, pp. 1–6.
[90] A. Sharma, P. Vanjani, N. Paliwal, C. M. W. Basnayaka, D. Nalin K. Jayakody, H.-C. Wang, and P. Muthuchidambaranathane, "Communication and networking technologies for UAVs: A survey," 2020, *arXiv:2009.02280*. [Online]. Available: http://arxiv.org/abs/2009.02280
[91] J. Sánchez-García, J. García-Campos, M. Arzamendia, D. Reina, S. Toral, and D. Gregor, "A survey on unmanned aerial and aquatic vehicle multi-hop networks: Wireless communications, evaluation tools and applications," *Comput. Commun.*, vol. 119, pp. 43–65, Apr. 2018.
[92] T. Greicius, "Robotic navigation tech will explore the deep ocean," Jet Propuls. Lab., California Inst. Technol., Pasadena, CA, USA, Tech. Rep., 2021.
[93] T. D. E. Silva, E. D. Melo, P. Cumino, D. Rosário, E. Cerqueira, and E. P. D. Freitas, "STFANET: SDN-based topology management for flying ad hoc network," *IEEE Access*, vol. 7, pp. 173499–173514, 2019.
[94] G. M. Leal, I. Zacarias, J. M. Stocchero, and E. P. D. Freitas, "Empowering command and control through a combination of information-centric networking and software defined networking," *IEEE Commun. Mag.*, vol. 57, no. 8, pp. 48–55, Aug. 2019.

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