A systematic literature review on communication patterns in multi-drone missions

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***Abstract*—Unmanned aerial vehicles, colloquially known as drones, have gained significant attention for its application in various fields. Multi-drone missions involve the coordinated operation of multiple drones working together on some common task. There are many different processes and characteristics that complicate multi-drone missions. The communication between the drones is in particular crucial for a successful operation.**

This systematic literature review addresses a gap in existing research by reviewing primary studies on multi-drone missions. It investigates used communication patterns, categorizes and analyzes them based on some characteristics. Finally it investigates what should be included in a high-level communication layer between agents in a multi-drone mission.

The review was done following the approach proposed by Kitchenham. Multiple databases were searched, and after study selection 27 articles were used for data extraction. Data extraction and synthesis was done on these articles to derive insights. Multiple categories of communication patterns, specific communication patterns and characteristics were identified.

The findings highlight the prevalence of certain communication patterns, and their association with some characteristics. In particular it underscored the importance of drone hierarchy and structure, swarm coordination, and communication targets in multi-drone missions. Command messages, location data, sensor data, and multimedia data were identified as crucial components. Based on these findings the study proposes that a high-level communication layer between drones should address the communication pattern categories and be tailored for autonomous and hybrid agent in a general mission context.

***Index Terms*—multi-drone, communication patterns, software engineering, systematic literature review**

I. Introduction

Unmanned Aerial Vehicles (UAVs), also commonly called drones, are aircraft without an onboard human pilot [1]. A multi-drone mission refers to a coordinated operation involving multiple drones that work in tandem to achieve a specific objective. These missions can vary in complexity, from simple tasks like aerial photography to more advanced operations such as search and rescue, surveillance, data collection and more [2]. Multi-drone missions can cover larger areas and handle more complex tasks.

Effective communication between drones is crucial for the success of these missions, as sharing important data and coordinating actions in real-time is vital for achieving the mission goals [2] [3]. Other studies have categorized some parts related to the communication patterns, data and structure of multi-drone missions, however, they have not focused on all aspects, nor provided a perspective of what should be included in a high-level communication layer between agents in a multi-drone mission [2] [3] [4].

Previous studies either focus on a specific point of interest or a specific mission in communication between agents, or conduct a survey to compare techniques. Conducting a systematic literature review could offer a more comprehensive understanding of communication patterns and their relationship to missions. Specifically, there is a lack of research that provides a holistic view of a high-level communication layer, including the data sent, received, and the methods of communication used.

To this end, this paper aims to address the following research questions:

- **RQ1**: *What communication patterns are used in multi-drone missions?*
- **RQ2**: *How can these communication patterns be categorized based on related characteristics?*
- **RQ3**: *What should be included in a high-level communication layer between agents in a multi-drone mission based on the categorization of communication patterns?*

The contribution of this study is a systematic literature review that offers an overview of communication patterns used in multi-drone missions. Additionally, the study will categorize these communication patterns based on related characteristics. Such as the type of data sent and received, mission context, communication method, and types of agents involved. Finally, the study provides a holistic perspective of what should be included in a high-level communication layer between agents in a multi-drone mission.

The remainder of the paper is organized as follows. The research method in section II details the research method used and each step within it. The following results and analysis section, in section III, goes through the synthesis data. The discussion in section IV discusses the results and the threats to validity. Finally, in section V, a conclusion is given to the study.

II. Research Methods

To address the research questions identified in section I the systematic literature review method proposed by Kitchenham [5] was selected.

This method was selected as it is suitable for this domain as it is targeted towards software engineering.

A systematic literature review is a secondary study that involves collecting and aggregating evidence from multiple primary studies through a systematic search and data extraction process.

A. Search Process

The search process was done using several scientific databases to provide a wide coverage. The list of databases is provided in table I. Only conference papers and journal articles were included in the search results. Results after 2022 were excluded from the search. A search string was developed by finding related keywords that match those commonly found in relevant literature.

The following query was used for each database:

(”multi-drone” OR ”multi drone” OR ”multi uav” OR ”multi-uav” OR ”swarm”)
AND
(”mission” OR ”missions” OR ”mission context” OR ”mission type” OR ”planning”)
AND
(”communication pattern” OR ”protocol” OR ”architecture”)
AND
”communication”

TABLE I
Searched Databases

Source	Results	Search Date
IEEE Xplore	426	2023-11-16
Scopus	261	2023-11-16
ACM Digital library	519	2023-11-17
Web of Science Core	139	2023-11-18
EI Compendex	166	2023-11-17
Total	1551	

B. Article exclusion

Following the search process, the resulting articles were reviewed and articles that fit the exclusion criteria or didn’t fit the inclusion criteria were removed. The list of criteria is displayed in table II. In the first stage, all duplicates were removed. Subsequently, papers were excluded based on title and abstract to remove off-topic papers. All papers with less than 10 citations were removed at this point. In the final exclusion stage papers were excluded based on full text where each paper was reviewed again. This process is detailed in fig. 1 and includes the amount of papers removed or included at each stage in the process.

TABLE II
Exclusion Criteria

Criterion	Type
Published after 2022-12-31	Exclusion
Not a journal article or conference paper	Exclusion
Secondary study	Exclusion
Less than 10 citations	Exclusion
Focus on a single drone system	Exclusion
Paper on or concerning multi-drones	Inclusion
Concerns or mentions protocols, architectures, frameworks or similar in the context of communication	Inclusion

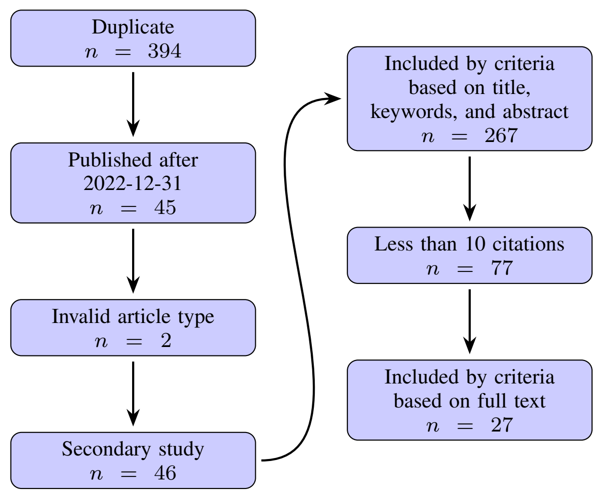

Fig. 1. Exclusion Process

C. Quality assessment

Quality assessment was based on a quality checklist proposed by Dybå, T. Dingsøyr, T. [6]. The assessment evaluated research methodology, minimizing bias and enhancing the objectivity of the SLR. A total of 4 quality checklist questions were created, any paper with 2 or more questions answered negatively were rejected due to lack of quality. No papers had 2 or more questions answered negatively and thus no papers were rejected.

The following questions were formulated based on the previously mentioned quality checklist:

1) Is there a clear statement of the aims of the research?
2) Was the research design appropriate to address the aims of the research?
3) Is there a clear statement of the findings?
4) Are validity and limitations of the study discussed?

D. Data extraction

Extraction of data was done using an adapted version of the data extraction form proposed by Dybå and Dingsøyr [6]. The form was split into two parts, one dealing with the study metadata and one dealing with the specific findings of the study. The suggested form was tailored to fit this study and only relevant fields were left in consideration. The form can be seen in table II in Appendix A. All papers were read through and the relevant data was extracted for each article. The outcome of this process is a list of extraction forms for each of the 27 articles.

E. Data synthesis

Data synthesis was done on the collected data from the data extraction step. The goal of the process was to identify communication pattern categories shaping multi-drone missions, and to relate the identified categories to predefined characteristics. In the following, (1) the identified communication pattern categories will be presented, (2) the characteristics to relate the communication pattern categories will be presented.

In the first step, the communication pattern categories were identified based on the extracted data. They can be found in table III. While inspecting the extracted data communication patterns were identified and grouped into categories. Each category represents a container for similar communication patterns. A scientific study was placed in a category if it described a fitting communication pattern. Thus, a paper can show up in multiple communication pattern categories if it describes multiple patterns.

TABLE III
IDENTIFIED COMMUNICATION PATTERN CATEGORIES

ID	Category	Description	Papers
CP1	Routing protocol	Routing strategy between networks.	[7]
CP2	Drone Hierarchy & Structure	Drones connected in some hierarchy or structure, and swarm architecture.	[8] [9] [7] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21]
CP3	Communication Targets	What entities does the drone communicate with? UAV, GCS, Satellite, terrestrial vehicles?	[22] [23] [24] [25] [10] [20] [26] [27]
CP4	Task Distribution	How tasks are distributed within the drone swarm and the implications for the network topology.	[13] [28] [29] [30]
CP5	Swarm Coordination & Communication Strategies	Communication strategies, and swarm organization.	[23] [17] [11] [28] [30] [13] [18] [31] [19]

In the second step, typical characteristics of multi-drone communication were collected to relate them to communication patterns at a later step. Therefore, tables were created for the characteristics addressed in RQ2: mission context, data sent and received, communication method, and types of agents. The tables were filled with the different expressions of the characteristics by analyzing the extracted data.

In the following, an overview of the four characteristics is given:

- *Mission context*. The characteristic describes the context in which the multi-drone mission was carried out. The contexts were chosen based on the analyzed papers and mostly comprise of specific contexts (e.g. disaster response). However, a considerable group of the papers does not provide a specific context. Those papers are grouped in an abstract context category called 'General'. The related studies can be found in table IV.
- *Data sent and received*. The characteristic describes the data sent and received within the communication of the multi-drone mission. The data is grouped into high-level data categories like 'Command Messages' or 'Multimedia Data'. This conforms with the overall study design, which aims to analyze the high-level communication layer of multi-drone missions. The related studies can be found in table V.
- *Communication method*. The characteristic describes how data was distributed between the different agents of the multi-drone mission. The selected communication methods focus less on technical protocols, but more on communication methods on an architectural level, thus conforming with the other characteristics. The related studies can be found in table VI.
- *Types of agents*. The characteristic describes the agents that were involved in the multi-drone mission. The identified agents range from human operators to fully autonomous drone swarms, including hybrid agent setups respectively. The related studies can be found in table VII.

III. RESULTS AND ANALYSIS

In this section, the results from the data synthesis are gone through and analyzed.

A. Identified Communication Patterns

With RQ1 in mind, the analysis of the extracted and synthesized data identified multiple communication patterns in multi-drone missions. Due to the enormous variety of patterns, categories of patterns were formed. Of the five formed categories, four address communication on a conceptual level. Only one of the categories, 'Routing Protocol' (CP1), tackles a more algorithmic level. The observed distribution is a consequence of the study design, which aims at identifying and describing the high-level communication layer in multi-drone missions.

Considering the distribution of the studies between the different communication pattern categories, 15 of the 25 papers involved the category 'Drone Hierarchy & Structure' (CP2) in their argument. That is nearly 100% more often than the third largest category, 'Communication Targets' (CP3), and at least 66% more often than the second largest category, 'Swarm Coordination & Communication Strategies' (CP5). Hence, the organization and structure of drone swarms seems to be an essential aspect of multi-drone mission communication.

TABLE IV
MISSION CONTEXT

ID	Mission Context	Description	Papers
MC1	General	Performing general missions that are not specific to any context.	[7] [18] [11] [12] [19] [17]
MC2	Disaster Response (including search and rescue)	Supporting or performing disaster response missions.	[10] [31] [28] [21] [15] [27]
MC3	Patrol, Reconnaissance & Attack	Localizing targets and attacking them.	[14] [13] [10] [29]
MC4	Network Support	Extension, support, or hotspot of networks. Improving network performance.	[24] [25] [30] [26]
MC5	Detection and Tracking	Detect and track something. Could be a hazardous plume from a biological weapon.	[10] [20]
MC6	Critical Infrastructure Maintenance and Surveillance	Protecting critical infrastructure by regularly checking the premises.	[32]
MC7	Crowd Surveillance	Especially in pandemic situations	[22]
MC8	Coordinated Formation Flight	Flying in formation. Could be for light shows or similar.	[16]

TABLE V
DATA SENT AND RECEIVED

ID	Data	Description	Papers
D1	Command Messages	Messages for communication and control	[7] [10] [16] [25] [32] [30] [27] [31] [17] [11] [12] [28] [19] [14] [20] [29]
D2	Multimedia Data	Images, Videos	[23] [7] [16] [27] [31] [11] [28]
D3	Location Data	Position, GPS, etc.	[30] [27] [7] [18] [24] [16] [31] [17] [11] [19] [20] [29]
D4	Drone Diagnostics	Sensor Data, General Drone Health, etc.	[13] [24] [22] [18] [10] [17] [14]
D5	Geometric Data	Edges and vertices of multi-drone graph for optimized routing of packets	[7]
D6	Attack, Weapon or Military related Data	Weapons available, distance from target, etc.	[13]
D7	WiFi Data	Hotspots	[25]

TABLE VI
COMMUNICATION METHOD

ID	Communication method	Description	Papers
CM1	Multicasting	Agent sends data to a specific group of other agents.	[9] [12] [28] [19] [14] [20]
CM2	Broadcasting	Agent sends data to all other agents.	[16] [25] [18] [31] [19]
CM3	Bidirectional communication	Bidirectional data flow, Sender and Receiver can switch roles	[13] [17] [11] [12]
CM4	Request Response	Unidirectional data flow	[16] [18] [29]

TABLE VII
TYPES OF AGENTS

ID	Types of agents	Description	Papers
A1	Hybrid	Both autonomous and human-operation possible	[8] [9] [23] [16] [10] [13] [33] [18] [11] [12] [28]
A2	Autonomous		[22] [7] [24] [25] [16] [10] [13] [21] [15] [27] [19] [14] [20]
A3	Human		[13] [31] [17] [28] [29]

B. *Identified Multi-Drone Mission Characteristics*

In order to answer RQ2, four characteristics to categorize the identified communication patterns from RQ1 have been defined: mission context, data sent and received, communication method, and types of agents involved. Regarding mission context, several contexts could be identified. However, most of the analyzed studies appear to have no specific mission context (MC1), or appear to claim to be universally applicable. Besides that, the most occurring contexts were disaster response (MC2) and military applications (MC3). As to be seen in the study distribution for the data sent and received, most papers involve some kind of command messages (D1). Other mentionable data types are location data (D3), followed by 'Drone Diagnostics' (D4) and 'Multimedia Data' (D2), however, less frequently mentioned than command messages.

Multi-casting (CM1), broadcasting (CM2), bidirectional communication (CM3), and request-response (CM4) were identified as occurring communication methods. Compared to the other characteristics, the distribution of the papers between the different communication methods is more even. While multi-casting seems to be the most mentioned method, broadcasting, and bidirectional communication come close to that number. Even request-response, which is mentioned the least, is mentioned in at least three studies. Another characteristic that should be related to the earlier identified communication patterns is the types of agents involved. A majority of the papers described multi-drone missions involving autonomous drone swarms (A2), i.e. drones communicate only with their fellow drones or other autonomous systems to accomplish their mission goal. The number of papers further increased when hybrid approaches (A1) were considered to be autonomous too. In the present table, they are not combined because hybrid approaches allow the mission to be controlled by a human operator or by an autonomous computational intelligence. Multi-drone missions that require a human operator (A3) are mentioned the least, if compared to the autonomous and hybrid approaches.

C. Relating Communication Patterns to Mission Characteristics

Each identified communication pattern category was categorized based on the extracted characteristics described in the former tables. This was done in order to answer RQ2 and lay the foundation for answering RQ3. More specifically, categorization was done by relating each communication pattern to every characteristic where one paper was associated with both. With the purpose of better identifying the significance of these associations the frequency of papers for each association per characteristics was also noted down. These results were tabulated in table VIII. Additionally, the table also includes examples of the specific patterns identified for each category.

A better overview of these results is shown in fig. III-C. Here the results from the previous table are shown in a heat map where the frequency is clearly visible. These results show that some of the identified communication pattern categories are covered significantly more than others. Particularly of note is CP2, Drone hierarchy and structure, which was associated with many characteristics and frequently associated with the same ones. Similarly, some of the characteristics were much more frequent than others. In part, this is due to how essential they are for the context of the paper, such as the type of agent characteristic, while those much more specific such as MC8, coordinated formation flight, weren't relevant in the context of most papers. Notably the general mission context, MC1, was highly frequented, however, the mission context as a category was not.

In all, the three communication patterns that were most frequented were CP2, Drone hierarchy and structure, CP5, swarm coordination, and lastly CP3, communication targets. The three categories of characteristics, that were most represented, were type of agent, communication method, and data sent & received. This would suggest that a high-level communication layer between drones should consider these things in order to be applicable to a wide, general use-case.

TABLE VIII
COMMUNICATION PATTERNS RELATED TO CHARACTERISTICS

ID	Category	Patterns	Related Characteristics
CP1	Routing protocol	Proactive, Store-carry-forward, LTA-OLSR SSR	MC1(1), A2(1), D1(1), D2(1), D3(1), D5(1)
CP2	Drone Hierarchy & Structure	Leader-follower hierarchy, Heterogeneous, Homogeneous, Swarm Cooperation, Swarm Mission-Driven Formation	A1(11), A2(9), A3(5), MC1(7), MC2(3), MC5(2), MC8(1), CM1(4), CM2(3), CM3(4), CM4(2), D1(9), D2(3), D3(8), D4(4), D5(2), D6(1)
CP3	Communication Targets	Drone, GCS, Satellite, Hotspot (for cellphones), Terrestrial vehicles	A1(2), A2(5), MC1(1), MC2(1), MC4(2), MC5(2), MC7(1), CM1(1) CM2(1), D1(3), D2(1), D3(2), D4(3), D7(1)
CP4	Task Distribution	Task Assignment (Coordinator assigns task), Task Propagation (Drones pick up tasks themselves)	A1(2), A2(1), A3(3), MC2(1) MC3(2), CM1(1) CM3(1), CM4(1), D1(2), D2(1), D3(1), D4(1), D6(1)
CP5	Swarm Coordination & Communication Strategies	The coordination method of the swarm, e.g. imperative commands, a shared digital map, etc. Covert & semi-covert strategies	MC1(6), MC2(2), A1(5), A3(4), CM1(2) CM3(4), CM4(1), D1(6), D2(5), D3(6), D4(3), D6(1)

IV. Discussion

In this section, the results are discussed. First, threats to validity are acknowledged and addressed. Secondly, a perspective is given on the implications of this study in terms of the meaning, importance and relevance of the results.

A. Threats to validity

Some threats to the validity of the study were identified. Due to time constraints, it was not possible to have every paper reviewed twice independently during the quality assessment and data extraction part. Because of this, the papers may have been interpreted differently introducing a bias in the extracted data and by extension the synthesized data. Furthermore, due to the aforementioned time constraints, an exclusion criterion for having less than 10 citations was added during the article exclusion stage. While this is not necessarily a threat to the validity of the study, it may have been selected for certain types of paper, and in such a case the study might not have wide coverage of papers or produce an inaccurate representation of the field. However, it was argued that selecting for highly cited papers could also increase the quality of the selected papers.

Another threat involved concerns about the definition and interpretation of what exactly constitutes a communication pattern. As this term isn't anything that is authoritatively defined it was largely left up to the interpretation of the data extractor. Again, this could have introduced a bias in the interpretation and categorization. It would have been appropriate to attempt to strictly define this term such that any bias would have been reduced.

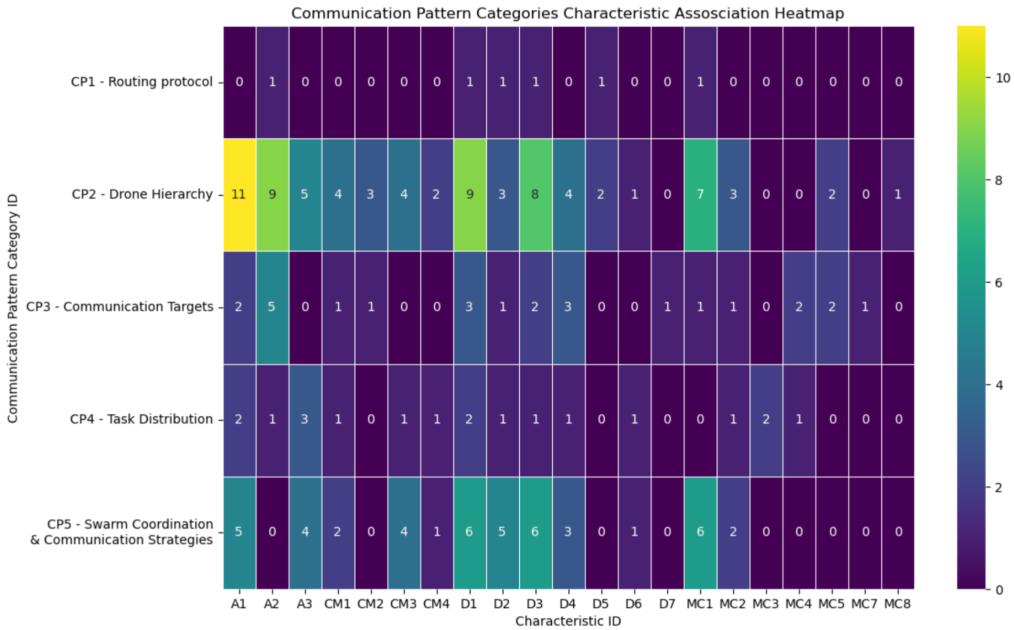

Fig. 2. Communication Patterns heat map

It is plausible that a number of limitations may affect the usefulness of these results. Particularly noteworthy is that the results are mostly focused on a general mission context, while it might be that a communication layer tailored to a specific mission context, such as search and rescue, could have different needs. This would hinder its usefulness in more fine-grained contexts. Moreover, the results are high-level in that they do not describe how the patterns are used, nor go into depth with the identified characteristics. As such, it may be too general for application where greater detail is needed.

B. *Implications*

The results of this study provided an insight into communications patterns used in multi-drone missions, how these are categorized and associated with related characteristics and finally a perspective on what should be included in a high-level communication layer between drones in a multi-drone mission.

Using the analysis and results, in relation to RQ3, a perspective on what should be included in a high-level communication layer between agents in a multi-drone mission is given. The communication layer should foremost include, and perhaps be structured around, a drone hierarchy & structure, in relation to CP2. Such structure should also be tailored towards incorporating different types of agents, primarily hybrid and autonomous ones. The behaviour of this structure, CP5, should be defined by including information on how these drones coordinate with the multi-drone structure. In regards to the data being sent, the communication layer should include command messages, location data and drone sensor data as these are often associated with the usage of a drone hierarchy & structure. To a lesser extent, they are also important in regards to the behavior of the multi-drone structure. Additionally, multi-media data is also important in this regard and should also be included. The mission context, based on the analysis done, should be aimed towards a general mission context that may support any mission context in which multi-drones are used.

Researchers and practitioners can utilize the findings of this paper in the creation or analysis of communication patterns addressing multi-drone missions. Also, the findings can be used to reason about the high-level communication layer of such missions. Having this knowledge in an aggregated form could make the process easier, faster and alleviate the need for a literature review on this subject where the intention is to figure out what such patterns or a communication layer should include.

V. Conclusion

In this paper, a systematic literature review was performed on communication patterns within the context of multi-drone missions. Multiple categories of communication patterns, individual patterns, and related characteristics were identified based on the reviewed papers.

Based on the synthesised data and categories, a perspective on what should be included in a high-level communication layer between agents in a multi-drone mission was given. The findings suggest that such a communication layer should include a specification in regards to the drone hierarchy and structure and the behavior of this structure. It should be tailored towards hybrid and autonomous agents in a general mission context. Moreover, such a communication layer should include command messages to transmit instructions between agents, location data of each drone, sensor data and multimedia data.

Some threats to the validity of the study were identified. There was a lack of thoroughness in the review due to articles not being analyzed twice, and there was a possibility of bias during the interpretation of data in the process of data extraction. While these results may have affected the validity it was argued that the results are still sufficiently useful.

The results provide researchers and developers with the necessary knowledge needed to develop or analyse a high-level communication layer in the described context. There are limitations in this regard as it can be too high-level for some use cases, and thus lacks sufficient depth, in particular in regards to specific mission contexts, as the results in this study were primarily targeted towards a general mission context. Further research can focus on providing a finer insight into what is relevant for a specific mission context.

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APPENDIX A
DATA EXTRACTION FORM

TABLE IX
DATA EXTRACTION FORM

Study description	Study identifier	Unique id ...
	Date of data extraction	
	Bibliographic reference	Article title
	Multi-drone mission context of the study	What was the context of the investigated multi-drone mission?
	Communication patterns of multi-drone missions tackled in the study	List of communication patterns
	Data types sent and received within the multi-drone mission of the study	Video data, image data, location data, ...
	Agents involved into the multi-drone mission of the study	Autonomous, human, hybrid, etc.
Study findings	Findings and conclusions, if relevant to RQs	
Quality assessment	Is there a clear statement of the aims of the research?	YES,NO:ELABORATION
	Was the research design appropriate to address the aims of the research?	YES,NO:ELABORATION
	Is there a clear statement of the findings?	YES,NO:ELABORATION
	Are validity and limitations of the study discussed?	YES,NO:ELABORATION