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

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***Abstract*—This document is a model and instructions for LaTeX. This and the IEEEtran.cls file define the components of your paper [title, text, heads, etc.]. *CRITICAL: Do Not Use Symbols, Special Characters, Footnotes, or Math in Paper Title or Abstract.**

***Index Terms*—component, formatting, style, styling, insert**

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. However 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].

This systematic literature review aims to explore the communication patterns, types of data exchanged, and the structure in multi-drone missions. By categorizing and analysing current communication patterns based on these aspects, this review seeks to provide insights into what a high-level communication layer should include to ensure effective communication in multi-drone missions.

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. We believe that 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.

The specific research questions we address in this paper is:

- **RQ1**: *What communication patterns are used in multi-drone missions?*
- **RQ2**: *How can these communication patterns be categorized based on the type of data sent and received, mission context, communication method and types of agents involved?*
- **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?*

II. Research Methods

In this process, we followed the guidelines for conducting a systematic literature review proposed by Kitchenham [5]. 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.

We first combined and synthesized findings from various studies related to the research topic. Relevant studies were gathered from the electronic databases of IEEE Xplore and Scopus using specific search strings.

Only studies published in peer-reviewed journals or conference proceedings were included. Specific criteria related to the research topic were used to determine which studies to include and assess their quality. The data extracted from these studies was then organized into relevant identified categories. The categorized data was further compiled and analyzed.

Overall, the systematic literature review process involved a rigorous and comprehensive approach to gather, analyze, and synthesize data, providing valuable insights and supporting evidence-based conclusions related to the research topic.

The expected outcome of this study is a systematic literature review that offers a more comprehensive understanding of communication patterns and their relationship to multi-drone missions. This study will classify data types transferred, agent-types, outline mission contexts like search and rescue or goods transport, architecture layer, and define the communication mode between agents. It aims to provide a holistic perspective of what should be included in a high-level communication layer in a multi-drone mission between agents.

A. Search Process

The search process was done using several scientific databases to provide a wide coverage. Databases such as ScienceDirect that imposes constraints on the amount of boolean operators in the query were not selected. During the search process it was also not possible to use SpringerLink due to errors with the database. 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 in the search. For each database the following query was used:

("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"

A total of 1551 results were found from all of the databases together.

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

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. In the first stage all duplicates were removed. Subsequently papers were excluded based on title and abstract to remove off-topic papers. In the final exclusion stage papers were excluded based on full text where each paper was reviewed for quality and suitability.

EXCLUSION CRITERIA NOT FORMATTED !!!DRAFT!!!

- Papers after 2022
- Papers that are not conference papers or journal articles
- Secondary studies
- Paper concerns solely single drone systems

Inclusion desu (generally relates to answering the RQs)

- Paper on multi-drone systems
- Speaks about protocols, architectures, frameworks or similar for communication

!!!DRAFT!!! Go over the number of papers excluded at each step.

C. Data extraction

The papers that remained after the article exclusion process have been used for data extraction. Because the number of papers after exclusion was still relatively high (concretely 96 papers), it has been decided to trim this number down by keeping only reviewed papers to ensure their sufficient quality. The exclusion criteria for this case was the number of paper citations, which we selected to keep only articles with 10 or more citations. After this process, we have been left out with 26 papers.

To extract data we used an adapted version of the data extraction form proposed by Dybå and Dingsøyr [6]. The form is split into two parts, one dealing with the study metadata and one dealing with the specific findings of the study. This suggested form has been tailored to our needs and only relevant fields have been left in consideration. Then all papers have been read through and the relevant data have been extracted for each article from the previous step. The outcome of this process is a list of extraction forms for each article.

D. Quality assessment

Quality assessment is crucial in a systematic literature review (SLR) on communication patterns in multi-drone missions. It serves as a gatekeeper, ensuring the validity and reliability of chosen studies. The assessment evaluates research methodology, minimizing bias and enhancing the objectivity of the SLR. Inclusion of high-quality studies improves generalizability and relevance to the research question. Beyond the review, it establishes a solid foundation for future research and decision-making. We adapted and followed the generic study quality checklist which is proposed by Dybå, T. Dingsøyr, T. [6] and made these following questions:

Q1: Is there a clear statement of the aims of the research?

Q2: Was the research design appropriate to address the aims of the research?

Q3: Is there a clear statement of the findings?

Q4: Are validity and limitations of the study discussed?

As a part of the extraction, also quality assessment of the papers has been conducted and is represented by the second part of the mentioned form. All the extraction forms can be found in the appendix **[?]**. The extracted data is synthesized in the next section.

Fig 1, shows the number of the papers where their quality assessment is positive. The Y-axis indicates the paper number.

Fig. 1. All positive result

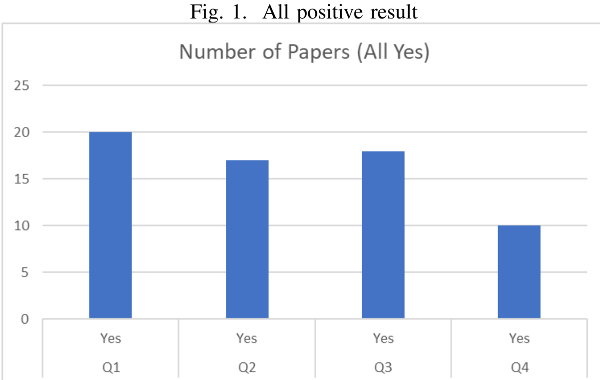
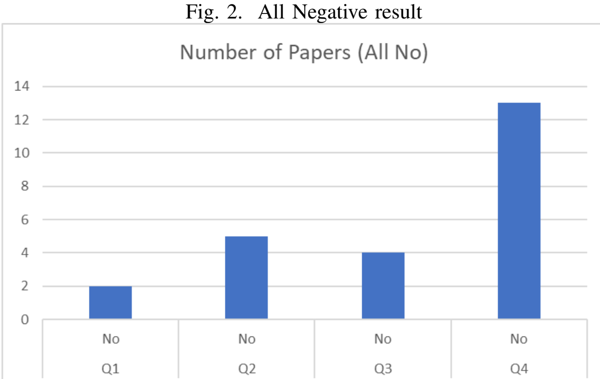


Fig 2, shows the number of the papers where their quality assessment is Negative. The Y-axis indicates the paper number.

Fig. 2. All Negative result



E. Data synthesis

Using the results of the data extraction and quality assessment, this subsection conducts the synthesis of the collected data. The goal of the proposed process is 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 to will be presented.

In a first step, the communication pattern categories were identified based on the extracted data. They can be found in table II. While inspecting the extracted data, the authors identified communication patterns and grouped them 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 II
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 a 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, a overview over 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 III.
- *Data sent and received*. The characteristic describes the data sent and received within the communication of the multi-drone mission. The data is grouped on 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 IV.
- *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 V.
- *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 VI.

TABLE III
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 attack 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 IV
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]

III. RESULTS AND ANALYSIS

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

TABLE V
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 VI
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]

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 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 a essential aspect of multi-drone mission communication.

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 multicasting 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 are 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 increases when hybrid approaches (A1) are 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 VII. Additionally the table also includes examples of the specific patterns identified for each category.

A better overview of these results are shown in fig. 3. Here the results from the previous table are shown in a heat map where the frequency are clearly visible. These results show that some of identified communication pattern categories are 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, wasn'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 was most represented was 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 VII
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)

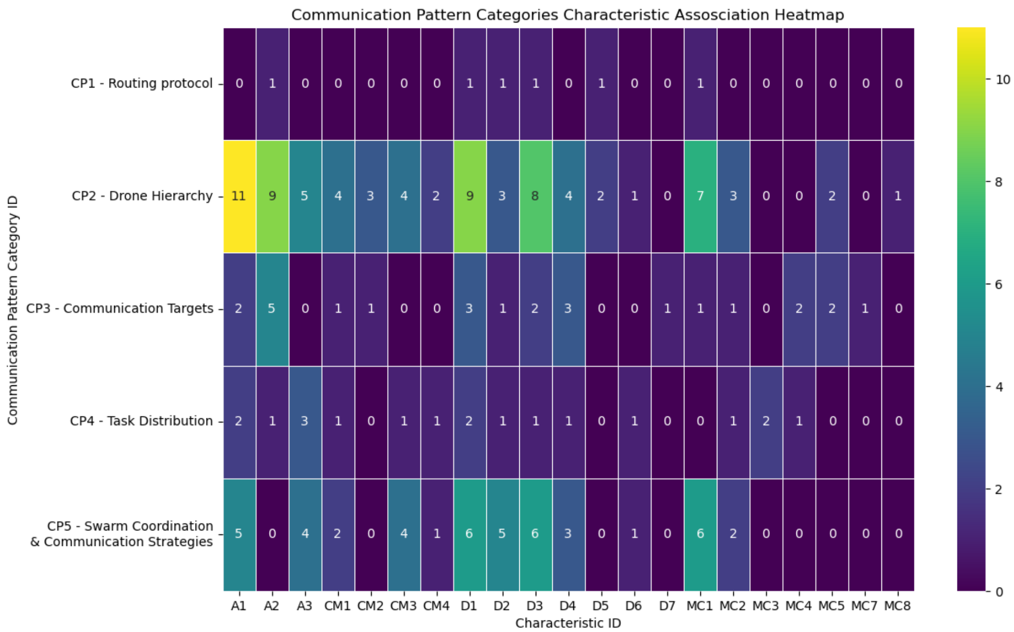
IV. DISCUSSION

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

A. Threats to validity

Some threats to the validity of the study have been identified. These threats revolve mainly around the data extract, quality assessment and by extension. Respectively these relate to interpretive and conclusion validity. Due to time constraints

Fig. 3. Communication Patterns heat map



it was not possible to have every paper be reviewed twice independently. Because of this the papers may have been interpreted differently introducing a bias in the extracted data and by extension the synthesized data. Additionally the same problem occurred during the quality assessment step.

Moreover, there were 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.

It is plausible that a number of limitations may affect the usefulness of these results. Particularly noteworthy is that these results are mostly focused on a general mission context, while it might be that a communication layer tailored to a specific mission context 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 some use.

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 to 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 done 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 multi-media data. Some threats to the validity of the study were identified as there was a lack of thorough review and a possibility of bias during the interpretation of data when the data extraction. The results may provide researchers and developers with the necessary knowledge needed to develop or analyse a high-level communication layer in the described context. However there may be limitations in this regard as it may be too high-level and insufficient, in particular in regards to specific mission contexts as the results in this study were primarily targeted towards a general mission context.

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