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Review

The Use of Swarms of Unmanned Aerial Vehicles in Mitigating Area Coverage Challenges of Forest-Fire-Extinguishing Activities: A Systematic Literature Review

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Abstract: The use of Unmanned Aerial Vehicles (UAVs), colloquially known as drones, has grown rapidly over the past two decades and continues to expand at a rapid pace. This has resulted in the production of many research papers addressing the use of UAVs in a variety of applications, such as forest firefighting. The main purpose of this paper is to provide a comprehensive overview of UAV-based forest-fire-extinguishing activity (FFEA) operations. To achieve this goal, a systematic literature review was conducted to answer a specific set of questions, which were carefully formulated to address the results of research conducted between 2008 and 2021. This study aims to (i) expand our understanding of the development of UAVs and their current contributions to the FFEA; (ii) identify particularly novel or unique applications and characteristics of UAV-based fire-extinguishing systems; (iii) provide guidance for exploring and revising further ideas in this field by identifying under-researched topics and other areas in which more contributions are needed; and (iv) explore the feasibility of using UAV swarms to enable autonomous firefighting in the forest without human intervention. Of the 1353 articles systematically searched across five databases (Google Scholar, ACM Digital Library, Science Direct, Scopus, and IEEE Explore), 51 highly relevant articles were found to meet the inclusion criteria; therefore, they were analyzed and discussed. The results identified several gaps in this field of study among them the complexity of coordination in multi-robotic systems, the lack of evaluation and implementation of fire extinguishing systems, the inability of handling multiple spot fires, and poor management of time and resources. Finally, based on the conducted review, this paper provides significant research directions that require further investigations by researchers in this field including, the deployment of UAV-based Swarm Robotics, further study on the characteristics of the fire extinguishing systems; design more effective area coverage; and the propose of a self-firefighting model that enables individuals to decide on the course of events efficiently and locally for better utilization and management of time and resources.

Keywords: unmanned aerial vehicle; swarm robotics; firefighting systems; forest fire; area coverage

1. Introduction

Mobile robots are among the most essential modern technologies that have gained significant attention in many applications over the past two decades [1]. Robotic systems can support or replace human beings in a wide range of tasks due to their ability to operate in different situations and environmental conditions [2]. One particular type of these robots is the UAVs, or drones that move in three-dimensional space [3]. Indeed, the ability to reach difficult and dangerous environments is a limitation for humans, as is short response time, low cost and low speed to the target. This makes drones a promising technology for the FFEA and many other tasks such as disaster management, emergency response, product delivery, surveillance, inspection, photography, agricultural pesticide control, infrastructure, and firefighting in the forests [4,5].

Forests are one of the most important aspects of nature, and have many important functions related to nature. They are involved in improving the climate, stabilizing soil, storing carbon, purifying water, etc. They also provide shelter and an integrated breeding environment that supports the biological diversity of wildlife. Economically, a forest provides thousands of jobs through industrial products derived from it, contributing to billions of dollars in economic wealth. Unfortunately, forest fires destroy millions of hectares every year and cost governments millions of dollars to extinguish, resulting in economic losses, human deaths, and major environmental damage [6,7]. Firefighting in the forest is one of the most challenging and dangerous tasks for human beings because it demands the ability to determine the state of the environment in a limited time, detect the fire spot, and effectively suppress the fire. Many research studies have been conducted to develop a novel system to address this issue by controlling the firefighting mission remotely. Recently, there has been a great interest in detecting and fighting forest fires autonomously by using UAVs [8]. The most common fundamental challenges in firefighting missions are the monitoring, organization, coordination, and management of a large number of robots working under complex and unpredictable conditions [2]. The risk of the task in firefighting is the most challenging. Therefore, it is necessary to perform the task at the highest possible level and in the shortest possible time [5]. Fire extinguishing is the last stage of firefighting after the fire has been detected and evaluated. Thus, firefighting in real-time is a major issue that requires the development of advanced control strategies. In this respect, UAV-based technology in firefighting systems has been used for forest fire detection and monitoring, post-fire recovery monitoring [9], building fire risk maps, bushfire hotspot detection [10], forest surveillance [11], and support for disaster relief operations. Despite the fact that fire monitoring and detection problems have been increasingly stressed in the state of the art, the development of effective UAV-based FFEA techniques is still missing in the literature [4]. Given these promising research efforts and the lack of literature assessing the current status of UAV technology use in forest firefighting, it is, therefore, extremely important to address and review this topic. UAVs are used in activities where both response time and efficiency in completing a mission are critical. Therefore, researchers have focused their advances and research toward the use of multi-robotic systems (MRS), in which a group of Unmanned Aerial Vehicles operate autonomously and coordinate in the same environment. This technological solution, based on the coordinated use of multiple UAVs, makes it possible to obtain a more versatile instrument capable of performing more complex tasks, thus improving the overall load capacity of the system, as well as increasing its efficiency and independence.

Therefore, there is a need to research and develop new technologies and applications that will allow these aircraft to perform more complex tasks with greater versatility (e.g., load capacity, longer mission time, and independent operations), even as new tools become available to improve the effectiveness of firefighting missions. In parallel with these developments, legislative changes are needed to make the use of UAVs professional, powerful, and more flexible, with a maximum launch mass that is quite large relative to the weight of the UAV. This will enable the integration of autonomous UAVs into airspace, and equipment with artificial intelligence (AI) systems that can operate without a pilot.

The research conducted in this study can be divided into two parts:

i. We conduct a systematic literature review (SLR) of the literature addressing the use of UAVs in firefighting applications and provide a comprehensive overview of the use of drones in FFEA. Additionally, we highlight the most important studies and research that use UAVs in firefighting applications, especially those that depend on multi-robotic systems.
ii. We display and discuss an outline of the research topics in UAV-based FFEA application.

It should be noted that the terms “drone technology” and “unmanned aerial vehicle (UAV)” are used interchangeably in this article to describe the same concept.

The rest of this paper is organized as follows: In Section 2, we introduce, in detail, the SLR methodology steps. The main results are analyzed and discussed in Section 3. Section 4 concludes the paper with a conclusion and describes the future work planned.

2. SLR Methodology

Prior to conducting the systematic review in this paper, we searched the Google Scholar database to identify whether there were any other secondary works such as surveys, reviews, taxonomies, and SLRs about FFEA (performed on 15 January 2021). The following was used as a search string:

(Unmanned Aerial Vehicles OR Drones) AND (Forests Firefighting) AND (Review OR SLR OR Survey OR Taxonomy OR Research overview).

The search revealed no SLRs related to FFEA except for three articles that discussed fire detection, localization, and forest fire monitoring using UAVs [12–14]. However, these studies mainly focused on monitoring and detecting forest fires, ignoring the task of fire extinguishing and the challenges faced by drones while performing the task of extinguishing fires. In addition, they overlooked the most critical topics covered by various research articles, such as system design, control and motion planning, path planning, cooperative control, tracking, coordination, resource allocation, coverage, and task assignment, which focused on the applications of fire extinguishing using UAVs. Below is a brief discussion of them.

In Yuan et al. [4] and Akhloufi et al. [12], a survey about using UAVs and remote sensing techniques in forest fire monitoring, detection, and fighting was conducted. However, the study focused only on UAV-based forest fires on the subject of monitoring, detection, diagnosis, and prognosis systems, and yet, this research did not consider the fire-extinguishing characteristics. In addition, the challenges that UAVs face in these applications and the potential importance of emerging technologies in UAV applications were not addressed in these surveys.

Roldán-Gómez et al. [13] conducted interviews and surveys with fire professionals by preparing two sets of questions, to find out the main problems they face in their work, and their views on possible technological solutions to basic firefighting tasks such as prevention, control, and extinguishing. However, the above article did not highlight the most effective methods, current challenges, algorithms, and strategies that contributed to extinguishing the fire using a swarm of drones.

It is worth noting that the number of papers above was 16% for [4], 5% for [12], and 1% for [13], respectively, of the number of papers covered by our paper. The papers mentioned above can help to understand the principles with regard to firefighting missions with drones. Still, none discussed UAV-based forest-fire-extinguishing activities—such as specification, classification, algorithms, strategies, and implementation on robotics systems—in great detail. Therefore, to the best of our knowledge, no systematic literature study has been conducted to review the research addressing UAV-based FFEA applications.

The significant increase in research in the fields of computer science in general, and the artificial intelligence that uses UAV-based applications, in particular, has made SLR a very important tool to help analyze evolution in these fields. Following recent studies, a systematic literature review is performed, following a well-defined procedure to retrieve papers relevant to this research scope.

According to Kitchenham [14], the SLR is “a form of secondary study that uses a well-defined methodology to identify, analyze, and interpret all available evidence related to a specific research question in a way that is unbiased and (to a degree) repeatable”. The term “secondary study” refers to “a study that reviews all the primary studies relating to a specific research question”. A primary study is defined, in this paper, as a research paper that answers a specific research question in the domain of UAV-based FFEA. The aims of these SLRs can be summarized in three points: (i) to summarize the current evidence about a commonly used technology; (ii) to find gaps in recent research in order to recommend areas for further research; and (iii) to provide a framework in which new research activities can be positioned. In order to achieve these aims, we based our SLR on the guidelines proposed by Budgen and Brereton [15] and Kitchenham et al. [16], which are two of the most popular SLR methodologies for computer science. This method guarantees objectivity, fairness, and repeatability. Figure 1 illustrates each step of the methodology adopted for this review, in which the number of corresponding articles retrieved or retained is illustrated at the end of each step [17,18]. In addition, the research followed Kitchenham's SLR methodology guidelines for capturing the required scholarly materials—planning, conducting, and reporting [14]—to avoid the possibility of bias.

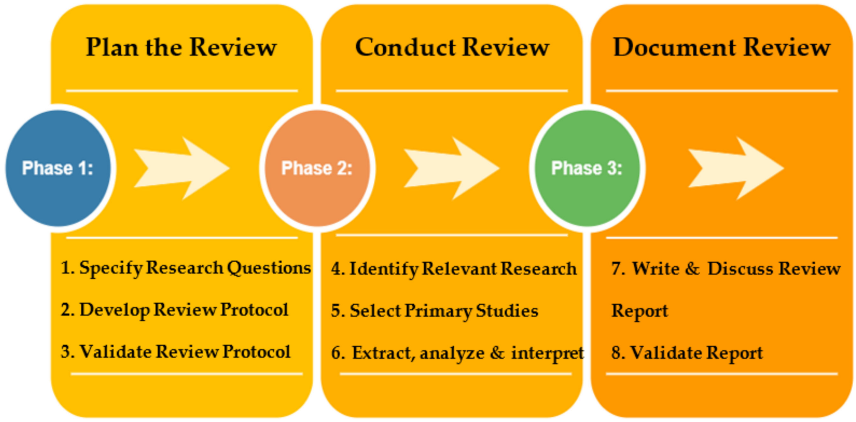

Figure 1. Systematic literature review process.

2.1. Specifying Research Questions

The main objective of this SLR is to identify the essential research questions outlined in Table 1 and find the answers, analyze the existing studies, and highlight the most critical challenges and research gaps. For this study, the research questions outlined in Table 1 were formulated. The aim is to comprehend and summarize the empirical proof of the most recent UAV-based FFEA studies. The research questions, we believe, will aid researchers in identifying areas for further investigation.

2.2. Development of Review Protocol

As shown in Figure 1, the review protocol was defined after the RQs were set. The steps in the protocol that we used for this article are as follows: The first section, Section 2.2.1, selects the databases used as information sources and defines the stop criterion. The exclusion/inclusion criteria used by reviewers to exclude/include articles selected from databases before the stop criterion was activated are specified in Section 2.2.2. Finally, the quality criteria that reviewers use to determine the quality of primary studies are presented in Section 2.2.3.

2.2.1. Database Selection

This process consisted of the following two steps:

i The first stage was to narrow down a collection of standard search engines in order to collect relevant literature from five online electronic database resources. The search engines were Google Scholar, ACM Digital Library, Science Direct (SD), Scopus, and IEEE Xplore, which were used to identify papers with a high impact factor. Google Scholar was chosen because it contains many documents that are not indexed in the other two databases, such as conference papers, and Ph.D. and Master's theses. Although they are not peer-reviewed, the articles obtained from Google Scholar may be significant given the recent increase in interest in the studied subject.

ii In the second stage the search strings, queries, or keywords listed in Table 2, below, were used in the search strategy for all papers.

Table 1. SLR research questions.

Research Questions		
No.	**Research Question**	**Motivation**
RQ1	What has been the evolution of the use of UAVs in firefighting in the forest over the past decade in terms of geographical distribution, major shareholders, and growth over the years?	To define the liveliness of the field of UAV-based forest-fire-extinguishing activities, in addition to helping researchers to quickly find new contributions in the field of forest fire fighting by highlighting the most active contributors in this domain.
RQ2	What are the main characteristics of UAV-based fire-extinguishing systems?	To identify the most essential characteristics addressed by previous studies in UAV-based fire-extinguishing systems and provide researchers interested in this field with a general vision and guidance that adopts the exploration and revision of their ideas.
RQ3	What are the main research topics for UAVs used in firefighting applications covered in the research papers?	It is crucial to recognize active research topics, to demonstrate less active research topics as areas where more contributions are needed.
RQ4	How can a swarm of UAVs meet the requirements of firefighting in the forest without human intervention?	To investigate the potential and feasibility of using Swarm Robotics to form self-coordination and avoid direct communication among firefighting drones.

Table 2. SLR search string.

Search String	
Concept	**Alternative Terms and Synonyms**
UAV	("drones" OR "drone" OR "UAV" OR "aerial robotics" OR "UAS" OR "Unmanned Aerial Vehicles" OR "Unmanned Aerial System" OR "unmanned aircraft systems")
	AND
Firefighting	("firefighting" OR "fire-fighting" OR "forest fire" OR "forest-fire" OR "wildfire" OR "wild-fire" OR "Extinguishing" OR "Bushfire" OR "Bush-fire" OR "Bush fire")

When queried with these keywords, each database responded with a set of articles that were considered by the reviewing process. For the Google Scholar and IEEE Explore databases, the number of articles provided by the queries was relatively high. However, a few articles obtained were relevant to the research questions conducted in the previous section. For that purpose, as in [15] the following stop criteria were used: stop collecting papers after a list of 10 titles emerges that are completely unrelated to the query in the keywords list.

We used the search strategy shown in Figure 2 to find papers based on the search strategy used in [19]. The relevant keywords were extracted from the search questions to build our search string. We conducted an empirical search on Google Scholar to assess the quality of the proposed research series.

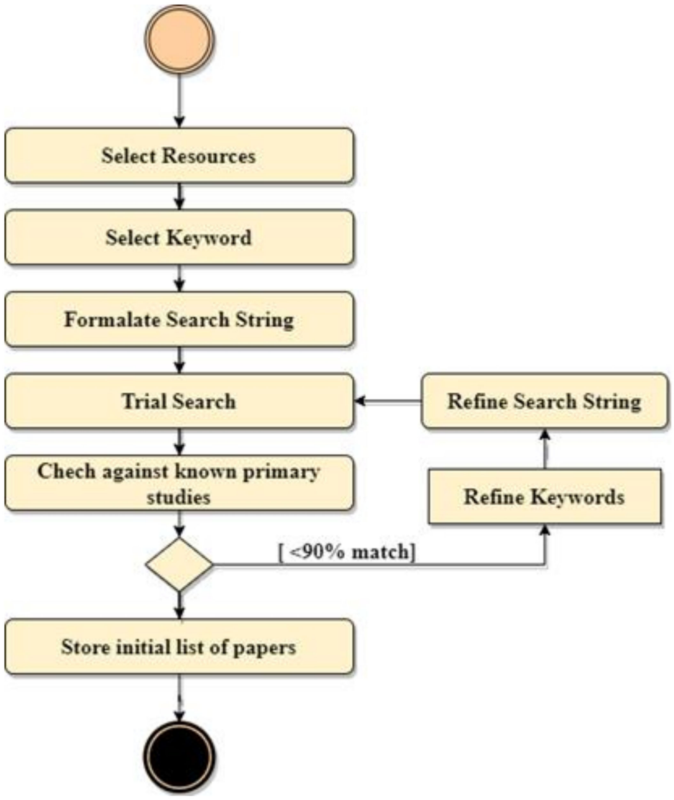

Figure 2. The steps for creating and improving the search string.

We manually picked ten relevant articles in the field of forest firefighting with drones and compared them to the trial search results. A total of 90% of the reference articles were found using the adopted search string. A selection of keywords was used to search the databases. The authors developed these keywords based on their knowledge of the UAV and FFEA domains. The following is the final version of the search keywords shown in Table 2:

2.2.2. Exclusion/Inclusion Criteria

The inclusion and exclusion criteria were determined after the research questions, databases, and keywords were defined. The papers that appeared in the resulting pool of publications may or may not be helpful in answering the research questions mentioned above. As a result, most existing literature methodologies, such as [18,20], use a set of exclusion criteria to ensure that only relevant publications are retained. The published paper must be a peer-reviewed journal or conference paper, and the proceedings must be included and studied until May 2021 for the SLR. The inclusion and exclusion criteria were used during the planning and conducting phases to ensure that the research materials collected were relevant to the research objectives. As shown in Table 3 below, the set of inclusion and exclusion criteria identified by the authors in this article were:

The criteria of exclusion were applied to the papers in two steps. Papers were only excluded in the first step if their titles and abstracts met at least one of the exclusion criteria in Table 2. The remaining papers were screened in the second step, but this time, the full text of the paper was read.

2.2.3. Quality Criteria

There are many SLRs, as recommended in [21,22], that depend on quality criteria to determine the quality of primary studies (for more details and another example, see [18,20]). A common practice is to define the quality criteria as a set of questions. The standard quality criteria include the following:

(i) Whether primary study authors provide solid justification for their work;
(ii) Details of how the technical evaluation mechanism is to be designed are yet to be revealed;
(iii) How results are reported.

It is worth noting that the quality criteria are not used to exclude or include primary studies, as they are in [18]. Instead, they are used to evaluate the overall quality of the SLR and its preliminary studies. For this, Table 4 defines four questions of quality, adapted from [18]. The purpose of this question is to assess the quality of the work reviewed. In this regard, Q2 is exciting, as it can give a good understanding of the maturity of the research issue by providing an analysis of the results of the evaluations of several papers dealing with one specific research question.

Table 3. Exclusion criteria determined in this SLR study.

#	Exclusion Criteria of the Study
ExC1:	***Not a recent research paper***—Papers published before the year 2008. This means papers with a year of publication <2008 will be excluded. Due to the high evolutionary rates of UAV technology and use, non-recent studies may not be up-to-date.
ExC2:	***Invalid paper type, i.e., a poster or a demo***—A poster or demo document is supposed to be unable to include sufficient information on the contributions when there is not enough content for evaluation.
ExC3:	***Invalid paper type, i.e., a review or survey paper***—These are secondary studies (i.e., survey papers and review papers) that are unable to explain the contribution that is made directly in firefighting-based UAV models or firefighting-based UAV technologies.
ExC4:	***Other types of studies*** include: PhD theses, Master's theses, research reports, literature review papers, industry trade articles, comments, letters, editorials, and book chapters.
ExC5:	***Extended paper***—Another paper by the same authors extends the original paper. The contributions in the extended article enclose the ones from the original article.
ExC6:	***Irrelevant to firefighting using UAV***—The article does not contribute to either firefighting-based UAV models or firefighting-based UAV technologies.
ExC7:	***Studies outside the context of the field of research, research questions,*** such as the field of monitoring or surveillance for firefighting in the forest using UAV. Due to the fact that most of the researchers highlighted forest fire monitoring and detection in their papers, while researches and studies in the development of UAV-based fire-extinguishing activities were lacking, detailed techniques and still scarce.
ExC8:	***Studies related to the manufacture of UAVs for firefighting and their sensor only***—Articles that contribute to designing and manufacturing the UAV (i.e., hardware, mechanical and electronic components) and is relevant to the design and implementation of these components.
ExC9:	***Duplicated papers***—Within the query method, no duplicate search articles should be kept. Each paper should be focused on a specific domain of research.
ExC10:	***Studies written in a language other than English.***

2.3. Review Protocol

One crucial phase in an SLR is the self-assessment, which highlights its essential points. We discuss such validation threats in this section. Some strategies have been adopted to resolve conflicts and mitigate biases in order to reduce the subjectivity of the reviewing process. For example, we performed each procedure of phase 2 in Figure 1 based on at least two reviewers, which will be discussed in the next section. In other words, all steps, such as excluding/including material (refer to Section 2.2.2), answering questions for RQs, and assessing quality (refer to Section 2.2.3), were performed by at least two reviewers for each article. A third reviewer was assigned to the intervention in answering RQs and in the exclusion/inclusion of the steps as a referee to resolve conflict. On the other hand, the average quality assessments provided by the reviewers were calculated for each paper.

Table 4. The quality questions to verify the SLR's usefulness.

The Quality Questions	
#	Quality question
Q1	Do the researchers have a sound justification (i.e., motivation) for their research?
Q2	Are the findings and results clearly stated, including the evidence supporting the findings?
Q3	Does the context in which the study has been conducted include an adequate description?
Q4	Did they address and discuss the limitations or challenges of the study?

2.4. Performing the Review

In this section, the SLR steps are explained in detail, and the exclusion/inclusion step results are discussed. The search string mentioned in Table 2 was used to obtain primary studies from the electronic databases resources (Google Scholar, ACM Digital Library, Science Direct (SD), Scopus, and IEEE Explore) presented in Section 2.2.1, based on Section 2.2—Development of Review Protocol. The primary studies were selected based on the criterion for exclusion/inclusion presented in Section 2.2.2. On the keywords and databases chosen, the stop criterion for every ten articles mentioned in Section 2.2.1 was considered.

The studies were selected by searching and reading their titles, abstracts, and keywords as an initial step, and the total number of papers was 1353, obtained from the five databases after the stop criterion was applied.

Table 5 shows the number of studies obtained for each of the five databases with the following details: About 53.1% (719) of the articles were obtained from the Scopus database, 16.9% (229) were obtained from Google Scholar, 15.2% (205) were obtained from IEEE Explore, 11.8% (159) were obtained from ACM Digital Library, and 3.0% (41) were obtained from Science Direct.

Table 5. Number of articles selected for each database in the initial step.

Number of Articles Selected for Each Database in the Initial Step		
Database	**Number of Papers**	**Percentage**
Science Direct	41	≈3.0%
ACM	159	≈11.8%
IEEE Explore	205	≈15.2%
Google Scholar	229	≈16.9%
Scopus	719	≈53.1%
Total	**1353**	**=100%**

After that, the inclusion and exclusion criteria were applied from the primary studies presented in the previous section. Table 6 shows the results of the 1st step of exclusion/inclusion, which are listed in detail for each database as follows: About 35% (57) of the articles were included from the Scopus database, 28.8% (47) were included from IEEE Explore, 27% (44) were included from Google Scholar, 6.7% (11) were included from ACM, and 2.5% (4) were included from Science Direct. This results in about 12.0% (163 papers) were included and about 88.0% (1190 papers) were excluded from the total number of papers through the exclusion/inclusion stage of the first step.

Table 6. The outcomes of the 1st step for exclusion/inclusion.

The Outcomes of the 1st Step for Exclusion/Inclusion.		
Database	**Number of Papers**	**Percentage**
Science Direct	4	≈2.5%
ACM	11	≈6.7%
Google Scholar	44	≈27.0%
IEEE Explore	47	≈28.8%
Scopus	57	≈35.0%
Total exclusion	**1190**	≈88.0%
Total inclusion	**163**	≈12.0%

In the next step, the full text of the paper was read and screened for content; after that, only those papers that did not satisfy any of the exclusion criteria referred to in Section 2.2.2 were included. Where this process was applied, 163 papers were obtained from the previous step.

Table 7 shows the results of the 2nd step of exclusion/inclusion, which are listed in detail for each database as follows: About 39.2% (20) of the articles were included from the Scopus database, 33.3% (17) were included from IEEE Explore, 21.6% (11) were included from Google Scholar, 3.9% (2) were included from ACM, and 2.0% (1) were included from Science Direct. This results in about 31.3% (51 papers) being included, and about 31.3% (112 papers) being excluded from the total number of papers through the exclusion/inclusion stage of the previous step.

Table 7. The outcomes of the 2nd step for exclusion/inclusion.

The Outcomes of the 2nd Step for Exclusion/Inclusion.		
Database	**Number of Papers**	**Percentage**
Science Direct	1	≈2.0%
ACM	2	≈3.9%
IEEE Explore	17	≈33.3%
Google Scholar	11	≈21.6%
Scopus	20	≈39.2%
Total exclusion	**112**	≈68.7%
Total inclusion	**51**	≈31.3%

It is worth noting that most of the papers included in the previous step were highly related to the research questions referred to in Section 2.1. On the other hand, Figure 3 shows the number of papers by country after the last stage of exclusion/inclusion steps to understand the geographic distributions of significant contributors in the UAV-based fire-extinguishing activities field. Figure 3 shows that the highest number of published papers worldwide in the area studied comes from researchers in the U.S. Figure 4 indicates the number of publications per year after the 2nd step of exclusion/inclusion was applied. The figure shows that the growth rate of papers has increased from 2008 until 2021.

Furthermore, Figures 5 and 6 plot the percentage of papers excluded for each exclusion criterion before the first step and after the second step of the exclusion process. Regarding Figure 5, it is noted that most of the papers that were excluded satisfied the ExC7 criterion, which refers to most of the researchers highlighting forest fire monitoring and detection in their papers. At the same time, the research and studies in the development of UAV-based fire-extinguishing activities (FFEA) lacks detailed techniques and is still scarce [4].

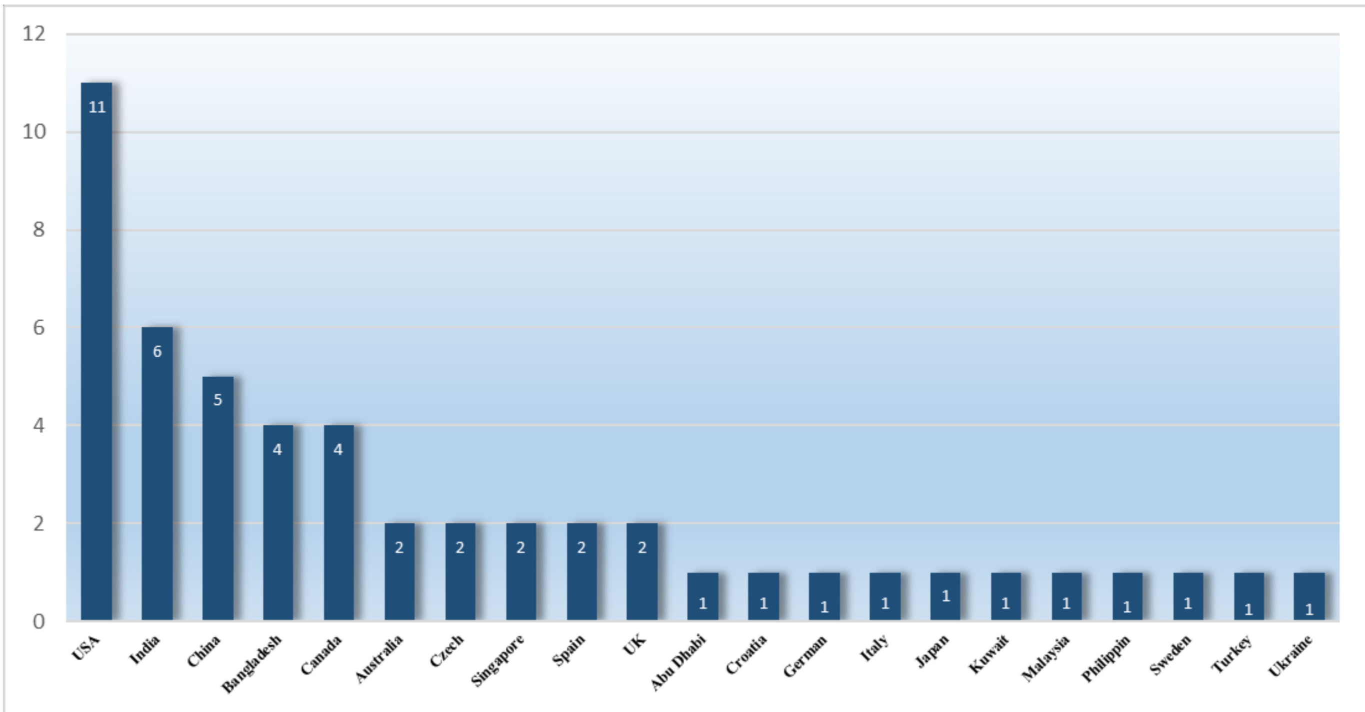

Figure 3. The results of the geographical distribution classification of papers after 2nd step.

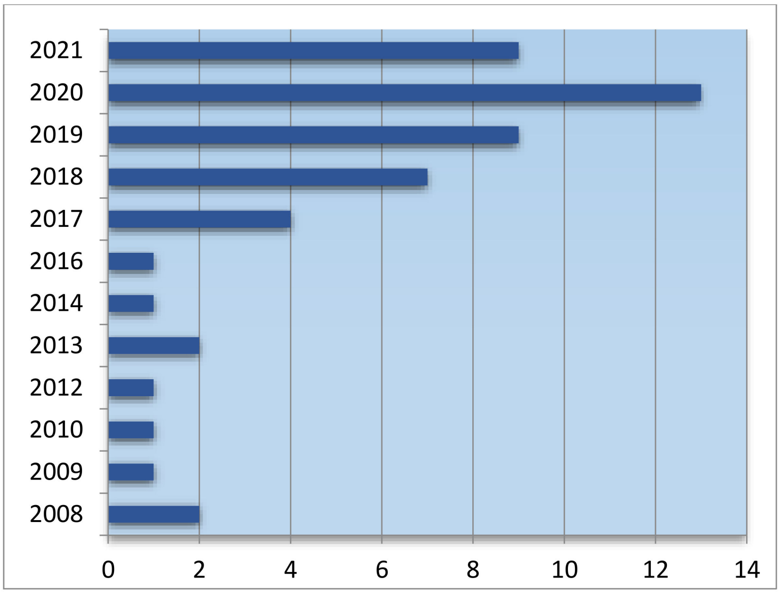

Figure 4. The number of publications per year after 2nd step.

As shown in Figure 5, most of the papers that were excluded addressed fire monitoring and detection, with a percentage of 34% for ExC7, and did not address firefighting using UAV, with a percentage of 23% for ExC6. Figure 6 shows the number of papers that were excluded because the ExC7 and ExC6 criteria were still highest for the rest of the exclusion criteria by a percentage (25.9%) and (23.59%), respectively.

In this section, a detailed understanding and usage statistics were provided on how the exclusion and inclusion process for papers was conducted. In addition, the most common criteria for exclusion were discussed. The SLR results on the research questions mentioned in Section 2.1 are given and discussed in the next section.

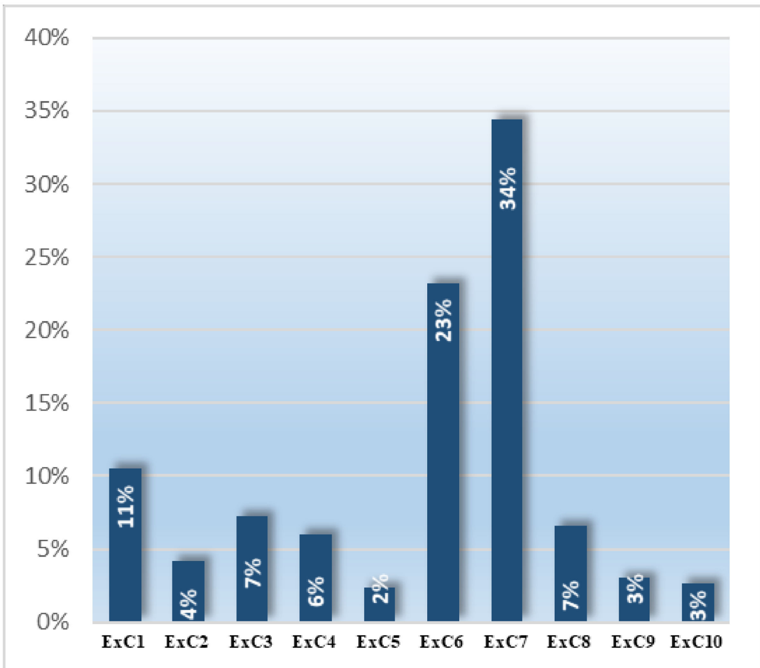

Figure 5. Percentage of papers excluded for each exclusion criterion.

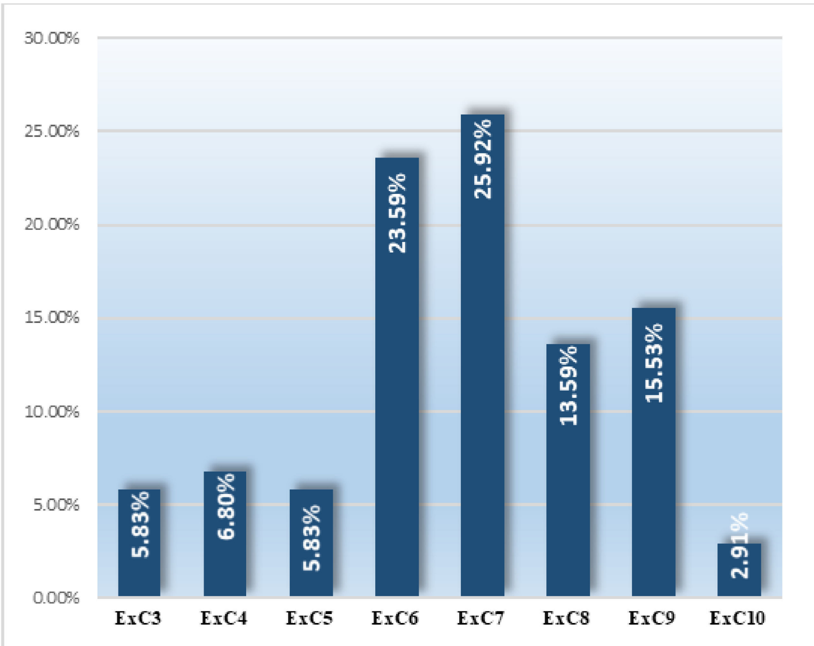

Figure 6. Percentage of papers excluded for each exclusion criterion after 2nd step.

3. Results and Analysis of the Review

In this section, the results obtained from the previous stage are analyzed in detail. Each of the RQs referred to in Section 2.1 is discussed and answered after retaining the papers from the 2nd steps of the exclusion/inclusion steps. As a last point, it is important to note that all of the results related to UAV-based FFEA in firefighting applications were obtained from the research questions and exclusion criteria, based on the research methodology of this paper.

This section provides the most critical challenges facing the use of UAVs in FFEA, to highlight the challenges that must be considered when adopting drones in forest firefighting applications.

3.1. Demographic Data (RQ1)

To understand the evolution and growth of UAVs, rather than humans, used in firefighting applications in the last decade (as in RQ1), Figure 4 shows the number of studies per year after the second step of inclusion and exclusion. Although the number of research papers on the use of UAVs as firefighting tools declined between 2008 and 2016, the growth in the number of research papers becomes apparent in subsequent years, especially in the last three years, as shown in Figure 4 (this review was conducted in August of 2021; therefore, 2021 should not be considered).

After the second step for exclusion/inclusion, Figure 3 shows the number of papers per country to better understand the geographic distributions of the key contributors in the area under study. Figure 3 shows that the highest number of published papers worldwide in the area studied comes from researchers in the U.S. This fact may be explained by the high number of publications for this country compared to other countries due to the increase in the number of fires in the USA, not to mention its investments in research and development. Finally, due to lower investment in research and development in EU countries, researchers from these countries have less opportunity to fund the deployment of drones in related fields of study.

3.2. Characteristics of the Fire-Extinguishing Systems (RQ2)

This section discusses the results of the analysis to answer the research question RQ2 (refer to Section 2.1); it highlights all the characteristics of the fire-extinguishing systems using a single drone (Section 3.2.1), and all the characteristics of the fire-extinguishing systems using multi-drones (Section 3.2.2), that were discussed in the literature.

Identifying the characteristics of fire-extinguishing systems analyzed in the context of this SLR is one of the main issues for which researchers are interested in conducting research in the field of fire extinguishing using UAVs. This analysis provides researchers interested in this field with a general vision and guidance that adopts the exploration and revision of their ideas.

Research in the literature dealing with the study of this research topic can be described by classifying fire-extinguishing systems into several characteristics. The addressed characteristics of the fire-extinguishing systems are:

Ch1: System approaches:
(57% single-drone, 43% multi-drones);
Ch2: Type of task performed:
(51% detect and extinguish, 49% only extinguish);
Ch3: The environment:
(53% structured, 47% unstructured);
Ch4: Control methods:
(41% remote control, 6% semi-autonomous, 53% autonomous);
Ch5: Extinguisher fuel:
(37% water, 45% balls, 18% not specified);
Ch6: Fire propagation model:
(22% YES, 78% NO);
Ch7: Collision avoidance:
(31% YES, 69% NO);
Ch8: Experimental verification approach:
(45% simulation, 55% practical).

Figure 7 shows the general characteristics of fire-extinguishing systems using UAVs for all the studies reviewed in this paper, according to accurate statistics addressed by relevant studies during the past decade, with percentages of the number of papers per characteristic.

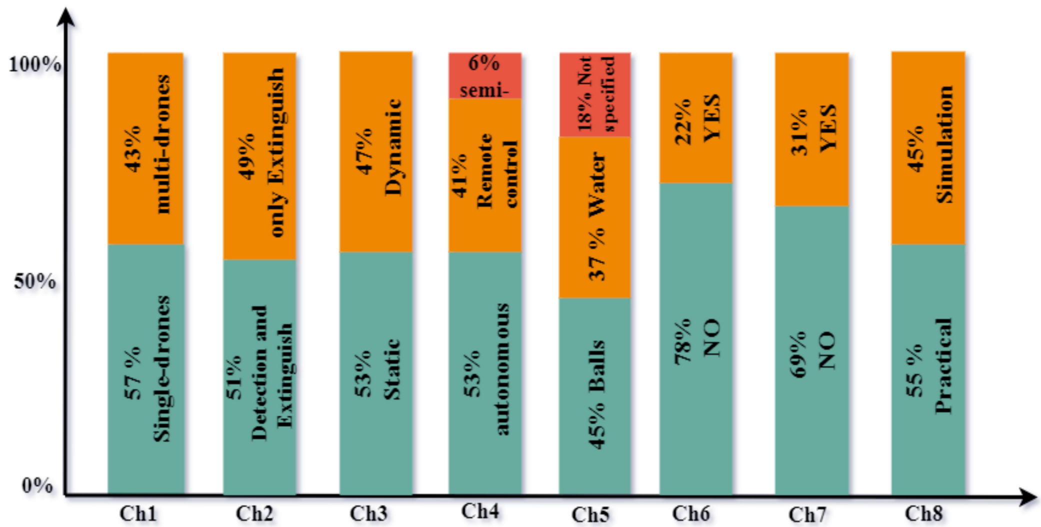

Figure 7. The number of papers per characteristic of the fire-extinguishing systems.

Fire-extinguishing systems using UAVs can be classified into two main groups based on the number of drones used in that system: (1) extinguishing using a single drone and (2) extinguishing using multi-drones. Tables 8 and 9 group and analyze the existing characteristics to identify strengths and weaknesses in this field; this enables researchers interested in this field to identify issues that still need to be addressed and developed, and lists the papers per key characteristic, with references.

3.2.1. Characteristics of the Fire-Extinguishing Systems Using a Single Drone

As can be seen from Table 8, most previous studies (29 papers) tend to use a single drone. They demonstrate that single UAVs, whether small aerial systems or giant airships, may be used for detecting and extinguishing the fire, due to their maneuverability and ease of use. The use of a single drone provides many benefits, as it supports or replaces human beings in a wide range of tasks due to the ability to operate in different environmental situations and conditions. In addition, this type of robot is used to work in environments that pose a danger to humans, reduce risks to operators, decrease manpower needs, minimize costs, and increase efficiency, especially in difficult environments.

Figure 8 shows that the number of papers for fire-extinguishing tasks only (21 papers) was highest in the studies discussed and analyzed in this SLR, relating to the use of a single drone in firefighting systems; these were not used as a detection system to track the spread of fire, except in limited studies such as [23–29]. Regarding the study environment, most of the experimental environments that were used to validate the proposed systems were structured environments with 24 papers (e.g., a building, a skyscraper, or a lab, etc.).

On the other hand, fire-extinguishing balls were the most commonly used for firefighting (19 papers), as they were environmentally friendly and proved effective, resulting in no physical damage to burning buildings. For example, the authors in [25] discussed the idea of using drones with firefighting balls to fight fires. They used a collaboration between drones and remote sensing to build a three-stage system: a scouting UAS, a communication UAS, and a firefighting UAS. The scouting UAS was used to find out the fire's location, and the communication UAS was used to establish and extend communication. The firefighting UAS was used to drop fire-extinguishing balls at the waypoints. As can be seen, most of the previous studies discussed are based on the remote control of UAVs in the task of detecting and extinguishing fires (17 papers). Therefore, using a single drone based on remote control requires centralized coordination and direct communication between the drone and the operator; this may pose a great danger to the operator, not to mention the limited resources and problems associated with using a single robot. The lack of autonomy to control the drones during their tasks leads to neglect of the issue of collision avoidance, which depends primarily on the human operator. Autonomy of control provides a high degree of task performance, optimal coverage and coordination, as well as collision avoidance. However, studies that have adopted autonomy in management are few.

Table 8. Summary of fire-extinguishing systems using a single drone.

System Approaches	Ref.	Tasks		Environment		Extinguisher Type			Control Type			Result Validation		Propagation Model		Collision Avoidance	
		Extinguish	Detect and Extinguish	Unstructured	Structured	Water	Ball	Not Specified	Controlled Remotely	Semi-Autonomous	Autonomous	Practical	Simulation	yes	No	yes	No
Single-drone	Barua et al. [30], Nazar Zadeh et al. [31], Mnaouer et al. [32], Zhang et al. [33], Abu Bakar et al. [34], Manimaraboopathy et al. [35], Rupali Patil1 [36], Yuvraj Akhade [37]	✓			✓		✓		✓			✓			✓		✓
	Spurny et al. [23], Walter et al. [24], Aydin et al. [25]		✓		✓		✓				✓	✓			✓		✓
	Qin et al. [26]		✓		✓	✓					✓				✓		✓
	Imdoukh et al. [38], Benavente [39], Manuj et al. [40], Pathak et al. [41]	✓			✓		✓			✓		✓			✓		✓
	Sujatha et al. [27], Gupta et al. [28]		✓		✓	✓			✓			✓			✓		✓
	Wang et al. [42], Moore and Aberdeen [43]	✓			✓	✓			✓			✓			✓		✓
	Cervantes et al. [44], Beachly et al. [45], Soliman et al. [46]	✓		✓			✓		✓			✓			✓		✓
	Chaikalis et al. [47]	✓			✓	✓					✓		✓		✓	✓	
	Jaber et al. [48]	✓			✓	✓			✓				✓		✓		✓
	Jayapandian [49]	✓			✓		✓				✓		✓		✓	✓	
	Saikin et al. [50]	✓		✓		✓					✓	✓			✓		✓
	Chen et al. [29]		✓		✓			✓	✓			✓		✓			✓
	Wang et al. [51]		✓	✓				✓			✓		✓	✓			✓

In addition, Figure 8 shows the adoption of UAV systems in firefighting for practical validation in most of the papers reviewed—with 25 papers and very few studies that proposed simulation models—to be certain that the FFEA areas for drones are proposed models and have been validated.

Table 9. Summary of fire-extinguishing systems using multi-drones.

System Approaches	Ref.	Tasks		Environment		Extinguisher Type			Control Type			Result Validation		Propagation Model		Collision Avoidance	
		Extinguish	Detect and Extinguish	Unstructured	Structured	Water	Ball	Not Specified	Controlled Remotely	Semi-Autonomous	Autonomous	Practical	Simulation	yes	No	yes	No
Multi-drones	Ausonio et al. [52], Harikumar et al. [53]		✓	✓		✓					✓		✓	✓		✓	
	Shaffer et al. [54], Gašparović et al. [55], Shaffer et al. [56]		✓	✓		✓					✓		✓		✓	✓	
	Phan and Liu [57]	✓		✓		✓					✓		✓	✓		✓	
	Subramaniam et al. [58]	✓		✓		✓				✓			✓		✓		✓
	Sato et al. [59]	✓			✓		✓		✓			✓			✓		✓
	Kumar and Cohen [60]	✓		✓			✓				✓		✓	✓		✓	
	Innocente and Grasso [61], Innocente and Grasso [62]		✓	✓		✓					✓		✓	✓			✓
	Moffatt et al. [63]		✓	✓		✓					✓	✓			✓	✓	
	Howden and Hendtlass [64], Bjurling et al. [65]		✓	✓				✓			✓		✓		✓	✓	
	Haksar and Schwager [66]		✓	✓				✓			✓		✓	✓		✓	
	Chan et al. [67]		✓	✓				✓			✓		✓		✓		✓
	Luo et al. [68]		✓	✓			✓				✓		✓		✓	✓	
	Sherstjuk et al. [69]		✓	✓			✓		✓		✓		✓		✓		✓
	Quenzel et al. [70]		✓		✓	✓					✓	✓			✓		✓
	Mohandes et al. [71]		✓		✓			✓			✓		✓		✓	✓	
	Ghamry et al. [72], Madridano et al. [73]		✓	✓				✓			✓		✓	✓			✓

Fire propagation factors lead to the dynamic spread of fires in multiple hot-spots in the environment that have frequent and severe changes in location and severity. Unfortunately, as shown in Figure 8, most of the previous studies that used a single drone did not address the use of the fire propagation model, except in limited studies such as [29,51]. They also ignored the issues of collision avoidance while performing their mission, except for in two studies [47,48], wherein they relied on the human operator, as well as the specifications of some types of UAVs.

Finally, a single drone has limited resource and computation capacity, and cannot provide services for a long time due to the finite payload and battery consumption, spatially, in a complex environment. In addition, single robots cannot share information, which would help to process information in order to complete their tasks efficiently, especially tasks that require cooperation and collaboration between several robots.

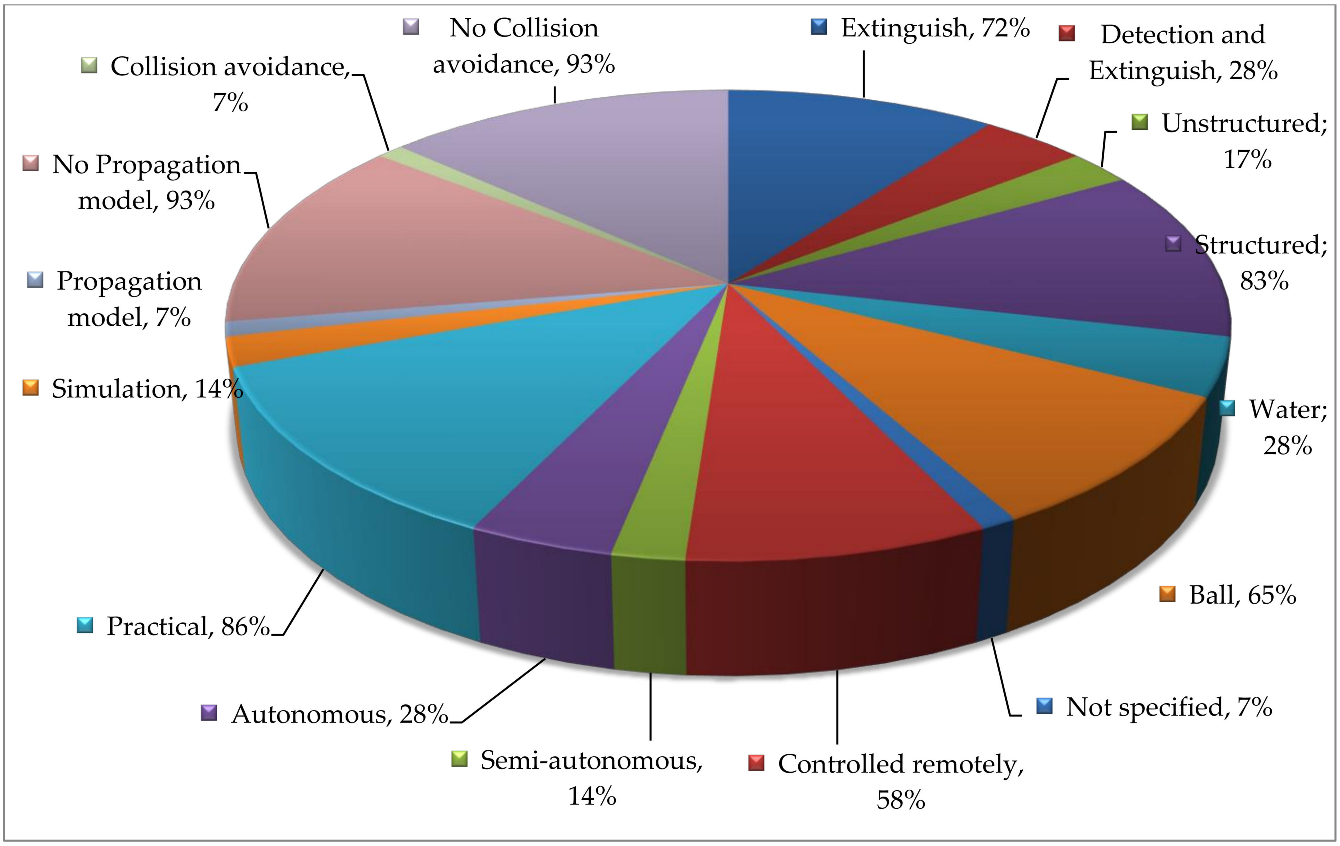

Figure 8. The percentages of number of papers per characteristic of fire-extinguishing systems using a single drone.

3.2.2. Characteristics of the Fire-Extinguishing Systems Using Multi-Drones

Multi-Robotic Systems (MRS) are designed to increase the capability for sharing and processing information and many other aspects of single robots that are unable to accomplish their tasks; to be completed efficient, this requires cooperation and collaboration between several robots [74]. In particular, efficiency in executing the mission, wider coverage of the area, low cost, more power in sharing information and collecting data, and the reduction of the risk of the human operator can lead to a more intelligent decision, especially in missions such as extinguishing fires [75].

Multi-drone detection, and even fighting the fire, can be performed when multi-drones are deployed instead of only one drone [76–78]. Currently, there are many applications in which cooperative robots are used in real-world scenarios, such as disaster management, complex manufacturing, and structural health monitoring. However, the amount of research that studies and discusses firefighting using multi-drones is still scarce and limited, and has not yet reached optimal solutions [4].

It is worth noting that by analyzing the characteristics of fire-extinguishing systems from studies that rely on UAVs, we noticed that the characteristics of the systems in a firefighting mission using multi-drones differ when it comes to the characteristics of a single drone, as can be seen from Table 9. Figure 9 shows the percentage of papers that dealt with the use of multiple drones according to each of the characteristics of fire-extinguishing systems.

As can be seen, the studies that dealt with the task of detecting and extinguishing fire are the highest, with 18 papers, compared to those that dealt only with fire-extinguishing tasks (e.g., [52–56,61–73]). In contrast, the studies analyzed and discussed in this paper indicate that in 19 of 22 papers, the fire-extinguishing systems relied on unstructured environments (e.g., forests, etc.) in their experiments due to the complex environment.

Moreover, uncontrollable fires often have negative impacts on many health and social aspects, as well as environmental impacts; to provide wider coverage of the burned areas, multi-drones are used.

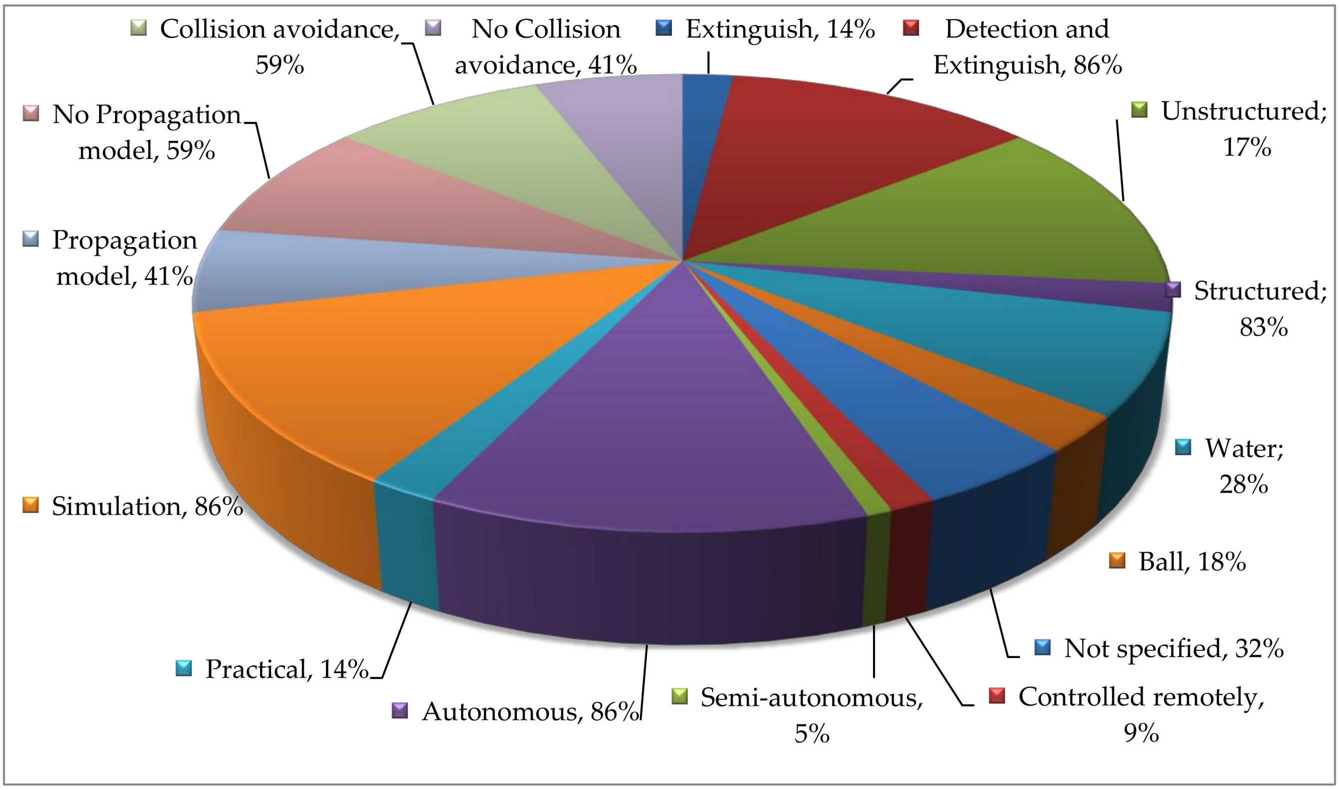

Figure 9. The percentages of the number of papers per characteristic of fire-extinguishing systems using multi-drones.

On the other hand, water was the most commonly used method to extinguish fire compared to other liquids, due to its low price and its availability in large quantities; the number of studies that used water as a means to extinguish fire was 18 papers. The tools used in forest firefighting differed from one study to another. Researchers relied on water for forest firefighting. Researchers proposed a model based on an airship to monitor the area and drones loaded with water tanks for forest firefighting. The researchers in [8] relied on water for firefighting, and proposed a collaborative approach between drones and an automatic fire extinguisher mounted on a firefighter truck. The researchers in [61] relied on water for firefighting, and suggested a cooperative approach between drones. On the other hand, balls were used to firefighting in the forest according to the study presented by the researchers in [69], and the total payload of the drone was 30 balls with a weight of 15 kg. The researchers in [60,72] suggested using a fire-retardant liquid in a sufficient quantity for firefighting, which is practically impossible. It is necessary to have a base for reloading drones with firefighting materials. In emergencies, a direct attack can often include cooling with chemical additives combined with water to improve firefighting efficiency. Inorganic salts, primarily ammonium phosphates, are retardant additives that prevent the combustion of flames and can slow the propagation of fire when the water used during its propagation has evaporated [79].

Although water is one of the resources that enters into the task of fighting the fire, none of the studies dealt with a strategy to manage the resources in firefighting missions. Lone resources are not enough to fight the fire, but an effective strategy must be designed and used in such disasters to take advantage of these resources. Intelligent systems are now used to develop these strategies, and play the roles of decision-makers in the management of disasters. However, every one of these goals has the same importance in the case of forest fires, so it is essential to consider all of them together [80].

Most of the research that used multi-drones to extinguish forest fires relied on assumptions regarding the amount of liquid needed to extinguish the fire, and the battery life (as it is unlimited). Where the researchers focused on reaching the fire points, the coordinates, and avoiding the collision of drones, without addressing the issue of recharging or refueling by returning to the docking stations, those were the factors affecting mission success. [72,81]. On the other hand, in previous studies [8,57,60,61,69,72], the researchers proposed a new approach to the cooperative control framework. They designed the forest firefighting plan optimally based on coordinating activities between vehicles in an efficient manner. The proposed model in [57,69], depending on a heterogeneous UAV team and deployment team, is based on pre-prepared coordinates of fire sites. The researchers in [81] relied on real-time coordinates discovered using sensors and infrared rays of IR; they dropped the liquid used to extinguish the fire in the area directly below each drone, where the researchers suggested using liquid to extinguish fires cooperatively. Given the importance of considering the payload and power charging of vehicles, these assumptions cannot be ignored in a task such as extinguishing a fire.

Moreover, the multi-drone systems depended on autonomous control in most studies, to control the cooperating team to achieve the highest efficiency of the system. Autonomous control is essential for good execution over long periods of significant uncertainties in the design and environment, and enables the system to work and complete its task and compensate for failures without the intervention of a human operator. The studies that used multi-robot systems, which were analyzed, relied on simulations to verify the validity of the proposed systems. So far, there is no verified system for using multiple UAVs in the real world.

However, the promising outcome demonstrated by these studies to firefighting using multi-drones suffers from major limitations, which are: (i) the complexity of coordination in MRS requires advanced software and hardware technology, as well as direct communication between members in real-time, which is quite challenging in a forest-firefighting mission; and (ii) ignoring the water resource and docking station issues.

3.3. Research Topics (RQ3)

This section discusses the analysis results to answer the research question RQ3 (refer to Section 2.1), and highlights all the research topics discussed in the literature. This analysis provides researchers interested in this field with a general vision, and guidance that adopts the exploration and revision of their ideas. It is worth mentioning that the most important issue is to learn about active research topics, so that less-active research topics can be shown as areas that require more contributions.

Before starting to classify the reviewed studies according to research topic, it should be noted that the majority of the studies that used a single drone in the firefighting mission highlighted "System Design" as a research topic, except in some studies such as [23,45,51]. Figure 10 shows the main research topics that were addressed in the previous studies that used a single drone, and Table 10 lists the papers per research topic.

T1: System Design (90%): This focuses on the design and implementation of advanced fire-extinguishing systems frameworks in order to understand and verify the behavior of using a single drone to accomplish their mission;

T2: Controlling and Motion planning (3%): This deals with the optimal assignment of the missions, i.e., targets, to drones. The tasks are those in which the drones rely on human interaction and the description of their goals without much detail;

T3: Path Planning (7%): This focuses on the dynamic and statistical computation of optimal flight trajectories given environmental limitations;

Accordingly, papers in which fires were extinguished using a single drone did not discuss many research topics, and there was a greater focus and diversity of research topics in studies that used multi-drones.

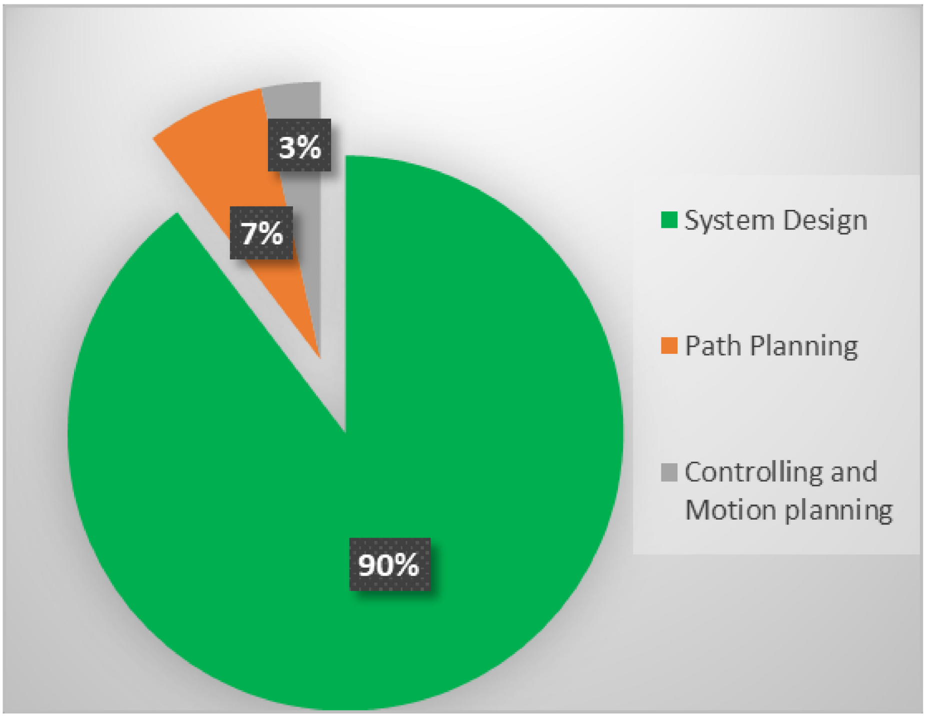

Figure 10. The main research topics that used a single drone were covered in the papers reviewed.

Table 10. Papers reviewed for different research scopes using a single drone.

Research Topic	Papers per Topic
System Design	Walter et al. [24], Aydin et al. [25], Sujatha et al. [27], Gupta et al. [28], Chen et al. [29], Barua et al. [30], Nazar Zadeh et al. [31], Mnaouer et al. [32], Zhang et al. [33], Abu Bakar et al. [34], Manimaraboopathy et al. [35], Rupali Patil1 [36], Yuvraj Akhade [37], Benavente [39], Manuj et al. [40], Pathak et al. [41], Wang et al. [42], Moore and Aberdeen [43], Cervantes et al. [44], Soliman et al. [46], Chaikalis et al. [47], Jaber et al. [48], Jayapandian [49], Saikin et al. [50], Qin et al. [26], Imdoukh et al. [38]
Controlling and Motion Planning	Spurny et al. [23]
Path Planning	Beachly et al. [45], Wang et al. [51]

Figure 11 shows the main research topics covered in the articles reviewed that used multi-drones, and Table 10 lists the papers for each research topic. It is worth noting that some papers were marked as containing more than one research topic. Therefore, to normalize the weights given to each paper for the distribution of research topics, we decided to assign the most common.

The research topics that were addressed in the studies that used multi-drones are:

T1: System Design (5%): This focuses on the design and implementation of advanced fire-extinguishing system frameworks in order to understand and verify the behavior of using UAVs team to accomplish their mission;

T2: Controlling and Motion planning (4%): This deals with the optimal assignment of the missions, i.e., targets, to the UAV team. The tasks are those in which the team relies on the description of their goals without much detail and human interaction;

T3: Path Planning (14%): This focuses on the dynamic and statistical computation of the optimal flight trajectories given environmental limitations;

T4: Cooperative control (9%): This is related to the definitions of the control mechanism in terms of cooperation between the UAVs and their team members (UAV, UAG) and ground infrastructure;

T5: Tracking (4%): This focuses on target identification and tracking in the UAV's environment;

T6: Coordination (36%): This focuses on the interaction behavior of drones with each other in order to coordinate their mission to achieve common goals.

T7: Resource Allocation (14%): This focuses on managing resources in an optimal way—especially in tasks in which robots cooperate to perform a specific task due to heterogeneity, energy and time consumption—as well as the number of robots used.

T8: Coverage (9%): This focuses on area-coverage problems and finding an efficient way to visit the entire area of interest

T9: Task Assignment (5%): This focuses on the most efficient dynamic task allocation for UAVs.

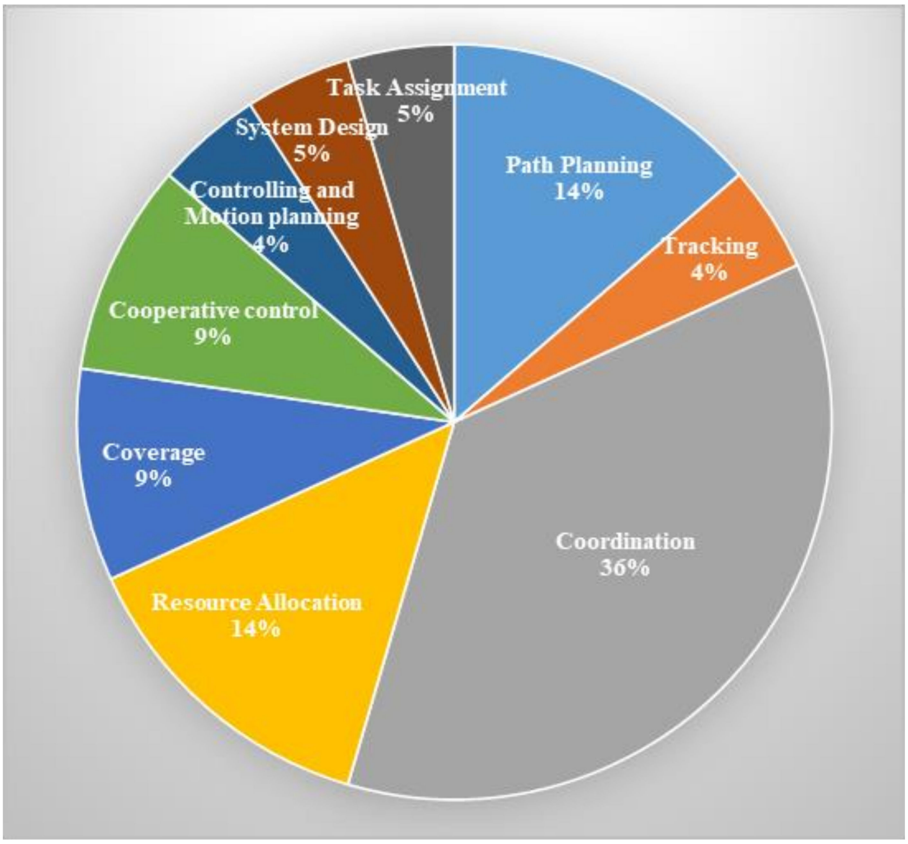

Figure 11. The main research topics that used multi-drones were covered in the papers reviewed.

Consequently, the research topics in Figure 11 address different objectives that are compatible with many aspects related to the task of extinguishing a fire using multi-UAVs—for example, ranging from a normal level of problems (e.g., system design) to a difficult level of problems (e.g., path planning, cooperative control, and task assignment) that need to be at a high level of UAV independence.

As shown in Figure 11, some research topics (e.g., controlling and motion planning, path planning, and coverage) tend to use a multi-robot system, with robots interacting with each other to successfully extinguish a fire; this often needs more autonomy than other research topics. As a result, the primary goal of these studies is to validate the feasibility of using multiple UAVs in firefighting via autonomous cooperation between UAVs. Note that research topics such as coordination, resource allocation, and path planning achieved a relatively high level of attention, as shown in Figure 11. However, these studies lack details about the evaluations, applications, and implementation of UAVs provided by the works cited.

Concerning coverage, despite the studies covering the target area, they did not discuss the issue of multiple-hotspot situations. Through reviewing studies on firefighting missions, only two studies [61,72] that used the PSO algorithm to handle the search space were found. In the approach mentioned above, drones converge due to the attraction factor, which makes the area coverage limited, with drones unable to scan all locations in the search space. In other words, the team of drones will move to one hot-spot and leave the rest of the areas. So, the current studies demonstrate a major limitation in terms of area coverage, in which drones converge on each other due to the attraction factor in the deployed algorithm (PSO); this limits the area coverage to a single spot, with drones unable to scan other possible hot-spots in the search space.

Furthermore, to fight forest fires in the shortest possible time, taking into account the limited resources and the environmental conditions, a practical model is required to solve the problems of resource limitation, such as battery capacity and liquid extinguishing. The firefighting system will be more efficient if the resources are maximized, by providing fuel or recharging drones after dropping their first payload at the fire points. However, just a few studies in the literature have proposed strategies for firefighting in the forest using UAVs. After reviewing the current state of firefighting projects and robotic system strategies [8,57,60,69,72,81], we found that these studies make the assumption that all drones can access resources in any capacity and at any time. This assumption does not accurately meet the mission requirements, ignoring the problem of recharging or refueling by returning to the docking stations. To mitigate this problem, drones could be based on a self-firefighting model that relies on each member of the team moving, on its own, towards a recharging station, or towards the water source for replenishment, and returning to work separately from the rest of the swarm. This allows the creation of a continuous flow of extinguishing liquid while trying to firefight in the forest, simulating a rain effect on the fire front.

3.4. Investigation of the Potential and Feasibility of Using Swarm Robotics Domain in Fire-Extinguishing Tasks (RQ4)

This section discusses the results of the analysis to answer the research question RQ4 (refer to Section 2.1), and highlights the most essential criteria of the Swarm Robotics (SR) approach and its differences from Multi-Robotic Systems (MRS). On the other hand, the feasibility of using swarm robots in a firefighting mission is investigated by analyzing the relevant studies, in order to provide a full view of those interested in the field and to explore the appropriate approach to such a task.

SR is an approach used to refer to a type of MRS that discusses how to self-coordinate large groups of homogeneous and relatively simple robots by using local rather than global rules, to make them cooperate in conducting common tasks [82]. It is worth noting that SR is closely related to the Swarm Intelligence (SI) approach as it has the same common characteristics of dealing with decentralized, self-organizing systems that have good fault tolerance. Hence, it provides several advantages for robotic applications, such as robustness and scalability due to redundancy [83,84].

The main goal of using swarm robotics theory in firefighting tasks is to develop a self-coordination approach for a number of UAVs. However, achieving self-coordination efficiently may require further investigation of the existing approaches, since most of the literature studies on autonomous firefighting missions do not address self-coordination. Moreover, it is possible to apply the main properties (indicated in [83]) of a typical SI approach to either MRSs or SRs; in [85], the authors highlighted a set of criteria to overcome confusion that included the use of the term "swarm" and the overlapping meanings applied to the MRS domain. These specific criteria are not to be used as a checklist, but may help us determine the degree to which SR can be applied and how it differs from other MRSs as follows:

- Autonomy: The swarm-robotic system should consist of independent robots that can interact with all swarm members, and can interact with and affect the environment.
- Large number: The swarm-robotic system is usually made up of a large number of homogeneous members, and highly heterogeneous groups of robots fall outside of the swarm robots.
- Limited capabilities: The swarm-robotic system must be ineffective or relatively unable to perform tasks independently, but is highly efficient when cooperating.
- Scalability and robustness: A swarm-robotic system is made up of robust and scalable components. On the other hand, reducing some robots or removing failing ones will not affect the breakdown of the system; on the other hand, increasing the number of robots will not require reprogramming or refunding the system. It will improve the performance of the overall system.
- Distributed coordination: In the swarm-robotic system, the coordination between individuals or agents must be distributed or decentralized; this means every robot has local and limited communication and sensing abilities only.

For further understanding, we analyzed previous studies that used multi-drones in firefighting and categorized them according to their compliance with the swarm mentioned in the above robot criteria (see Table 11).

Table 11. Papers reviewed for different research scope using multi-drones.

Research Topic	*Papers per Topic*
System Design	Subramaniam et al. [58]
Controlling and Motion planning	Mohandes et al. [71]
Path Planning	Moffatt et al. [63], Haksar and Schwager [66], Luo et al. [68]
Cooperative control	Kumar and Cohen [60]
Tracking	Quenzel et al. [70]
Coordination	Gašparović et al. [55], Innocente and Grasso [61], Innocente and Grasso [62], Howden and Hendtlass [64], Madridano et al. [73]
Resource Allocation	Shaffer et al. [54], Shaffer et al. [56], Chan et al. [67]
Coverage	Ausonio et al. [52], Harikumar et al. [53], Sato et al. [59], Bjurling et al. [65], Sherstjuk et al. [69]
Task Assignment	Phan and Liu [57], Ghamry et al. [72]

It is worth noting that the cooperation of the members of a multi-robot system requires a complex coordination process [86]. In this context, the system architecture design and the coordination process for a difficult task, e.g., a forest firefighting mission, makes it more complicated. Consequently, the complexity of coordination for forest firefighting missions using multi-drones requires increasingly complex software and hardware capabilities, as well as a high system cost. To identify papers that meet the criteria for a swarm-robotics approach, Table 12 shows a list of papers based on the systems approach used in terms of the type of coordination (centralized, decentralized, distributed) and the type of cooperating team in robotics in terms of homogeneity and heterogeneity.

On the other hand, the main problem with performing a challenging task such as firefighting in a forest is the direct communication between team members. Members discuss and make decisions between each other and assign duties to individuals to achieve their mission goals, which requires a high degree of direct communication.

Table 12. List of papers based on system approaches.

Ref.	Coordination Control	Robot Type	Team Type	Approach Type	Description
[57,71]	Distributed	UAV/UGV	Heterogeneous	Not SR	Did not meet the criteria
[58,59,69]	Centralized	UAV/UAV	Heterogeneous	Not SR	
[68,70]	Decentralized	UAV/UGV	Heterogeneous	Not SR	
[52–56,60,63,65–67,72,73]	Decentralized	UAV/UAV	Homogeneous	Not SR	
[61,62,64]	Decentralized	UAV/UAV	Homogeneous	SR	Met the criteria

Communication should be sufficient between team members to share information in real time, to ensure the robustness and flexibility of the system. Multi-robot systems share information with a central node or ground station to make joint decisions [5,86]. Due to sensing and communication limitations, this central node is a single fault point, and due to its centrality, it may not receive complete and updated information. Communication problems are significantly affected by centrally controlled robots if one or more robots are missing (permanently or temporarily), affecting available decisions and information. Due to the limited amount of bandwidth, communication cannot always be shared. Swarm robotics systems and self-coordination could be proposed to overcome this limitation, to reduce the reliance on coordination through direct communication.

This section discussed the results that were obtained from the analysis of the studied domain to help understand the recent trends addressed by drones in the field of fire suppression. Therefore, it is possible to consider the analysis results drawn in this paper in Section 3 as valid only for UAV applications in firefighting; these depend on the exclusion criteria defined in Section 2 and the specific keywords that cannot be considered valid for all other UAV applications.

4. Research Gaps and Recommendations

This section identifies four research gaps, limitations, and recommendations based on the findings and discussion given in Section 3 above.

4.1. The Complexity of Coordination in Multi-Robotic Systems

The cooperation of team members based on a multi-robot system approach requires a complex coordination process [86]. In this context, the system architecture design and the coordination process for a complex task, e.g., a forest firefighting mission, make it more complicated. Consequently, the complexity of coordination for forest firefighting missions using multiple drones requires increasingly complex software and hardware capabilities, as well as a high system cost. On the other hand, the main problem in performing a demanding task such as firefighting in a forest is direct communication between team members. Members discuss and make decisions among themselves and assign tasks to individuals to achieve the objectives of their mission, and this requires a high level of direct communication. Communication between team members should be suitable to share information in real time and ensure the robustness and flexibility of the system. Multi-robot systems exchange information with a central node or with ground stations to make joint decisions [5,86]. This central node is a single point of failure, and due to limitations in sensing and communication, it may not receive complete and up-to-date information. Communication problems are significantly affected by centrally controlled robots when one or more robots are missing (permanently or temporarily), affecting the available decisions and information. Due to limited bandwidth, communication cannot always be shared.

4.2. The Lack of Evaluation and Implementation of Fire-Extinguishing Systems

The studies that specialized in the field of firefighting activities, which were referred to in the previous sections, show that no real mechanisms have been identified. Very few of the studies reviewed in this paper used simulations of several scenarios in firefighting activities using UAVs, whereas the majority did not have simulations. Implementing test automation and benchmarks for difficulties and problems—such as fire-suppression mechanisms and sensor fusion—to assess the ability to meet both safety and reliability requirements in general will be critical to UAV development and the validation of novel techniques. To evaluate the performance of models of UAV applications in firefighting activities, one needs to use platforms to simulate the process of fire propagation, coupled with the process of extinguishing it using UAVs by creating such simulations in a realistic way. Typically, this evaluation is based on either a synthetic dataset or a real dataset. The difficulty in testing the proposed systems increases as the complexity of programming the mission of UAVs increases [87]. The models that were used in those studies are evaluated, as are the lack of tools for verifying simulations that specialize in multi-bot systems (such as NetLogo, Collective Cognitive Robots (CoCoRo), Webots, Milybot, Polybot, Colias, and Kilobot). Through the use of good test procedures with datasets, this assists in the unification of the evaluation process and enables systematic comparisons of the approaches proposed in the literature.

4.3. The Multiple-Spot Fire Situation

To address the area coverage issue, Particle Swarm Optimization (PSO) has been widely adopted, as it is considered one of the most important algorithms to determine the optimal solution in many optimization problems [87,88]. Through reviewing studies on firefighting missions, only two studies [61,72] that used the PSO algorithm to handle the search space were found. The PSO algorithm was initially developed in the field of social behavior as a model inspired by earlier bird-flock simulations [88]. Every particle in a swarm population in the PSO algorithm moves and changes its position through problem space based on several factors, usually an attraction factor towards the best position related to the target and an attraction factor towards the position relation to neighboring swarm members (or neighborhood) [61,72]. Additionally, the swarm suffers from momentum, so it is difficult for the swarm to immediately change direction. In the above-mentioned approach, drones converge on each other due to the attraction factor, which limits the area covered, with drones unable to scan all locations in the search space. In other words, the swarm of drones will move to one hot-spot and leave the rest of the area. On the other hand, the convergence of a swarm of drones toward each other can generate a high air current, causing an increase in the intensity of the fire and its spread to become faster. Because of this, despite the efficiency of the PSO algorithm in many applications of multi-robot systems, it is ineffective and unrealistic in an application such as firefighting, especially if the fire spreads to multiple places (multi-hot-spots) in the search space. Fire propagation factors cause the fire to spread dynamically into multiple hot-spots in the environment, with frequent and severe changes in location and severity. Therefore, a time-sensitive search approach in firefighting applications requires spreading the drones in all directions, rather than converging in the problem area, to cover the area with the highest fire spread.

4.4. The Lack of Inflexibility in the Use of Limited Time and Resources

There are just a few studies in the literature that propose strategies for firefighting in the forest using UAVs. After reviewing the current state of firefighting projects and robotic system strategies [8,57,60,69,72,81], we found that these studies make the assumption that all drones can access resources in any capacity and at any time. This assumption does not accurately meet the mission requirements, ignoring the problem of recharging or refueling by returning to the docking stations. Innocente and Grasso [61] proposed a very rudimentary firefighting model in which each drone searches for fire spots in the forest, and one-third of its total water payload is dropped when it detects the location that has a hotter temperature than the hottest one stored in its individual memory. Then, all the drones in the swarm will go back to the water source after dropping their payload. Likewise, the swarm must return to its recharging docking station after covering all of its flight range.

In other words, for each drone, after completing its specific goal, it must move forward to a recharging station or move towards the water source for replenishment based on the updated temperature for all individual memories in the swarm. However, the parallelism of the swarm of drones that is proposed by using the PSO algorithm leads to the synchronous updating of global memory by simply updating all individual memories in the swarm, by extracting the location and temperature of the last member of the swarm from the current memories of all drones at the same time, in which all drones work collectively on a single task; this leads to the poor utilization of time and resources. In some of the cases discussed in the aforementioned study, the swarm of drones returned to the docking station without completely extinguishing the fire; this poses a problem if the fire grows back unchecked. An effective model is required to solve the problems of resource limitation, such as battery capacity and liquid extinguishing. The firefighting system will be more efficient if the resources are maximized through the provision of fuel or through the recharging of drones after dropping their first payload at the fire points. To mitigate this problem, we could propose a self-firefighting model that relies on each member of the team moving, on its own, towards a recharging station, or towards the water source for replenishment, and returning to work separately from the rest of the swarm. This allows the creation of a continuous flow of extinguishing liquid while trying to firefight in the forest, simulating a rain effect on the fire front.

5. Discussion

This section provides further details and the results obtained by answering the research questions proposed in Section 2.1 of the paper. The main objective of this paper was to provide a comprehensive overview of UAV-based forest-fire-extinguishing activity (FFEA) operations, and to examine the studies that describe UAV technology.

The main results were as follows:

- *The evolution of the use of UAVs for firefighting in the forest in terms of geographical distribution and major shareholders*
    - (i) The highest number of published papers in the field studied, worldwide, was occupied by researchers from the USA in the past decade. This fact may be explained by the high number of publications for this country compared to other countries due to the increase in the number of fires in the USA, not to mention its investments in research and development. The majority of the studies reviewed were published in Europe, followed by Asia. Although the amount of research on the use of UAVs as firefighting tools declined between 2008 and 2016, the growth in the amount of research has become apparent in subsequent years, especially in the last three years.
- *The main characteristics of UAV-based fire-extinguishing systems*
    - (i) Most of the previous studies tend to use a single drone instead of multi-drones. Regarding the characteristics of a single drone in firefighting systems, the number of papers in which the only task was to extinguish fires was the highest in the studies discussed and analyzed in this SLR [23–29]. In addition, single robots cannot share information; this helps to process that information in order to complete their tasks efficiently, especially in tasks that require cooperation between several robots [29,51].
    - (ii) Unfortunately, most of the previous studies did not address the use of the fire propagation model, except in limited studies. Despite the few existing studies that relied on autonomy of control, most of the previous studies discussed are based on the remote control of UAVs [47,48].
    - (iii) On the contrary, autonomy provides a high degree of task performance, optimal coverage, and coordination, as well as collision avoidance. Finally, the use of a single drone requires centralized coordination and the provision of direct communication between the drone and the operator; this may pose a great

danger to the operator, not to mention the limitation in providing services for a long time due to the finite payload and battery consumption, spatially, in a complex environment.

(iv) Regarding the characteristics of multi-drones in firefighting systems, most studies tend to rely on the tasks of detecting and extinguishing the fire, while the studies analyzed and discussed in this paper indicate reliance on unstructured environments (e.g., forests, etc.) in their experiments due to the complex environment. Moreover, the multi-drone systems depended on autonomous control in most studies, to control the cooperating team and to achieve the highest efficiency of the system. Although the promising outcome demonstrated by these studies of firefighting using multi-drones is significant, they suffer from major limitations, that is, the complexity of coordination in MRS requires advanced software and hardware technology as well as direct communication between members in real-time; this is quite challenging in a forest firefighting mission.

(v) On the other hand, water was the most commonly used method of extinguishing the fire compared to other liquids, due to its cheap price and its availability in large quantities [25].

- *The main research topics for UAVs used in firefighting applications covered in the research papers*

    (i) Most of the studies on extinguishing fires using a single drone did not discuss many research topics, and there was a greater focus and diversity of research topics in studies that used multi-drones. Some research topics (e.g., controlling and motion planning, path planning, and coverage) tend to use a multi-robot system, with robots interacting with each other to accomplish the task of successfully extinguishing a fire; this often needs more autonomy than other research topics [23,45,51].

    (ii) Research topics such as coordination, resource allocation, and path planning received a relatively high level of attention. However, these studies lacked details about the evaluations, applications, and implementation of UAVs provided by the works cited. Despite studies dealing with coverage of the target area, they did not discuss the issue of multiple-hot-spot situations, which means that area coverage was limited to a single spot, and other possible hot-spots in the search space were unable to be scanned [61,72].

    (iii) Furthermore, in order to fight forest fires in the shortest possible time, taking into account the limited resources as well as the environmental conditions, an effective model is required to solve the problems of resource limitation, such as battery capacity and liquid extinguishing.

- *The swarm of UAVs to meet the requirements of firefighting in the forest without human intervention*

    (i) The main goal of using swarm robotics theory in firefighting tasks is to develop a self-coordination approach for a number of UAVs. However, achieving self-coordination efficiently may require further investigation of the existing approaches, since most of the literature studies on autonomous firefighting missions have not addressed self-coordination. It is worth noting that the cooperation of members using a multi-robot system requires a complex coordination process [88]. In this context, the system architecture design and the coordination process for a complex task, e.g., a forest firefighting mission, make it more complicated.

    (ii) Consequently, the complexity of coordination for forest firefighting missions using multi-drones requires increasingly complex software and hardware capabilities, as well as a high system cost. On the other hand, the main problem with performing a challenging task such as firefighting in the forest is the direct communication between team members. Communication problems are significantly affected by centrally controlled robots if one or more robots are missing (permanently or temporarily) for available decisions and information. Due to the limited amount of bandwidth, communication cannot always be shared. To overcome this limitation, swarm robotic systems and self-coordination could be proposed to reduce the reliance on coordination through direct communication.

6. Conclusions

UAV-based technology in firefighting systems has been used for forest fire detection, monitoring, and extinguishing. Since there is a lack of literature that assesses the current state of using UAV technology in forest-fire-extinguishing activities (FFEA), the main objective of this research is twofold. First, we conducted a systematic review of the literature on the use of UAVs in firefighting applications, to provide a comprehensive overview of the use of drones in FFEA and highlight the most important studies and research on the use of UAVs in firefighting applications. Second, we displayed and discussed an outline of the research topics in UAV-based fire-extinguishing activity (FFEA) application. The main results were stated, discussed, and analyzed. Based on a well-established SLR methodology, we identified four research questions (RQs) that help assess the most active contributions in the field of UAV firefighting.

As a result, we outlined the following key challenges and recommendations: (i) A model should be designes based on swarm robotics approaches to form self-coordination and, thus, avoid direct communication among firefighting drones; (ii) the characteristics of fire-extinguishing systems must be further developed, taking into account all of the factors that affect the task of extinguishing the fire in the shortest possible time; (iii) a model must be designed to handle multiple fire spots in an unknown environment for effective area coverage in forest firefighting; (iv) A self-firefighting model should be designed that allows individuals to decide on the course of events locally, increasing the flexibility and utilitarianism.

The results of this SLR will be used in the future to close major gaps in previous studies, and to define the criteria for designing and evaluating a more realistic multi-drone firefighting model based on specific civilian UAV application considerations.

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References

1. Theodoridis, T.; Hu, H. Toward Intelligent Security Robots: A Survey. *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.* **2012**, *42*, 1219–1230. [CrossRef]
2. Rivera, A.J.A.; Villalobos, A.; Monje, J.; Marinas, J.; Oppus, C. Post-disaster rescue facility: Human detection and geolocation using aerial drones. In Proceedings of the 2016 IEEE Region 10 Conference (TENCON), Singapore, 22–25 November 2016.
3. Zhang, H.; Wei, S.; Yu, W.; Blasch, E.; Chen, G.; Shen, D.; Pham, K. Scheduling methods for unmanned aerial vehicle based delivery systems. In Proceedings of the 2014 IEEE/AIAA 33rd Digital Avionics Systems Conference (DASC), Colorado Springs, CO, USA, 5–9 October 2014.
4. Yuan, C.; Zhang, Y.; Liu, Z. A survey on technologies for automatic forest fire monitoring, detection, and fighting using unmanned aerial vehicles and remote sensing techniques. *Can. J. For. Res.* **2015**, *45*, 783–792. [CrossRef]

5. Yan, Z.; Jouandeau, N.; Cherif, A.A. A survey and analysis of multi-robot coordination. *Int. J. Adv. Robot. Syst.* **2013**, *10*, 399. [CrossRef]
6. McAlpine, R.; Wotton, B. The use of fractal dimension to improve wildland fire perimeter predictions. *Can. J. For. Res.* **1993**, *23*, 1073–1077. [CrossRef]
7. Dios, J.M.-D.; Arrue, B.; Ollero, A.; Merino, L.; Gómez-Rodríguez, F. Computer vision techniques for forest fire perception. *Imag. Vis. Comput.* **2008**, *26*, 550–562. [CrossRef]
8. Merino, L.; Dios, J.R.M.-D.; Ollero, A. Cooperative Unmanned Aerial Systems for Fire Detection, Monitoring, and Extinguishing. In *Handbook of Unmanned Aerial Vehicles*; Valavanis, K.P., Vachtsevanos, G.J., Eds.; Springer: Dordrecht, The Netherlands, 2015; pp. 2693–2722.
9. Torresan, C.; Berton, A.; Carotenuto, F.; Di Gennaro, S.F.; Gioli, B.; Matese, A.; Miglietta, F.; Vagnoli, C.; Zaldei, A.; Wallace, L. Forestry applications of UAVs in Europe: A review. *Int. J. Remote Sens.* **2017**, *38*, 2427–2447. [CrossRef]
10. Graml, R.; Wigley, G. Bushfire hotspot detection through uninhabited aerial vehicles and reconfigurable computing. In Proceedings of the 2008 IEEE Aerospace Conference, Big Sky, Montana, MT, USA, 1–8 March 2008.
11. Casbeer, D.; Li, S.-M.; Beard, R.; Mehra, R.; McLain, T. Forest fire monitoring with multiple small UAVs. In Proceedings of the 2005 American Control Conference, Portland, OR, USA, 8–10 June 2005.
12. Akhloufi, M.A.; Couturier, A.; Castro, N.A. Unmanned aerial vehicles for wildland fires: Sensing, perception, cooperation and assistance. *Drones* **2021**, *5*, 15. [CrossRef]
13. Roldán-Gómez, J.J.; González-Gironda, E.; Barrientos, A. A Survey on Robotic Technologies for Forest Firefighting: Applying Drone Swarms to Improve Firefighters' Efficiency and Safety. *Appl. Sci.* **2021**, *11*, 363. [CrossRef]
14. Kitchenham, B. *Procedures for Performing Systematic Reviews*; Keele University: Keele, UK, 2004; Volume 33, pp. 1–26.
15. Budgen, D.; Brereton, P. Performing systematic literature reviews in software engineering. In Proceedings of the 28th International Conference on Software Engineering, Shanghai, China, 20–28 May 2006.
16. Kitchenham, B.A.; Brereton, P.; Turner, M.; Niazi, M.K.; Linkman, S.; Pretorius, R.; Budgen, D. Refining the systematic literature review process—Two participant-observer case studies. *Empir. Softw. Eng.* **2010**, *15*, 618–653. [CrossRef]
17. Brereton, P.; Kitchenham, B.; Budgen, D.; Turner, M.; Khalil, M. Lessons from applying the systematic literature review process within the software engineering domain. *J. Syst. Softw.* **2007**, *80*, 571–583. [CrossRef]
18. Galster, M.; Weyns, D.; Tofan, D.; Michalik, B.; Avgeriou, P. Variability in software systems—A systematic literature review. *IEEE Trans. Softw. Eng.* **2013**, *40*, 282–306. [CrossRef]
19. Unterkalmsteiner, M.; Gorschek, T.; Islam, A.M.; Cheng, C.K.; Permadi, R.B.; Feldt, R. Evaluation and measurement of software process improvement—A systematic literature review. *IEEE Trans. Softw. Eng.* **2011**, *38*, 398–424. [CrossRef]
20. Calvaresi, D.; Cesarini, D.; Sernani, P.; Marinoni, M.; Dragoni, A.F.; Sturm, A. Exploring the ambient assisted living domain: A systematic review. *J. Ambient Intell. Humaniz. Comput.* **2017**, *8*, 239–257. [CrossRef]
21. Kitchenham, B.; Budgen, D.; Brereton, P.; Turner, M. 2nd International Workshop on Realising Evidence-Based Software Engineering (REBSE-2): Overview and Introduction. In *Second International Workshop on Realising Evidence-Based Software Engineering (REBSE '07)*; IEEE: Piscataway, NJ, USA, 2007.
22. Kitchenham, B.A.; Brereton, O.P.; Budgen, D.; Li, Z. An Evaluation of Quality Checklist Proposals-A participant-observer case study. In Proceedings of the 13th International Conference on Evaluation and Assessment in Software Engineering (EASE), Karlskrona, Sweden, 15–16 June 2009.
23. Spurny, V.; Pritzl, V.; Walter, V.; Petrlik, M.; Baca, T.; Stepan, P.; Zaitlik, D.; Saska, M. Autonomous Firefighting Inside Buildings by an Unmanned Aerial Vehicle. *IEEE Access* **2021**, *9*, 15872–15890. [CrossRef]
24. Walter, V.; Spurny, V.; Petrlik, M.; Baca, T.; Zaitlik, D.; Saska, M. Extinguishing of Ground Fires by Fully Autonomous UAVs motivated by the MBZIRC 2020 Competition. In Proceedings of the 2021 International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece, 15–18 June 2021.
25. Aydin, B.; Selvi, E.; Tao, J.; Starek, M. Use of fire-extinguishing balls for a conceptual system of drone-assisted wildfire fighting. *Drones* **2019**, *3*, 17. [CrossRef]
26. Qin, H.; Cui, J.Q.; Li, J.; Bi, Y.; Lan, M.; Shan, M.; Liu, W.; Wang, K.; Lin, F.; Zhang, Y.F.; et al. Design and implementation of an unmanned aerial vehicle for autonomous firefighting missions. In Proceedings of the IEEE International Conference on Control and Automation (ICCA), Kathmandu, Nepal, 1–3 June 2016.
27. Sujatha, C.N.; Lakshmi, P.S.; Reddy, Y.S.; Sai, I.M. Application of fire fighting drone in containment of small-scale fires. *J. Crit. Rev.* **2020**, *7*, 7533–7539.
28. Gupta, A.D.; Akhtar, Z.B.; Sarkar, M.C.; Dhar, T.; Das, P. Unmanned Disposal Rover Along with Fire Extinguishing Capacity on Both Ground and Air. In Proceedings of the 2019 Global Conference for Advancement in Technology (GCAT 2019), Bangaluru, India, 18–20 October 2019.
29. Chen, R.; Cao, H.; Cheng, H.; Xie, J. Study on Urban Emergency Firefighting Flying Robots Based on UAV. In Proceedings of the 2019 IEEE 4th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC 2019), Chengdu, China, 20–22 December 2019.
30. Barua, S.; Tanjim, M.S.S.; Oishi, A.N.; Das, S.C.; Basar, A.; Rafi, S.A. Design and Implementation of Fire Extinguishing Ball Thrower Quadcopter. In Proceedings of the 2020 IEEE Region 10 Symposium (TENSYMP), Dhaka, Bangladesh, 5–7 June 2020.

31. Zadeh, N.R.N.; Abdulwakil, A.H.; Amar, M.J.R.; Durante, B.; Santos, C.V.N.R. Fire-fighting UAV with shooting mechanism of fire extinguishing ball for smart city. *Indones. J. Electr. Eng. Comput. Sci.* **2021**, *22*, 1320–1326. [CrossRef]
32. Mnaouer, H.B.; Faieq, M.; Yousefi, A.; Mnaouer, S.B. FireFly Autonomous Drone Project. *arXiv* **2021**, arXiv:2104.07758.
33. Zhang, Y.; Xiong, M.; Dong, M.; Lin, X. Research of electromagnetic launched fire-extinguishing bomb fire-fighting system. *Power Laser Part. Beams* **2020**, *32*, 025023. [CrossRef]
34. Abu Bakar, M.H.; Shamsudin, A.U.; Rahim, R.A. Simulation of drone controller using reinforcement learning AI with hyperparameter optimization. In Proceedings of the 2020 IEEE 10th International Conference on System Engineering and Technology, Shah Alam, Malaysia, 9 November 2020.
35. Manimaraboopathy, M.; Christopher, H.V.; Vignesh, S. Unmanned fire extinguisher using quadcopter. *Int. J. Smart Sens. Intell. Syst.* **2017**, *2017*, 471–481. [CrossRef]
36. Patil, R.; Patil, P.; Sawant, N.; Thakur, H.; Surve, D. Fire fighting drone using extinguisher bomb. *Int. Res. J. Eng. Technol.* **2020**, *7*, 3395–3398.
37. Akhade, Y.; Kasar, A.; Honrao, A.; Fire, N.G. Fire Fighting Drone Using CO_2 Boll Extinguisher. *Int. J. Innov. Res. Comput. Commun. Eng.* **2017**, *5*. [CrossRef]
38. Imdoukh, A.; Shaker, A.; Al-Toukhy, A.; Kablaoui, D.; El-Abd, M. Semi-autonomous indoor firefighting UAV. In Proceedings of the 2017 18th International Conference on Advanced Robotics (ICAR 2017), Hong Kong, China, 10–12 July 2017.
39. Benavente, D. Semi-expendable Unmanned Aerial Vehicle for forest fire suppression. *WIT Trans. Ecol. Environ.* **2010**, *137*, 143–148.
40. Manuj, C.; Adarsh, M.R.; Rahul, S.; Suhas, C.N.; Vismay, K.G. Design and Development of Semi-Autonomous Fire Fighting Drone. *J. Mech. Civ. Eng.* **2019**, *16*, 44–47.
41. Pathak, A.; Tasin, A.H.; Esho, A.A.; Munna, A.R.; Chowdhury, T. A smart semi-autonomous fire extinguish quadcopter: Future of Bangladesh. *Int. J. Adv. Res.* **2020**, *8*, 1–15. [CrossRef]
42. Wang, Y.; Shi, X.; Zheng, Z.; Yin, B.; Yao, X. CFD-based numerical simulation method of fire-fighting robot jet. In Proceedings of the ACM International Conference, Milan, Italy, 3–6 May 2021.
43. Moore, J.; Aberdeen, M. UAV Fire-Fighting System. U.S. Patent 20130134254 A, 29 May 2013.
44. Cervantes, A.; Garcia, P.; Herrera, C.; Morales, E.; Tarriba, F.; Tena, E.; Ponce, H. A Conceptual Design of a Firefighter Drone. In Proceedings of the 2018 15th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), Mexico City, Mexico, 5–7 September 2018.
45. Beachly, E.; Detweiler, C.; Elbaum, S.; Duncan, B.; Hildebrandt, C.; Twidwell, D.; Allen, C. Fire-Aware Planning of Aerial Trajectories and Ignitions. In Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Madrid, Spain, 1–5 October 2018.
46. Soliman, A.M.S.; Cagan, S.C.; Buldum, B.B. The design of a rotary-wing unmanned aerial vehicles–payload drop mechanism for fire-fighting services using fire-extinguishing balls. *SN Appl. Sci.* **2019**, *1*, 1259. [CrossRef]
47. Chaikalis, D.; Tzes, A.; Khorram, F. Aerial Worker for Skyscraper Fire Fighting using a Water-Jetpack Inspired Approach. In Proceedings of the 2020 International Conference on Unmanned Aircraft Systems (ICUAS 2020), Athens, Greece, 1–4 September 2020.
48. Al Jaber, R.; Sikder, M.S.; Hossain, R.A.; Malia, K.F.; Rahman, M.A. Unmanned Aerial Vehicle for Cleaning and Firefighting Purposes. In Proceedings of the ICREST 2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques, Dhaka, Bangladesh, 5–7 January 2021.
49. Jayapandian, N. Cloud Enabled Smart Firefighting Drone Using Internet of Things. In Proceedings of the 2019 International Conference on Smart Systems and Inventive Technology (ICSSIT), Tirunelveli, India, 27–29 November 2019.
50. Saikin, D.A.; Baca, T.; Gurtner, M.; Saska, M. Wildfire Fighting by Unmanned Aerial System Exploiting Its Time-Varying Mass. *IEEE Robot. Autom. Lett.* **2020**, *5*, 2674–2681. [CrossRef]
51. Wang, C.; Liu, P.; Zhang, T.; Sun, J. The Adaptive Vortex Search Algorithm of Optimal Path Planning for Forest Fire Rescue UAV. In Proceedings of the 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Chongqing, China, 12–14 October 2018.
52. Ausonio, E.; Bagnerini, P.; Ghio, M. Drone Swarms in Fire Suppression Activities: A Conceptual Framework. *Drones* **2021**, *5*, 17. [CrossRef]
53. Harikumar, K.; Senthilnath, J.; Sundaram, S. Multi-UAV Oxyrrhis Marina-Inspired Search and Dynamic Formation Control for Forest Firefighting. *IEEE Trans. Autom. Sci. Eng.* **2019**, *16*, 863–873. [CrossRef]
54. Shaffer, J.A.; Carrillo, E.; Xu, H. Hierarchal Application of Receding Horizon Synthesis and Dynamic Allocation for UAVs Fighting Fires. *IEEE Access* **2018**, *6*, 78868–78880. [CrossRef]
55. Gasparovic, G.; Klarin, B.; Grebo, A.; Mladenovic, S. New Concept of Firefighting Aerial Support with Autonomous Unmanned Aerial Systems (AUAS). In Proceedings of the 2020 New Trends in Aviation Development (NTAD), Košice, Slovakia, 25–26 November 2020.
56. Shaffer, J.; Carrillo, E.; Xu, H. Receding Horizon Synthesis and Dynamic Allocation of UAVs to Fight Fires. In Proceedings of the 2018 IEEE Conference on Control Technology and Applications (CCTA), Copenhagen, Denmark, 21–24 August 2018.
57. Phan, C.; Liu, H.H. A cooperative UAV/UGV platform for wildfire detection and fighting. In Proceedings of the 2008 Asia Simulation Conference-7th International Conference on System Simulation and Scientific Computing, Beijing, China, 10–12 October 2008.

58. Subramaniam, E.; Joseph, N.; Rose, A.; Bil, C. Design of a fire-fighting unmanned air vehicle. In Proceedings of the 50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Nashville, TN, USA, 9–12 January 2012.
59. Sato, M.; Torikai, H.; Iwatani, Y. Flame extinguishment by a prototype of an aerial extinguisher with an inert gas capsule. In Proceedings of the SICE Annual Conference, Nagoya, Japan, 14–17 September 2013.
60. Kumar, M.; Cohen, K. Wild land fire fighting using multiple uninhabited aerial vehicles. In Proceedings of the AIAA Infotech@ Aerospace Conference and AIAA Unmanned, Unlimited Conference, Seattle, WA, USA, 21 July 2009.
61. Innocente, M.S.; Grasso, P. Self-organising swarms of firefighting drones: Harnessing the power of collective intelligence in decentralised multi-robot systems. *J. Comput. Sci.* **2019**, *34*, 80–101. [CrossRef]
62. Innocente, M.S.; Grasso, P. Swarms of autonomous drones self-organised to fight the spread of wildfires. In *CEUR Workshop Proceedings*; Sun SITE Central Europe: Aachen, Germany, 2018.
63. Moffatt, A.; Turcios, N.; Edwards, C.; Karnik, A.; Kim, D.; Kleinman, A.; Nguyen, V.; Ramos, V.; Ranario, E.; Sato, T.; et al. Collaboration between Multiple UAVs for Fire Detection and Suppression. In Proceedings of the 2021 International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece, 15–18 June 2021.
64. Howden, D.; Hendtlass, T. Collective Intelligence and Bush Fire Spotting. In Proceedings of the 10th Annual Conference on Genetic and Evolutionary Computation (Gecco '08), Atlanta, GA, USA, 12 July 2008; pp. 41–48.
65. Bjurling, O.; Granlund, R.; Alfredson, J.; Arvola, M.; Ziemke, T. Drone Swarms in Forest Firefighting: A Local Development Case Study of Multi-Level Human-Swarm Interaction. In Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society, Tallinn, Estonia, 25–29 October 2020.
66. Haksar, R.N.; Schwager, M. Distributed Deep Reinforcement Learning for Fighting Forest Fires with a Network of Aerial Robots. In Proceedings of the 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 1–5 October 2018.
67. Chan, H.; Tran-Thanh, L.; Viswanathan, V. Fighting wildfires under uncertainty: A sequential resource allocation approach. In Proceedings of the IJCAI International Joint Conference on Artificial Intelligence, Yokohama, Japan, 11–17 July 2020.
68. Luo, Z.; Zhang, Y.; Mu, L.; Huang, J.; Xin, J.; Liu, H.; Jiao, S.; Xie, G.; Yi, Y. A UAV Path Planning Algorithm Based on an Improved D* Lite Algorithm for Forest Firefighting. In Proceedings of the 2020 Chinese Automation Congres (CAC 2020), Shanghai, China, 6–8 November 2020.
69. Sherstjuk, V.; Zharikova, M.; Sokol, I. Forest Fire Fighting Using Heterogeneous Ensemble of Unmanned Aerial Vehicles. In Proceedings of the 2019 IEEE 5th International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD), Kiev, Ukraine, 22–24 October 2019.
70. Quenzel, J.; Splietker, M.; Pavlichenko, D.; Schleich, D.; Lenz, C.; Schwarz, M.; Schreiber, M.; Beul, M.; Behnke, S. Autonomous Fire Fighting with a UAV-UGV Team at MBZIRC 2020. In Proceedings of the 2021 International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece, 15–18 June 2021.
71. Mohandes, A.; Farrokhsiar, M.; Najjaran, H. A Motion Planning Scheme for Automated Wildfire Suppression. In Proceedings of the 2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall), Vancouver, BC, Canada, 14–17 September 2014.
72. Ghamry, K.A.; Kamel, M.A.; Zhang, Y. Multiple UAVs in forest fire fighting mission using particle swarm optimization. In Proceedings of the 2017 International Conference on Unmanned Aircraft Systems (ICUAS), Miami, FL USA, 13–16 June 2017.
73. Madridano, Á.; Al-Kaff, A.; Flores, P.; Martín, D.; de la Escalera, A. Software Architecture for Autonomous and Coordinated Navigation of UAV Swarms in Forest and Urban Firefighting. *Appl. Sci.* **2021**, *11*, 1258. [CrossRef]
74. Shi, Z.; Tu, J.; Zhang, Q.; Liu, L.; Wei, J. A survey of swarm robotics system. In *International Conference in Swarm Intelligence*; Springer: Berlin, Germany, 2012.
75. Perez-Montenegro, C.; Scanavino, M.; Bloise, N.; Capello, E.; Guglieri, G.; Rizzo, A. A Mission Coordinator Approach for a Fleet of UAVs in Urban Scenarios. *Transp. Res. Procedia* **2018**, *35*, 110–119. [CrossRef]
76. Chao, H.; Chen, Y.Q. Cooperative Remote Sensing Using Multiple Unmanned Vehicles. In *Remote Sensing and Actuation Using Unmanned Vehicles*; Wiley: Hoboken, NJ, USA, 2012; pp. 121–142.
77. Sharifi, F.; Zhang, Y.; Aghdam, A.G. Forest Fire Monitoring and Detection using a Network of Autonomous Vehicles. In Proceedings of the International Conference on Intelligent Unmanned Systems, Orlando, FL, USA, 27–30 May 2014.
78. Sharifi, F.; Chamseddine, A.; Mahboubi, H.; Zhang, Y.; Aghdam, A.G. A Distributed Deployment Strategy for a Network of Cooperative Autonomous Vehicles. *IEEE Trans. Control Syst. Technol.* **2015**, *23*, 737–745. [CrossRef]
79. Àgueda, A.; Pastor, E.; Planas, E. Different scales for studying the effectiveness of long-term forest fire retardants. *Prog. Energy Combust. Sci.* **2008**, *34*, 782–796. [CrossRef]
80. Tian, G.; Ren, Y.; Zhou, M. Dual-Objective Scheduling of Rescue Vehicles to Distinguish Forest Fires via Differential Evolution and Particle Swarm Optimization Combined Algorithm. *IEEE Trans. Intell. Transp. Syst.* **2016**, *17*, 3009–3021. [CrossRef]
81. Kumar, M.; Cohen, K.; HomChaudhuri, B. Cooperative control of multiple uninhabited aerial vehicles for monitoring and fighting wildfires. *J. Aerosp. Comput. Inf. Commun.* **2011**, *8*, 1–16. [CrossRef]
82. Tan, Y. Swarm robotics: Collective behavior inspired by nature. *J. Comput. Sci. Syst. Biol.* **2013**, *6*, e106.
83. Sharkey, A.J. Swarm robotics and minimalism. *Connect. Sci.* **2007**, *19*, 245–260. [CrossRef]
84. Khaldi, B.; Cherif, F. An overview of swarm robotics: Swarm intelligence applied to multi-robotics. *Int. J. Comput. Appl.* **2015**, *126*, 2. [CrossRef]

85. Dorigo, M.; Sahin, E. Guest editorial: Swarm robotics. *Auton. Robot.* **2004**, *17*, 111–113. [CrossRef]
86. Farinelli, A.; Iocchi, L.; Nardi, D. Multirobot systems: A classification focused on coordination. *IEEE Trans. Syst. Man Cybern. Part B* **2004**, *34*, 2015–2028. [CrossRef] [PubMed]
87. Eberhart, R.; Kennedy, J. A new optimizer using particle swarm theory. In *MHS'95, Proceedings of the Sixth International Symposium on Micro Machine and Human Science, Nagoya, Japan, 4–6 October 1995*; IEEE: Piscataway, NJ, USA, 1995.
88. Kennedy, J.; Eberhart, R. Particle swarm optimization. In Proceedings of the ICNN'95-International Conference on Neural Networks, Perth, Australia, 27 November–1 December 1995.