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Review Article

Computational Architectures, Cyber-Physical Integration, and Technology Readiness for Remote Wildfire Suppression: A Systematic Review and Bibliometric Analysis

Victor Romero-Alva[1], Jandra Rojas Chavez[2], Jonathan Arzapalo-Torres[3], Linett Velasquez-Jimenez[4]

[1,2,3,4]*Image Processing Research Laboratory (INTI-Lab), Universidad de Ciencias y Humanidades, Lima, Peru.*

[1]*Corresponding Author : vromero@uch.edu.pe*

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Abstract - *Remote wildfire suppression systems utilize air or ground vehicles, loads, outputs, and computing tools for perception, guidance, planning, management, and communication. But due to differences in structures, it is hard to compare their performance or understand the maturity of cyber-physical systems. The present research investigated the development, technology design, evidence quality, and technology readiness rate of remote wildfire suppression systems. A systematic review following PRISMA 2020 procedures was conducted, as well as a bibliometric analysis of Scopus and IEEE Xplore publications dated from 2005 to July 15, 2026. Of 967 identified records, 6 duplicates were removed, and 961 items went through the screening. The final corpus included 190 records:70 primary core articles, 109 primary auxiliary articles, and 11 secondary articles. The 179 primary articles represented 175 studies. Eight core studies with sufficient information were evaluated by the level of evidence quality and of technology readiness. Five studies provided evidence with moderate quality, while three studies provided evidence with low quality; none of the studies achieved high-quality evidence. The most advanced components included perception, navigation, planning, control, and multi-UAV control, while the least mature were related to payload delivery, release, delivery, and assessment of suppression results. A number of problems remained related to communication continuity, fault tolerance, repeatability, and reliability issues, as well as environment evaluation and end-to-end validation of systems. The research authors suggest a framework for integration which helps distinguish between the maturity of parts and the verified level of performance of the system as a whole.*

Keywords - *Cyber-Physical systems, Wildfire suppression, Unmanned Aerial Vehicles, Multi-UAV systems, Technology readiness level.*

1. Introduction

Wildfires represent ever-changing scenarios characterized by inconsistent flame spread, low visibility, hard-to-access land and poor weather conditions, limiting on-ground efforts of firefighters and traditional aerial resources. Within this context, remotely controlled technology can serve as a complementary alternative for minimizing human engagement, reaching inaccessible locations, and delivering agents for suppression purposes [1-3].

The use of drones has become especially relevant due to their capability of building integration of visual and thermal sensors, positioning and navigation systems, onboard systems processing, and communications tools, as well as having various degrees of automation. Studies in the field have mostly focused on detecting fires, monitoring heated objects, localizing them, navigating toward their locations, and organizing the work of different drones. The increase in operational complexity that comes with switching operations from monitoring mode to carrying out suppression tasks changes the operation of the UAV from that of just an information-gathering and reporting tool to an initiator of the interaction with its payload and release mechanism in unforeseen conditions.

The consideration of cyber-physical systems indicates that remote suppression missions incorporate the arrangement of data collection with actuation. The process should include the utilization of data coming from imaging devices, thermal sensors, or global positioning systems for finding the target, planning the course, controlling the platform in use, as well as establishing the time and place of suppression. The action is possible due to communication, telemetry, human control and allocation of tasks in case of multi-UAV systems [4-6].

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This paper describes a cyber-physical remote suppression system as a system consisting of a carrier, an agent or a payload, and a delivery mechanism alongside all the required computational systems. The general system consists of perception, localization, processing, planning, navigation, control, communication, and coordination systems. Guidance of sensors assists computational choices, while those choices change the activities of the platform and the means of suppression.

Such interaction does not allow for assessment of the technology solely by algorithmic parameters. Even high accuracy of detection, low error of positioning, or effective planning experience becomes evidence of nothing when it comes to transportation, use, and placement of the agent. Likewise, the performance of a delivery device shows nothing on its interaction with navigation, control, communication, energy independence, or changes of mass during the mission. Thus, algorithmic performance and component and system validation should be based on their interdependence.

The literature presents individual, cooperative, and multi-UAV architectures with heterogeneous levels of automation. Some proposals incorporate only waypoint tracking, whereas others integrate thermal perception, position correction, application-point selection, flight control, and activation of the release mechanism. Multi-UAV systems add task allocation, role distribution, communication relay, and coordinated execution functions. [7-10]. Nevertheless, a substantial proportion of these capabilities has been evaluated through simulations, models, or optimization, without an equivalent physical demonstration of the complete mission.

Comparison among proposals is also limited by the heterogeneity of platforms, sensors, agents, application mechanisms, algorithms, communication architectures, environmental conditions, and validation environments. Reported indicators may correspond to nominal specifications, simulated results, component tests, integrated prototypes, or operational demonstrations. [11] When these modalities are not distinguished, there is a risk of attributing to the complete system capabilities or maturity levels demonstrated only by one of its components.

Previous reviews have addressed specific dimensions of the field, including fire detection and monitoring, sensor integration, UAV cooperation, swarm deployment, task allocation, and the challenges of physical implementation [3, 12]. Within the set of secondary publications examined, these studies provided relevant syntheses on autonomy, communications, multi-agent coordination, resource management, and UAV applications. However, these dimensions were treated in a fragmented manner. No review was identified that simultaneously integrated the bibliometric evolution of the field, computational architectures, physical application platforms and mechanisms, validation environments, evidence quality, and the differentiated technological maturity of components and the integrated cyber-physical system.

It is important to note the gap between the advancements of computational functions and the physical evidence of their application. The existing literature reveals advancements within various aspects such as perception, navigation, planning and control, artificial intelligence, communication and multi-UAV coordination, but there are scarce proofs regarding the connection of the above capabilities to the stable payload transportation, controlled releasing, depositing and proving the suppressing effect. Moreover, it is important to mention that no systematic differentiation between the maturity of the platform, sensor, algorithm, or device and the maturity of the integrated architecture has been made.

Thus, the aim of this research was to analyze the computational and cyber-physical architectures applied in the remote application of agents for the purpose of forest fire suppression. The focus was on the bibliometric evolution of the area under study, the platforms and payloads involved, perception, navigation, planning, control, and communication subsystems, the Technology Readiness Levels (TRL) of both components and the integrated system.

The review addressed the following research questions:

RQ1: How has scientific production evolved, and what is the bibliometric structure of the field?

RQ2: What platforms, payloads, and transport, release, or application mechanisms have been proposed or evaluated?

RQ3: What perception, localization, navigation, planning, control, communication, and coordination technologies are integrated into these systems?

RQ4: What performance indicators and validation environments are used to evaluate the proposed architectures?

RQ5: What is the quality of the evidence, and what TRLs have been demonstrated by the components and the integrated system?

RQ6: What computational and operational limitations, safety risks, reliability issues, and environmental aspects constrain their transition toward operational applications?

The contribution of the study is structured around three elements. First, it provides a functional cyber-physical integration framework that links perception and localization, processing and planning, navigation, control and communications, transport and release, deposition, suppression effect, and verification. Second, it distinguishes nominal, simulated, experimental, and operational

performance, avoiding the automatic transfer of the performance or TRL of a component to the complete system. Third, it adopts an end-to-end perspective that makes it possible to identify where the connection between data acquisition, computational decision-making, physical actuation, and result verification is interrupted.

The remainder of the article presents the review design and analytical procedures; it then describes the bibliometric composition of the corpus, technological configurations, computational subsystems, validation environments, evidence quality, and TRLs. Finally, it discusses gaps in integration, safety, reliability, and environmental performance and proposes an agenda for the validation of cyber-physical remote suppression systems.

2. Materials and Methods

2.1. Review Design

To begin with, a systematic review, which included a bibliometric analysis and technological synthesis, was performed to study computational and cyber-physical systems aimed at the remote deployment of agents for firefighting operations.

The process of finding, removing duplicates, choosing and processing published articles has been carried out following the method of PRISMA 2020 [13]. The framework for the paper consisted of four stages: bibliometric analysis of the field, classification of technology architecture, estimation of the quality of evidence, and evaluation of the Technology Readiness Levels (TRL).

The technological platform under consideration is a cyber-physical remote suppression technology that involves the interaction among the platform, agent, vehicular system, and the computing subsystem intended for performing and monitoring the project. These subsystems include various facilities for perception, localization, navigation, planning, controlling the entire system, establishing communication, coordination, and providing human supervision.

To make sure that the results of the analysis of one component do not get transferred to the whole architecture, all elements were studied separately, including the platform, agent, delivery equipment, computing subsystem, and their joint system. The rationale for such an approach is the technological coherence that can be observed in the literature on UAVs, swarms, and firefighting systems [1, 2, 7].

Due to the differences between systems in terms of platforms, agents, methods of application, environment, and conditions of validation, meta-analysis has not been conducted. The integration of information has been carried out by means of descriptive statistics, bibliometric analysis, technological classification, and structured narrative synthesis.

2.2. Information Sources and Search Strategy

A systematic search was carried out on Scopus and IEEE Xplore. The main purpose of using Scopus was because the platform offers multidisciplinary sources to help find publications within computer science, robotics, automation, aerospace engineering, mechanical engineering, operations research, and environmental sciences. The search on IEEE Xplore was utilized as a supplementary to help find studies in artificial intelligence, computer vision, navigation, path planning, control, and multi-agent systems. OpenAlex was solely used to check the metadata, find certain documents, and complete bibliographic information and hence did not act as a third independent source in the systematic process.

The search covered the papers published between 2005 to 15 July 2026. Papers from 2026 were considered as incomplete. In total, thirteen additional search equations were used- seven in Scopus using the TITLE-ABS-KEY feature and six in IEEE Xplore, where All Metadata was used. The strategies involved the combination of keywords of wildfires and active suppression, UAVs and robotic platforms, agents and payloads, dispatching, spraying, launching, dispersing, and depositing, and perception, navigation, planning, control, communication, autonomy, coordination and multi-UAV systems.

The search equations were used as means to widen the retrieval of the heterogeneous technological arrangements and not as an independent set where the sums of the equations could be tallied for the number of publications found. The same publication could appear within different queries or databases. Consolidation was done first in each of the sources and then from one database to another. Duplicates were established based on exact match of DOIs, Scopus EID, or IEEE ARNUMBER; combined normalized title of authors and year; and manual matching of DOI versions, spelling discrepancies, and insufficient metadata.

2.3. Eligibility Criteria and Selection

The publications included in the study were those that explicitly showed how to use distant control agents in the context of fire suppression. The eligible studies examined fixed wing, rotary-wing, ground, or hybrid platforms; separate UAVs or a fleet of UAVs; types of payloads and agents; types of discharge, spraying, launching, spreading, or depositing; physical models of dispersion or drift; and computer subsystems concerned with planning, coordinating, or carrying out the agent delivery. The design concepts, mathematical models, simulations, optimization studies, component tests, prototypes, experiments, test runs, and operational use of the innovations were taken into consideration as well. The presence of the algorithm, sensor, or computer subsystem was necessary but not sufficient for inclusion in the analysis. It had to demonstrate how they were directly related to the transport, delivery, or utilization of the agents. Thus, papers that deal with UAVs, computer vision,

and artificial intelligence in monitoring only were excluded. They concentrated solely on the scope of UAVs and monitoring without agent use, the prediction of spreading, or post-fire restoration, without practical solutions and without being transferable to the field of fire suppression.

Two reviewers participated in the evaluation of the literature. Initially, calibration training was done based on 60 records, followed by 961 consolidated records. Disagreement was countered by discussion, leading to a consensus. The screening was done independently, and the control matrix was developed, where arbitrational cases were reflected. To check it more thoroughly, another review of 77 excluded papers was conducted.

After the evaluation of the papers, the remaining publications were divided into core primary, complementary primary, and secondary papers. Core primary papers directly referenced those technologies and agents being applied in the field; complementary primary papers dealt with technologies for coordination of this effort, while secondary papers were used strictly for comparison purposes during the analysis.

2.4. Data Extraction and Technological Classification

The 70 core primary publications were independently coded by two reviewers, generating 140 extraction records. For each publication, the following information was recorded: bibliographic identification, platform, number of vehicles, payload or agent, transport or release mechanism, perception, localization, navigation, planning, control, autonomy, communications, coordination, validation modality, number and type of tests, performance indicators, safety, reliability, environmental performance, extraction confidence, and disagreements between reviewers.

Computational data extraction focused on visual and thermal cameras, sensors, information processing, positioning, navigation, planning, trajectory tracking, control, artificial intelligence, telemetry, communications, multi-agent coordination, and human supervision. Physical elements were retained when they enabled examination of the interaction among computational decisions, platform dynamics, and agent application.

Nominal specifications were distinguished from simulated, experimental, and operational results. A projected transport capacity was not interpreted as an effectively released quantity; a detection or navigation metric was not considered evidence of deposition or suppression effectiveness; and an isolated test of a mechanism was not attributed to the integrated system.

Missing data were coded as “not reported” when the variable was relevant to the study, but insufficient information was provided. The category “not applicable” was used when the variable did not correspond to the scope or type of subsystem analyzed. Both categories were retained separately in the matrix and were grouped in the synthesis only when the distinction did not alter the interpretation.

2.5. Validation Modality and Environment

Publications were initially classified according to the highest verifiable level of evidence as conceptual design, simulation or modeling, component testing, controlled experimental testing, integrated prototype, demonstration in a relevant environment, or operational application. Classification was based on the functions and tests actually reported and not exclusively on terms such as “autonomous,” “integrated,” or “operational” used by the authors. For example, automatic waypoint tracking was not interpreted as complete autonomy, and an isolated physical release was not considered an end-to-end mission.

To present the results compactly, the detailed categories were consolidated into four general modalities: simulation, modeling, or optimization; experimental testing or prototype; field testing or operational application; and conceptual design or other modalities. When a publication combined several procedures, the modality corresponding to the highest level of technological evidence demonstrated was assigned, without automatically transferring that condition to all system functions.

2.6. Bibliometric Analysis

The bibliometric analysis was conducted on the 190 included publications. The annual evolution of scientific production, document distribution, sources, keywords, and the thematic and intellectual structure of the field were examined. Processing was performed using Bibliometrix/Biblioshiny, executed in R version 4.6.0 through the RStudio environment, for quantitative analysis and scientific literature mapping [15]. Keyword co-occurrence and bibliographic coupling networks were constructed using VOSviewer version 1.6.20 [16]. Each publication was retained as an independent documentary unit, even when it belonged to a shared study unit. Keywords were normalized using a thesaurus that grouped abbreviations, spelling variants, singular and plural forms, equivalent expressions, and related technological terms. The expressions drone, drones, UAV, UAS, and unmanned aerial systems were integrated when they represented the same concept.

The co-occurrence network was constructed using full counting and a minimum threshold of three occurrences. Node size represented the frequency of term occurrence, links indicated co-occurrence, and clusters reflected the identified thematic communities. Bibliographic coupling analysis was applied to the 132 publications with usable cited-reference information. The remaining publications were retained in the corpus and participated in the other analyses. Bibliometric indicators were interpreted as descriptive measures of productivity, thematic proximity, and scientific structure, rather than as indicators of methodological quality, technological effectiveness, or operational maturity.

2.7. Evidence Quality Assessment

A tool for quality evaluation has been specifically prepared to carry out this review. This instrument is aimed at evaluating the clarity, reproducibility, and adequacy of methodology and did not serve as a criterion for exclusion but for grading the strength of evidence utilized in the synthesis.

Quality evaluation was performed on 70 original publications. Ten criteria were rated by two reviewers independently: clarity of the objective, description of architecture, reproducibility of the procedure, the documentation of tests applied, presence of comparators, reporting of quantitative metrics, representativeness of the environment, consideration of uncertainty, correspondence between results and conclusions, and limitation statements.

Each criterion was rated on the following ordinal scale of three levels: 0 means that this aspect was not satisfied or there was not enough information available; 1 means that this aspect was partially met; 2 means that this criterion was well satisfied. Thus, the total mark on the ten criteria started from 0 and had a perfect round figure of 20.

The evidence was characterized as insufficient for scoring between 0 and 7 points, limited between 8 and 12, moderate between 13 and 17, and high when scoring between 18 and 20. The classification of evidence was followed by the identification of critical omissions connected with testing, comparators, representativeness of the environment, uncertainty, and limitations.

2.8. Technology Readiness Assessment

Applying the nine-stage TRL rating method, which shows TRL 1 signifying the lowest level and TRL 9 the highest level of technological sophistication [17]. For each critical document, an independent rating was given to the platform, payload, or agent, release mechanism, computing unit, and complete system.

The grade assigned was based on the highest credible demonstration achieved, as opposed to the projected attributes, design targets, or claimed capabilities. Therefore, the level of component maturity was not needed to apply to the system in its entirety. For instance, a coordination simulation cannot be considered a full-fledged mission with multiple UAVs, and a release test cannot be treated as proof of deposition/suppression effect if no analysis of these conditions is available. Any assignment of this kind included the criterion that was used, the available evidence, and the reasons why further assignment of the level was not possible.

2.9. Inter-Reviewer Agreement and Statistical Analysis

The agreement was examined according to the nature of each decision. For the pilot, screening, and eligibility stages, observed agreement, Cohen's κ, and Gwet's AC1 were calculated. AC1 was included to complement κ in stages with markedly imbalanced distributions between inclusion and exclusion decisions.

For the quality assessment, overall agreement and Cohen's κ were calculated for the final classification. For TRL, exact agreement, agreement within ±1 level, and weighted κ were estimated, considering the ordinal nature of the scale. Disagreements were resolved through consensus, and cases requiring arbitration were retained in the control matrix.

Descriptive and agreement analyses were performed using [specify the software and version actually used]. Frequencies, percentages, medians, and ranges were calculated for the descriptive synthesis. Agreement statistics were used to describe the consistency of the procedure and did not replace the qualitative review of disagreements.

2.10. Safety, Reliability, and Environmental Performance

Safety was examined by identifying risks and mitigation measures related to communication loss, positioning errors, control or release failures, falling or displaced loads, changes in the center of gravity, thermal turbulence, interaction with infrastructure, proximity between aircraft, and collision prevention.

Reliability included repeatability, completed or failed releases, availability, operational continuity, mission aborts, and performance after successive operations. Environmental variables included water consumption, evaporation, runoff, off-target deposition, agent persistence, and waste. The absence of measurements was not interpreted as the absence of risk, failure, or impact, but as a lack of documented evidence.

2.11. Evidence Integration and Synthesis

The synthesis was developed according to the six research questions. It involved three analysis domains: the bibliometric collection of 190 articles, the 70 main papers that went through technology data processing, and the assessment of quality and TRL that was used on the same publications.

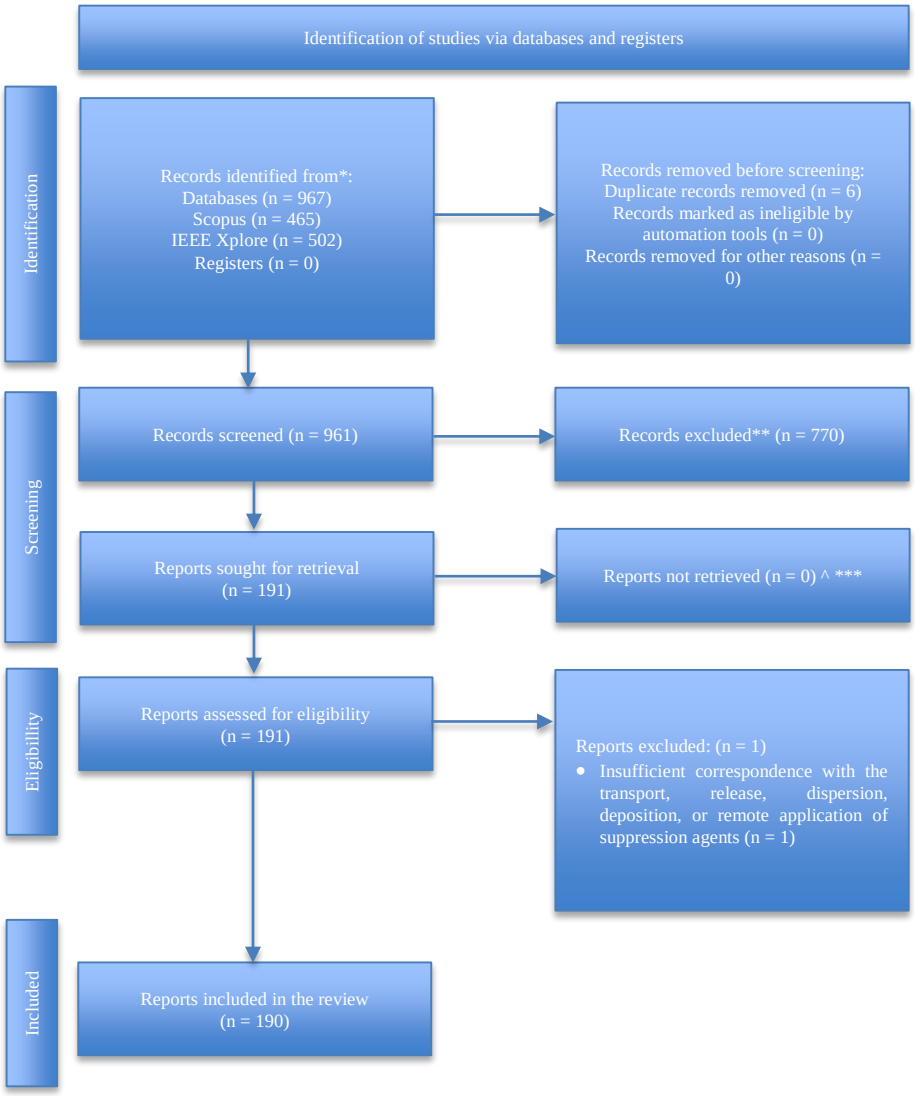
The results were represented using frequencies, percentages, medians, ranges, and written summaries. The metrics coming from platforms, agents, scales, or research conditions that were different from each other were not combined quantitatively. The term end-to-end validation was used to define the connection between perception and target definition, localization, processing, planning, navigation, control, stable moving, complete releasing, deposition, proof of effectiveness, and feedback. Only part of that chain means that the evidence was connected to the component, not the complete system. This procedure allowed finding the moment when the process of data collection, data processing, physical action, and proofs stopped working well together.

3. Results

3.1. Selection and Composition of the Corpus

The implemented procedures in Scopus and IEEE Xplore led to a total collection of 967 records. Following the DOI or document identifier investigations, as well as the evaluation of titles and metadata, six duplicates were eliminated. As a result, 961 records were screened according to the titles, abstracts, keywords, and metadata. At this point, 770 records were discarded as not matching eligibility requirements. The remaining 191 records were analysed based on the links to the transport, release, dispersion, application, or use of suppression agents. One record was discarded during the eligibility process, and the total number of records was 190.

190 publications can be classified as primary, secondary, and tertiary publications. Primary publications contain information on platforms, agents, payloads, or methods of application; secondary publications investigate computational sub-systems, security, reliability, or environmental performance that can be utilized in execution of the task; and tertiary publications are used to illustrate the results of previous studies. Considering 179 primary publications, it is obvious that 175 research units were analysed as some technological systems or research activities are presented in several publications.



* Databases searched: Scopus and IEEE Xplore
** Excluded based on title, abstract, keywords, and bibliographic metadata, according to the inclusion and exclusion criteria.
***All 191 reports were successfully retrieved.
Note: This diagram follows the PRISMA 2020 template for new systematic reviews using databases and registers only.

Fig. 1 PRISMA 2020 flow diagram of the publication identification, screening, eligibility, and inclusion process

To present the results compactly, the detailed validation categories were consolidated into four general modalities. Simulation, modeling, or optimization constituted the predominant modality, with 79 primary publications, equivalent to 44.1%. Experimental testing or prototype development comprised 43 publications, or 24.0%, while 24 publications, corresponding to 13.4%, presented field tests or operational applications. The remaining 33 publications, equivalent to 18.4%, corresponded to conceptual designs and other modalities. The composition of the review corpus and the predominant evidence modalities are summarized in Table 1.

Table 1. Composition of the corpus and predominant evidence modality

Analytical universe	Category	n	%
Included corpus, n = 190	Core primary publications	70	36.8
	Complementary primary publications	109	57.4
	Secondary publications	11	5.8
Primary publications, n = 179	Simulation, modeling, or optimization	79	44.1
	Experimental testing or prototype	43	24.0
	Field testing or operational application	24	13.4
	Conceptual design and other modalities	33	18.4

The predominance of simulations, models, and optimization processes was especially evident in studies on planning, task allocation, multi-agent coordination, control, and resource optimization.

However, classification by modality represented the highest level of technological evidence demonstrated by each publication and did not imply that all system functions had been validated to the same extent.

3.2. Evolution and Bibliometric Structure of the Field-RQ1

Between 2005 and 2018, 28 publications were identified, equivalent to 14.7% of the corpus. Subsequently, eight publications were recorded in 2019, seven in 2020, ten in 2021, 17 in 2022, 21 in 2023, 34 in 2024, and 47 in 2025. For 2026, 18 publications available up to July 15 were included. Because this represented a partial period, this value was not directly compared with complete years. The period between 2022 and July 2026 contained 137 publications, equivalent to 72.1% of the corpus. The most visible growth occurred after 2021 and reached its highest annual value in 2025. Keyword normalization grouped abbreviations, spelling variants, and equivalent expressions. The most frequent terms included uncrewed aerial vehicles, wildfire, firefighting, wildfire suppression, fire-extinguishing agent, aerial firefighting, and task allocation. The co-occurrence network developed using VOSviewer (Figure 2) distinguished five thematic communities: UAVs, swarms, and task allocation; agents and application mechanisms; conventional aviation and discharge modeling; detection and perception; and operational resource management. Concepts associated with perception, autonomy, planning, and coordination were concentrated in communities that were partially differentiated from those related to agents, discharge, dispersion, and deposition.

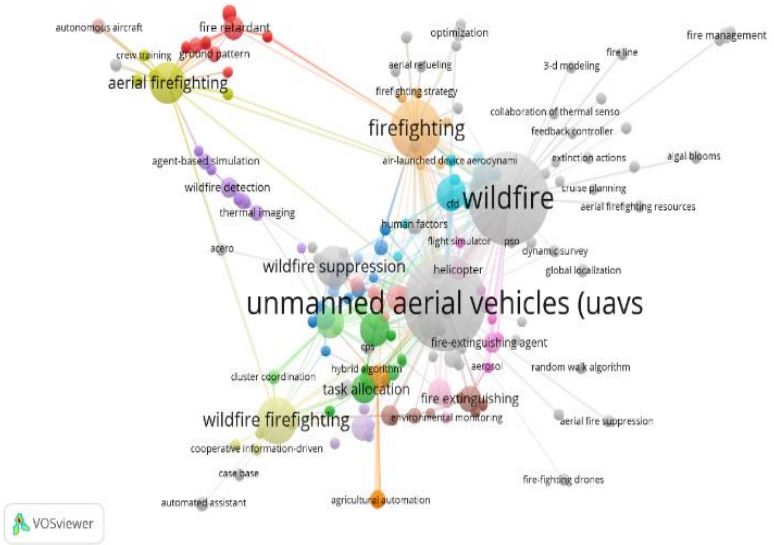


Fig. 2 Keyword co-occurrence network and thematic communities obtained using VOSviewer

Bibliographic coupling was conducted on the 132 publications with usable cited-reference information. Two main intellectual clusters were identified.

The first was related to crewed aircraft, retardants, fluid dynamics, and discharge patterns; the second was associated with robotic platforms, multi-UAV systems, task allocation, planning, and autonomous control. The 58 publications without sufficient reference information remained in the corpus and participated in the other analyses.

3.3. Platforms, Payloads, and Application Mechanisms-RQ2

A total of 70 researched articles were evaluated independently by two reviewers, with each producing 140 documents. The majority of publications focused on Multirotor UAVs, accounting for 38.6% of all articles published. Other effective platforms were helicopters and other aircraft types, ground robots, and fixed-wing UAVs.

However, in 11 instances, platforms were too generalized to be categorized. Among the publications, 60 studies assessed single-platform configurations and 10 addressed multi-platform systems. Multi-UAV systems distribute responsibilities such as recognition, transmission, transportation, usage, or coordination.

The analysis of the payloads showed that the most common type used is water or mist, used in 18 publications. The second most common is encapsulated systems, which were discussed in 13 publications. Retardants academic papers featured 10 articles, and 23 other publications were too vague in terms of defining what the payload was.

Gravitational or sequential release mechanism was used in 25 articles, making these methods the most common. At the same time, the spraying or atomization mechanism was described in 8 articles, launching in 5 publications, and direct supply in another 5. In addition, there were 27 articles that did not cover any mechanism or used unsure terminology when explaining what kind of mechanism was discussed.

When it comes to consistency, the configurations were balancing between the capacity, endurance, stability, reachability, and power. At the same time, the introduction of tanks produces additional weight and builds further dependencies in flight. The systems that are connected to the ground do not use their main reservoir but have another weight-related constraint.

3.4. Computational Subsystems and Cyber-Physical Integration-RQ3

The highest frequency of reporting belonged to navigation and planning processes. Out of 70 publications, 46 (65.7%) studied concepts of navigation, positioning, planning, and path tracking, including techniques of waypoint navigation, GNSS, classic GPS, RTK-GNSS, and route planning algorithms.

Automation, autonomy, and coordination were identified in 43 publications (61.4%). In 35 papers, it meant partial automation encompassing concepts of waypoint tracking, the approach of a target, position correction, and programming the mechanism to act. Among 43 papers, 8 works addressed the topic of multi-agent cooperation or the distribution of duties among cars.

The topic of perception was mentioned in 28 papers (40.0%), which included the topics of machine vision, thermal cameras, combined visual and thermal information, and thermal sensors. The topic of communication appeared in 24 papers (34.3%), where various techniques, including cooperative links, terrestrial telemetry systems, and LTE or 5G, were being used, which is clearly illustrated in Table 2. The dissemination of information related to the latency, packet loss, availability, effective distance, and overcoming outages was very limited.

Table 2. Computational subsystems identified in the core publications

Dimension	Publications, n (%)	Predominant implementations	Main observed limitation
Perception	28 (40.0)	Computer vision, cameras, and thermal sensors	Absence of integrated perception in 42 publications
Navigation and planning	46 (65.7)	Waypoints, GNSS, GPS, RTK-GNSS, and route planning	Limited validation under variable environmental conditions
Communications	24 (34.3)	Cooperative links, telemetry, and LTE/5G	Limited reporting of latency, availability, and packet loss
Automation, autonomy, and coordination	43 (61.4)	Automatic tracking, position correction, and multi-agent coordination	Heterogeneous definition of the level of autonomy

The architecture that comprised the largest number of functions combined perception, navigation, planning, control, communication, and activation of the mechanism of release. However, the functional chain often broke down before performing either deposition measurement or suppression verification.

Based on the determined functions, a five-level functional framework was devised (Figure 3): perception and localization, processing and planning, navigation, control and communication, transportation and release, deposition, suppression, and verification.

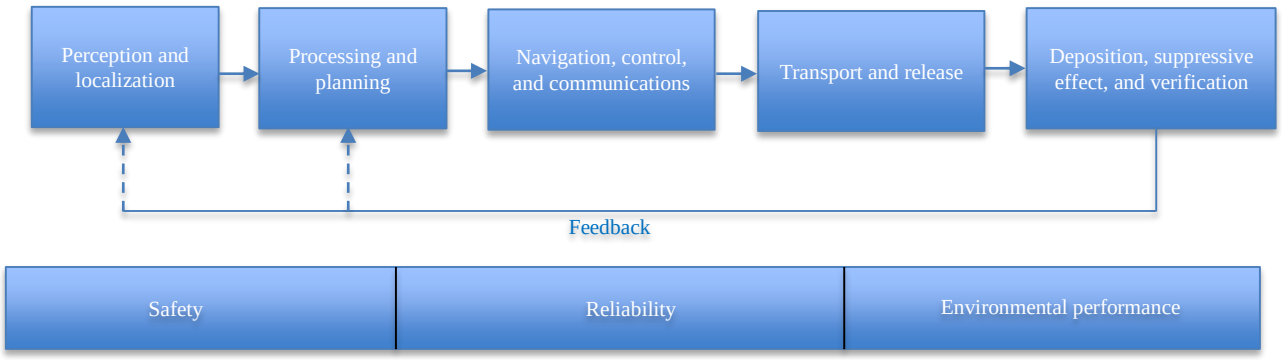


Fig. 3 Functional cyber-physical integration framework derived from the synthesis of the architectures and functions identified in the core primary publications

3.5. Performance Indicators and Validation Environments-RQ4

The found indicators comprised detection precision, positioning inaccuracy, accuracy in discharge, duration of flight, carrying capacity, height and speed of discharge, distance, surface area, dispersal zone, droplet size, emptying duration, agent consumption, thermal decline, extinguishing and reigniting. The difference of platforms, agents, levels and tests stopped the combinability of the aforementioned variables.

[18] combined satellite navigation and thermal visualization. At an altitude of 10 m, horizontal error was reduced from above 1 m to approximately 0.05 m after visual correction. The results indicated the precision of UAV positioning but did not involve measuring deposition, coverage, or suppression efficiency.

[19] combined modeling and simulation with six outdoor discharges. The average error was found to be 0.75 along the longitudinal axis and -1.02 along the lateral axis, while the maximum error reached 4.53 m. The experiments indicated the approach to, the discharging of and the recovery after change of mass, but a passive payload was used.

[20] Assumed the dispersion area of aqueous agents ranging from 45 to 90 m², while the area of dry agents varied from 130 to 700 m², but only in the cases of wind velocity below 1.5 m/sec. The heavier dry agents extinguished all four fuels used in the tests, though deposition uniformity and repeatability of operation were not measured.

[14] stated that the design aims of the WILD HOPPER platform were 600 L volume, 30 min maximum flight duration and 4 km of distance. These values indicated design aims, but did not provide proof of the practicality of the operations.

The environments comprised conceptual design, modeling, component testing, controlled outdoor tests, fire experiments, exercises, prototypes, and isolated operation. Tests showing a connection between perception, planning, transportation, release, deposition and verification of suppression effect were infrequent.

3.6. Evidence Quality and Agreement-RQ5

The quality assessment was applied to the 70 core primary publications. Two publications, equivalent to 2.9%, achieved high quality; 48, corresponding to 68.6%, were classified as moderate quality; and 20, equivalent to 28.6%, presented limited quality. None received an insufficient classification. Consensus scores ranged from 9 to 18 points. A summary of the evidence quality, inter-rater agreement, and TRL assignment reliability is presented in Table 2.

The best-documented criteria were clarity of the objective and correspondence between results and conclusions. The architecture, reproducibility, and quantitative metrics were also reported relatively frequently. The main weaknesses were related to the treatment of uncertainty, representativeness of the environment, availability of comparators, adequacy of the number of tests, and reporting of limitations.

Observed agreement for the overall quality classification was 82.9%, with Cohen's κ of 0.655. Nineteen publications required arbitration. In the calibration pilot involving 60 records, agreement was 85.0%, with $\kappa = 0.680$. In the complete screening of 961 records, agreement was 91.4%, with $\kappa = 0.747$ and Gwet's AC1 = 0.869. In the eligibility

assessment of 191 publications, agreement reached 99.0%, with $\kappa = 0.496$ and Gwet's AC1 = 0.989. The lower magnitude of κ during eligibility assessment occurred in a context of a marked prevalence of inclusion decisions because 190 of the 191 documents assessed were ultimately included.

Table 3. Evidence quality, inter-rater agreement, and TRL assignment reliability

Assessment	Result
High quality	2/70; 2.9%
Moderate quality	48/70; 68.6%
Limited quality	20/70; 28.6%
Observed agreement for quality	82.9%
Cohen's κ for quality	0.655
Cases submitted to arbitration	19/70
Agreement in screening pilot	85.0%; $\kappa = 0.680$
Agreement in complete screening	91.4%; $\kappa = 0.747$; AC1 = 0.869
Agreement in eligibility assessment	99.0%; $\kappa = 0.496$; AC1 = 0.989
Exact TRL agreement	283/350; 80.9%
TRL agreement within ±1 level	350/350; 100.0%
Weighted κ for TRL	0.964

3.7. Technology Readiness of Components and Integrated Systems-RQ5

The TRL evaluation had five elements across all 70 fundamental references: a platform, a payload or an agent, a mechanism of release, a computational subsystem, and an integrated system. The individual reviewer did 350 assignments before making a summary. The reviewers were fully in accord on 283 assignments, which translates into 80.9 percent agreement. 67 discrepancies involve one category only, thus ±1 level agreement was gained at 100 percent. Weighted κ was equal to 0.964.

The median TRL was 4, while its values ranged between 3 and 7 for the platform. For the payload or an agent and release mechanism median was also equal to 4, while representing the range of 1-7. The TRL figure recorded for the computational subsystem was also equal to 4, with a range of 3-7. However, that of an integrated system is much lower, having its median equal to 3 and a range of 2-7.

The integrated system featured as many as six records at TRL 2, 33 publications at TRL 3, 11 at TRL 4, six at TRL 5, two at TRL 6, and 12 at TRL 7. There were no records supporting TRL 8-9.

The integrated system had a lower level of TRL in comparison to that of the platform in 49 publications and the same level in 21 cases. It fell lower than the level that of the computational subsystem in 43 cases, while it matched it in 27 cases.

3.8. Safety, Reliability, Environmental Performance, and Integrated Validation-RQ6

Out of the 70 published studies, safety assessment was fully carried out in 8 publications and partially carried out in 18 publications, whereas 44 publications failed to offer any identifiable options regarding any procedure. Hazards that were noted included communication loss, positional errors, control or release failures, shift of load, changes in center of gravity, thermal turbulence, proximity to infrastructures, and interaction with other aircraft.

Reliability assessment was fully carried out in 9 publications, while partially carried out in 10 publications, whereas 51 publications failed to offer any credible reliability assessments. The factors that were not mentioned include failure rate, operational availability, repeatability of iterations, the total number of successful and unsuccessful releases, and operational performance.

In 14 of the publications discussed above, environmental criteria (such as water consumption, evaporation, runoff, off-target deposition, environmental persistence, and waste) were incorporated. However, they were determined inconsistently and thus, while their absence is interpreted as a lack of evidence, it does not automatically infer absence of impact.

Integrated mission validation is not very common in the literature. The publications discuss individual elements or partial sequences associated with perception, navigation, planning, control, and transportation. The literature describes a few demonstrations that link perception with target characterization, localization, planning, stable transportation, and controlled release.

This particularly applies to multi-UAV systems. The literature presents a lot of data on task allocation, planning, and computational coordination; however, it lacks adequate evidence of the multitasking systems transporting their agents in a reliable and consistent manner.

4. Discussion

4.1. Computational Development and Cyber-Physical Integration

The primary outcome of the review was the unequal growth of technological systems and the actual demonstration of remote suppression techniques. The development of navigation and planning was identified in 65.7% of the relevant papers, whereas automation, autonomy, and coordination had a lower presence at 61.4%. On the other hand, findings concerning the different steps in the delivery of the suppression effect were much less represented; thus, it can be stated that these two processes do not correlate with each other, which means that while the research achieved success in its development, it failed to ensure the full integration of the entire cyber-physical chain.

The bibliometric analysis also demonstrated this separation in the field. The co-occurrence of key terms allowed one to identify clusters with regard to perception, autonomy, planning, and multi-UAV systems, as opposed to those dealing with agents, discharge, dispersion, and deposition.

Bibliographic coupling revealed the existence of two key approaches in the field-the first one is related to aircraft, retardants, and fluid dynamics, while the other deals with robotics, coordination, distribution of tasks, navigation, and autonomous control-thus confirming the fact that the application of computing, on the one hand, and the physical side of delivery have developed almost independently from each other.

The consensus among reviews of UAV applications in firefighting is that research has undergone significant advancement in the areas of remote sensing, detection, navigation, forecasting, and decision support. Nonetheless, drawbacks regarding autonomy, payload size, and battery duration, as well as communications, resilience to harsh conditions, and validation of the technology in practice have been brought to attention [1-3].

The authors of this review substantiate the claim that the existing gap is not only about the shortcomings of sensors, platforms, or algorithms but also the necessity of establishing an interrelationship between perception, computation, action, and feedback within a single mission.

The high level of simulation, modeling, and optimization, accounting for 44.1 percent of the publications analyzed, can partly explain this inconsistency. Though these technologies can be utilized for route estimation, resource distribution, and the estimation of coverage, algorithmic stability, and coordination, they do not reflect such phenomena as wind, mass variations, and physical effects during the operation of the robot [11, 12].

4.2. Interpretation of Technological Maturity

The findings of the TRL assessment indicate that while the platform, payload, release apparatus, and computing system achieved an average score of 4, the integrated system scored a total of 3 points only. Moreover, while the integrated system capability was lower than the platform capability in 49 documents and also less than the computational capability in 43 documents, at no point did the integrated system get a score above the parameters of the said systems. The findings highlight that the technology readiness varies across the various technology levels and cannot be transferred automatically. For example, a commercial UAV can be classified as technology-ready, but when it comes to its payload integration, unloading, and task execution aspects, its readiness can be low. In other words, the confirmation that a certain route planning or positioning method is validated cannot guarantee that the platform is ready for transporting and dropping the payload in the appropriate conditions.

The abundance of findings that relate to TRL 2 and 3 shows that a significant part of the field is at the stages of conception, proof of concept, or experimental verification. Thus, while there are 12 examples of TRL 7 systems mentioned in the study, there was no information relevant to TRL 8 or 9 technology found. The existence of TRL 7 systems indicates that certain prototype systems were demonstrated in the relevant or actual environment, but this does not mean that they were complete, validated, and proven during extended commercial operation that would meet TRL 8 and 9 criteria. As a result, the presence of TRL 7 systems only confirms the idea of the existence of a technology gap and confirms that certain concepts are already at the demonstration stage, but the qualification and validation processes necessary for achieving TRL 8 and 9 levels are not there yet [17].

Although WILD HOPPER and similar systems demonstrate relevant developments in efficiency, anticipated flight time, and evolution of designs targeting fire extinguishing missions, these specifications should not be misunderstood as complete and consistent validation of operating architecture [14]. Likewise, hose-connecting systems help partly overcome limitations of onboard systems, although they lead to new physical interactions and risks that need validation, including forces of tension, drag, stability, and entanglement of hoses [21].

Quality of evidence and TRL are connected yet separate concepts. TRL indicates the degree to which the technology demonstration has been achieved. Quality, on the other hand, is the result of the clearness, repeatability, and completeness of tests carried out. What is published may show that a sophisticated prototype exists; however, its methodological rating can be average or low if no repetitions, uncertainty, or comparison with something else or lack of suitable experimental settings are reported. In this way, high TRL does not prevent from getting solid methodological evidence.

4.3. Autonomy, Communications, and Multi-UAV Coordination

As reported in 43 sources, the operation of the automation, autonomy, and coordination only refers to incomplete functions. All of the above doesn't suggest the presence of full autonomy, as this would require environmental perception, destination determination or update, plan adjustment, control, fault detection, communication handling, and outcome supervision. The presence of different terms has complicated system comparison. Some reports refer to some operation with fixed routes and human supervision as autonomous, while others use the word only about architectures that can perceive, decide, and act to a greater extent independently. In the latest reviews, the autonomy of UAVs is divided into automatic navigation, mission autonomy, and the ability to change and adapt to changing conditions [11, 12].

The implementation of a multi-UAV architecture can segregate search, relay, delivery, and verify functions between the multiple units. This configuration aids in ensuring better reach and less intervention time, as pointed out by theoretical models of swarms for suppression [7]. However, it makes the performances of the multi-UAV system highly dependent upon communication, coordination, safety at separation, and backup's realization [22, 23]. Literature review on multi-UAV missions shows that coordinating these missions means fulfilling such tasks as mission assignment and resource management, path function, and alteration of assignments according to situations. Other approaches to reinforcement learning and consensus can also be considered viable; nevertheless, their implementation in practice faces certain limitations of scalability and effectiveness of communication, and credibility of results with the usage of real physical systems [8-10].

There are only 24 publications that contain information regarding communications, reporting on latency, packet loss, availability, effective distance, and recovery. However, it needs to be considered that although a multi-UAV architecture may perform effectively in simulation, it may completely fail during deployment due to delays with making decisions.

In addition to the various algorithms used, it is crucial that the fleet is also measured based on the parameters such as maintaining links, avoiding collision, reallocating tasks, the ability to act after the loss of the platform, and ensuring the physical application is successful. The lack of these parameters explains why the number of studies on coordination using computers is bigger than the number of studies on cooperation achieved through using more than one UAV, which was also pointed out by [2].

4.4. Performance, Deposition, and Suppression Effect

The measured parameters were diverse and represented various stages of the system. Similarly, navigational precision, release errors, payload capability, estimated range, and spread space do not show the same degree of effectiveness. Each indication describes some function and should be attached to specific testing conditions, as well as to different stages of the cyber-physical chain being examined. [18] proved that there is a significant advancement in the positioning error due to thermal imaging correction. Nonetheless, this advancement did not involve the subsequent measurement of deposition or suppression. Thus, it represents progress in navigation and approach only, but not the full confirmation of the task accomplished. [20] indicated the dispersal zones of wet and dry agents and proved the extinction of experimental fuels at some altitude in moderate wind conditions. This kind of proof gets closer to measuring the physical result, but it requires additional information about comparability, repeatability, offsite deposition, and the behavior in other environmental conditions.

The modeling of aerial dropping shows that the trajectory and deposition of agents can be influenced by wind, updrafts, the form and weight of particles, altitude of discharge, and the principles of aircraft management. [24] Simulated the correlation between these factors by means of a digital twin concept developed for modeling flight trajectory and the effect of the agent, proving that the discharge point is not the only factor influencing the deposition pattern. However, the simulation needs to be compared with the physical measurements in order to check its reliability outside this numerical model. The results show that the vehicle does not affect the accuracy of the agent [21, 25, 26]. Wind, height, speed, shape of the container, fragmentation, and evaporation act between the point of discharge and the resulting effect. Therefore, the analysis should at least differentiate between the vehicle, discharge point, deposited distribution, and the effect on fire. The deposition is the main link of the chain between computing and extinguishing, as without measuring the agent arriving at the target and its distribution over space, the nominal capacity or the discharged volume can miscalculate the actual efficiency. The assessment of the resulting effect should consist of thermal reduction, monitoring, extinguishing, time of response and possibility of revival. The computing models need to report wind conditions, altitude, speed, weight, and substance features to be comparable to the experimental trials.

4.5. Safety, Reliability, and Environmental Performance

A comprehensive evaluation of safety has been documented in only eight studies, while there are 18 studies that have done a partial evaluation of safety. Furthermore, in 44 studies, no convincing treatment has been established. The relevance of the absence of treatment of safety lies in the fact that while remote control decreases exposure to personnel, it also opens up new risks of falling loads, loss of communication, problems with positioning, defects in release operation, mistakes in the center of gravity calculation and coordination with other aerial vehicles.

Different configurations have different risk profiles. Onboard tanks increase the dimension of the mass and can make an impact on stability; Ground connected systems decrease the mass of the payload, while adding tension and resistance to drag and the risk of hoses getting entangled. Encapsulated payloads can bring some benefits regarding stealth, but also bring uncertainty regarding the trajectory and other parameters.

This limitation aligns with the recent body of literature on cyber-physical systems that considers reliability and resilience as the emergent properties of the interaction of physical components, software, control, and communication. Failure of a link, degradation of a sensor, or wrong computation may spread to the physical process and interfere with the normal operation of the system. Therefore, evaluation must take into account not only the likelihood of failure of individual components but also availability and recovery, adaptability, and continuity of critical functions [27-30].

Maintainability is another underdeveloped aspect. In the literature review of software maintenance, it was noted that the combined development of physical and logical components calls for specific techniques for diagnosis, updating, verification and change management [31]. In the fire and explosion suppression systems, this requirement is applicable to sensors, navigation algorithms, actuation functions, communication links, and payload configurations, the change in which might influence the performance of the mission as well as make it safe.

The fact that there are no failures that have been reported should not serve as a notion of reliability. Evaluation of a given process entails recognition of successes and failures, establishing the number of repetitions, registering failure modes, and checking recovery mechanisms. This need is more evident in multi-UAV systems, where the failure of any particular vehicle or link could affect the big picture. Only 14 papers considered ecological factors. Water consumption, evaporation, surface run-off, off-target deposition, retardant persistence, and waste from the payload were analyzed in a fragmented manner. Thus, it is still impossible to state which configurations are better for ecology purposes. The future similarity analyses have to relate the efficiency of one or another configuration to the amount of agent used and percent of the agent which did not hit the target.

4.6. Functional Framework and Research Implications

The integration framework that is suggested divides the operation into five parts, which are perception and localization, processing and planning, navigation, control and communication, transport and release and deposition, suppression, and verification. The main purpose of the framework is to differentiate between the already used functions and the functions that have only been suggested. One piece of writing might show the perception and planning very well, but stop after releasing it, and another might indicate a working mechanism. The purpose of the framework is to recognize these gaps, while an unproven performance should not be attributed to the device.

In future studies, it is important to follow the rules of the research that require constant registration of the different parameters, such as the device itself, the mass, the type of agent, the height, the velocity, the wind speed, the humidity, the fuel type, the number of repetitions, the accuracy of release, deposition, thermal and extinction stage, and rejuvenation. This information will make comparisons among systems easier and will allow for distinction between regular, modeled, experimental, and working operations. It is important to go stepwise through testing: verification of the element, subsystem integration, testing in controlled conditions, demonstration in a relevant environment, and testing again. The idea of a gradual increment of TRL must be based on the system performance only, regardless of how commercially available the platform is. Transition between TRL numbers 7 and 8 and then number 9 must be proven through showing that the system works in all the stipulated conditions, rather than simply showing the prototype working during one demonstration [17].

For multi-UAV systems, priorities include robust communications, safe separation, fault tolerance, task reallocation, coordination with crewed assets, and simultaneous physical validation of multiple platforms. Research must advance from algorithmic efficiency toward mission effectiveness, safety, resilience, and reliability.

4.7. Limitations of the Review

The methodical investigation took place in the databases of Scopus and IEEE Xplore, while OpenAlex was utilized only for bibliographic verification purposes. Therefore, there could be studies that are relevant, but that warrant attention, though they were not found in the primary sources. The search carried on up until 15th July 2023. Papers published in 2026 represent a part of the period only and cannot be directly compared to the whole years.

Bibliography coupling allowed to refer to 132 publications with reliable cited reference data to use. The other 58 publications were included in various analyses, however, were not taken into account in that network. The variation of platforms, agents, means, metrics, and conditions did not allow for making the joint quantitative synthesis. Evidence-based modality categories play the role of simplifiers when applied to publications that include simulation, prototype creation, and trials.

Quality and TRL evaluations depended on the information available in the documents. Some technologies could have achieved different levels of readiness, and the information is just not provided. To mitigate the risk of

overestimation, assignments were based on the maximum verified evidence component rather than the expected one. In conclusion, the review synthesized the published evidence and did not evaluate operational activities. Hence, the outcome reflects the documented position in the area and not the proof of efficient operations.

5. Conclusion

It aims to evaluate the scientific development, computational framework, evidence quality, and technological sophistication of systems that facilitate the remote use of agents for fire fighting. A total of 190 publications constitute the final set of documents, which includes 70 original primary research papers, 109 complementary primary papers, and 11 secondary publications. The main part of the reviewed materials consists of 179 primary publications corresponding to 175 study units, which enables differentiating between documentary and technological analysis.

It was found that the functions of perception, navigation, scheduling, control, communication, and multi-UAV coordination have been more developed than the physical integration that is required for transporting, releasing, and depositing agents used for the verification of the suppression result. As a result, the use of an algorithm, platform, or release mechanism in isolation cannot provide sufficient proof that the cyber-physical mission has been completed properly.

The evaluation of the 70 core primary publications established that 48 articles were of moderate quality, 20 articles were of low quality, while 2 papers were of high quality. The major problems relate to the adequacy of test environments, dealing with uncertainty, the availability of comparators, repetition of trials, and reporting on limitations. The data received confirm that a number of publications has increased without its appropriate experimental base. The advanced architecture yielded an average level of technology of 3, associated with values of technology from 2 to 7, with no evidence of technology 8 or 9. Architectures were less advanced than their components in 49 studies and less advanced than the computational subsystem in 43 studies.

The significant gap identified corresponded to the lack of substantial demonstrations of end-to-end validation, which was not fulfilled in practice. Very few examples of demonstrating perception and localization, processing and planning, navigation and control, stable transport of agents in a defined area, controlled release of agents, detection of deposition, verification of magnitude of suppression effects, and feedback were found.

Safety, reliability, and environmental performance of the systems were noted. Different aspects of communication loss, positioning errors, failure in releases, mass changes, repeatability, operational availability, deposition off-target, drainage, agent persistence, and waste disposal were poorly addressed as well. Therefore, having been demonstrated separately does not provide for establishing the fact of operational readiness of a system.

The research provides the integrated cyber-physical model of five phases, where the main parts of the model are the following ones: perception and localization; processing and planning; navigation control and communication; transportation and release; and deposition and suppression effects verification. The model allows separating the validation of individual components from the validation of the integrated architecture.

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