Unmanned Aerial Vehicles: State-of-the-Art on Swarm Control

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Abstract: The focus of researchers to develop Unmanned Vehicles, capable of moving on land, water or through air, increased over time. In the last decade the research and development for this domain started to focus on developing and making Unmanned Aerial Vehicles (UAVs) more efficient, observing the huge potential to integrate them in a large set of applications. This paper presents the state of the art of the existing UAV systems, applications, and control strategy implementations on Swarm of UAVs by analyzing and referencing the newest publications in the last few years. A literature review of all relevant papers related to swarms of UAVs and how these multi-agent systems are implemented was conducted. This article highlights the current challenges, solutions and directions that are revealed in the literature. The final goal is to propose a specific control strategy solution for a swarm of drones, based on the conclusions extracted from literature.

Keywords: UAV, Swarm of UAVs, Swarm Control, Formation Control, Literature review.

1. INTRODUCTION

Robots are expected to become indispensable in the way of how our society is evolving. In the past years, the increase in hardware capabilities and performances, complex software development and the need of these entities in day-by-day applications determined a rapid evolution of autonomous robots. Although it refers to software bots or physical ones, they are one of the main factors that accelerate the evolution of our society.

The current state of technology allowed researchers to design and conduct experiments on different types of Unmanned Vehicles. One of these are Unmanned Aerial Vehicles (UAVs) or commonly known ‘drones’. Having great flexibility, easy deployment, excellent maneuverability and with numerous existing commercial solutions, they are used in a high range of applications (Malang et al., 2023). Some of these applications are disaster management (Masroor et al., 2021), search and rescue (Alsamhi et al., 2022), construction and civil industry (Guan et al., 2022), traffic monitoring (Gupta et al., 2021), agriculture (L. Wang et al., 2022) and many more. Moreover, the potential to extend the usability of drones in other fields is possible due to their flexibility and market opportunities.

The potential of UAV market is very significant especially in the coming decade. The main indicator that the UAV sector is of high interest and that this sector has huge potential is the market evolution and market prediction. According to (Shakhatreh et al., 2019), the market in 2016 was estimated at $8.5 billion dollars and in 2017 the estimation of the market for 2021 was $12 billion dollars. In reality the market value for 2021 was $22.1 (Imarcgroup, 2024) or $27.4 (Butterworth-Hayes and Beechener, 2022) billion dollars. The difference between the initial prediction and the evaluation after 2021 is almost double, according to whatever available source. This difference indicates that the interest in this industry was more than expected.

As a forecast for this market, there are several sources which are estimating the value of the market for the current decade. According to (Ed, 2022) the estimated market value in 2027 will be $45.2 billion dollars and according to (Mehra, 2024) $38.3 billion dollars. The estimated value is different for these two sources, but the Compound Annual Growth Rate (CAGR) for the first source is 7.8% and for the second one is 7.9%. Both references predict the same growing value of this market, which will keep the effort of future research towards developing this sector and making it more affordable.

Another important impact will be in the related sectors responsible for providing components for drones, such as: flight controllers, cameras, RADAR and LiDAR, positioning systems and many more. Also, it is estimated that more the 100.000 new jobs globally for this sector will be created by 2025, according to a study from 2013 (Gupta et al., 2021; Shakhatreh et al., 2019). In 2018 PwC estimated in a report “Skies without limits (SWL1)” (Elaine et al., 2018), that more than 650.000 new jobs will be created for the drone industry, only for the UK economy. In the most recent study, from 2022 “Skies without limits v2.0” (PricewaterhouseCoopers, 2022) the prediction is even bigger: 900.000 jobs in the same sector, for UK economy. Both studies are referring to 2030 year. The difference of 250.000 jobs between these 2 studies is significant, confirming that the UAV sector is continuously growing. Comparing the initial study from 2013 with the recent one from 2018/2022, indicates that the initial was underestimated, and the real figure will be much higher in 2025.

In the last decade the research and development for this domain started to focus on developing and making the UAVs more efficient, observing the huge potential to integrate them in a large set of applications. More and more articles were published over this period and this trend keeps growing. This growing trend is described in some review articles. For example, in (Otto et al., 2018) the authors were conducting a state-of-the-art review covering 217 articles on UAV civil sector. That research serves as a foundational basis for any future studies involving drones. The paper presents the current knowledge on this field and what are the best directions to be taken for future studies. The growing research interest is highlighted by this paper. From 2010 to 2017, 6 times more papers have been published covering UAV civil application sector. A similar trend is evident in (Skorobogatov et al., 2020) as well. Here survey is conducted on applications of multiple UAV systems. The article covers 87 publications for their study. Once again, the number of papers is increasing from 2010 to 2018.

The potential of UAVs can be further enhanced using them in extensive collaboration systems named swarms of drones or UAVs in general. Most of the applications have a complex goal that can't be achieved by a single agent, due to the limitations of the existing solutions, especially hardware. For example, the battery capacities currently available on the market do not enable drones to operate for extended periods. This disadvantage reduces the time frame needed of an UAV to reach the application purpose and makes it impossible to realize the task it was designed for (Puente-Castro et al., 2022). To overcome this challenge a multiagent system of UAVs is designed and proposed in the literature. Each component of this collaborative system may have a dedicated hardware to implement a specific job in the network, such as communication, environmental recognition, or leading capabilities (Tahir et al., 2019).

A few commercial applications are available now on the market (Duflo et al., 2020). This recent success being possible mainly because of the intense scientific work. This research topic became popular in recent years with a considerable number of papers published. In (Phadke and Medrano, 2022) this rising trend is described and documented. The authors used Dimensions.ai (*Dimensions AI | The Most Advanced Scientific Research Database*, n.d.) online tool to search for papers on swarm of drones' topic, between 2011 and 2021. The result highlighted this ascending trend.

A similar study was conducted of the existing articles on this topic, papers available on ScienceDirect (*ScienceDirect.Com | Science, Health and Medical Journals, Full Text Articles and Books.*, n.d.) and IEEE Explorer (*IEEE Xplore*, n.d.) platforms. The search was looking for "swarms of UAVs" term to be found in title, abstract of among the key words. The searching period was from 2010 to 2022. Fig. 1 confirms the research article rising trend.

The complexity of these systems opens new ways to solve more complex problems, necessary to implement and develop them, such as: swarm management, path finding, communication between agents, robustness, and fault tolerance. Some solutions are already under implementation which solve some of the needs presented above, for example: Particle Swarm Optimization (PSO), self-organizing map method, path finding methods, or through other various swarm intelligence-related technologies (Zhou et al., 2020).

This paper presents the state of the art of the existing UAV swarm systems, and control strategy implementation. A literature review of all relevant papers related to UAV applications, swarms of UAVs and how these multi-agent systems are implemented was conducted. This article highlights the current challenges, solutions and directions that are revealed in the literature. The final goal is to propose a specific control strategy solution for a swarm of drones, based on the conclusions extracted from literature. This purpose solution will be a subject for a future applied study. After this short introduction on the topic of UAVs, the paper continues with a short presentation of the multi-Agent UAV concept in the second section. The article continues then with 3 sections, one for each important concept of such a system: in section 3 Communication, section 4 Formation Control and section 5 Swarm Control. The last part of this study is the conclusion.

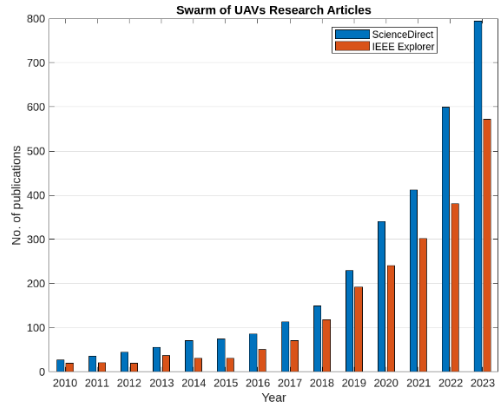

Fig. 1. The evolution of publications on swarm of UAVs.

2. MULTI-AGENT UAVs

This paper conducted an extensive literature review on the topic of drones' swarms. The research aims to understand how multiple UAVs can be effectively integrated into a collaborative structure (or swarm) to increase the performance and capabilities of a single agent usage in different applications. In the introduction was mentioned that this study is preliminary research, for an extended work dedicated to the creation of a collaborative multi-UAVs system for a Search and Rescue application, capable of identifying persons in danger.

The first step was to analyze the most relevant and up to date review papers on multi-agent UAVs or swarm of UAVs topic. Following this reading, the present study aims to identify how such systems are structured, which are the most important components, and which are the most relevant aspects to be further examined. Based on the findings, the paper continues its search for works in literature that address only the topics identified in the preliminary study as important. Table 1 presents the articles reviewed for this preliminary research. It highlights what is the research focus and what are the most representative contributions or findings of the analyzed paper.

The authors in (Chen et al., 2020) conducted a literature review of the existing solution of communication architectures for UAV Swarms. The focus of this work is only on communication and how does it influence the overall performance of the collaborative structure. The paper presents various architectures, including centralized, decentralized, and hybrid approaches. Each type is described with its advantages and disadvantages. It also discusses various routing technologies and classifies routing protocols into categories like topology-based, geographic/position-based, and others. The protocols within each category are explored in detail. The paper evaluates four distinct communication architectures for UAV swarms such as: Centralized Communication Architecture, Single-Group Swarm Ad hoc Network, Multi-Group Swarm Ad hoc Network and Multi-layer Swarm Ad hoc Network. Additionally, to the communication architectures presented above, the article realizes a systematic overview of routing protocols. A rerouting protocol is a mechanism used in network communication, particularly in dynamic environments like UAV swarms or mobile ad hoc networks, to establish a new path for data transmission when the existing path becomes unusable or inefficient. The paper presents three main protocols: Topology-based Routing Protocols, Geographic/Position-based Routing Protocols and Swarm Intelligence-based (SI-based) Routing Protocols. The study highlights the critical nature of UAV swarms' high mobility and frequently changing topology, necessitating communication networks characterized by low latency and high reliability. Therefore, the communication infrastructure and architecture are an essential key for a Swarm to function.

Table 1. Study on Swarm of UAVs literature review research.

Article	Year	Research focus	Applications
(Zhou et al., 2020)	2020	Reviewing the basics and advances of UAV swarm intelligent technology, focusing on decision-making, path planning, control, communication, and application layers.	Decision making algorithms. Path planning. Swarm control. Communication. Application
(Chen et al., 2020)	2020	The design and evaluation of communication architectures and routing protocols for UAV swarms, considering performance, stability, and applicability in different scenarios.	Communication architecture. Centralized vs. Decentralized architecture. Routing Protocols.
(Diller et al., 2022)	2022	Reviewing and comparing UAV formation control strategies, focusing on the superiority of distributed over centralized methods.	Formation management. Communication. Swarm control.
(Javaid et al., 2023)	2023	Collaborative communication in multi-UAV systems, focusing on the need for advanced control strategies and algorithms for UAV swarms.	Communication. Collaborative tasking. Swarm control.

Research on key features of the UAV swarm systems is conducted in (Zhou et al., 2020). It is a literature review, focusing on five key aspects or layers of such a system: decision-making, path planning, control, and communication. Each one of these key layers is analyzed based on the existing solutions and available research. The Decision-making layer is essential for tasks planification, that being the core of a swarm system. This layer optimizes the operations of the UAV swarm by integrating structural design, performance evaluation and efficient task management. The Path planning layer transforms decision data into practical flight paths by generating waypoints and using UAV attitude and environmental perception information. Algorithms such as the A* algorithm and Particle Swarm Optimization (PSO) are used to solve path planning problems. The Control layer keeps all UAVs on their planned paths, by managing formation reconstruction, search and tracking, and anti-collision. This layer is vital for the real-time operational control and coordination of UAV swarms. The Communication layer manages the acquisition and transmission of information within the swarm. This layer is fundamental for the effective operation of UAV swarms, guaranteeing efficient and secure communication across the network.

Article (Diller et al., 2022) is another example of literature review for Swarm of drones. The research compares two UAV formation control strategies, and it presents the commonly used UAVs models for swarm applications. The paper discusses the formation task process, communication networks, and the comparison of existing formation control strategies, demonstrating that distributed formation control is superior to centralized methods. The paper is structured based on the following key aspects: The Formation Task Statement where the UAVs are required to track a predetermined path while maintaining a specific formation shape. The Communication section presents different network types crucial for UAV swarm coordination (the star topology network, the ad-hoc network, and the mesh network). The Formation Control section compares centralized and distributed control strategies for UAV swarm formations. Centralized control involves a control center processing all UAV data. On the other hand, the distributed control permits each UAV to take self-made decisions, based on the swarm share information. The comparison study of this paper highlights the superiority of distributed formation control over centralized control, suggesting that it is the future development trend in this field.

In (Javaid et al., 2023) the authors conducted a literature review of collaborative communication in multi-UAV systems, examining the features of intelligent UAVs and their communication and control requirements for autonomous collaboration and coordination. As in the review articles presented above, this one is also structured around several key points that are essential for a UAV swarm to function: The Collaboration in UAVs section shows the evolution from single UAV systems to multi-UAV systems. The paper analyzes decision-making mechanisms such as Joint Multi-Target Probability Distribution (JMTPD) or Partially Observable Markov Decision Processes (POMDPs). The collaboration can be improved using these algorithms, which can reduce the response delays and can predict uncertainties in dynamic environments, therefore promising stable operation of the swarm. The Communication in UAVs section presents several methods such as: Wi-Fi and UHF radio links, Cellular network-based links or with LoRaWAN-based links which offer long-distance communication with high bandwidth and connectivity. In the Swarm Control section, the paper presents control algorithms like reinforcement learning for coordination, trajectory formation techniques, swarm-based communication methods, and deep reinforcement learning for path planning and target tracking. Particle Swarm Optimization (PSO) method can be used for optimal localization and UAV-agent positioning in the formation. The review paper examines the potential and challenges of collaborative UAVs. It highlights state-of-the-art developments in areas like trajectory formation, target localization, data collection, and cooperative decision-making.

Based on the review of the four articles above, a pattern can be noticed in terms of key aspects or components of a UAV Swarm. All articles have mentioned the importance of communication, which plays a fundamental role and a based layer for a robust and efficient system. Secondly formation control and the importance for the swarm to keep the formation, to avoid collisions and environment obstacles and to plan the flying path of the entire formation. Lastly the swarm control algorithm, which is the center of the swarm, is responsible for ensuring that the whole structure acts as a unified entity able to archive common goals.

The next part of this research paper will review the current state of the art based on articles that discuss one of the following research keys: communication within swarm of UAVs, drones' collaboration (formation management, task management and path planning), and swarms control algorithms.

3. SWARMS COMMUNICATION

Effective communication is the foundation of Swarm of drones, by setting up the base layer for better coordination, formation management and overall control. It increases the Quality of Service (QoS) in swarm networks and supports complex tasks like surveillance with precision. Communication also plays a key role in ensuring the resilience of the swarm. Therefore, it is essential for such a system to be designed starting with the communication architecture and strategy.

This subsection proposes to find the actual communications solutions that are implemented a validated on the swarms of drones.

The solution proposed in (Diller et al., 2022) involves Integrated Communication and Control in Swarms framework or ICCSwarms, which was designed to address the major challenges of wireless communication in UAV swarms. Each UAV within the ICCSwarm self-organizes itself considering both the communication range and the level of collaborative autonomy. The main advantage of the self-organizing component consists of its ability to work in a multi-hop ad-hoc mobile network for the mobile environment. The network formation was simulated for this study. The Ad-hoc On-Demand Distance Vector Routing (AODV) protocol was used for network routing. The results suggested a significant improvement in data collection and transmission. The multi-hop approach helped to increase the amount of data collection by 240.2% compared to the single-hop scenario.

(Xu et al., 2021) compares centralized and decentralized control schemes for UAV swarms. While centralized control features managing based on a collective state of the UAVs, decentralized control allows the specific UAV to adjust its control model in comparison to others, based on relative positions and the quality of the communication link. A critical communication channel model forms the basis of the UAV path planning. The model is based on Single Input Single Output communications links between the UAVs, to examine the performances of the network service. This paper introduces the algorithms essential for managing the UAV swarm dynamics and communication, specifically on the accuracy of the waypoint tracking and the stability of the communication links. The proposed algorithms are modelled and evaluated using MATLAB. Communication link quality, UAV distances, and waypoint tracking accuracy are among the performance metrics that were applied. These results were essential in evaluating the effectiveness of the decentralized concepts, the communication link quality, and the formation stability.

Table 2. Summary of Communication methods for Swarms of UAVs.

Article	Year	Research focus	Applications
(Diller et al., 2022)	2022	A comparison study on UAV formation control strategies, focusing on the superiority of distributed and intelligent control.	Integrated Communication and Control in Swarms framework. Ad-hoc On-Demand
(Xu et al., 2021)	2021	Communication in decentralized control strategies for low-altitude UAV swarm surveillance missions.	Hierarchical UAV Teaming Structure. Decentralized Control. Communication-Aware Algorithms.
(Raja et al., 2021)	2021	Developing an efficient and secured communication model, for swarm UAVs, addressing challenges of mobility, dynamic topology, and security.	Secured UAV (S-UAV) Wireless Mesh Network (WMN). A* search algorithm. Cryptographic Techniques.
(Gao et al., 2022)	2022	The development and validation of a distributed learning approach of advanced wireless coverage within UAV swarm communication networks.	Distributed Learning Approach. Monte Carlo method for validation.
(Mou et al., 2021)	2021	The development of a resilient communication framework for UAV swarms using a Graph Convolutional Neural Network (GCN).	Self-healing aspect of UAV swarm network (USNET). Graph Convolutional Neural network. Trajectory Planning Algorithm.
(Boccadoro et al., 2020)	2020	The adoption of Internet of Drones concept in a Dual-Stack Communication architecture for a Swarm of UAVs.	Internet of Drones (IoD). mmWave 5G Dual-Stack Comm.
(Shah, 2022)	2022	Using meta-heuristic optimization algorithms to improve drones FANET communication.	Cuckoo Search Algorithm (CUCO) Differential Evolution Algorithm (DEA) Honey-Bee Algorithm (HBA)
(Zirak et al., 2021)	2021	Decentralized communication based on ad-hoc network for drones using the optimization of LoRa technology	Long Range (LoRa) Destination Sequenced Distance Vector (DSDV)
(Alsolami et al., 2021)	2021	The paper proposes a self-timing synchronization approached for large UAV networks.	Large UAV network Timing synchronization Cluster-Based Swarm
(Javed et al., 2023)	2023	Communication capacity maximization for swarm of drones	Mixed-Integer Nonlinear Programming (MINLP)

Paper (Raja et al., 2021) introduces a Secured UAV (S-UAV) model for efficient communication among mini-UAVs, addressing the limitations of larger UAVs in emergency situations. This model forms a Wireless Mesh Network (WMN) using a centralized controller. The UAVs' locations are inputs for this network formation. The A* search algorithm finds the shortest communication link between UAVs for efficient communication after WMN formation. The article includes advanced cryptographic techniques, such as Advanced Encryption Standard (AES) and Blowfish, which develop an S-UAV model to secure communication. Security attacks on the S-UAV model can efficiently overcome using these cryptographic methods because security is essential in a UAV's high-mobility and dynamic topology and UAV swarm. Simulation results of the presented paper have proved that the S-UAV model improves performances, decreases power consumption, and assures message transmission. Furthermore, the article describes that S-UAV also improves fault tolerance by parallelizing task achievement among UAVs as well as minimizes the threat from major security attacks UAV towards communications, such as GPS spoofing, de-authentication.

The authors in (Gao et al., 2022) focus on improving the downlink wireless coverage of UAV swarms, particularly for search and rescue missions. The proposed research offers a new cooperative wireless coverage algorithm for UAV swarms that can be implemented in a distributed framework and takes advantage of the constrained, limited communication range of UAVs, their delay sensitivity, and onboard energy. The proposed solution divided the wireless coverage problem into multiple distributed optimization subproblems and solved them through the UAV swarm communication coverage formulated on a random graph. The proposed solution was validated with simulations. More specifically, the simulations utilized the Monte Carlo method in a 200 m^2 area in 1,000 iterations, assuming that the UAV's initial positions were randomized. The performance analyses indicated that the developed algorithm outperformed other online methods such as the best response dynamic and random response strategy due to the substantial increase in usability. Notably, the final communication area increased by approximately 0.007 km^2, which corresponded to a significant 58% relative improvement compared to the initial UAV swarm area.

The issue of communication within UAV swarms, particularly focusing on the self-healing aspect of UAV swarm network (USNET) communication in response to Unpredictable External Destructions (UEDs) was studied in (Mou et al., 2021). The paper introduces a Graph Convolutional Neural network (GCN) designed to quickly rebuild communication connectivity in UAV swarms after one-off UEDs. UAVs can reestablish the communication connectivity during the self-healing process for more complicated and diversified external disrupters. By performing digital simulations, it is shown that the proposed GCN methods outperform the currently existing methods in terms of communication restoration under both UED and one-off UED events. It is confirmed that the meta-learning method is also able to reduce the time complexity of online performance of GCN across the phases.

The concept of Internet of Drones (IoD) is introduced in (Boccadoro et al., 2020), where the authors propose a Dual-Stack communication strategy within a swarm of drones. The UAVs form a spherical formation with the master drone in the center of it. The swarm flies on a predetermined flying trajectory which includes ground terminals for communication. The Dual-Stack Communication approach include the master-slave drones communication based on Bluetooth technology for small data transfer (information related to the formation control) and 5G technology where each agent in the swarm can receive and send big data (video images) with the ground terminals. The simulation results show good performances in terms of energy efficiency for the proposed method.

Usually, a swarm of drone communication networks are known as Flying Ad-hoc Networks (FANETs). Paper (Shah, 2022) evaluated three meta-heuristic optimization algorithms used to improve the efficiency for FANETs. These three methods are Cuckoo Search Algorithm (CUCO), the Differential Evolution Algorithm (DEA) and the Honey-Bee Algorithm (HBA). Using a simulated environment performances such as communication delays, packet dropping rate channel busy probability, collision and successful transmission probability are evaluated. The simulation results show an improvement in the quality and reliability of communication compared to the traditional methods, especially when the number of drones within the swarm is higher (50 drones). The performance ranking of these three methods is the following one: CUCO, DEA and HBA, the difference between them being minor.

The authors in (Zirak et al., 2021) implements a customized Destination Sequenced Distance Vector (DSDV) routing protocol, by optimizing the Long Range (LoRa) technology to enable direct communication between drones, thus creating a decentralized communication strategy. The proposed solution is validated through field test, showing a good reduction in idle time using Lister Before Talk (LBT) mechanism, improvement of Packet Delivery Ratio (PDR) and reduction in the route construction time for LoRa. Long distance communication and optimized operational efficiency in remote environments are the main contribution of this study to this field.

Paper (Alsolami et al., 2021) addresses the critical need for precise timing synchronization in drone swarms, where existing methods are efficient for single-hop synchronization but struggle with larger, multi-hop networks. Semi-flat Swarm Drone Networks (SDN) approached is proposed, designed for self-timing synchronization for large-scale communication networks. To coordinate timing across clusters, intermediate drones are used. Simulations show that this approach significantly improves system performances and reduces synchronization delay by up to 75%, making it a flexible and scalable solution for timing precision in extensive drone networks.

The Authors in (Javed et al., 2023) propose a communication capacity maximization architecture for swarm of drones using Mixed-Integer Nonlinear Programming (MINLP) approach. This solution enables drone swarms to adapt by selecting the most suitable communication architecture and topology for various scenarios, including changes in range, the number of nodes, groups (gateways), and QoS requirements. This approach ensures maximum data throughput in each situation. The proposed method was validated through simulation by defining a quantified mathematical model and it demonstrated being effective across various communication architectures, including centralized, multi-grouped, and multi-layered systems.

4. FORMATION CONTROL

Table 3. Summary of Formation Control methods for Swarms of UAVs.

Article	Year	Research focus	Applications
(Fan et al., 2023)	2024	The development of control strategies for UAV swarm formation to improve air-to-ground communication efficiency in sixth generation (6G) wireless networks.	Sixth generation (6G) wireless network. Multi-Agent System Theory. UAV-enabled Wireless Network Model.
(Pyke & Stark, 2021)	2021	The development of a formation control system for autonomous drones navigating through dynamic environments.	Particle Swarm Optimization Pathfinding (PSOP). Drone Flock Control (DFC).
(Fu et al., 2020)	2020	The development and validation of formation control method for maintaining and reconstructing the UAV swarms structure based on distributed control.	Consensus-Based Bundle Algorithm (CBBA). Artificial Potential Field method. Collisions Prediction mechanism.
(Azam, Mittelmann, et al., 2021)	2021	The development and validation of UAV swarm shape control.	Markov decision processes (Dec-MDP). Nominal Belief-State Optimization (NBO) method.
(Xie et al., 2021)	2021	The development and validation on formation tracking and control for UAV swarms, utilizing principles derived from the hunting strategies of grey wolves	Bio-inspired adaptive formation tracking. Adaptive Control Strategy.
(Ali & Zhangang, 2021)	2021	UAV formation control using a hybrid PSO CM strategy	Particle Swarm Optimization (PSO) Cauchy Mutant (CM)
(Yasin et al., 2020)	2020	Formation control and collision avoidance in swarm of drones	Formation-Collision Co-Awareness Collision Avoidance Algorithm
(Wadood et al., 2024)	2024	Formation control using a novel fractional swarming strategy approach	Fractional -order Velocity-pausing Particle Swarm Optimization (FO-VPPSO)
(Zhang et al., 2022)	2021	Drone formation control using visual-based relative localization and graph-based attention planning	Active vision Graph-Based Attention Planning (GAP) OpenCV ArUco
(Ma et al., 2023)	2023	Drone formation control using visual-based for UAV swarm with hierarchical architecture	Active vision YOLOv7 DeepSORT

A swarm of UAVs is a collection of multiple agents, that are acting in a collaborative manner to achieve a common objective. Each agent in the swarm has its own intelligence, being capable of self-stabilization control, self-positioning control, communication, and decision-making tasks, but they must coordinate with the neighbors to keep the unity of the swarm. Regardless of the application type or the scope of the system, the swarm formation must be maintained and controlled. This can be achieved through a series of essential sub-tasks like: path finding, collision avoiding, decision making and tasks management. The swarm formation control is an abstract aspect, that is required to be implemented as part of the "global" intelligence of the system. It can be either a centralized entity that acts as the master or the brain of the swarm (being implemented a dedicated computer or on one of the agents) or a distributed algorithm that runs on all agents and the overall decision is calculated based on the collective response.

The focus of this section is on finding and understanding what current strategies are implemented for swarms' formation control, by conducting a literature review of papers that are covering this topic as a primary research objective.

(Fan et al., 2023) is an example of a research article that covers both communication and formation control aspects for a swarm of drones. The paper proposes a wireless network development using UAVs where the UAVs act as network relays for remote terrestrial user equipment (UEs). The swarm is distributed over a certain geographic area to cover as many UEs as possible. The authors highlight that this approach could be a key aspect within the topic of ground to air communication for the novel sixth generation (6G) wireless network. The paper proposes a blueprint for such a wireless structure, concentrating on formation control and deployment. For static UEs, the formation is guided through a pinning control strategy, where a flying path is calculated for a leader drone. The leader will fly to the desired point and by using graph theory methods, the neighbor UAVs will adjust their velocity and position to cover the pinned area and to avoid collision or interference among them. For mobile UEs an impulsive control strategy is proposed, where the UAV swarm adapts its movement and maintains their position, based on the updating position of UEs. The simulation results show that the swarm can follow the moving ground target and keep the desired formation.

The main research focus of (Pyke and Stark, 2021) study is to explore and propose a system for controlling the movement of autonomous drone groups through unknown and unpredictable environments using Swarm Intelligence (SI) algorithms. The formation control strategy is concentrated around the integration of Particle Swarm Optimization Pathfinding (PSOP) with the Drone Flock Control (DFC) model. The DFC model merges three modules: flocking for cohesive motion, obstacle avoidance for secured flight, and a pathfinding one with the PSOP algorithm for dynamic pathfinding. It provides cooperative motion of UAVs in 3D space, considerably reducing the number of collisions, as the agents' locations are being improved over time in an iterative manner. In addition, the quality decay system allows for old positions to be updated by newer ones. The modular nature of DFC makes it adaptable and compatible with multiple strategies for obstacle avoidance and pathfinding. Systems with 10 or 20 drones, PSOP drones required less time to find the target than D* Lite drones and on the other hand PSOP obtained fewer environment and drone-to-drone collisions than D* Lite drones in systems with 10 or 20 drones, applied on multiple scenarios.

The authors in (Fu et al., 2020) developed a swarm formation control method for maintaining and reconstructing the structure of this system. The control law is based on consensus theory, aiming to control the relative positional relationship between each UAV and a virtual leader. The UAVs are exchanging constantly their position and speed with their neighbors through the communication system. To achieve it the Consensus-Based Bundle Algorithm (CBBA) is used for real-time allocation of positions from the initial formation to the target formation. The system is important to have obstacle avoidance and collision avoidance capability. To achieve that, the study proposes a method called Artificial Potential Field, which requires to create virtual forces between each neighboring agent and between the agents and the obstacle. This helps the swarm to manage the distance between itself and the obstacle and guarantees that the agents are not colliding, and the formation is kept when the swarm must change its position or the course. On top of this, a Collisions Prediction mechanism is built, where each UAV predicts if it will have to avoid or not a newly detected obstacle, thereby reducing unnecessary maneuvers and maintaining efficient flight paths. The proposed solution was validated through simulation, where it showed that the UAV swarm can avoid obstacles while maintaining or reforming the formation structure.

(Azam et al., 2021) is another example of formation control research, which addresses the shape control problem for a swarm of UAVs. The main goal of this study is to realize a swarm of drones, capable of flying to a specific geographical location, hovering over it and to form a specific 3D-shape, for example a sphere. The approach is based on decentralized Markov decision processes (Dec-MDP). This decentralized control strategy allows each agent in the system to make its own decision, thus reducing the computation complexity and making the solution more robust to individual UAV communication interruptions or failures. Another key component of the proposed solution is the novel cooperative behavior strategy, being realized by implementing the Nominal Belief-State Optimization (NBO) method. To validate this solution, the authors conducted two MATLAB simulations (for spherical shape with and without obstacles). Each UAV in the swarm picked a random location in the swarm and by using the NBO method had to navigate to its target location. The decentralized method was more efficient compared to the centralized one, getting 16.7 seconds to get in formation, compared to 25.98 seconds. Overall, this research succeeded in creating and validating a robust, efficient, and scalable solution for autonomous UAV swarms.

The way nature organizes itself can be an inspiration for control strategies as well, particularly for formation control. The author in (Xie et al., 2021) proposes a formation control strategy for swarms of UAVs inspired by the grey wolf behavior. The agents within the swarm mimic the social behavior and hunting tactics used by the wolf packs, being organized as leaders and followers. The position and velocity of a drone is calculated based on a dynamic model and the movement behavior of the swarm. The leaders' task is to determine the target location and to create a motion target plan, which will be used by the followers to adjust their position accordingly to the leaders' flying path. When the target is reached the drones will fly around it, as wolves do when the prey is encircled. This final stage will ensure that the drones will not collide. The simulation results showed that the solution can find the target location, creating flying courses, following the leader, and maintaining the desired formation with no collisions. The tracking error converged to zero, demonstrating that the agents could follow exactly the path determined by the leader.

The authors in (Ali and Zhangang, 2021) implemented a hybrid control strategy involving, by optimizing Particle Swarm Optimization (PSO) with Cauchy Mutant (CM) operators. CM method can optimize the performance of PSO algorithm by avoiding solution falling in a local minimum. The proposed solution is applied and tested on fixed UAV swarm of drones and simulated. The terrain and the obstacles are mathematically modeled, and the hybrid formation control algorithm is continuously fed with environmental information around the flying formation. The algorithm calculates the best future position of the drone, to avoid the terrain and the obstacles. The research concluded that this hybrid algorithm gives better results, compared to the classical PSO method.

In some cases, formation control and obstacles avoidance methods can interfere and can result in collision of the agents. Research (Yasin et al., 2020) proposes a method to address this conflict, particularly in leader-follower setups. The paper proposes an Energy-efficient Formation morphing for Collision Avoidance (EFMCA) algorithm composed of two partial feedback-based algorithms: one for controlling the formation and the second one for collision avoidance. This novel approach uses thin-plate splines and a non-rigid mapping function to minimize formation deformation and reduce lag during obstacle avoidance. The algorithm was validated in SwarmLab (MATLAB simulator for drones), and the results demonstrate the efficiency of the proposed method. The results demonstrate that this method optimizes formation integrity, response time, and energy efficiency, while mitigating delays caused by obstacles, making it ideal for time-critical missions.

As in (Yasin et al., 2020), the authors in (Wadood et al., 2024) proposes a different solution for formation control of swarm of UAVs on mountainous terrain, but using an different approach. Traditional PSO proved to be an efficient method for path finding problems applied on positioning robots or drones. The main disadvantage of this algorithm is the premature convergence and an unbalanced exploration–exploitation trade-off.. This research proposes an enhanced PSO algorithm called Fractional-Order Velocity-Pausing Particle Swarm Optimization (FO-VPPSO). FO-VPPSO addresses these issues through adaptive fractional-order dynamics and a velocity-pausing mechanism, improving adaptability and robustness. The method optimizes flight path length, mitigates terrain-related costs, and prevents collisions in UAV swarms. In this study the performance of this algorithm compared to the classical one, was evaluated through simulation, the terrain being modeled. FO-VPPSO showed superior convergence rates and improvements in flight length and collision avoidance. The new solution was 29.05% more efficient than the traditional one for 100 trials.

Formation control can also be achieved using only image processing, without the need for GPS or any similar positioning system. In both (Zhang et al., 2022) and (Ma et al., 2023), the author proposed a similar solution but using different implementation methods for it. The swarm of drones is built in a hierarchical manner, consisting of a leader drone and the following ones. The leading drone is equipped with advanced image processing equipment, and it is responsible to identify the position of the drones and to arrange it according to the information received from the Ground Control Station (GCS). The leading drone can directly interact with each follower (by setting their relative position), and it is the only one that communicates with the GCS for mission command, formation control arrangement and swarm global positioning. The leader flies above the swarm to have the overall image of the entire swarm. In (Zhang et al., 2022) each follower is equipped with a marker for an easier identification. OpenCV ArUco library to detect markers was used for visual identification and Graph-Based Attention Planning (GAP) for formation control. On the other hand, in (Ma et al., 2023) YOLOv7 was used for visual detection of the drone (no marker was used) and DeepSORT for formation control. For both papers the methods were validated through simulation and real experiments obtaining good results in both cases for formation control.

5. SWARM CONTROL

The swarm control component represents the intelligence or the brain of the swarm. It can get all the information gathered by all agents in the field and decide where the system should head, what formation shape it should take and how to optimize all processes in order to reach the desired target. This component encapsulated both communication and formation control aspects discussed above.

It also represents the interface with the human operators and can continuously take inputs from them and can transmit real time information of the swarm status. The control algorithm can be created based on Machine Learning algorithm or can use problem solving solutions like Genetical Algorithm (GA), Particle Swarm Optimization (PSO) or Ant Colony Optimization (ACO), for determining the next position where the system should be.

This section proposes to review the state of the art for swarm control techniques, to understand what the proposed solutions are, what efficient they are and what are the future challenges that must be addressed.

The first example of swarm control research is presented in (Khalil et al., 2022). Here a swarm communication and control model using machine learning is proposed applied on search and rescue applications (SAR) for fast deployment and response. The paper simplifies the problem to a swarm of three UAVs. In the proposed solution, a master UAV is defined, which is followed by the other two drones and a master-slave communication system is installed for each agent. The control strategy will determine the velocity of each component, and they will take care of the minimum distance between them. The novelty of this research is the utilization of Machine Learning (ML) to determine the communication loss and the received signal strength (RSS) between agents. For this Task Random Forest Regression algorithm was implemented and tested. In terms of swarm control, ML techniques were utilized to predict the optimal formation and position of the swarm. To accomplish swarm control and to predict the clustering of UAVs within the swarm K-means clustering learning algorithm was utilized. The validation of the proposed solution was realized in a simulation environment using a heat map. The results demonstrated that this solution is efficient in swarm operational control, communication, and formation control for swarms of UAVs.

Table 4. Summary of Swarm Control methods for Swarms of UAVs.

Article	Year	Research focus	Applications
(Khalil et al., 2022)	2022	Swarm communication and control model development using machine learning for UAV swarms.	Machine Learning (ML). Task Random Forest Regression algorithm. K-means clustering.
(Zhao et al., 2022)	2020	The development and validation of a distributed coordinated control scheme for UAV swarms based on heterogeneous roles.	Distributed Model Predictive Control (DMPC). Role-based Cost Functions.
(Bassolillo et al., 2020)	2020	The development and validation of a decentralized mesh-based model predictive control strategy for swarms of UAVs control	Delaunay Triangulation Graph (DTG). Trajectory Tracking and Collision Avoidance Algorithm (TTCAA).
(X. Wang et al., 2021)	2021	The development of an improved swarm control strategy through the implementation of a sliding mode formation controller.	Sliding Mode strategy. Internet of Things (IoT). Artificial Intelligence (AI).
(Azam, Dey, et al., 2021)	2021	The development of a decentralized control strategy for maximizing target tracking performance in UAV swarm applications.	Markov decision processes (Dec-MDPs). Nominal Belief-state Optimization (NBO).
(Bertizzolo et al., 2020)	2020	An automated framework for distributed optimization and control of UAV networks, enabling self-optimization.	Network Control Problem (NCP) Self-Optimizing Drone Networks
(Siemiatkowska & Stecz, 2021)	2021	Mission planning and execution for UAV swarms using routes planning	Mixed Integer Linear Programming (MILP).
(Qamar et al., 2022)	2022	Multi-target tracking and navigation for swarm of drones in dynamic environments.	Reinforcement Learning (RL) Island modelling
(Venturini et al., 2021)	2021	Swarm control method to enhance the autonomy, adaptability and scalability	Distributed Reinforcement Learning
(Saffre et al., 2021)	2021	Human interaction with swarm control.	Graphic User Interface Self-Organization

The proposed swarm control solution in research (Zhao et al., 2022) is based on role assignment of the UAVs, coupled with Distributed Model Predictive Control (DMPC) framework. One UAV will get the leading role, being responsible for determining the flying path, based on the mission objective. This role is assigned to only one agent. The coordinator is responsible for managing the relative position of its neighbors, to keep the desired formation shape and to avoid collision. The follower role is assigned to the remaining drones, they are responsible for following the flying instructions received from the coordinators. The MDPC algorithm is implemented at each agent level. That will allow the UAV to anticipate their position in the formation and to adjust their behavior to keep the desired shape. The overall swarm control strategy consists of Role-based Cost Functions, with each role being assigned to a unique cost function that reflects its particular objective. The solution was validated on a simulation environment built in MATLAB. Several scenarios and performances were tested: formation control and trajectory tracking, role dynamics and transitions, velocity and yaw angle convergence, and the distance maintained between agents. The simulations show the advantages of the proposed swarm control strategy.

The authors in (Bassolillo et al., 2020) propose an advanced solution for swarm control involving a decentralized strategy based on the interaction of Delaunay triangulation with a Model Predictive Control (MPC) algorithm. The algorithm can determine a Delaunay Triangulation Graph (DTG) for the swarm, which represents the connection between three agents. Each drone calculates this triangulation using its position and the information received from its neighbors. Moreover, this method increases the robustness and scalability of the swarm control system. The second component of the control is the Swarm Guidance Algorithm (SGA), which is responsible to maintain the desired formation of the swarm. This is realized using the potential field approach, where drones are constrained to keep a safe distance among themselves. The last component is the Trajectory Tracking and Collision Avoidance Algorithm (TTCAA). This solution is created using MPC, where each agent in the swarm implements it. The proposed solution was validated using MATLAB/SIMULINK simulations. Three scenarios were evaluated with multiples agents in the swarm (three, five and ten) and considering different environmental conditions like obstacles or narrow flying paths. For all scenarios the proposed decentralized swarm control method proved to be robust and capable of adapting to any challenges.

Another example of swarm control research has been conducted in (Wang et al., 2021). The proposed researched solution is based on a sliding mode control strategy integrated with Internet of Things (IoT) and Artificial Intelligence (AI) technologies. The first component is the sliding mode control method, used to keep the desire flying formation, which can be applied to both centralized and decentralized swarms. The control law is designed to drive the system to the stability point and to keep it there. The sliding mode method minimizes the error between the dynamic model (where the system should be or the sliding surface) and the real measured data (where the system is). The second component is an intelligent communication system, based on IoT solutions which can self-organize the communication links through the network. The utilized solution is AP+STA, which involves AI algorithms. Although it is not clear how the solution was implemented, validated and how the presented results were obtained, the authors acknowledge their solution being efficient and robust in terms of overall swarm control.

Paper (Azam, Dey, et al., 2021) is another comparison example between centralized and decentralized swarm control strategies. This research promises to optimize the target tracking performance of swarm of UAVs using a decentralized approach. The control method is based on the theory of decentralized Markov decision processes (Dec-MDPs) and an approximate dynamic programming method called Nominal Belief-state Optimization (NBO). The UAV will calculate its flying course (acceleration, speed and heading). This method involves a heuristic approximation of the solution, by considering a nominal (predicted or estimated) sequence of belief states instead of all possible belief states. The algorithm narrowed down the random variables to nominal values to remove the expectation from the optimization problem and it can be implemented at each UAV level (decentralized) or on one single entity (centralized). To validate the proposed solution, the authors ran different simulated scenarios. For a single tracking target, the decentralized solution was 20% more efficient from computation time point of view than the centralized approach. For multiple targets tracking scenario, the tracking error was higher compared with the previous scenario for both setups, but the decentralized approach was notably more computationally efficient than the centralized one.

The authors in (Bertizzolo et al., 2020) proposes a novel framework for managing UAV swarms in an automated, scalable, and distributed manner. The proposed method tries to optimize the UAV control strategy for tasks like communication and flight control while addressing challenges such as interference, adversarial environments, and decentralization. The proposed control architecture is organized as a centralized Network Control Problem (NCP), which includes variables such as UAV positions, transmission power, and routing policies. The NCP is decomposed in smaller sub-problems using techniques such as Lagrangian Duality and Decomposition by Partial Linearization. Each sub-problem is assigned to specific UAVs or network layers. Using sequential quadratic programming, each sub-problem is solved by the agents and the centralized result represents the swarm control decision. The study validated the proposed method using simulation, obtaining a significant improvement in network throughput, with an average gain of 159% in simulated environments.

Both (Siemiatkowska and Stecz, 2021; Qamar et al., 2022) presents swarm control techniques utilizing decentralized control and artificial intelligence algorithms for path planning and navigation in dynamic 3D environments. The papers highlight the need for adaptability in unpredictable or hostile environments incorporating re-planning capabilities based on threat detection. Both studies integrate machine learning for improving system efficiency (Siemiatkowska & Stecz, 2021) incorporates heuristic methods such as particle swarm optimization with Convolutional Neural Networks (CNNs) for object detection while (Qamar et al., 2022) leverages reinforcement learning for adaptive navigation and decision-making. Both studies demonstrate effective mission planning and superior swarm adaptability and precision in navigating 3D environments with dynamic obstacles during simulation.

(Venturini et al., 2021) proposes a swarm control framework based on Distributed Reinforcement Learning (DRL). This solution aims to overcome the traditional control methos disadvantages related to scalability, adaptability, and robustness to dynamic and uncertain environments. The proposed algorithm enables the UAVs the capability to learn and act autonomously while maintaining coordination within the swarm. The DRL algorithm is based on deep Q-Learning (DQN), Proximal Policy Optimization (PPO), or Multi-Agent Deep Deterministic Policy Gradient (MADDPG), where each UAV is trained to analyze the environment and to take decisions, this being shared with the nearby neighbors. The performance of this framework was validated through simulation on multiple scenarios and the results show robust communication, efficient obstacles identification and adaptive response to the changes.

As this paper described above the three fundamental layers of a swarm of drones are: communication, formation control and swarm control. These three elements form the swarm as an entity. It is important to mention that nowadays the swarms are not fully automated, and the human factor decides what is the mission and where these swarms should be deployed to. The authors from (Saffre et al., 2021) propose a Graphic User Interface (GUI) to interact with a swarm of drones. The paper shows the elements of the GUI and how it is connected with the swarm. The swarm control is organized based on "leader-follower" approach; each agent being organized on different layers. The human operator can adjust the position of the leader and can decide the distance between each agent. Based on these setpoints, the swarm has the capacity to adapt to the requirements. The proposed solution is evaluated through simulation.

The literature review presented in this section was an extended exploration of the current solutions and concept of Swarm of UAVs. The findings show that this domain has received considerable attention in recent years and the proposed solutions are promising. The key components of these systems lie in three aspects: communication architecture, formation control and swarm management or swarm control. The efficiency of swarm operation consists of robust communication networks that can sustain long distances coverages and effective rerouting of the shared information among each agent in the swarm. There are several examples of robust and efficient communication networks integrated a validated into swarms of UAVs. Furthermore, to ensure a unified action response of the whole system (to get the assigned objective) the swarm must maintain cohesion, avoid obstacles, and avoid inter-agent collisions. For all these 3 components to effectively work a control mechanism must be ensured, to distribute the tasks among the agents to reach the target the system was assigned to. The nature of the topic is such that there is an unlimited potential for improving existing communication, collaboration, and control mechanisms.

6. CONCLUSIONS

In the coming age of artificial intelligence and remote operating applications, the use of Unmanned Aerial Vehicles is almost inevitable. The UAV market is in a continuous expansion, and it is expected to grow considerably over the next decade because of the growing need of remote working using drones and the continuous research and development that is invested into this sector.

The most vital component or aspect that influences the quality of such an application is its capability of identifying the surrounding environment, using image processing or other sensors such as: LiDAR, spectral or thermal cameras. For image process a large set of algorithms such as: YoLo, Meshlab or TensorFlow platform combined with Convolution Neural Networks (CNN), proved to be reliable tools for identifying the environment or other key shapes (humans, buildings, infrastructure, or obstacles). Finding a way to integrate the image processed information with the data collected from the other sensitive sensors mentioned above is crucial to develop an autonomous UAV capable of navigating through a real word environment. The current research is still focusing on realizing this important milestone and substantial progress has been achieved in this direction.

Moreover, the Multi-agent UAV systems where a swarm of multiple drones can be deployed to achieve a common goal is continuously growing. These solutions can be integrated in any of the sectors mentioned above and can improve the capabilities of a single drone application. To realize such a system, it is important to ensure three vital components: Communication, Formation Control and Swarm Control. Stabile communication among the components of the swarm is vital and should be as stable as possible to ensure the overall collaboration of the agents. On top of that, communication with the base is also important but not vital since this system is supposed to operate autonomously. The current 5G technology is a reliable and accessible tool that contributes to enhance this functionality. The formation control component represents the coordination algorithm used to ensure that all agents keep the desired shape of the swarm, avoiding collision among each agent and with the surrounding obstacles. The swarm control is responsible to ensure that the common objective is achieved, by implementing advanced algorithms such as: Particle Swarm Optimization, Genetic Algorithms, Ant Colony Optimization, Model Predictive Control and many more.

In conclusion, this study highlights the current state of the art of the UAV's applications in general, showing current technologies, algorithms, results, and future trends of this research topic. Concrete solutions have shown that from the technical point of view these systems are almost capable of being deployed on real-live applications. The time horizon for that to happened being also dependent on how and when the legislation is regulated in this area.

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