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UAV swarms: research, challenges, and future directions

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Abstract

Unmanned Aerial Vehicle (UAV) swarms represent a transformative advancement in aerial robotics, leveraging collaborative autonomy to enhance operational capabilities. This paper provides a comprehensive exploration of UAV swarm infrastructure, recent research advancements, and diverse applications. Key areas such as coordinated path planning, task assignment, formation control, and security considerations are examined, highlighting how Artificial Intelligence (AI) and Machine Learning (ML) are integrated to improve decision-making and adaptability. Applications span civilian sectors, including entertainment, infrastructure inspection, and delivery services, as well as military applications in surveillance, combat support, and logistics. The paper addresses technical challenges, regulatory constraints, and ethical considerations, while outlining future directions focused on scalability, robustness, and societal integration. This review consolidates the evolving landscape of UAV swarms, identifying critical challenges and guiding future research endeavors.

Keywords: UAV swarms, Multi-robot systems, Autonomous aerial systems, Formation control, Distributed coordination, Swarm intelligence

Introduction

Advancements in Swarm Robotics (SR), particularly within the field of aerial robotics, have introduced transformative capabilities embodied in Unmanned Aerial Vehicle (UAV) swarms. These swarms leverage aerial mobility, high-speed maneuverability, and expansive coverage capabilities, making them pivotal across diverse applications [1–3]. SR aims to develop scalable, robust systems where groups of robots collaborate with each other and their environment to execute complex tasks efficiently. Inspired by natural social behaviors, such systems surpass single-robot counterparts in multitasking, scalability, cost-efficiency, robustness, and adaptability [4, 5], especially in flying robots requiring coordinated interaction and collaboration among multiple autonomous agents.

A swarm robotics system refers to a coordination method used in Multi-Robot Systems (MRS), comprising a group of autonomous and relatively simple robots with similar capabilities. These robots are equipped with local sensing and communication abilities, enabling them to interact locally among themselves and with the environment. This collective interaction enhances their efficiency in performing predefined tasks compared to individual robots [6–8]. Central to SR is the coordination of MRS, where autonomous aerial agents operate collectively in path planning, task allocation, and formation control. These agents, diverse in capabilities yet harmoniously interacting, contribute individually while benefiting collectively from their shared environment.

One significant research area for UAV swarms involves optimizing path planning for multiple robots within swarm environments. Swarm Intelligence (SI) algorithms, inspired by natural behaviors, facilitate collaborative decision-making and coordination for UAV swarms, enabling effective exploration and navigation in dynamic environments. Combinatorial optimization approaches further enhance swarm efficiency by maximizing collective performance through optimal task allocation and resource management [9, 10]. Another critical focus area is swarm formation control, aiming to achieve stable flight formations and minimal inter-robot distance variations. Research efforts in this domain aim to enhance swarm operational efficiency and enable synchronized movements essential for tasks requiring precise coordination among swarm robots [11, 12].

Within the field of SR for UAV swarms, the existing literature covers a diverse range of research topics and advancements. Exploration of SR features and characteristics has shed light on the decentralized and self-organizing nature of swarms, which empowers them with robustness, adaptability, and fault tolerance. Nevertheless, implementing SR in flying robots presents unique challenges, including communication, control, scalability, and resource limitations. To overcome these obstacles, ongoing research is focused on innovative algorithms and the integration of Artificial Intelligence (AI) techniques. Recent advances in AI, Deep Learning (DL), and Machine Learning (ML) play pivotal roles in overcoming challenges and enhancing overall SR performance [13, 14]. These technologies enable better swarm coordination, task allocation, and navigation, empowering UAV swarms to operate with increased efficiency and adaptability. DL algorithms, capable of processing extensive data and learning from experience, contribute significantly to the development of intelligent autonomous flying robots within swarms. The integration of AI, DL, and ML not only optimizes swarm operations but also unlocks new capabilities across various industries [15].

The application spectrum of SR for UAV swarms spans various domains, where decentralized and self-organized behavior enhances efficiency, reliability, and adaptability. Collaborative efforts among robots not only improve operational safety by mutual monitoring and assistance but also ensure adaptability to dynamic environmental changes [16–18].

This paper comprehensively explores swarm robotics (SR) in the context of flying robots, examining recent advancements, current challenges, and future directions. By delving into principles, algorithms, and techniques enabling SR, this study provides valuable insights into the potential and limitations of UAV swarms across diverse applications. The contributions of this paper include:

- An exploration of key research aspects such as coordinated path planning, task assignment, formation control, and communication.
- An analysis of security and privacy considerations.
- An overview of the integration of AI and ML in enhancing UAV swarm capabilities.

- Identification of technical challenges and potential solutions.
- A detailed review of the infrastructure and features of UAV swarms.
- An assessment of the diverse applications in civilian and military sectors.
- Outlining future research directions to address current gaps and challenges.

The remainder of this article explores key facets of UAV swarms, beginning with an examination of their infrastructure and distinctive features. This section delves into coordinated path planning, task assignment, formation control, communication protocols, and considerations of security and privacy. Following this, the research aspects of UAV swarms are explored, focusing on recent advancements and ongoing developments in AI integration and ML techniques. The discussion then shifts to the diverse application areas of UAV swarms, detailing their roles in civilian and military domains. Subsequently, the article addresses the challenges, limitations, and future directions in the field, encompassing technical hurdles, regulatory issues, and prospects for scalability and societal integration. Finally, the conclusion synthesizes the findings and outlines potential avenues for future research in enhancing the capabilities and applications of UAV swarms.

Infrastructure and features of UAV swarms

This section provides an overview of the essential components and characteristics of UAV swarms, which enable their effective operation and coordination. We begin by detailing the infrastructure of UAV swarms, followed by an examination of their key features and characteristics.

UAV swarms infrastructure

The infrastructure of UAV swarms comprises several critical components that collectively ensure the effective operation and coordination of the swarm as depicted and detailed in Fig. 1 and Table 1 respectively. Each drone or quadrotor serves as an individual unit within the swarm, equipped with sensors, processors, and necessary hardware to facilitate communication and coordination with other drones. The control unit plays a central role in managing the swarm, ensuring that the drones operate within the desired parameters. This

Table 1 Infrastructure components of UAV swarms

Component	Description
Drones/Quadrotors	Individual units equipped with sensors, processors, and hardware for communication and coordination
Control Unit	Manages the swarm, ensuring operation within desired parameters, can include a ground station or cloud-based system
Communication System	Wireless network for real-time information exchange, using protocols like Wi-Fi, Bluetooth, or Zigbee
Sensors	Integrated sensors (e.g., cameras, LiDAR, GPS) for environmental data gathering and processing
Algorithms	SI algorithms for path planning, collision avoidance, formation control, and decision-making
Power Source	Batteries or tethered power supplies critical for flight time and performance
Navigation System	GPS, inertial navigation, and visual odometry for autonomous navigation and collision avoidance

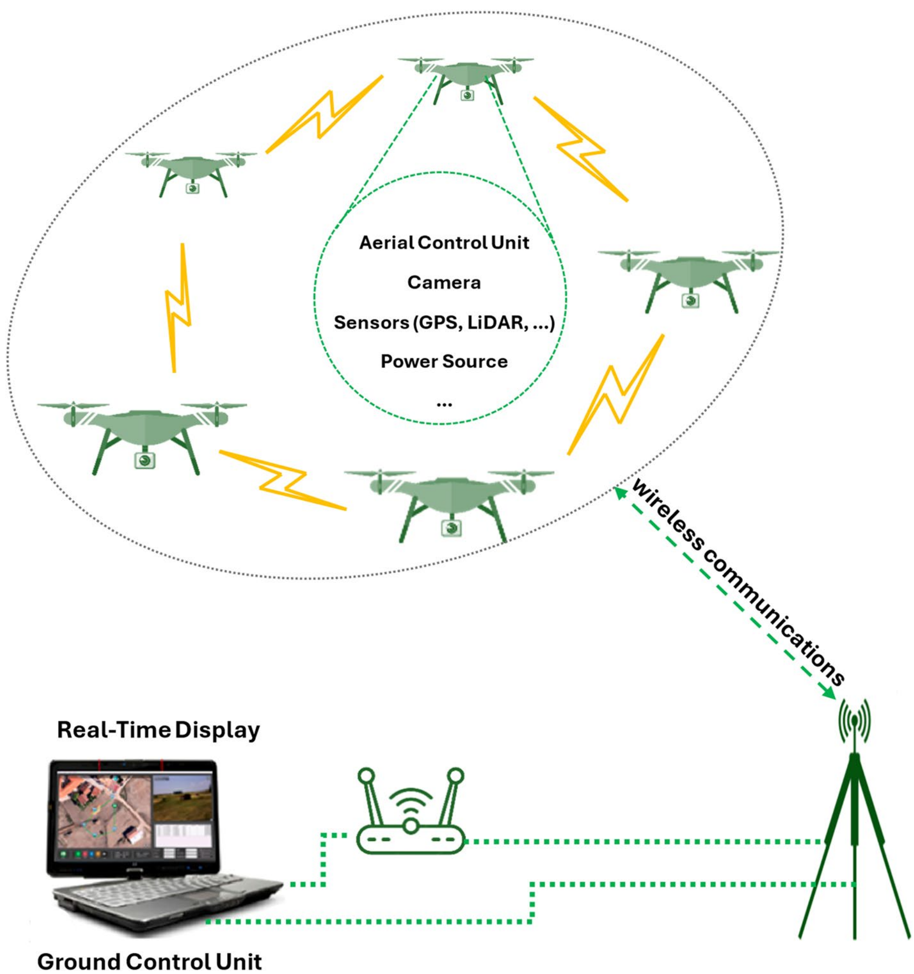

Fig. 1 Basic components of UAV swarms

control can be achieved through a ground station or a cloud-based system, providing a central interface for control, monitoring, and data reception.

A robust communication system is essential for the real-time exchange of information among UAVs and with the ground control station. This system typically employs wireless protocols such as Wi-Fi, Bluetooth, or Zigbee. Integrated sensors, including cameras, LiDAR, GPS, accelerometers, and gyroscopes, enable the drones to gather and process environmental data. Algorithms, particularly those based on SI, are crucial for autonomous coordination, including path planning, collision avoidance, formation control, and decision-making.

The power source, often batteries or a tethered supply, is critical for UAV operation, influencing flight time and overall performance. Finally, navigation systems, such as GPS, inertial navigation, and visual odometry, allow UAVs to navigate autonomously and avoid collisions, ensuring efficient and safe operations.

Table 2 Features and characteristics of UAV swarms [16–19]

Feature	Description
Cost-effectiveness	Utilizing a group of specialized robots for various tasks is more cost-effective than building a single versatile robot
Scalability	Maintaining effectiveness and performance even as the number of robots increases.
Robustness & Survivability	Maintaining functionality in adverse conditions, reconfiguring to mitigate impacts of robot failures.
Adaptability & Flexibility	Adjusting collective behavior to respond to environmental changes or new mission objectives
Parallelism	Performing tasks concurrently and independently, enhancing system performance and efficiency
Redundancy & Fault-tolerance	Overcoming single points of failure by reconfiguring remaining robots to compensate for failures.
Multi-tasking	Dividing tasks into sub-tasks for simultaneous completion, leading to faster mission completion.
Distributability	Coordinating and distributing tasks based on individual robot capabilities, increasing efficiency and adaptability.

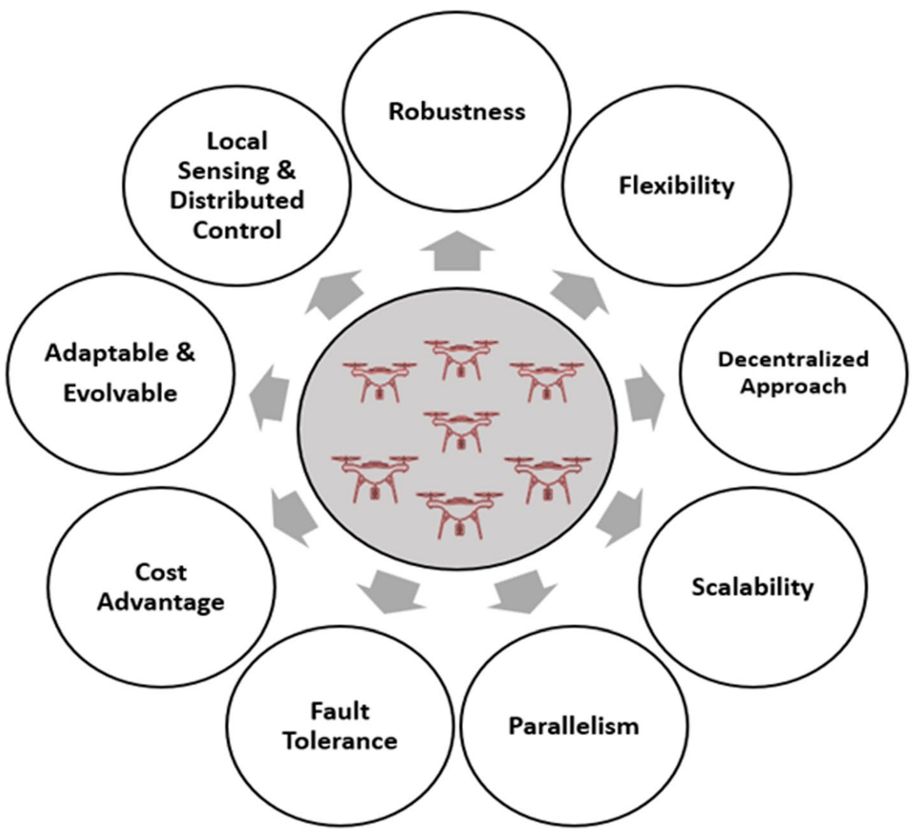

Fig. 2 Remarkable features of UAV swarms

Features and characteristics of UAV swarms

The goal of developing sophisticated robotic systems capable of performing complex tasks in various environments drives the growing interest in MRS. As a subset of MRS, UAV swarms offer several advantages and key features, as illustrated in Fig. 2.

Compared to a single robot system, a SR system can achieve a given complex task with a team of simple, cooperative robots, which results in lower construction and maintenance costs. In a single robot system, the design must be complex and equipped with several control modules, leading to high design costs and maintenance requirements. Any failure in any part of the robot can affect the mission completion efficiency [4, 5].

Table 2 outlines the significant features and characteristics of UAV swarms. One of the primary advantages is cost-effectiveness. Building a single, highly versatile robot can be impractical due to size and payload limitations. Instead, using a group of specialized robots allows for cost-effective solutions without compromising on task performance [18].

Scalability is another key feature, allowing UAV swarms to maintain their effectiveness even as the number of robots increases. Robustness and survivability refer to the swarm's ability to function under adverse conditions and reconfigure in the event of robot failures. This enhances the swarm's reliability, particularly in dangerous or unpredictable environments [19].

Adaptability and flexibility enable UAV swarms to adjust their collective behavior to respond to changes in the environment or mission objectives. Parallelism allows multiple robots to work concurrently and independently, significantly improving system performance and efficiency. This parallel operation is vital for tasks requiring rapid completion.

Redundancy and fault-tolerance are critical for overcoming single points of failure. If one or more robots fail, the remaining robots can reconfigure to mitigate the impact, enhancing overall system reliability [17, 18]. Multi-tasking involves breaking down tasks into sub-tasks that can be completed simultaneously, leading to faster mission completion times. Finally, the distributability allows for the efficient coordination and distribution of tasks based on the capabilities of individual robots. This feature increases the swarm's efficiency, scalability, and adaptability to changing conditions and task requirements [16].

Research aspects of UAV swarms

Interdisciplinary research has led to significant advances in science and engineering, including breakthroughs in the field of robotic systems. One of the key challenges in the context of multiple robots is how to make decisions about their actions in order to achieve the overall system objective optimally. This problem can be viewed as a generalization of decision-making problems, where objective functions evaluate solutions to find optimal values. Combinatorial optimization problems arise when attempting to optimize objective functions over a combination of finite discrete objects, and they have numerous applications in various fields, such as task allocation, vehicle routing, and transportation [20]. Table 3 summarizes the key research areas in UAV swarms, detailing various combinatorial optimization problems and scenarios involving multiple robots.

The path planning involves finding efficient routes for multiple robots to navigate complex environments while avoiding obstacles and collisions, ensuring UAV swarms operate safely and efficiently. Resource allocation addresses the distribution of essential resources like energy, time, and communication bandwidth among robots, optimizing the swarm's overall performance. Formation control coordinates the movements of

Table 3 Key research areas in UAV swarms [5, 8]

Research area	Description
Task Allocation	Assigning tasks to a group of robots to maximize overall performance while considering the capabilities and limitations of each robot.
Path Planning	Finding the most efficient routes for multiple robots to navigate a complex environment while avoiding obstacles and collisions.
Resource Allocation	Distributing resources such as energy, time, and communication bandwidth among multiple robots to optimize performance.
Formation Control	Coordinating the movements of multiple robots to maintain a specific formation, such as a swarm or flock.
Network Optimization	Optimizing communication and data exchange between multiple robots to minimize latency and maximize efficiency [21].
Sensor Placement	Determining the optimal locations for sensors on multiple robots to maximize coverage and accuracy of sensing tasks.

robots to maintain specific formations, crucial for tasks requiring synchronized movements and collective behavior. Network optimization focuses on enhancing communication and data exchange between robots to minimize latency and maximize efficiency, which is essential for real-time coordination and decision-making within the swarm [21]. Sensor placement determines optimal locations for sensors on robots to maximize coverage and accuracy of sensing tasks, improving the swarm's ability to gather and process environmental information. These research areas are fundamental to advancing UAV swarm capabilities, ensuring reliability, efficiency, and adaptability in various environments and scenarios.

The following subsections explore the critical research areas within UAV swarms, focusing on the fundamental aspects that enable their effective operation and coordination. These include coordinated path planning, task assignment and role interchangeability, formation control, communication and networking, and security and privacy considerations. Each of these areas is essential for advancing the capabilities and applications of UAV swarms, ensuring their reliability, efficiency, and adaptability in various environments and scenarios.

Coordinated path planning for UAV swarms

Coordinating the path planning for a team of robots navigating within a shared environment, while avoiding Robot-to-Robot (R2R) collisions is oneof the crucial challenge in UAV swarms. Addressing this challenge requires adopting diverse approaches to plan coordinated and collision-free paths for multiple robots. Each approach offers distinct advantages and drawbacks in terms of completeness and scalability [9]. One strategy is to use centralized (coupled) planning algorithms [22], which deal with multiple robots as if they represent a single, higher-dimensional flying robot. The degrees of freedom (DOFs) of all agents are combined, and a single robot planning algorithm searches the configuration space to find feasible paths for the combination. While the coupled methods provide a complete solution, the number of required samples grows linearly with the number of team robots, which reduces scalability [9].

Alternatively, the decoupled planning algorithms [23, 24] deal with each robot individually by planning for each agent separately and then combining the individual solutions to form path plans for the combination. In the first stage, the algorithm searches for a collision-free path for each robot while disregarding other robots. In the second stage, the relative velocities of the robots are considered to avoid R2R collision while following the planned paths. This approach leads to searching lower-dimensional configuration spaces than the coupled planning methods and thus guarantees scalability. However, the decentralized planning approach is inherently incomplete [9], which requires further coordination or incorporation of other considerations to overcome the lack of completeness. Overall, each approach has its advantages and drawbacks. Centralized planning algorithms guarantee completeness but may not be scalable for a large number of robots. Decoupled planning algorithms are scalable but may require additional coordination or considerations to ensure completeness [25, 26].

The illustrative scenario shown in Fig. 3 clarify the completeness issue associated with the basic decoupled planning algorithms. Consider a team of two 2D circular robots R_1 and R_2 assigned to reach the two goals G_1 and G_2, respectively as shown in Fig. 3a. It is required to find the shortest path for every robot to its assigned goal without colliding with other robots and workspace obstacles. It is assumed a four bidirectional connection for each node.

The results from the first phase of basic decoupled methods are the optimal free path for each robot such that, the first robot moves from (0,0) → (1,0) → (1,1) → (1,2) to its goal at (2,2), and the second robot moves from (1,1) → (1,2) → (2,2) → (3,2) → (3,1) to its goal at (4,1). For simplicity, it is assumed a constant speed for each robot, such that each robot either stays motionless or moves with a constant speed of a unit distance at every unit of time.

The second stage is to incorporate the notion of robot prioritization to avoid R2R collision so that robots with a higher priority move first and so on. One feasible solution is shown in Table 4. It is assumed that the second robot has the higher priority to start moving from the initial configuration to (2,2) until it reaches its designed goal. The first robot, R_1 will remain stationary until the second robot traverses G_1, then will follow its planned path.

If goals positions are switched as shown in Fig. 3b, then the decoupled planning algorithm will not be able to find a collision-free paths for all robots to their designed goals. However, the algorithm won't be able to guarantee that no feasible solution exists, and thus it lacks completeness.

Task assignment and role interchangeability

Effective multi-robot task planning and coordination are crucial for robotic systems, involving the efficient allocation of tasks among a team of robots and synchronizing their actions to achieve shared objectives. To optimize task assignment, combinatorial optimization techniques are often used, framing the problem as an optimization challenge with an objective function representing the system's overarching goal. Auction-based algorithms, where robots bid on tasks based on their unique capabilities and associated costs, are widely adopted for multi-robot task planning. These algorithms have proven effective in diverse applications, such as warehouse automation and search and rescue (SAR) missions [27]. Other approaches, like market-based algorithms and swarm-based

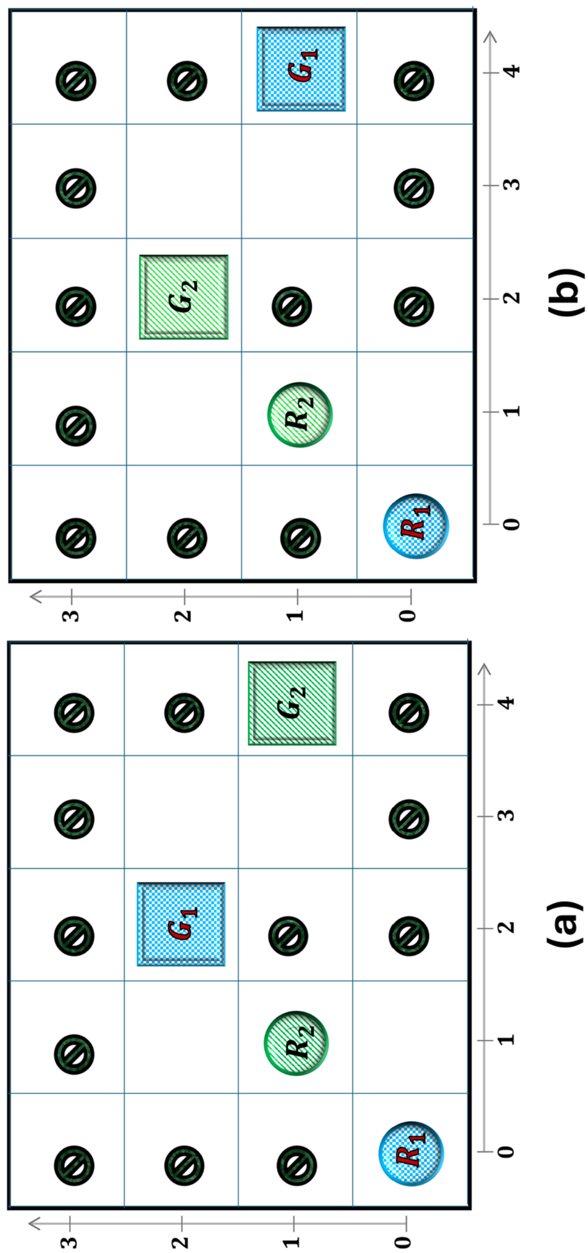

Fig. 3 A scenario illustrating the completeness issue associated with basic decoupled planning algorithms. **a** Two 2D circular robots, R_1 and R_2, are assigned to reach goals G_1 and G_2 respectively, demonstrating a feasible solution with robot prioritization to avoid collisions. **b** When the goal positions are switched, the decoupled planning algorithm fails to find collision-free paths, highlighting its lack of completeness

Table 4 Position history over time of each robot

Robot\time	t_0	t_1	t_2	t_3	t_4	t_5	t_6
Position of the first robot	(0,0)	(0,0)	(0,0)	(1,0)	(1,1)	(1,2)	(2,2)
Position of the second robot	(1,1)	(1,2)	(2,2)	(3,2)	(3,1)	(4,1)	(4,1)

algorithms, have also been proposed for multi-robot task planning and coordination [28].

Task interchangeability, a related yet distinct concept, involves allocating tasks based on individual robot capabilities and adaptability to specific tasks. This ensures that the right robot is selected for each task, maximizing efficiency. While task assignment and interchangeability focus on task allocation and adaptability, multi-robot task planning and coordination encompass a broader set of activities, including creating action sequences for each robot, resource allocation, and implementing mechanisms to prevent collisions and resolve conflicts during task execution.

Task assignment is a well-known combinatorial optimization problem with numerous applications in task allocation, scheduling, and vehicle routing. It involves assigning each task to at most one agent and each agent to at most one task in a way that minimizes the total assignment cost. When the number of agents equals the number of tasks ($N = M$), it is called a balanced assignment problem; otherwise, it is an unbalanced allocation problem [29].

Linear assignment, a subset of the task assignment problem, deals with problems where the total assignment cost equals the summation of individual agent costs. Various approaches have been proposed to solve the Linear Assignment Problem (LAP), each with its own time complexity [30]. The Hungarian algorithm (HA) is one of the most efficient algorithms for optimally solving LAP, with a polynomially-bounded computational complexity of $O\left(\max(N, M)^3\right)$ [31]. Studies, such as the one presented in [32], address the assignment problem for a team of robots.

In MRS, when tasks are independent of the robot assigned to them (i.e., any robot can complete any task), the team is considered completely interchangeable. This scenario is common when all robots are identical and equipped with the necessary sensors for task completion. For example, UAV swarms can support precision farming, monitoring multiple rows of crops for health, soil condition, and yield data, providing valuable insights for analysis and decision-making. In such cases, it is irrelevant which aerial robot is assigned to which row, offering additional flexibility in algorithm design [33]. The goal is not only to find the shortest, collision-free paths between robots and goals but also to select assignments that ensure mission objectives are achieved at optimal total cost.

Formation control in UAV swarms

Formation control in UAV swarms involves coordinating multiple flying robots to maintain specific formations while achieving a common goal. This field of study, part of SR, addresses the challenge of coordinating large groups of relatively simple robots to perform complex tasks. One of the primary challenges in MRS is automating the motion and control of the team to operate cohesively.

Formation control research focuses on developing control strategies and algorithms that allow a team of flying robots to fly in coordinated patterns. This has proven beneficial in various applications, such as surveillance, mapping, and SAR operations. Robust and scalable control algorithms are essential to handle real-world uncertainties and disturbances, as well as to manage communication and information exchange among swarm robots [34, 35].

As illustrated in Fig. 4, pattern formation control is a prominent research area in multiple robotics systems. It aims to coordinate UAV swarms to meet specific state constraints. Instead of planning unique actions for each robot, a prescribed formation is maintained, and a single action drives the entire formation, significantly reducing computational complexity. However, robust control approaches are necessary to maintain these formations.

As summarized in Table 5, several strategies have been proposed for multi-UAV formation control, including virtual-structure-based methods [36], leader-follower methods [37, 38], and behavior-based methods [39]. These strategies are particularly effective in applications requiring coordinated movements, such as reconnaissance, mapping, and data collection from various sensors. Additionally, formation control can be utilized in advertising, entertainment, persistent monitoring and inspection, precision agriculture, and cooperative transportation of heavier objects.

Formation control is vital for various UAV swarm applications. Virtual-structure-based methods guide UAVs using a virtual framework, ideal for rigid formations in surveillance and mapping. Leader-follower methods, where specific UAVs lead and others follow, are beneficial in following precise paths, such as in SAR missions. Behavior-based methods, which rely on simple behavioral rules, are suited for dynamic environments and tasks like reconnaissance and data gathering. These strategies ensure coordinated motion and efficiency in UAV swarm operations.

Communication and networking in UAV swarms

Effective communication and networking are vital for the successful operation of UAV swarms. These systems rely on robust communication protocols to share information, coordinate movements, and make collective decisions in real-time. One of the primary challenges in this domain is ensuring reliable and efficient communication among a large number of UAVs, which often operate in dynamic and unpredictable environments.

UAV swarms require low-latency communication to perform synchronized actions and respond to environmental changes promptly. This necessitates the development of

Table 5 Summary of formation control strategies in UAV swarms

Formation control strategy	Description and applications
Virtual-Structure-Based	Use a virtual structure to guide the formation of UAVs. Effective for maintaining rigid formations in applications like surveillance and mapping [36]
Leader-Follower based	One or more UAVs act as leaders, and the rest follow. Useful in scenarios where specific paths need to be followed, such as SAR operations [37, 38]
Behavior-Based based	Each UAV follows simple behavior rules that result in the desired formation. Applicable in dynamic environments and tasks like reconnaissance and data gathering [39]

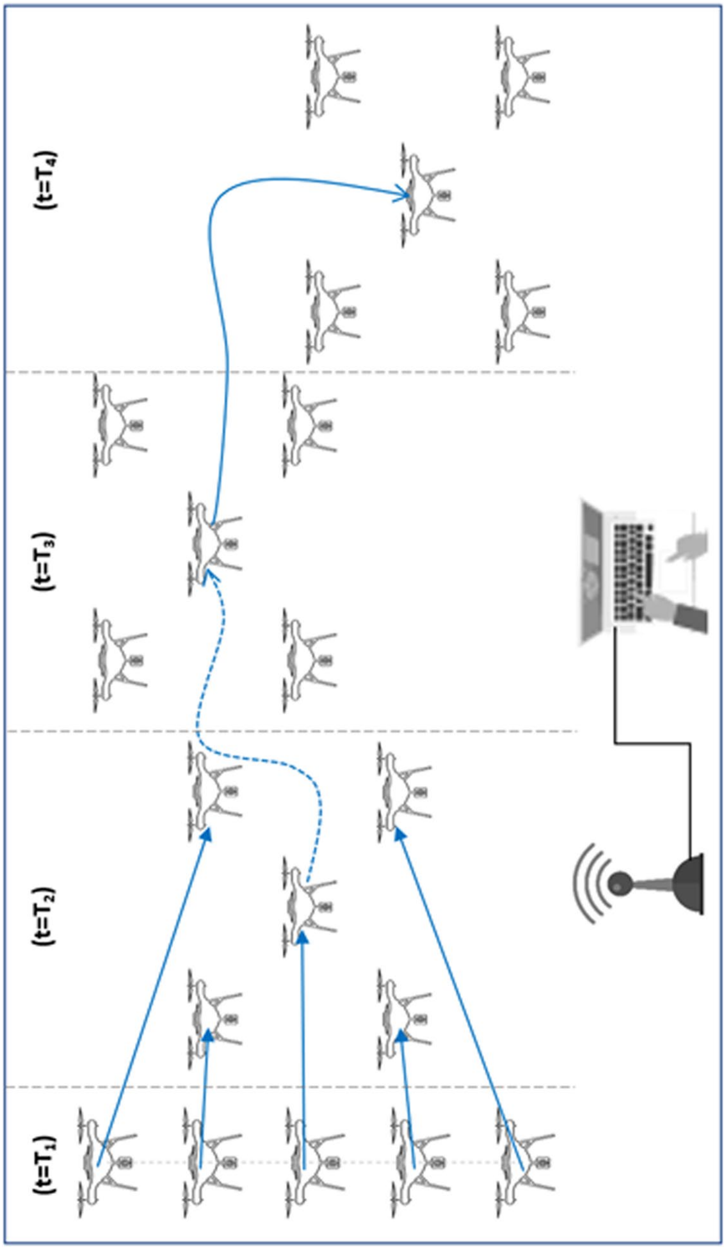

Fig. 4 Swarm formation control

advanced communication protocols that can handle high data rates and maintain stable connections even in the presence of interference and signal degradation [40]. Ad hoc networks, particularly Mobile Ad hoc Networks (MANETs), are commonly used to facilitate direct communication between UAVs without relying on fixed infrastructure [41]. However, maintaining network stability and avoiding congestion in MANETs is a significant challenge.

Security & privacy considerations

Security and privacy are critical concerns in the deployment of UAV swarms, particularly in sensitive applications such as surveillance, military operations, and infrastructure inspection. Ensuring the confidentiality, integrity, and availability of communication within the swarm is essential to prevent unauthorized access, data breaches, and malicious attacks.

One of the primary security challenges in UAV swarms is protecting the communication links from cyber-attacks [42]. These can include jamming, spoofing, and eavesdropping, which can disrupt operations and compromise mission-critical data. Developing robust encryption techniques and secure communication protocols is crucial to mitigate these risks [40].

Privacy concerns also arise when UAV swarms are used for surveillance and data collection. Ensuring that the collected data is used responsibly and protecting the privacy of individuals and sensitive locations is paramount. This requires implementing strict data governance policies and incorporating privacy-preserving techniques in the data processing and storage systems [43].

Towards intelligent UAV swarms

Swarm Intelligence is a branch of AI that studies the collective behavior of decentralized, self-organized systems inspired by natural systems such as ant colonies, bird flocks, and fish schools. The concept of SI was first introduced in the 1980s by researchers studying the behavior of ant colonies. Since then, the field has grown significantly and has found applications in various domains, including robotics [44, 45].

Research in SI for flying robots is currently focused on developing algorithms and techniques that enable UAVs to operate autonomously and collaboratively in complex and dynamic environments. This includes developing SI algorithms that can handle communication delays, sensor and actuator failures, and other challenges that arise in real-world applications. Additionally, there is ongoing research on developing more robust and scalable SI algorithms that can handle large numbers of UAVs and achieve higher levels of performance [46, 47].

Recent advancements

Recent advancements in SI for UAV swarms have seen significant progress, enabling flying robots to perform complex tasks and operate in challenging environments. One major area of progress is in algorithms for swarm navigation and control, which have allowed UAVs to fly in coordinated formations with high precision and efficiency. These algorithms use distributed decision-making, allowing individual robots to interact and coordinate with each other to achieve a common goal. Additionally, swarm sensing and perception algorithms have been developed, enabling UAVs to gather information about their environment and share it with other robots in the swarm. This collective perception allows the swarm to adapt and respond to changing environmental conditions [45].

Another area of advancement is in swarm decision-making algorithms that enable the swarm to make collective decisions based on the information gathered by individual robots. This allows the swarm to respond to changing situations quickly and efficiently. Swarm decision-making algorithms can also optimize the performance of the swarm by allocating tasks to individual robots based on their capabilities and the current state of the swarm [46, 47]. Furthermore, the operational efficiency and reliability of UAV swarms can be greatly enhanced by applying differential geometry principles, which significantly improves their guidance, navigation, and control [48, 49].

Integration of AI and ML in UAV swarms

The integration of AI and ML techniques into UAV swarms has facilitated the development of intelligent algorithms capable of autonomous decision-making, improved object recognition, obstacle detection, and optimized flight paths as demonstrated in Fig. 5. These advancements have led to the creation of numerous applications, including SAR operations, environmental monitoring, and precision agriculture [24, 45].

In SAR operations, UAV swarms equipped with intelligent algorithms can quickly survey large areas and relay critical information to rescue teams on the ground, thus improving the overall effectiveness and efficiency of rescue operations. For environmental monitoring, UAV swarms can track weather patterns, air quality, water pollution, or detect forest fires, identifying areas that require attention or remediation. In precision agriculture, UAVs with SI algorithms can collect data on crop health and soil moisture levels, allowing farmers to optimize crop yields and reduce water usage [50].

The integration of AI and ML into UAV swarms continues to evolve, with ongoing research focusing on enhancing the efficiency, adaptability, and autonomy of these systems. Future innovations are expected to further expand the capabilities of UAV swarms, unlocking new applications and improving their impact across various industries.

Application areas of UAV swarms

The flying advantages and distributed behavior of UAV swarms enable them to explore, monitor, and collect data from large areas in a collaborative and integrated manner. These features, together with task allocation and cooperative behavior, make UAV swarms highly versatile and valuable in various civilian and military applications as dipicted in Fig. 6.

Civilian applications

- **Autonomous Monitoring**: UAV swarms can be programmed to collaborate in precision farming applications, such as pollinating crops, monitoring crop and soil health, and gathering yield data across vast areas [51–53]. Additionally, UAV swarms are increasingly being used for environmental monitoring and pollution detection, where they can cover large areas efficiently and provide real-time data

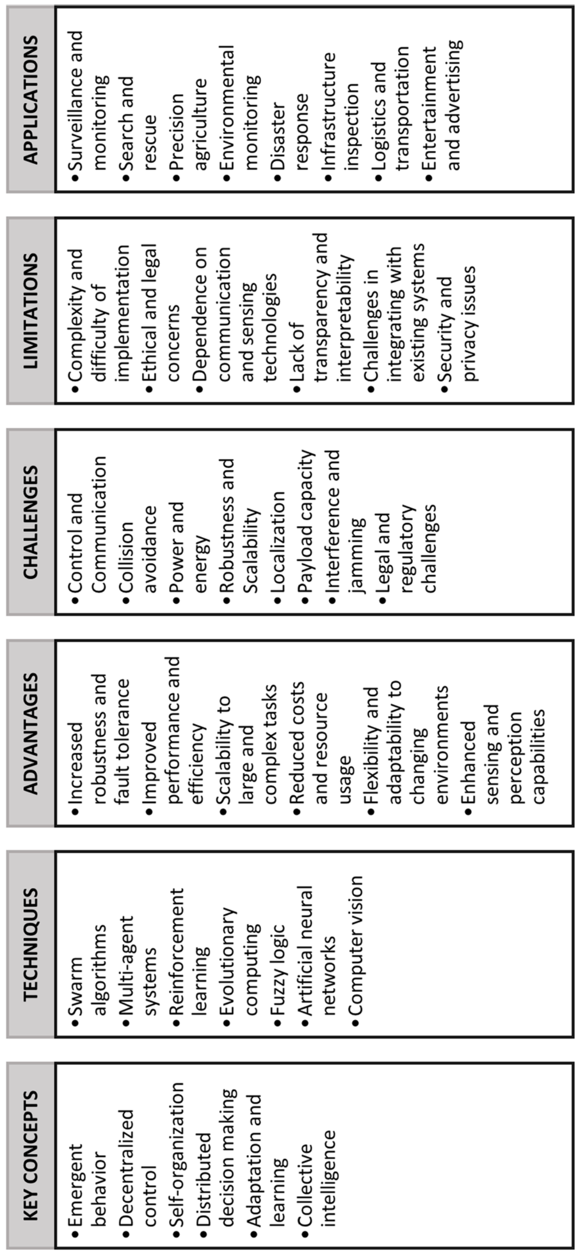

Fig. 5 Incorporating SI into flying robots

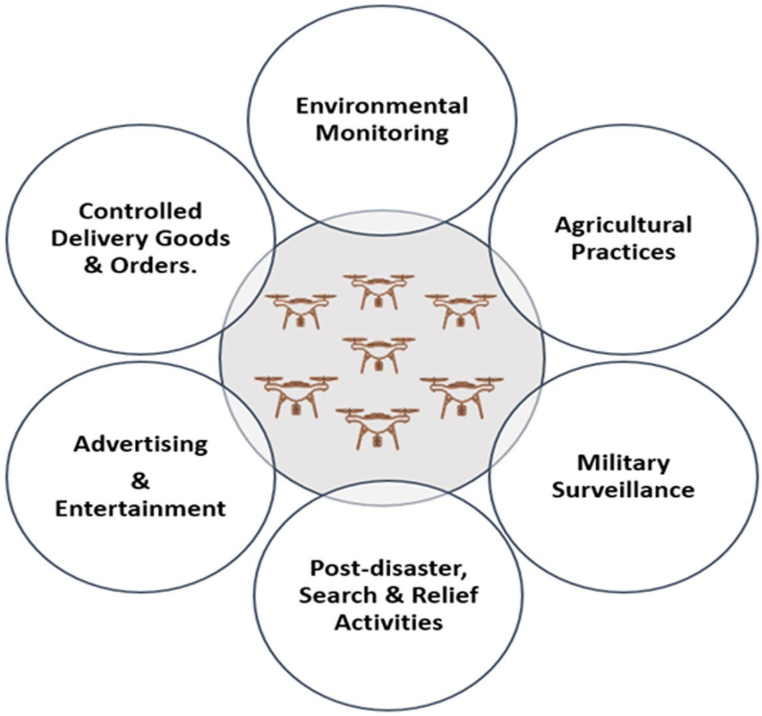

Fig. 6 Application areas of UAV swarms

[54]. Wildlife conservation efforts also benefit from UAV swarms, as they can monitor animal populations and track poaching activities with minimal human intervention. Infrastructure inspection is another critical area, where UAV swarms can inspect bridges, pipelines, and power lines, identifying issues quickly and accurately.

- **Delivery Services**: In logistics and delivery services, UAV swarms can deliver packages quickly and efficiently, reducing delivery times and costs [7]. Medical supply transport is another promising application, where UAV swarms can deliver essential supplies to remote or disaster-affected areas, ensuring timely medical assistance. UAV swarms also play a crucial role in emergency response scenarios, where they can transport equipment and supplies to rescue teams in dangerous or inaccessible locations.
- **Search and Rescue Operations**: In post-disaster scenarios, UAV swarms can be deployed for SAR operations, where they assist rescuers in quickly reaching dangerous or inaccessible areas. By providing real-time aerial imagery and data, UAV swarms enhance the effectiveness of rescue missions, potentially saving lives [55].
- **Entertainment and Events**: UAV swarms have found innovative uses in entertainment and events. Drone light shows, where multiple drones fly in coordinated patterns to create visual spectacles, have become popular attractions. Additionally, UAV swarms are used in advertising, where they can display logos and messages in the sky, creating unique and eye-catching promotions [7].

Military applications

UAV swarms are highly effective in military surveillance and reconnaissance missions. They can conduct border patrols, monitoring large areas and providing real-time intelligence on potential threats [56, 57]. UAV swarms can also perform reconnaissance operations, gathering crucial data on enemy positions and movements, thus enhancing situational awareness.

In combat support roles, UAV swarms can assist in target identification and tracking, providing accurate and timely information to ground forces. They can also be deployed for electronic warfare, jamming enemy communications and disrupting their operations. UAV swarms' ability to operate in coordinated formations makes them ideal for executing complex missions with high precision and efficiency [58].

In military logistics, UAV swarms can be used to transport supplies and equipment to frontline troops, ensuring a steady flow of resources. Their ability to operate autonomously and cover large areas makes them ideal for supply chain management in challenging environments [58].

These diverse applications of UAV swarms highlight their potential to revolutionize various industries by improving efficiency, reducing costs, and enhancing safety and effectiveness in both civilian and military contexts.

Challenges, limitations and future directions

To successfully achieve the promising applications of using multiple robotics systems for complex tasks, robust solutions to various challenges are required, as shown in Fig. 7. These challenges can be classified into traditional and advanced categories. Traditional challenges include environment perception, simultaneous localization and mapping (SLAM), path planning, dynamically feasible trajectory generation [59], navigation, and autonomy. Advanced challenges encompass task allocation, motion coordination, and the design of algorithms that effectively consider completeness, computational scalability, planning time, and optimality [6]. Table 6 summarizes the challenges, limitations, and future directions in UAV swarms, providing a clear and organized overview of each aspect.

Heterogeneous swarms and ethical considerations

Exploring the use of heterogeneous swarms, consisting of robots with diverse capabilities and sensors, presents opportunities for specialized and efficient task allocation. Integrating emerging technologies like blockchain and the Internet of Things (IoT) will facilitate secure communication and coordination among swarm robots [60]. Additionally, ethical implications, especially in surveillance applications, must be carefully examined to ensure responsible and ethical use of UAV swarms.

Energy efficiency and algorithm development

The implementation of SR in flying robots poses challenges related to energy efficiency and algorithm development. Control algorithms capable of handling the complexity of large swarms are essential for efficient swarm functioning [11]. Advances in AI, ML, and DL have significantly impacted the development of SR, enabling

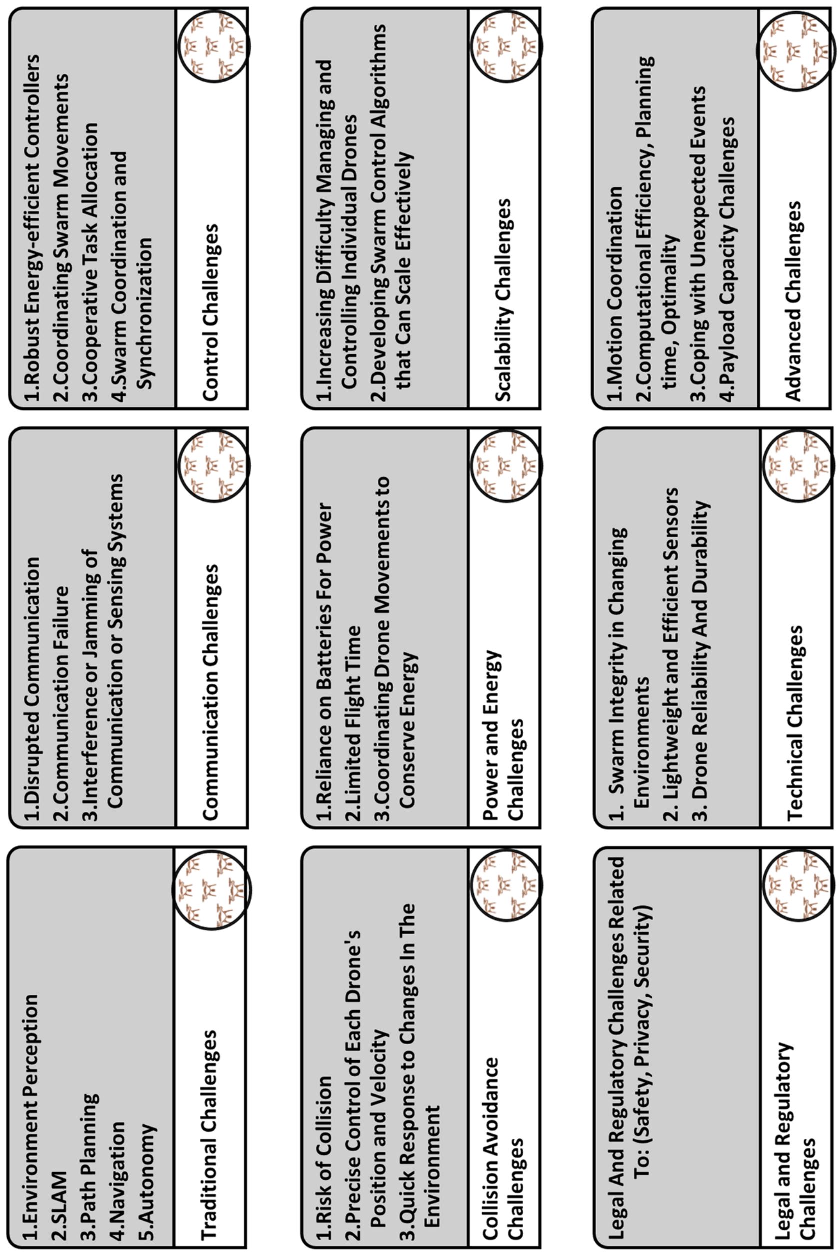

Fig. 7 Challenges in implementing swarm robotics for flying robots

Table 6 Challenges, limitations and future directions in UAV swarms

Challenge/ limitation	Description	Future directions
Heterogeneous Swarms and Ethical Considerations	Utilizing robots with diverse capabilities and addressing ethical implications in surveillance applications.	Integrate emerging technologies like blockchain and IoT, and ensure responsible, ethical deployment of UAV swarms.
Energy Efficiency and Algorithm Development	Addressing energy efficiency and developing control algorithms for large swarms.	Focus on creating energy-efficient algorithms to enhance operational endurance and leveraging AI, ML, and DL for improved capabilities.
Autonomous Control and Task Allocation	Cooperative task allocation and coordinated motion are essential for fully autonomous control over complex environments.	Integrating AI/ML based algorithms to enhance the efficiency and adaptability of UAV swarms.
Communication and Coordination	Ensuring effective communication among swarm agents, especially as the swarm size increases exponentially.	Utilizing the 6G technology to develop decentralized and robust communication protocols to maintain swarm autonomy and ensure efficient, reliable data exchange.
Robustness and Scalability	Developing stable, efficient algorithms for task allocation, path planning, and motion coordination.	Enhance robustness and scalability of algorithms to handle dynamic and unpredictable environments.
Synchronization and Environmental Disturbances	Achieving coordination and synchronization among drones while maintaining integrity amidst environmental disturbances.	Create adaptive control strategies that respond to dynamic environmental changes and disturbances.
Security and Safety	Ensuring effective communication and coordination while maintaining the security of the swarm.	Explore secure communication methods and develop algorithms to detect and mitigate potential security threats.

autonomous decision-making, improved object recognition, obstacle detection, and optimized flight paths [15]. Future research should focus on creating energy-efficient algorithms that enhance the operational endurance of UAV swarms.

Autonomous control and task allocation

The rapid development of UAV technology has led to new interests in autonomous control for teams of flying robots over complex environments. Fully autonomous control involves cooperative task allocation and coordinated motion to achieve specific goals [61]. Furthermore, the control mechanisms of UAV swarms can be strengthened by utilizing robust control strategies developed for underactuated and highly nonlinear systems operating in uncertain and disturbed environments [62–64]. The coordination and navigation capabilities of UAV swarms can also be enhanced by incorporating guidance optimization techniques and target tracking approaches which will significantly expands their application areas [65, 66]. Dividing tasks into smaller sub-tasks distributed among the robot team ensures mission requirements are met efficiently. Future research should focus on utilizing AI/ML based techniques to elevate swarm decision-making capabilities and thus develop more sophisticated algorithms for task allocation and autonomous control that enhance the efficiency and adaptability of UAV swarms.

Communication and coordination

One significant challenge in SR is ensuring effective communication between swarm agents. As the number of agents increases, the required communication grows exponentially [40]. Reliable communication systems among drones are crucial, especially in unexpected situations like equipment failure.

Future research in UAV swarm communication should focus on enhancing network scalability and robustness. One promising direction is the integration of 5G, 6G and beyond-6G technologies, which offer high data rates, low latency, and improved reliability [67, 68]. Additionally, the use of decentralized communication strategies, such as blockchain-based networks, can enhance security and reduce the risk of single points of failure.Furthermore, incorporating AI and ML techniques can optimize communication protocols and adaptively manage network resources based on real-time data. This can lead to more efficient bandwidth utilization and improved overall network performance, enabling UAV swarms to operate more effectively in complex missions [69].

Robustness and scalability

Developing stable and computationally efficient algorithms that handle basic swarm behaviors like task allocation, path planning, motion coordination, and dynamically feasible trajectory generation is vital [70, 71]. These algorithms should allow UAV swarms to collaborate, avoid collisions, and optimize performance. Future work should aim at enhancing the robustness and scalability of these algorithms to handle dynamic and unpredictable environments [35].

Synchronization and environmental disturbances

Achieving coordination and synchronization among drones while maintaining swarm integrity in the face of environmental disturbances is another major challenge [72, 73]. Developing robust and energy-efficient control algorithms, designing lightweight and efficient sensors, and improving the reliability and durability of drones are necessary. Future work should aim at creating adaptive control strategies that can respond to dynamic environmental changes and disturbances.

Security and safety

In addition to technical challenges, security and safety must be addressed in SR. Ensuring effective communication and coordination while maintaining swarm security is crucial [40]. Future research in this area should aim to enhance the security and privacy of UAV swarms by developing advanced threat detection and mitigation strategies. AI and ML can play a significant role in identifying and responding to security threats in real-time. Additionally, exploring the use of quantum cryptography may provide unprecedented levels of security for communication within UAV swarms. Moreover, interdisciplinary collaboration between cybersecurity experts, UAV developers, and policymakers is essential to create comprehensive frameworks that address both technical and ethical aspects of security and privacy in UAV swarm operations. This holistic approach will help ensure that UAV swarms can be deployed safely and responsibly in a wide range of applications [61].

Conclusions

The field of swarm robotics has witnessed remarkable progress, particularly in the context of flying robots. UAV swarms offer a unique and efficient approach to tackling complex tasks by harnessing the collective power of multiple robots working in harmony. This paper has provided an insightful exploration of various aspects of swarm robotics applied to flying robots, shedding light on critical features, core algorithms, and their real-world applications. The current state of research in swarm robotics for flying robots has demonstrated promising advancements with significant potential for various industries, such as agriculture, SAR, environmental monitoring, and infrastructure inspection.

Challenges in communication, control, and scalability have been identified and examined to show how the decentralized algorithms and AI/ML base techniques can effectively address them. These developments have contributed to the creation of more intelligent and autonomous UAV swarms, capable of navigating complex environments and performing intricate tasks with precision. Continued research is necessary to unlock the full potential of SR in flying robots, focusing on robust control algorithms, adaptive formation changes, and energy efficiency. Integrating advanced and energy-efficient AI and ML techniques will elevate swarm decision-making capabilities, while ethical considerations must guide the responsible deployment of UAV swarms. By embracing interdisciplinary collaboration and innovation, we can enhance the adaptability and intelligence of UAV swarms, empowering transformative advancements in diverse domains. This ongoing research will ensure that UAV swarms continue to evolve, addressing current challenges and exploring new opportunities for application and impact.

Abbreviations

AI	Artificial Intelligence
DL	Deep Learning
DOF	Degrees of Freedom
HA	Hungarian Algorithm
IoT	Internet of Things
LAP	Linear Assignment Problem
ML	Machine Learning
MANETs	Mobile Ad hoc Networks
MRS	Multi-Robot Systems
R2R	Robot-to-Robot
SAR	Search and Rescue
SI	Swarm Intelligence
SLAM	Simultaneous Localization and Mapping
SR	Swarm Robotics
UAV	Unmanned Aerial Vehicle

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