# Collaborative Control Technology and Mission Execution Capability of the Swarm Drone System

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**Abstract.** This paper explores the Swarm Drone System (SDS), focusing on core cooperative control technologies (e.g., Boids model, distributed vs. centralized systems) and key applications like aerial detection, reconnaissance, and logistics. Case studies, such as DARPA's OFFSET project and urban delivery pilots, highlight SDS's efficiency and versatility. Future directions include enhanced autonomy, adaptive communication, and multi-platform collaboration to advance swarm capabilities.

**Keywords:** Swarm Drones Control System, Swarm Drones, UAV

## 1 Introduction

With the development of Drone Technology and related Lightweight Electronics and Sensor Technology, Drone starts to move in the direction of low cost and miniaturisation. Meanwhile, with the widespread application and advancement of microprocessors, high-precision navigation and communication modules, the perception, communication, and computing ability of drones are greatly enhanced. This development trend reduces the costs of drones and expands drones' range of applications in real-world scenarios. Make the major Countries realise the vast application prospects of their related technologies and start investing in Drone technology-related projects.

As early as 2000, the U.S. military first proposed the concept of the SDS and provided a systematic definition of SDS [1]. SDS refers to a system composed of multiple small drones that operate collaboratively under the coordination of the same system, achieving the multi-drone collaborative task planning and decision making under a complex environment, environmental perception and analysis, control and real-time auto avoidance [1].

The SDS technology, with its high flexibility, redundancy and strong task adaptability, shows its vast application prospects in several critical fields. For example, in military use, SDS can be used for target reconnaissance and strike, reducing the personnel casualties and enhancing the combat effectiveness. In firefighting and disaster relief, SDS can assist rescue personnel in doing the disaster assessment, rescue,

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and delivery of emergency supplies to affected areas. Additionally, SDS can also be used in logistics, transportation and distribution, and environmental data collection.

For all, the SDS offers such vast application value, but it is still facing several technical challenges in development and application. First, the core of the SDS is the cooperative control system. To achieve collaborative and intelligent operations and task execution of swarm drones, a stable control framework and a reliable communication network are necessary. However, current swarm control systems and low-latency, high-interference-resistant communication protocols are still under development, which limits the deployment and application of SDS in complex, dynamic environments. Furthermore, for SDS applications, the system's autonomy, stability and mission execution efficiency still need further development. This ensures that even if facing complex environments and electronic interference, the SDS's decision-making accuracy and system responsiveness are reliable and timely. This issue is currently a major focus of technical research.

To promote the further development of the SDS, efforts can be made at the individual drone level and system level for optimisation and breakthroughs. First, at the individual drone level, integrating more sensors into it to break the functional limitations of single drones. It will enhance the drone's perception ability, task adaptability, and environmental interaction, thereby overcoming functional bottlenecks in different mission executions. Furthermore, at the system level, research on the cross-cluster collaboration mechanism of multiple SDS should be prioritised. Establishing an efficient data-sharing and collaborative decision-making framework will enable multiple SDS systems to interact and cooperate intelligently, providing the technical foundation for large-scale mission execution. Creating an efficient data sharing and collaborative decision-making framework will enable multiple SDSS to interact and cooperate intelligently, providing the technical foundation for large-scale mission execution.

## 2 The Fundamental Compositions of the Swarm Drone System

The SDS, as a system composed of many small drones working collaboratively, has a basic composition of the SDS includes the performance modules of individual drones and the communication and network structure. The Fundamental compositions of the SDS are briefly discussed in this section.

### 2.1 The Performance Parameters and Collaborative Architecture of Individual Drone

Each drone, though small the size is small, still needs to be equipped with various key performance modules as the basic execution unit of the swarm system, ensuring its ability to operate independently and collaborate in complex environments. The key structure mainly includes the Communication module, Navigation module, Flight control module and Payload module. The Communication module aims to achieve the communication of the individual drone between other drones and control centre, support the short-range wireless communications (Wi-Fi, ZigBee) and long-range communication (LTE, 5G); For Navigation modules such as GPS and RTK-GPS are commonly used, combined with inertial navigation (IMU) to improve positioning accuracy, providing a foundation for task planning and attitude control. The flight control module is Responsible for flight attitude adjustment, path tracking, and trajectory control. The flight control system is the core component for achieving stable flight and precise manoeuvring. For payload modules, different payload modules are integrated according to application scenarios, such as cameras, thermal imagers, sensors, and supply drop devices.

In terms of collaboration architecture, the SDS can be divided into two basic structures: task requirements and system design.

For designing the Self-organising swarm: Every individual drone makes decisions based on local perception and distributed algorithms, without central control, only communication between local drone to drones [2]. Therefore, the drone which uses this self-organising system composes a strong and flexible system, enhancing the ability to cope with uncertainty, errors, local disturbances, and the failure or loss of a few individual units.

For Command-driven swarm: Rely on a control unit for task assignment and status feedback. Each drone executes tasks based on the received commands, offering high control precision and making it suitable for scenarios that require a high degree of global consistency.

## 3 Collaborative Control Technology of Drone

Section 2, which discusses the performance parameters and communication network structure of individual drones, provides the fundamental capability required for the SDS to operate effectively.

However, to achieve the full ability of SDS, it is important to discuss the collaborative control technology of the drone.

The collaborative control technology of drones by simulating the natural collective intelligence (the swarm behaviour of bees and birds), integrating with a DCS and artificial intelligence methods, is restructured for fluent the efficient and autonomous collaboration in swarm drones.

### 3.1 Rule-based Control Technology (Boids Model)

Boids Model was a distributed behavioural model which was developed by Craig Reynolds in the 1980s. Originally developed for simulating flocking behaviour in bird swarms. The Boids Model operates based on three fundamental rules, the first is the Separation, which aid in drone-to-drone collision avoidance; the second is the alignment, which ensures the drone moves toward the heading of the swarm; the third is the cohesion, which guide the drone toward the average position of its neighboring drones.

In an individual drone swarm, the motion equations of an individual drone within a two-dimensional plane can be described as follows [3]:

$$\begin{cases} x_i = v\cos(\theta_i) \\ y_i = vsin(\theta_i) \\ \theta_i = \frac{\eta}{V} \end{cases} \tag{1}$$

In these equations, xi and yi refer to the x-axis and y-axis coordinates of the drone, and θi refers to the drone's heading angle. V is the drone's velocity, and $\eta$ corresponds to its acceleration.

For Cohesion: Following the cohesion principle, each drone i navigates toward the centroid of its neighboring agents' positions, maintaining swarm aggregation. This behavior is formally expressed as [3]:

$$\theta_{Ci} = \frac{\arctan\left(Y_{C_{p,i}} - y_i\right)}{X_{C_{p,i}} - x_i} \tag{2}$$

$(X_{C_{p,i}}, Y_{C_{p,i}})$ is the drones' centroid in sensor range.

For separation: In accordance with the separation rule, each drone i is required to maintain a minimum safe distance from nearby agents. The corresponding repulsion vector is determined by the following equation [3]:

$$\theta_{Si} = \frac{\arctan\left(y_i - Y_{C_{d,i}}\right)}{X_{C_{d,i}} - x_i} \tag{3}$$

$(X_{C_{d,i}}, Y_{C_{d,i}})$ is the drones' centroid in safe distance range.

For alignment, each drone matches its direction and speed with its neighbouring drones to maintain the same trajectory. For each drone i, the alignment rule is defined as:

$$\theta_{Ai} = (1/n_i)\sum_{j=1}^{n_i} \theta_j \tag{4}$$

$\theta_j$ is the heading angle of the j-th drone.

By implementing the Biods Model, drone swarms can achieve coordinated collective behaviour while minimising collision risks, demonstrating advantages such as computational efficiency, strong real-time performance, and low resource requirements. These characteristics enable large-scale, stable deployment and operation of drone clusters in resource-constrained environments. However, this model also presents limitations, including relatively fixed operational rules, difficulties in adapting to complex dynamic environments, and inadequate autonomous response to emergent situations. To address these constraints, current research predominantly focuses on integrating dynamic weight adjustment technologies, such as environment-adaptive rules and intelligent behavioural decision-making mechanisms. This integration is expected to significantly enhance the operational efficiency and anti-interference capabilities of drone swarms.

### 3.2 DCS (Distributed Control System) VS Centralised Control System (CCS)

For a drone swarm, a stable control system is indispensable. Therefore, establishing an infrastructure-independent drone network with a simple, resilient, and optimal control system design remains a challenging and open problem. To address this issue, there are currently two relatively mature solutions: DCS and CCS.

**Define genealogical and theoretical boundaries**. DCS and CCS represent two fundamental architectures in intelligent decision-making frameworks. DCS operates based on local information, enabling autonomous decision-making without relying on a central node. Such systems are typically applied in scenarios like coordinated electronic warfare and swarm saturation attacks. In contrast, CCS rely on a central node to perform global optimisation and command distribution, making them suitable for complex tasks such as urban air traffic management and search-and-rescue missions. Theoretically, the scalability of DCS is constrained by the network diameter, while CCS is limited by computational complexity. In terms of optimality, DCS generally achieve only local Nash equilibrium, whereas CCS can reach global Pareto optimal solutions. From a communication perspective, DCS are bound by Shannon-Hartley theorem constraints, while CCS require adherence to the Nyquist sampling rate. These distinctions highlight the trade-offs and application boundaries between decentralised and centralised control strategies [4].

**Technological evolution and paradigm shift**. The development trajectories of DCS and Centralised Control Systems (CCS) reflect distinct technological milestones. For DCS, a key breakthrough occurred in 2006 with the first engineering application of consensus algorithms in drone formation control, demonstrating the feasibility of decentralised coordination. In 2018, the integration of blockchain technology further advanced DCS by enabling secure and reliable distributed trust mechanisms. In contrast, CCS has seen significant innovations aimed at enhancing centralised optimisation. In 2021, the adoption of quantum annealing algorithms marked a pivotal advancement in accelerating global optimisation processes. By 2023, the incorporation of digital twin technologies will allow for real-time centralised control, improving the responsiveness and precision of CCS in dynamic environments. These developments underscore the evolving capabilities and complementary roles of DCS and CCS in modern control systems.

**Frontier fusion direction and the challenge faced**. The current development of drone swarm control technology shows a significant trend of interdisciplinary integration, driving comprehensive system performance improvements through the integration of advanced technologies from multiple fields. This integration is mainly reflected in the following aspects.

Operations Research-driven Hierarchical Optimisation Control.

Coo W J et al. argue that the mission planning problem for drone swarms constitutes a combinatorial optimisation of complex systems, proposing to address such challenges through hierarchical control methods from an operations research perspective [5]. Propose a three-layer control architecture based on operations research theory.

The first layer is the Execution Layer (Millisecond-level): Utilise model predictive control to complete local trajectory optimisation. The second layer is the Tactical Layer

(Minute-level): Implement distributed negotiation based on game theory. Finally, there is the Strategic Layer (Hour-level): Use integer programming for global task allocation.

This approach achieved a 30% reduction in energy consumption in logistics delivery simulations [5].

Breakthroughs in Bio-inspired DCS . Researchers designed the low-cost Kilobot robot, which supports collaborative functions such as foraging and formation, and conducted thousands of swarm demonstrations, successfully scaling up to a swarm of over a thousand robots [6]. This demonstrates the potential and feasibility of using ant colony behaviour logic for swarm cooperation in the future.

CCS (Cloud-Native Centralised Control) Evolution

Similarly, for CCS, the introduction of Kubernetes orchestration for elastic control containers can significantly enhance the resilience, scalability, and efficiency of the swarm. Additionally, Google Research's federated learning-enhanced privacy-preserving scheduling allows for collaborative learning and scheduling between drone swarms, while ensuring that the local data of each drone remains private, thus enhancing the security and anti-jamming capabilities of the drones.

## 4 Analysis of the Swarm Drone mission ability

Based on the basic understanding of the capabilities of individual drones and the cooperative control mechanism in section 2, section 4 discusses the classical mission scenarios, such as aerial detection and reconnaissance, as well as multi-point delivery operations, demonstrating how SDS utilises its collective intelligence and strong fault-tolerant capabilities to complete complex tasks.

With the rapid development of drone technology, SDS have demonstrated significant advantages in complex mission scenarios due to their high parallelism, strong robustness, and collaborative intelligence. Different from traditional single drones or drone formations, SDS depends on its collective coordination and autonomous decision-making abilities to efficiently accomplish long-range, highly dynamic tasks such as disaster monitoring, precision agriculture and military attack. For all, its task execution capabilities largely rely on key technologies such as dynamic obstacle avoidance, swarm coordination, and self-repair mechanisms, the progress of which directly determines the practical effectiveness of SDS. Currently, research on swarm drones has gradually shifted from theoretical exploration to real-world implementation, yet it still faces numerous challenges.

The first challenge lies in achieving adaptability to dynamic environments, which involves developing efficient path planning algorithms and ensuring real-time obstacle avoidance in unknown or rapidly changing conditions. The second challenge concerns system fault tolerance, requiring rapid reconfiguration of formations and timely task reassignment in the event of partial node failures. The final challenge involves the optimisation of swarm coordination, focusing on collision avoidance and efficient task allocation during high-density flight operations [7].

**Fig. 1.** The SDS mission ability. (Original)

This section will provide a comprehensive review of the Typical Task Scenario and Swarm Self-Healing and Task Reallocation mechanisms, analysing the strengths and limitations of existing technologies (Figure 1). It will also explore future research directions, aiming to offer a systematic reference for academic research and technological applications in this field.

### 4.1 Typical Task Scenario

SDS demonstrate unique advantages across various application domains due to their inherent characteristics of parallel operation, distributed coordination, and robust fault tolerance. This section analyses two representative mission scenarios that highlight the capabilities of SDS in real-world applications.

**Aerial detection and reconnaissance**. In environmental monitoring, disaster response operations such as forest fire surveillance, and military reconnaissance operations. SDS exhibit superior performance compared to single-drone solutions. The key advantages include the Long-range cover: By using the SDS, with up to 65% speed up for a single drone and a 40% increase in explored area for the same mission time [7].

Error tolerance: The distributed nature ensures mission continuity even with individual drone failures. And adaptive sampling: Dynamic task allocation enables focused monitoring of high-priority regions.

**Multi-point Delivery Operations**. Precision agriculture applications such as targeted pesticide spraying benefit significantly from swarm capabilities by following ways: Simultaneous operation: 100+ drones can service an entire field in a single coordinated sortie; Precision application: Individual drones can adjust spray patterns based on real-time plant health data; Efficiency optimization: Distributed algorithms minimize redundant coverage [8].

Field tests by reference 1, compared with the traditional method, the SDS provides a more efficient method in field coverage and weed mapping.

### 4.2 Swarm Self-Healing and Task Reallocation

Mechanism Swarm self-healing and task reallocation mechanisms are core mechanisms for SDS, because under the complex dynamic-task environment, the drone, which is a part of the SDS, will be strongly interference with. That's cause the drone loses communication with the SDS or breaks away from the swarm. So, establishing reliable Swarm self-healing and task reallocation mechanisms is are unmissable part of the SDS [9]. To establish these mechanisms, current research major focus on a method based on a reliable assessment of multi-layer complex network missions [9]. This method includes four steps:

First, Unit reliability prediction based on prevention: Predict drone health based on historical data and sensor information such as battery attenuation and vibration spectrum. Next is maintaining grouping policies and costs: Analyse whether the environmental communication conditions can meet the preset drone swarm grouping scale and adjust it to meet the stable operation of the drone swarm while maintaining a relatively low cost. Then is the Mission reliability assessment: The autonomous system evaluates the mission content, the surrounding environment and human factors, and sets backup plans for drone swarms and presets relay or backup mobile drone communication nodes. Finally, it is optimising grouping decisions: Minimise the scale of the drone swarm, optimise the grouping strategy of the cluster, reduce redundancy and decrease the system load.

For further development, emerging technologies such as cross-platform collaboration between drones and unmanned ground vehicles (UGVS), biomimetic strategies inspired by beehive regrouping mechanisms, and anti-electronic interference systems are expected to significantly advance the swarm's self-healing and task reallocation capabilities. These innovations will enhance the robustness, adaptability, and autonomy of swarm systems in complex operational environments.

## 5 Engineering Case Studies and Application Analysis

This section will mainly focus on the application of the SDS in the real environment.

### 5.1 OFFSET: Offensive Swarm-Enabled Tactics

This project was started by DARPA in 2017, aiming to develop a system with 250 small, unmanned aircraft systems (UAS) to cooperate with the unmanned ground systems (UGS) to accomplish several missions in complex city environments. This project verified the feasibility of the low-cost drone's sea tactics and developed the frequency hopping + MIMO antenna array technology to achieve the anti-interference communication between the drone and the SDS [10]. The most significant achievement of this project is the 92% self-repair success rate in a complex architectural environment [11].

## 5.2 The Swarm Drone Logistics System Pilot Program in Chinese cities

The most famous development case of the urban logistics swarm drone system in China is the "Low-altitude Logistics Corridor" initiative, which was launched by JD Logistics and SF Express in 2022. It has been implemented across 5 pilot cities in China: Hangzhou, Shenzhen, Chongqing, Nanjing and Chengdu. By using the 5 G-based Unmanned Traffic Management (UTM) system, the development group of this project employs 3 specialised drone swarms for collaborative operations.

In collaborative drone operations, three specialised swarm types are commonly employed, each tailored to distinct functional roles and operational scales. Large delivery drone swarms, accounting for 15% of deployments, are primarily designed for transporting bulky cargo and conducting trunk-line logistics. Medium multi-rotor drone swarms, which represent the majority at 60%, are optimised for last-mile delivery tasks within community and urban settings, balancing agility and payload efficiency. Meanwhile, micro monitoring drones comprise 25% of the swarm configuration and are equipped with real-time path detection and station status inspection capabilities, contributing to situational awareness and system responsiveness. This layered composition facilitates efficient, scalable, and resilient drone-based logistics systems.

**Fig. 2.** Medium multi-rotor drone swarm (Original)

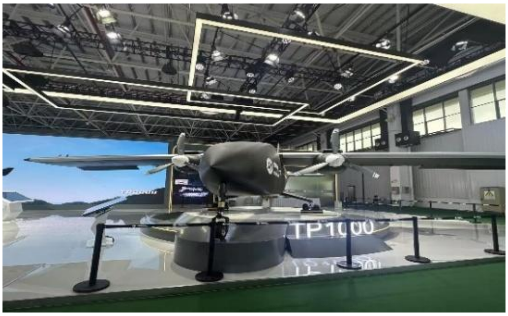

**Fig. 3.** Large delivery Drone swarm (Original)

As shown in Figures 2 and 3, in the Shenzhen pilot zone (June 2023), the system achieves a daily record throughput of 1200 orders, and at the same time, it creates a 38% reduction in operational costs compared to traditional delivery methods.

This project has significantly advanced urban logistics development, facilitating the cooperation between government and companies on establishing a "Digital Airspace" platform, enhancing the efficiency and scalability of government airspace approvals. As for the safety issue of drone swarms in urban areas, this project has proposed pioneering solutions such as sound and light alerts and ADS-Broadcast positioning.

### 5.3 Military application of the Swarm Drone system

Since the outbreak of the RU-UA conflict in 2019, over the past 6 years, the importance of drones in warfare has continued rising, with both sides having deployed more and more drones on the battlefield. In the early stage of the conflict, the drones used by both armies were primarily single, civilian drones with simple modifications or rudimentary FPVS assembled by soldiers at the frontlines. These drones are facing an inability to perform complex missions, poor anti-jamming capabilities, reconnaissance blind spots, and ineffectiveness against heavily armoured targets. However, the change began when Russia first deployed the loitering munition swarms like the “Lancet” on the battlefield.

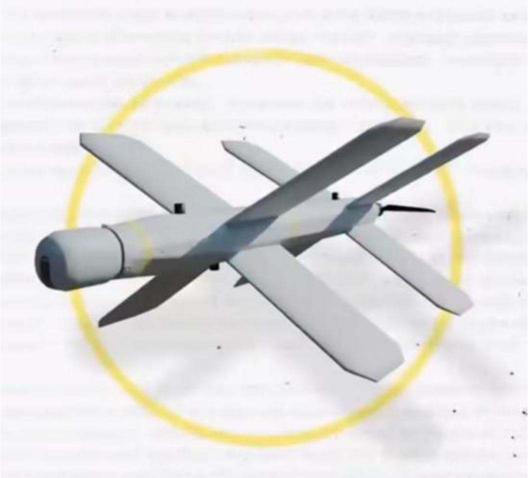

**Fig. 4.** Lancet (Original)

As shown in Figure 4, these drone swarms addressed many of the early limitations and marked the emergence of UAV swarms as a significant force in modern combat [11]. With both sides beginning to achieve increasing success through such drone swarms on battlefields, countries around the world have also turned their attention to researching and developing their swarm drone systems.

The widespread use of drone swarms shows its asymmetric advantages and autonomous capabilities, which change the rules of modern warfare. It plays an unmissable role in several operational domains, including area reconnaissance, electronic warfare, saturation attacks, and communication relays. Its deployment on the battlefield has also driven technological innovation. For example, to enhance autonomous decision-making, systems have incorporated the OODA (Observe–Orient–Decide–Act) loop and edge AI processors. Meanwhile, technologies such as fibre-optic control, frequency-hopping spread spectrum (FHSS), and very high frequency (VHF) control have significantly improved anti-jamming performance.

At present, major military programs such as Project Replicator (USAAF) and the Loyal Wingman Program (PLAAF) represent the forefront of global swarm drone development and signal the possible directions this technology may take in future military operations.

## 6 Conclusion

The rapid evolution of the swarm drone system (SDS) underscores a transformative shift in unmanned aerial vehicle (UAV) technology, Its simplicity is the collective intelligence, distributed control and robust mission adaptability. Through systematic discussions on single-drone performance modules, communication network structures, and advanced collaborative control mechanisms, SDS has demonstrated highly promising technical potential and possesses extensive application value across various fields.

From the theoretical basis, such as the Biods model to the DARPA Offset program, the Chinese urban logistic pilot zone, the SDS development tracking not only shows the growing maturity but also real-world feasibility. The systems have shown superior performance in performing complex tasks such as adaptive reconnaissance, multi-point deployment and self-healing coordination under jamming, thereby addressing the limitations of traditional single unmanned aerial vehicle (UAV) operations.

However, the future of SDS development will likely focus on 3 core directions: first, enhanced autonomy and adaptability through real-time environmental perception and machine learning; second resilient swarm communication through hybrid networks and redundancy mechanisms; and finally, standardized frameworks for multi-platform collaboration, enabling SDS to integrate seamlessly with other unmanned systems (UGVs, USVs) in coordinated missions.

In summary, SDS holds the ability to redefine the operational landscape across military, logistical, environmental, and disaster-response domains. By addressing the core technological gaps of it and embracing interdisciplinary innovation, SDS can become the foundational infrastructure for the next generation of autonomous systems.

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