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Main Concepts in the Control of Swarm Drones

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Abstract

Unmanned Aerial Vehicles have brought new opportunities in the security, efficiency and precision of aerial operations. Their application areas include military, search and rescue operations, perimeter security, environmental monitoring etc. The UAVs have proved to be useful in many operations and lately they are being utilized as groups to extend their capabilities. Swarm drones utilize the drones as a group of nodes that can communicate and collaborate with each other to realize the given mission. The use of drones as a group helps to overcome the problem of single point of failure while improving efficiency and scalability. Although swarm drones offer so many advantages, there are several challenges to be addressed to enable successful utilization of them. Depending on the UAV type, a corresponding network architecture, formation strategy and formation control method should be provided. To apply swarm drones on a large scale there are still some areas that need to be researched and improved. The paper aims to realize qualitative bibliometric analysis in the topic, cover main technical concepts and do comparative analysis of different approaches in different scenarios.

Keywords: UAV, swarm, drone, AI, computer vision, formation control.

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Dron qruplarının idarə olunmasının əsas konsepsiyaları

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Xülasə

Pilotsuz uçuş aparatları hava əməliyyatların təhlükəsizliyi, səmərəliliyi və dəqiqliyi üçün yeni imkanlar açmışdırlar. Onların tətbiq sahələrinə hərbi, axtarış və xilasetmə, perimetr təhlükəsizliyi, ətraf mühitin monitorinqi və s. daxildir. Bir çox əməliyyatlarda faydalı olan PUA-lar son vaxtlar bacarıqlarını artırmaq üçün qrup şəklində istifadə olunurlar. Dron qrupu verilən tapşırığın icrası üçün bir-biri ilə əlaqə qura və əməkdaşlıq edə bilən fərdi dronlardan ibarət olur. Dronların qrup şəklində istifadəsi bir komponentdən güclü asılılıq problemini aradan qaldıraraq effektivlik və daha böyük miqyasda tətbiq edilə bilmə bacarığını artırır. Dron qruplarının bir çox üstünlükləri olsa da, onlardan müvəffəqiyyətlə istifadəni təmin etmək üçün bir sıra məsələlərə diqqət edilməlidir. Dron tipinə uyğun olaraq düzgün şəbəkə həlli, düzülüş strategiyası və düzülüş idarəetmə metodu seçilməlidir. Dronlardan qrup halında istifadəni geniş miqyasa gətirmək üçün hələ də araşdırılmalı və həll olunmalı məsələlər mövcuddur. Məqalədə bibliometrik təhlilə əsasən müxtəlif tip pilotsuz uçuş aparatları, onların müxtəlif sahələrdə istifadə xüsusiyyətləri ümumiləşdirilmiş, istismar şəraitindən və tətbiq oblastından asılı olaraq dron sürülülərinin idarə olunması üçün əsas konsepsiyalar müəyyən edilmişdir.

Açar sözlər: pilotsuz uçuş aparatı, dron, süni intellekt, kompüter görməsi, idarəetmənin formalaşdırılması.

Основные концепции управления роевыми дронами

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Аннотация

Беспилотные летательные аппараты (БПЛА) открывают новые возможности в обеспечении безопасности, эффективности и точности воздушных операций. Их применение охватывает широкий спектр сфер: военные задачи, поисково-спасательные миссии, охрану периметра, разведку и патрулирование территории, экологический мониторинг и др. БПЛА доказали свою эффективность в различных операциях, а в последние годы всё чаще используются в составе групп для расширения функциональных возможностей. Управление роем дронов (или роевое управление) представляет собой сложную задачу, включающую координацию множества беспилотных летательных аппаратов, действующих как единая система по модели стаи. Групповое применение дронов помогает устранить зависимость от одного аппарата и повышает общую надёжность системы. Использование нескольких дронов вместо одного обеспечивает более высокую эффективность, особенно в условиях ограниченного времени, что критически важно при выполнении срочных операций. Несмотря на многочисленные преимущества, использование роевых дронов сопряжено с рядом вызовов. Для обеспечения их успешного функционирования необходимо решить вопросы, связанные с выбором подходящего сетевого решения, стратегии развертывания и метода управления. В данной статье обобщаются сведения о различных типах БПЛА, их применении в ключевых сферах, а также рассматриваются основные концепции управления роем дронов. Анализ проводится с учётом условий эксплуатации и области применения, на основе библиометрического исследования.

Ключевые слова: беспилотный летающий аппарат, рой, дрон, искусственный интеллект, компьютерное зрение, формирование управления.

Introduction

Unmanned Aerial Vehicle is an aircraft that operates without a need of a pilot on its cockpit. Usually, a ground control station is used to fly them and command tasks for them to realize. The UAV operator is responsible for the launch of the aircraft, its airborne movement, realization of the tasks and the safe landing of the UAV. Due to potential delays that may arise in the communication between UAV and ground control station, some of these phases are performed automatically or semi-automatically by the UAV itself. Usually, takeoff and landing of the larger UAVs are performed automatically by UAV itself since they are very time sensitive operations and if delay occurs with the communication crash may happen [1]. For smaller fixed wing drones, some help may be needed for takeoff and landing. During takeoff catapults can help to speed up the drones in short period of time (Fig. 1).

Figure 1 – Fixed wing UAV with Launcher [2]

Drones have proved to be useful in several fields including Search and Rescue operations, environmental monitoring, agriculture, military and etc. [3-5]. Search and Rescue operations are among the fields where drones are used widely. In their articles the authors have focused on the optimization of the search algorithms to minimize the time required to find the victim using UAVs [6]. They have emphasized the importance of quality sensory data from UAV for rescue teams. While improving search strategies, the authors also state the idea that other factors like energy constraints, environmental hazards and data sharing between UAVs should also be considered for achieving full potential of UAVs during operation. Considering recent developments in the computer vision technologies, the authors have investigated the use of different CNN detectors for automatic detection of person during SAR operations [7]. High quality dataset plays a critical role in the development of AI based automatic detectors and in [8] the authors have proposed a useful set of 2000 images along with their SSD model.

Agriculture is another field that drones have been utilized in for different purposes. The drones are used in precision agriculture to optimize crop yields and improve efficiency [9]. The authors have reviewed the use of drones for spraying pesticides where human labor is scarce, or manual spraying may cause health issues. Crop monitoring has also been covered by the authors using multispectral camera mounted to the drone. The application of AI based technologies with drones as alternative to satellite images and Unmanned Ground Vehicles have been analyzed by the authors [10]. The authors have achieved accurate crop classification results though the fuse of different UAV related data and deep learning techniques. The authors proposed a unique technique for corn counting method using UAV and RGB camera mounted to it [11]. Their approach utilizes deep learning-based computer vision approaches with data obtained by the UAV to count corn plants.

In the modern world drones are widely used in the military, and soon they will be cheaper alternatives to the expensive combat operation weapons [12]. The use of drones in military operations may be different, like reconnaissance, precision strikes and perimeter security etc. Drones have played crucial roles in recent clashes, but their operational efficiency highly depends on the environment they are used [13]. Although they can operate in dangerous operations without risk to pilots' lives, they may face limitations to answer threats by air defense systems. Fighter jet pilot shows much better capabilities to detect and react to threats to the security of the aircraft.

Generally, main concepts related to swarm drones and potential improvement areas can be considered in the following four directions.

Classification of UAVs

Since there are several types of UAVs that are currently in use, it is crucial to address the question of which platform the swarm formation will be applied on. Mainly, the swarm formation is applied on small platforms like quadrotors. It will be helpful to consider the potential of UAV grouping for much larger platforms like fixed wing UAV's.

The drones can be classified into four groups [14, 15]:

- multi rotor drones
- fixed wing drones
- single-rotor helicopter
- Hybrid – VTOL (Vertical Take-off and Landing)

Multi-rotor drones. Multi rotor drones use their rotors to generate lift force (Figure 2 a). There are several variations of them depending on the number of rotors they have. The most used version of them is the quadcopter which has 4 rotors.

Fixed-wing drones. The fixed wing drone's lift force is generated through its forward motion and the resistance of the wind (Figure 2 b). They are usually controlled through a ground control station by drone operators.

Single-rotor drones. The single-rotor drone consists of one big rotor for its lift force and a small one on its tail to direct the heading (Figure 2 c). They are like actual helicopters in structure and design. Compared to multi rotor UAVs they have higher flying times and can be powered by gas engines.

VTOL. VTOL is hybrid version of UAV that combines the benefits of multi-rotor drones and fixed-wing UAVs (Figure 2 d). When airborne, the UAV turns into a fixed wing drone utilizing its wing and propeller behind to fly.

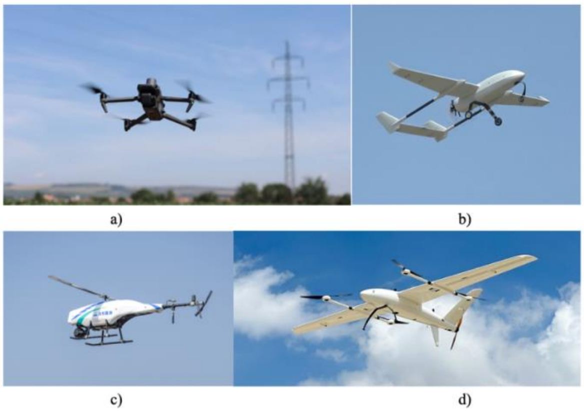

Figure 2 – Different type of UAVs

Formation Control Process for UAV Swarms

Formation control problem is the development and implementation of strategies to manage and coordinate the behavior and movement of the group of drones. The approaches for formation control are of three types.

Centralized - In this approach there is a single command center that processes all data, makes decisions and commands those decisions to the UAVs like ground control stations (Figure 3 a).

Decentralized - UAVs manage themselves through distributed decision-making processes. Each UAV acts based on its own information and pre-defined rules and may be communicating with its neighbors to maintain the formation (Figure 3 b). UAVs act based on their local perception and pre-defined rules without necessarily communicating with others.

Distributed - Each UAV has a certain level of autonomy but communicates closely with other UAV's (Figure 3 b). Different from decentralized, in distributed control each UAV works collaboratively to achieve the collective interest.

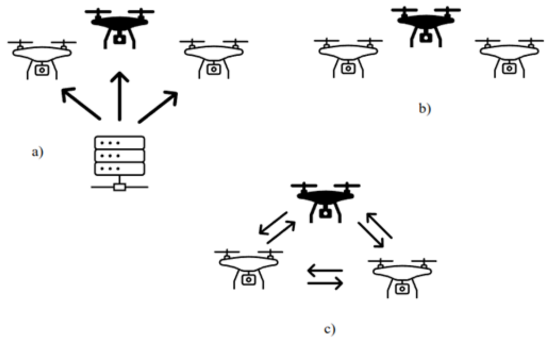

Figure 3 – Drone Formation Control

Formation Strategies for UAV Swarms

For the UAVs to be able to move as a group they must follow a specific formation pattern. Those patterns define the behavior of the group of UAVs as a single entity. For fixed wing drones there are following cooperation architectures.

Leader-follower methods - In this method there are one or several designated leaders and they have followers with predefined rules (Fig. 4). The leaders navigate according to the mission and the followers keep their relative position with respect to their immediate leaders.

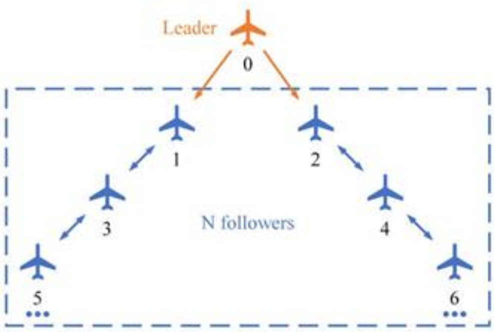

Figure 4 – The communication topology of the leader–follower multi-UAVs

Virtual Structure methods - The UAVs are organized in a virtual structure with each one having its position within the structure. It involves generation of a geometric pattern in which UAVs move as unified entity (Fig. 5).

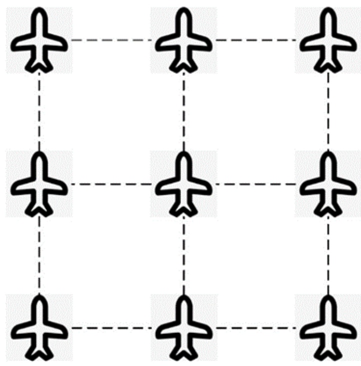

Figure 5 – Virtual Structure

Behavior-based methods - Each UAV makes decisions based on two sources of information. The first one is the information it gets through its sensors about its local surroundings. The second piece of information that each UAV acts upon is the state of its neighboring UAVs. Each drone within the group tries to stay close to the neighbors, avoid collisions and move in the same direction with its neighbors (Fig. 6).

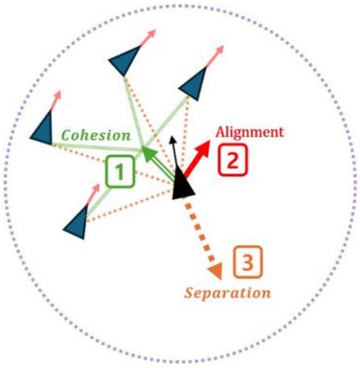

Figure 6 – Behavior Based Strategy

Artificial Potential Field – This approach is inspired by the concept of potential field in physics. The drones in swarm are acting based on the sum of two forces. The first force that acts on the drone is repulsion force. It tries to move the drone away from the obstacles. The second force is an attraction force that tries to force the drone to move towards the goal. The sum of the mentioned forces is the final force that defines the direction of the drone's movement (Fig. 7).

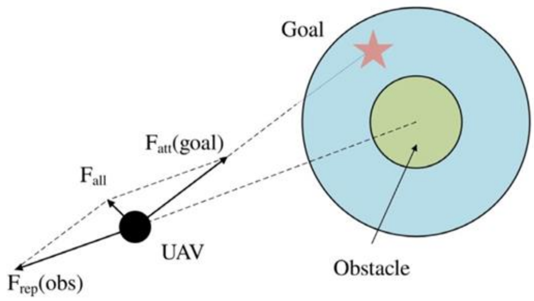

Figure 7 – Artificial Potential Field

<u>Network for UAV Swarms</u>

Generally, the network of the drone swarm can be divided into two categories:

Infrastructure based - In this scenario a ground or air control station is responsible for receiving and processing messages. The station is responsible for controlling the UAVs as well. Currently, the drones are mostly semi-automated which means the swarm completes the tasks under the control of central node. Central node-controlled swarms are useful in fixed-point surveillance and manned-unmanned teaming. The infrastructure-based architecture is more suitable for this scenario.

Flying Ad Hoc Network Architecture – Nodes can join and leave the network dynamically. Central nodes are negligible here and the drones communicate with each other through mutual relay (two or more entities take turns or collaborate in transmitting information).

Actuality of the problem – The use of drones as group and improvement of performance during swarm is among the main issues to address.

Purpose of the work

The paper intends to define main concepts for the improvements in the technical capabilities of swarm drones that are being utilized in different fields.

Problem statement

After thorough literature review about the topic, the following analysis has been carried out about the use of different approaches with swarm drones. Potential improvement areas are presented as well.

<u>Drone classifications</u>

The choice of drone platform to use within swarm platform is the first question to address. Swarm drones are usually applied on small classes of drones like quadcopters. The application of swarm robotics on larger platforms like fixed wing drones offers operational capability in higher altitudes, for longer period. Considering stability and wide use areas, quadcopters and fixed-wing UAVs

Herald of the Azerbaijan Engineering Academy
2025, vol. 17 (4), pp. 18-29
I.M. Ismayilov, I.R. Mirzayev

are further analyzed for use within swarm formations. They are cheap, commonly available and easy to operate. They require no special take-off and landing procedures. Their ability to hover on a specific point airborne gives them ability to maintain the continuous surveillance of precise location. However, they offer very limited operational time, around 1-2 hours. Due to their smaller size, they can carry a very limited amount of payload, usually having only a camera. On the other hand, fixed wing drones offer better operational efficiency and some of them can operate around 24 hours. Their airframe allows them to carry heavier payloads and be stable at higher altitudes. Fixed-wing drones have much more complex take-off and landing procedures and usually require a runway. Some variations of them may take-off utilizing catapult. The lift force of fixed-wing drones is generated through forward movement of it; thus, it cannot hover on a specific point airborne, and it makes the movement of them within swarm much more complex.

Formation Control

To operate seamlessly and realize given tasks, drones within swarm needs to be controlled effectively. Different formation methods can be utilized within the swarm drones, each with their own advantages and disadvantages (Table 1). While centralized method is the simplest one, it lacks scalability and flexibility to fit dynamic requirements. The distributed system may seem the most flexible approach among all others, but it requires very complex communication architecture and higher resources.

Table 1 – Comparative analysis of drone platforms

Type of Drone	Advantages	Disadvantage
Quadcopter	• Easy to operate • Cheap • No complex takeoff and landing	• Limited operation time • Small Payload
Fixed Wing UAV	• Longer Operational Time and Endurance • Higher Payload Carrying Capacity • Stable at high speeds	• Careful planning since cannot hover • Complex landing and takeoff • Less agile and operational in larger areas

When the task requires strict consideration of data from each UAV and there is a need to strictly control the behavior of each UAV, the best approach for the formation control is centralized approach. Centralized approach helps to unload all processing to the GCS, and it helps to decrease computational overhead in drones. Drone operators in GCs have a global view of the group and they can plan the behavior of drones clearly. Single processing center makes this approach unstable in case of failures. If GCS is unable to operate, the success of overall mission degrades. Managing the drones within swarm using a centralized approach requires continuous communication with each drone resulting in communication overhead. Due to critical central node in the control process, the

Herald of the Azerbaijan Engineering Academy
2025, vol. 17 (4), pp. 18-29
I.M. Ismayilov, I.R. Mirzayev

scalability of the drone swarm also becomes limited.

To improve the scalability, decentralized and distributed approaches may be utilized. A decentralized approach may be useful in Search and Rescue operations when the characteristic of the environment is unknown. In this case drones can explore the area relying on their sensor data and following predefined rules like avoiding collision and moving along with the group. Removing central control node helps to overcome the bottleneck for scaling up using additional drones. However, when the drones are controlled through decentralized approach, they need to do necessary computations for maintaining swarm onboard. Not having a single command center for maintaining the formation of the swarm makes the coordination complex and unpredictable as drones acts based on their current data.

In unknown and dynamically changing environments it is desirable that the drones move based on their shared goal that they achieve through continuous communication. In distributed control scheme each drone contributes to the final common interest. The approach offers scalability and structure formations that are resilient to single drone failures. For achieving shared common interest, there is a need of continuous communication among drones requiring a sophisticated infrastructure (Table 2).

Table 2 – Comparative analysis of drone swarm control

Centralized (Strict Reconnaissance)	• Simplicity - GCS based computation, drones require minimal processing power. • Consistency in actions - Global view of swarm by GCS • Easy to implement	• Communication overhead • Scalability • Single point of Failure
Decentralized (SAR)	• Scalability - can accommodate larger number of drones • Flexibility - • Adaptability - Can adapt when communication with central node fails	• Complex Coordination • Onboard computational complexity • Testing complexity
Distributed (Swarm Based Reconnaissance – share intel while adjusting positions)	• Shared decision making • Scalability • Resilient	• Requires more sophisticated communication infrastructure • More computational resources for continuous communication

Formation Strategies

Formation strategies that drone use within swarm robotics is the second issue to address. It defines the position of each drone within swarm. Depending on the requirements of the mission, it is important to define which strategy the drones in swarm should follow.

The first and simplest approach is the leader-follower approach. There are dedicated leaders beforehand and other drones act as followers. Followers are required to keep their

Herald of the Azerbaijan Engineering Academy
2025, vol. 17 (4), pp. 18-29
I.M. Ismayilov, I.R. Mirzayev

position with respect to their immediate leaders. Since the drones are just supposed to keep their relative position with respect to their leaders, the computational load on them is low. Leader-follower strategy lacks the capability to scale up effectively. As the number of followers increase, the mutual relay with followers and their drone may face delays. The overall system is very sensitive to failure with leader drones as they are main guidance for the followers (Table 3).

Virtual structure strategy lets the drones within the group as a single geometric shape. In this strategy each drone tries to keep its position within the geometric structure and the overall behavior of the structure is predictable due to unified movement. Compared to leader-follower this approach is not highly dependent on a single drone making the structure less affected by the loss of single drone. Virtual structure strategy requires the drones within the formation to communicate continuously during their movement.

Table 3 – Drone Formation Strategies

Formation	Advantages	Disadvantages
Leader Follower (Military reconnaissance)	• Simple to implement. • Computationally efficient	• Scalability - as size grows, communication delay may cause problems. • Single point of Failure - if anything happens to leader, system fails. • Adaptivity issues – difficult to adapt to dynamic environments
Virtual Structure (Large scale grid like surveillance)	• Stable – less affected by single drone failures • Predictable behavior – formation moves as a whole • Strict geometric formations.	• Rigid formations – less adaptable • Computational complexity – for maintaining structure • Complex as the number of nodes increase
Behavior Based (SAR dynamically explore)	• Scalable – works well with large swarms • Adaptive – easy to adapt to obstacles and dynamic environment • No central controller needed. Resilient to central node failure.	• Unpredictable • Immediate decisions may cause non-stable state. • Higher communication overhead.
Artificial Potential Fields (Obstacle rich environments)	• Adaptive to dynamic environment. • Decentralized approach. • Better collision avoidance	• Computational overhead – calculation of forces • May stuck – when forces zero out each other • Difficult to maintain structure – Individual Based

Herald of the Azerbaijan Engineering Academy
2025, vol. 17 (4), pp. 18-29
I.M. Ismayilov, I.R. Mirzayev

They need to have much complex processing power to handle the continuous communication requirement. As the number of nodes within the group increase, the number of mutual relays between the drones increases making the structure more complex.

Both of leader-follower and virtual structure techniques lack the ability to adapt dynamic environments and scale up effectively

In behavior-based approach drones are given independence to act based on their decision in dynamic environments. Having predefined rules and acting based on their local information, this approach enables addition of extra nodes to the group to scale up effectively. Since there is no central node in control of overall grid, the system is resilient to drone failures as well. The drones act based on the requirements of dynamic environment and their behavior may be unpredictable. Since they act based on the current information, their immediate decisions may cause the system to be in non-stable state. Lastly, the requirement of steady communication in this formation will cause communication overhead among the nodes.

Drones in this structure acts based on the forces that act on them individually, and it makes the maintenance of the whole group difficult. When the forces on the drone zeros out, it may get stuck. It is important to address these problems for successful utilization of this strategy.

Artificial potential field approach strategy is highly adaptable to environments with many obstacles. The drones within this structure need to compute the forces that act upon them seamlessly, thus they need to have better computation power.

Network in swarm

Network architecture is another important topic in swarm drones. It is important to address network related requirements to provide seamless operational capability.

Infrastructure based network architecture is the mostly used approaches for swarm drones. The drones connect to the fixed network and communicate through a central ground control station node or cloud. The approach is highly reliable due to well established infrastructure and protocols. Since the main computation occurs in the central note, the approach is efficient for the drones from the point of processing requirement. Well established infrastructure-based network architecture enables high bandwidth communication offering video streaming and real time decision making. However, in this approach the connection may get lost in low coverage areas like remote operation zones.

Having a central node as main processing power comes with the problem of single point of failure. Infrastructure based network architecture requires either ground control station, satellite or cloud connection which is expensive to maintain.

To overcome the issue of single point of failure and offer operational capability in low coverage areas, Flying Ad-hoc Network approach has been offered. The removal of central node as main processing power helps to overcome the bottleneck for scaling up and decreases high dependence from single node.

However, it is complex to maintain this type of network since the nodes may join and leave the and the network topology changes dynamically. The effective bandwidth of the network is decreased since all nodes share the same channel. Delay is inevitable since communication is multi-hop (Table 4).

Table 4 – Network for Swarm Drones

Network	**Advantages**	**Disadvantages**
Infrastructure Based (Military)	• Reliable – well established communication protocols • Computationally efficient – processing on GCS or cloud • High bandwidth - video streaming, real-time decision making available.	• Coverage - May be in remote areas where coverage is lost • Single point of Failure - if base fails, the whole system fails. • Costly – relies on expensive GCS or satellite
Flying Ad Hoc Network	• Scalable – nodes can join and leave. No central node bottleneck • Fault tolerant – problem with a single drone does not cause system failure. • Works in remote areas	• Latency – packet routing between UAVs may cause delays • Dynamic topology – Dynamic node join and break cause link breaks. • Power consumption – Communication should always be kept while performing other tasks

Conclusion

Using bibliometric analysis, this paper summarizes different types of UAVs along with their advantages and disadvantages. Furthermore, the paper highlights the main concepts in swarm drone approaches and the application areas of them.

While quadcopters may offer fast and easy setup for swarming, for missions that is realized in higher altitudes and lasts longer fixed wing drones may be useful.

Depending on the requirements of the mission, and characteristics of environment a correct way of control should be chosen. For missions that require strict consideration like reconnaissance, centralized control method may be utilized. If the environment is dynamically changing, and there is little information about it beforehand, it is desirable to give the drones ability to decide based on their local information using distributed or decentralized control scheme. This type of control scheme can bring advantage in search and rescue operations and intelligence collection.

Choosing the correct strategy for swarm is another crucial decision to make. For military reconnaissance and fixed surveillance, it is important to have fixed structure and predictable behavior is expected. Leader-follower or virtual structure approaches may be useful here. When it is required to scale up and operate in dynamic environments, it would be useful to choose behavior-based or artificial potential field approaches. They can operate in search and rescue operations and in the environments that are rich with obstacles much better.

The network to be used within swarm is highly dependent on the requirements of the mission. Infrastructure based networks is mainly used in military operations due to their reliability and high bandwidth. For missions that is not required to be highly reliable, FANET approach may yield cheaper and more scalable alternative.

Conflict of Interests

The authors declare there is no conflict of interests related to the publication of this article.

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