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# ARCHITECTURE OF THE UAV SWARM COMMAND AND CONTROL SYSTEMS – AN OVERVIEW

Karol Bęben[1], Robert Głębocki[2]

[1] Łukasiewicz Research Network – Institute of Aviation
[2] Warsaw University of Technology, Faculty of Power and Aeronautical Engineering

**Abstract**

This paper presents an overview of Command and Control Systems used for the swarm of Unmanned Aerial Vehicles. This problem is the object of scientific research carried out within the implementation doctorate (PhD) at the Warsaw University of Technology and the Łukasiewicz Research Network - Institute of Aviation. The first part of the article discusses the requirements for swarm control systems of Unmanned Aerial Vehicles – Multi-Rotor and Fixed-Wing platforms. The second part of the article presents the current applied drone swarm control architectures and specific directions of their development.

**Keywords:** command and control system, drone swarm, uav swarm, autonomous system

## 1. Introduction

The constantly growing interest in the practical use of Unmanned Aerial Vehicles in various industries (precision agriculture, transport, surveillance) makes many new requirements for UAVs. Unmanned platforms are mainly used as carriers of sensors and various sensors collecting an increasing amount of data. The increasing requirements for UAVs include higher performance during data acquisition. One of the current developing are in this field is the implementation of swarm flight systems.

The latest Commission Implementing Regulation (EU) 2020/639 as regards standard scenarios for operations executed in or Beyond Visual Line of Sight (BVLOS) identifies the Command and Control (C2) link as one of the main segments to be described when applying for a permission to fly in special category operation. In addition, the Command and Control link segment will be verified during the UAV class assignment after the update of EASA regulations in 2023. Drone swarms are becoming more popular. It is possible that the availability of drones performing flight in a swarm will converge with the publication of new European Aviation Safety Agency (EASA) regulations.

This paper will specifically look at Command and Control (C2) Systems architectures used in the UAV swarm in civilian market and proposed the choice of architecture depending on the most popular UAV applications.This paper is structured as follows.

Section 2 presents detailed literature review and current trend and researchers that involve swarm intelligence. Section 3 discuss key aspects of drone swarms and in Section 4 relates Command and Control System overview including types of architectures.. Section 5 suggests some recommendation for future works and coclusion

## List of acronyms:

C2 – Command and Control
CAC2S – Common Aviation Command and Control Systems
GCS – Ground Control System
IMU – Inertial Measurement Unit
MAVLink – Micro Air Vehicle Link
SoS – System of a System
UAV- Unmanned Aerial Vehicle
VTOL – Vertical Take-off Landing

## 2. Literature review

The methodology of research included a detailed literature review of Command and Control Systems in Swarms of Unmanned Aerial Vehicles. The review was limited to publicly available sources and included books, conference and scientific papers and press. The literature analysis stared by searching the databases (Google Scholar, World Web Science, Scopus, Microsoft Academic) with keywords: *Drone Swarm, UAV Swarm, UAS Swarm, RPAS Swarm*. Through the analysis of the results from the databases, it should be noted that the number of articles has increased significantly in the last 3 years. In this paper articles from the last 10 years were detailed analysed.

In order to speed up the review, an automatic database search tool has been designed.

For example:

**Database**: Google Scholar, World Web Science, Scopus, Microsoft Academic

**Keywords**: *Drone Swarm, UAV Swarm, UAS Swarm, RPAS Swarm*

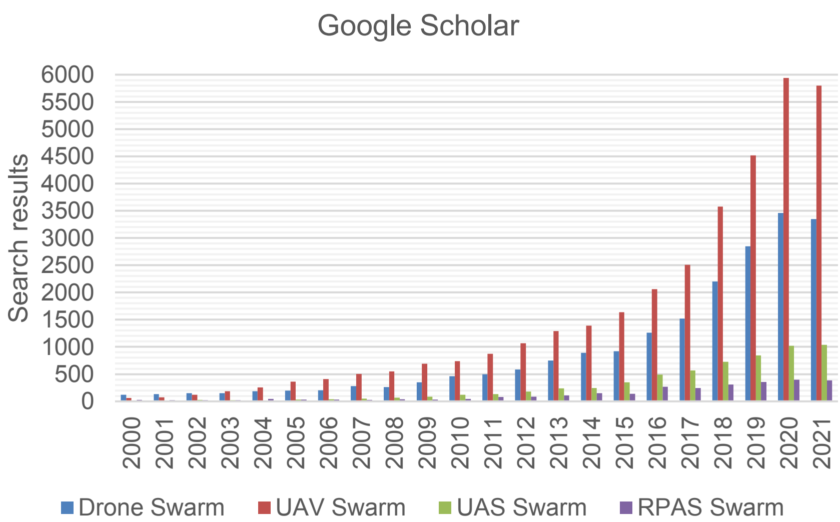
**Filters:** Year: 2000 – 2021

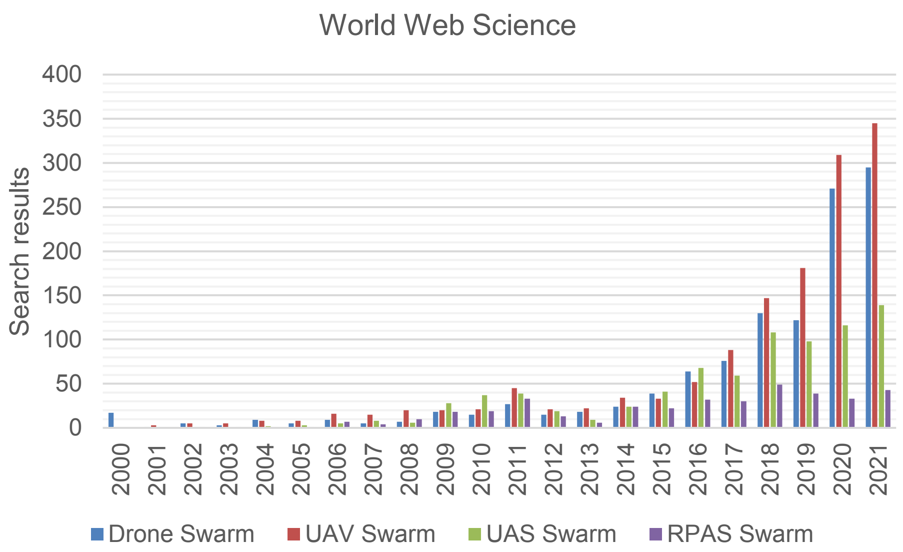
*Database* *Keywords*

https://**academic.microsoft.com**/search?q=**uav**%20**swarm**&f=Pt%3D%271%27&eyl=Y%3C%3D**2019**&syl=Y%3E%3D**2019**&orderBy=0

*Filters*

The search consisted of iterative replacement of keywords and filters. The results were saved to a * .txt file and then the results were visualized with the Excel software.




World Web Science
Search results
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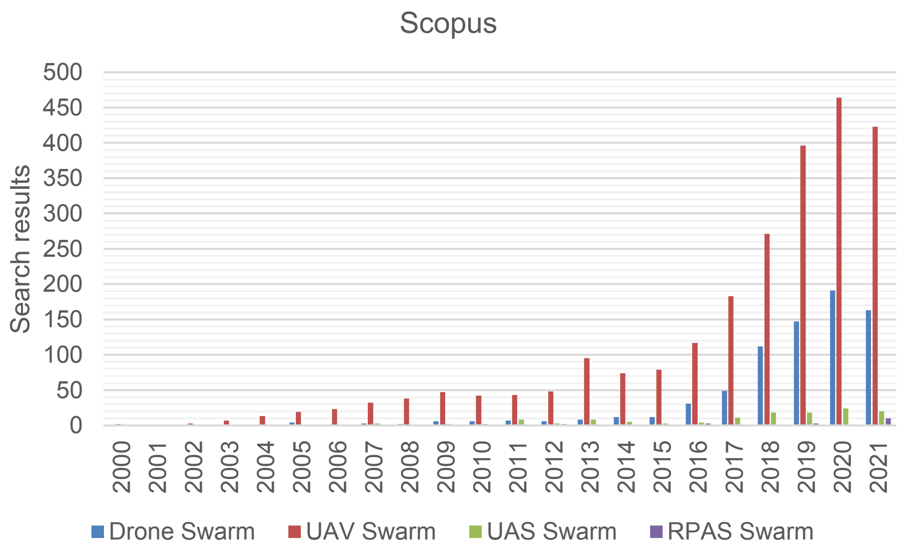
Drone Swarm
UAV Swarm
UAS Swarm
RPAS Swarm


Scopus
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Drone Swarm
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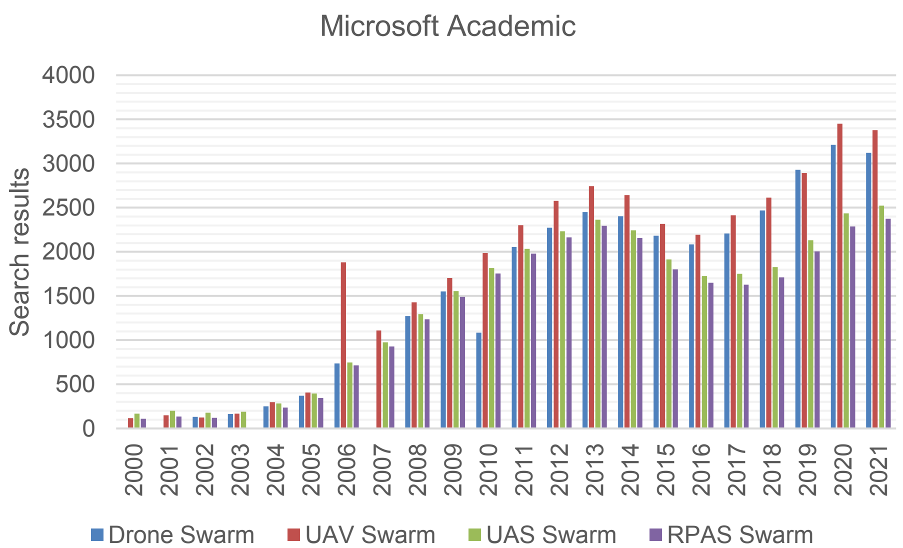
Microsoft Academic
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2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Drone Swarm
UAV Swarm
UAS Swarm
RPAS Swarm

A strong increase interest in Unmanned Aerial Systems Swarm has been perceived in recent years [10]. It is clear from the charts that a significant increase in articles related to the subject matter begins around 2016. Therefore, the table below includes results through 2016. During the literature analysis, due to frequent references, literature positions from the last 10 years were analysed.

| | Google Scholar | | World Web Science | | Scopus | | Microsoft Academic | |
|---|---|---|---|---|---|---|---|---|
| | 2016 | 2021 | 2016 | 2021 | 2016 | 2021 | 2016 | 2021 |
| Drone swarm | 1260 | 3350 | 64 | 295 | 31 | 163 | 2086 | 3122 |
| UAV swarm | 2060 | 5800 | 52 | 345 | 117 | 423 | 2193 | 3378 |
| UAS swarm | 491 | 1040 | 68 | 139 | 4 | 20 | 1726 | 2524 |
| RPAS Swarm | 269 | 385 | 32 | 43 | 3 | 10 | 1650 | 2373 |

Table 1 - The results of the analysis of the number of articles in 2016-2021. Own work.

The table below summarizes the most important publications that were the subject of the literature analysis.

| Year | Article | What information can be found | Key conclusions | Future research directions /Issue |
|---|---|---|---|---|
| 2019 | [20] | Very detailed survey of UAV swarm network architectures, communication and routing protocols: topology-based routing, position-based routing, hierarchical routing, deterministic routing, stochastic routing, social network-based network. Advantages and disadvantages, key parameters and metrics. | All routing protocols for UAV networks must be considered with low density of nodes and high mobility. | Communications security, Link disconnections, Energy – efficient and high-performance routing protocols Performance awareness |
| 2019 | [21] | Unmanned Aerial Vehicle to Unmanned Aerial Cehicle communication architecture using cellucar network. | Development of unmanned aerial vectors over the last decade requires IT-based and smart structure-based approaches | n/a |
| 2020 | [22] | Four main communications architectures, classification of existing routing protocols for UAV communications, namely topology-based, geographic/position-based, and SI-based | Multi-layer architecture combined with the meshed intra-swarm architecture is currently the most applicable communication architecture. Topology-based routing cannot cope with UAV networks. SI-based routing and geographic/position-based routing are more suitable for UAV networks. | Detecting the failure of gateway UAVs and how to select the next UAV to act as the gateway, intermittent connectivity, Communications security Energy efficient |
| 2021 | [23] | Description of the two building blocks of any drone swarm, the networking and computational systems, and a thorough analysis of how to integrate them to achieve a self-organized swarm system. Drone swarms as networked control systems | Building a networking system that does not rely on identifying hosts (e.g., drones) but rather computational functions, which can be deployed in any drone, provides the baseline to tackle the major challenges identified for the development of drone swarms as networked control systems. | effective integrated networking and computing architecture |

| | | | | |
|---|---|---|---|---|
| 2021 | [24] | Concept-level proposal, initial development, and literature review for the use of cellular networks as the communication infrastructure for UAV swarms. Overview of the sUAS industry, the applications of UAV swarm, and in-house development efforts for UAV swarm | *Infrastructure - based and FANET* drone swarm control architectures. Proposes a hybrid of Infrastructure and FANET architectures by providing a way to exchange informations in swarm via mobile 5G cellular infrastructure. | Further research into cellular infrastructure. |
| 2021 | [25] | A framework for planning and execution of drone swarm missions in a hostile environment. Methods of planning drone swarm routes and the methods of detecting potentially dangerous objects in photos sensors. Method of using data from the image analysis performed automatically by the UAV | One UAV as infomaton hub in swarm, mission management inckuding image analysis | Mission managements including image analysis in teal-time, mission replanning |

Table 2 - Most important publications according to literature review. Own work.

## 3. Unmanned Aerial Vehicles

Unmanned Aerial Vehicles (UAVs) are already common in many industries such as search and rescue, forest fire monitoring, powerline or pipeline inspections, precision mapping [3,4,8]. Moreover drones are an elementary tool for work (cinematography, photography, remote sensing) [13]. Essentially, these devices are regarded as payload - sensor carriers (multispectral, thermal, SAR, weather), medical or military payload. Limitations of UAVs (e.g. flight time, payload, range) do not allow for efficient data acquisition. Moreover, preliminary work is being done to integrate drones into the urban air mobility system (Assured-UAM). This creates a need for new directions of development. Recently, the main directions of development of unmanned aerial vehicles include the miniaturization of sensors and increasing the efficiency of unmanned aerial vehicles through: development of propulsion systems, resistance to interference, collision avoidance and the simultaneous use of multiple flying platforms [8].

Unmanned Aerial System consists of several components. According to the literature review we can distinguish the following main modules:

- Unmanned Aerial Vehicles (UAVs) with onboard equipment (e.g. sensors, weapon);
- Ground Control System (GCS)
- Command and Control (C2) System

It is necessary to point that the unmanned aerial vehicle contains on-board computer, which can work in autonomous or semi-autonomous mode.

### 3.1 Unmanned Aerial Vehicles Swarms

Generally there is not a precise definitions of swarms but based on the paper research and other authors proposals, it is possible to identify the most common features with which they define a swarm. The starting point of the considerations is Merriam-Weber dictionary definition of swarm: “a large number of animate or inanimate things massed together and usually in motion”.

A swarm is a technically termed as a group of UAV aircraft driven by artificial intelligence. Swarming drones communicate with each other while in flight and can respond to changing conditions autonomously. A good analogy would be a dense flock of starlings reacting to a sudden threat like a hawk. The entire flock manoeuvres like a single organism. A swarm is not to be confused with a group of UAVs flying together in formation and acting individually autonomously” [3,6]

Main key requirements to qualify Unmanned Aerial System as swarm

- Number of Unmanned Aerial Vehicles in mission ≥ 3,
- Real-time mutual communication between UAV-UAV or UAV - Control Station,
- Automatic or Autonomous mission planning of more than ≥ 3 UAVs,

As defined in the DoD Defense Acquisition Guidebook (DAG) [19], an SoS is “a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities.”

An SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [27]. Both individual systems and SoS conform to the accepted definition of a system in that each consists of parts, relationships, and a whole that is greater than the sum of the parts; however, although an SoS is a system, not all systems are SoS

SoS systems engineering deals with planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into an SoS capability greater than the sum of the capabilities of the constituent parts [27]. Consistent with the DoD transformation vision and enabling net-centric operations (NCO), SoS may deliver capabilities by combining multiple collaborative and autonomous-yet-interacting systems. The mix of systems may include existing, partially developed, and yet-to-bedesigned independent systems.

By detailing the above and due to the constantly growing popularity of the swarm of unmanned aerial vehicles, increasingly more advanced swarm systems and constant R&D activities in this filed, the authors propose to present the swarm of drones more complex as an element of the System of System Engineering. Moreover, a similar of requirements can be observed between SoS and UAV Swarms [18,27]

- SoS – integration of multiple systems into a higher level system,
- Function of a SoS generates capabilities beyond what any of the individual systems is independently capable of producing,
- integration into a SOS evokes some degree of constraint for previously independent systems,
- SoS brings systems in order to perform a higher level mission/purpose of which each member system plays an integral role, but none of the contributing systems can accomplish independently,
- complex system exhibiting dynamic and emergent behaviour is difficult to grasp and problematic to engineer,

The development of Unmanned Aerial Vehicles and the desire to use them in many complex mission scenarios (e.g. urban mobility, maneuvring missile) need to implement higher degree of autonomy. Advanced missions are characterised by larger complexity with usually more than one system in one moment. In this situation the role of operators is likely to be the monitoring and the supervision of the mission execution by a group of UAV systems, up to a swarm in the future.

The NATO autonomy of a UAV system classify was listed below [26]:

| Level | Description | Definition |
|---|---|---|
| 1 | Remotely Controlled Systems | System reactions and behaviour depend on operator input |
| 2 | Automated System | Reactions and behaviour depend on fixed built-in functionality (preprogrammed) |
| 3 | Autonomous non-learning system | Behaviour depends upon fixed built-in functionality or upon a fixed set of rules that dictate system behaviour (goal-directed reaction and behaviour). |
| 4 | Autonomous learning system with the ability to modify rules defining behaviours | Behaviour depends upon a set of rules that can be modified for continuously improving goal directed reactions and behaviours within an overarching set of inviolate rules/behaviours. |

Table 3 - NATO autonomy UAV categories. Own work based on [26]

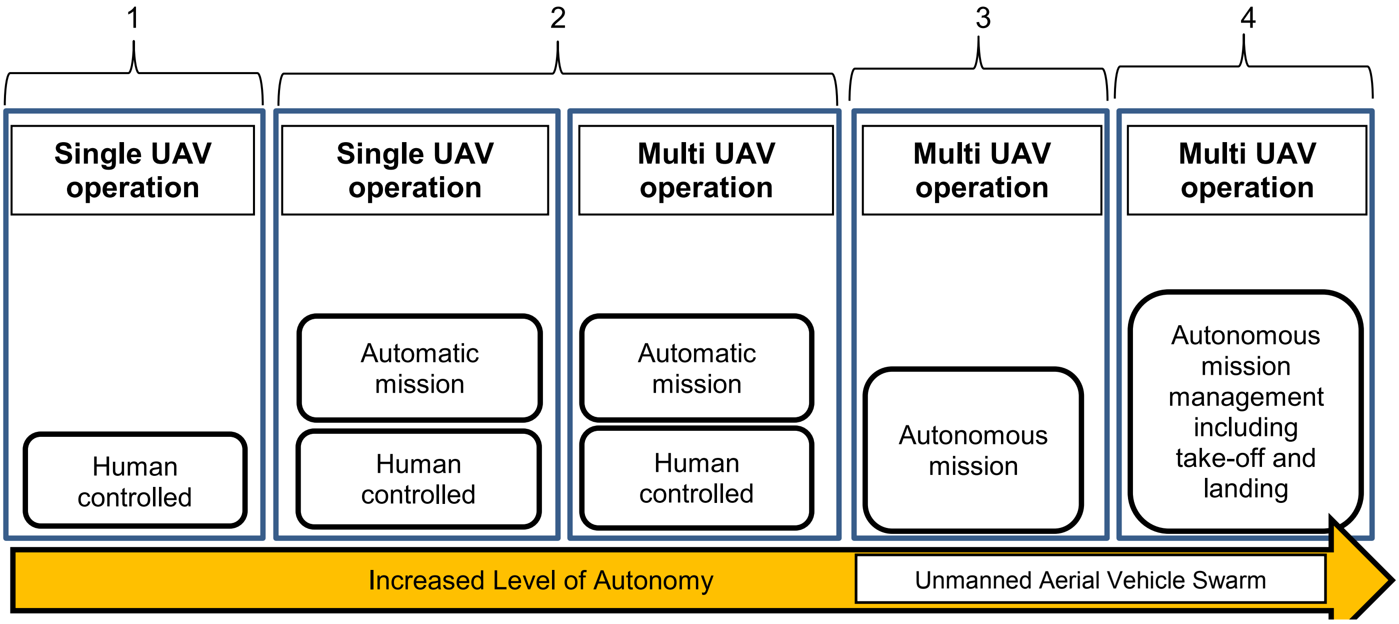



Figure 1 Proposal level of autonomy of UAV based on NATO classification. Own work.

Cooperative, swarming robots can be unsophisticated and highly replaceable. A major driver for the use of swarms is the high cost and relatively low response-time of human operators in situations which involve many robotic assets.

Comparasion of single UAV mission and drone swarms are listed in table below:

| | **Single UAV system** | **Swarm UAV system** |
|---|---|---|
| Flight endurance | Limited | High |
| Autonomy | Low | High |
| Susceptibility to malfunction | High | Low |
| Mission optimalization | Low | High |
| Scalability | Low | High |
| Information redundancy | Low | High |
| Require a remote pilot | Yes, always | Not always |

Flight endurance

Depending on the type of UAV, it is limited by a maximum flight time. Starting with the most popular battery-powered drones which flight time is up to 30 minutes and ending with professional UAVs powered by hybrid engines which flight time can be several hours. The use of several simultaneously flying unmanned platforms can allow for more efficient time management, which is a key requirement for e.g. a photogrammetric mission in which we mapping a large area.

Autonomy

The flight of a single UAV is typically controlled from a ground-based flight control station/human with RC equipment. In the case of a single BSP, it usually performs missions planned by the pilot in software. In case of a single BSP, the use of autonomous systems is reasonable for real-time analysis of the image from the on-board camera. Managing a fleet of UAVs requires providing a high level of autonomy in communication between devices, transmission and queuing of tasks, decision-making by flying platforms without constant communication with the control station.

Susceptibility to malfunction

Susceptibility of UAVs to communication link interference and magnetic field variations as well as unreliability of on-board systems (e.g.: propulsion, navigation systems, on-board cameras, cooling systems) are common causes of UAV platform failure. For drones flying in a swarm and consisting of dozens of unmanned platforms, failure of one of the group does not cause mission abrupt failure (exception is infrastructe based swarm where failure of the main UAV prevents control of the swarm).

Mission optimalization

In case of use drones in search and rescue missions, a key factor is the time in which we find the missing person. When we decide to use a swarm of drones, the time to search a large area can be significantly reduced. Additionally drone swarm is flexibility and can reconfigure to different tasks in real-time.

Scalability

Unmanned Aerial Vehicles in swarm can increase and decrease size depending on the needs of the global tasks

Information redundancy

A single UAV has a significantly limited payload which results in a limited number of sensors that can be used simultaneously. Data is stored on a single device and if that device fails, data is lost. In case we are doing a photogrammetric mission and our UAV unfortunately breaks down, we will not always be able to recover the information about the last place from which the image was taken. We will be forced to start the mission over again. Using multiple unmanned platforms flying simultaneously in a swarm, they exchange information with each other. If one device is lost, a duplicate of the information can be saved in another part of the swarm.

Require a remote pilot

For every use of a single UAV, a human operator is an necessary part. He has the ability to control the drone manually or with the use of on-board support systems - Altitude hold, GPS. Additionally, the pilot has the ability to design the flight route. For professional and military drones, the training a pilot is expensive. Swarms with the highest degree of autonomy should be able to perform missions without active human involvement in flight and decision making.

## 4. Command and Control System Architectures

**Command and Control (C2)** is the functionality to allow the remote pilot to exercise his control of the aircraft.C2 defined is also as "The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission." [1]

Command and control define who has the authority to make decisions, and what the parameters of that authority are. According to the literature review listed in table 1, we can specify the most important requirements and functions of Command and Control System Architectures.

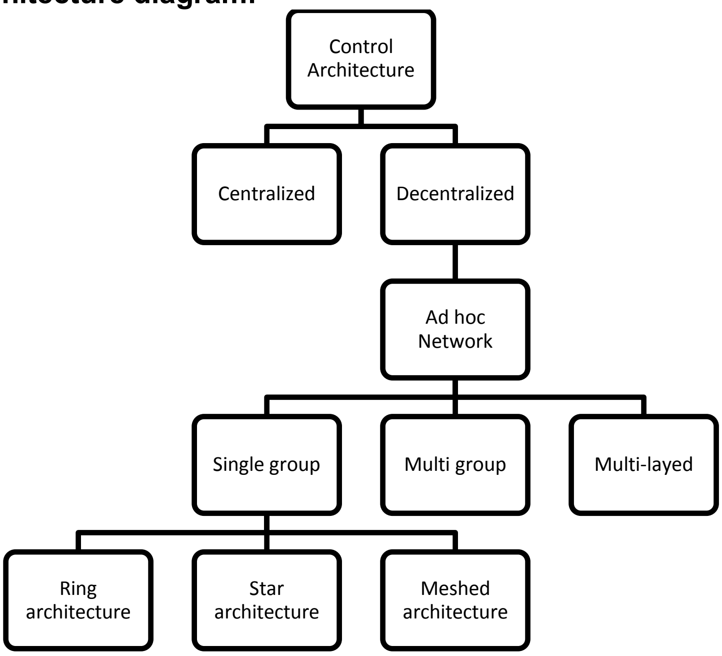
Requirements:

- Low latency,
- High Scalability,
- High Adaptability
- Support high-mobility UAVs and different types of UAVs
- Possibility to reconnect
- Interference resistant
- Ability to rapidly react to changes in the environment.

Functions [1]:

- Uplink of crew commands from the Control Station to the RPA
- Downlink of RPAS flight parameters and status data from the RPA to the Control Station.
- Pairing between the control station and the RPA.
- Means to indicate to the remote pilot:
  - The status of the Command and Control Datalink
  - The effective range of the Command and Control Datalink

**Proposed control architecture diagram:**



**Centralized control**

Fixed networking infrastructure, Infrastructure based swarm architecture, non – interactive deployment

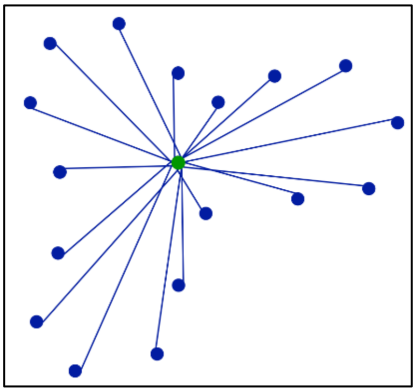


Figure 2 - Centralized control diagram [7]

Each UAV is in swarm is connected to central node and receives control commands from centralized planner. All UAVs in swam are controlled by a central node.

**Advantage**

- Relatively stable,
- Simpler routing algorithms
- Smaller scale
- Long distance
- Provide greater detail and more accurate information about small areas [ADA489366]
- Flight and mission computations can be realized in real time by a GCS via high performance computer carried on UAV (e.g.: NVIDIA Jetson)
- Pernament communication between drones is not necessary

**Disadvantage:**

- Delays between packages
- Every UAV requires a long-range communication link
- A failure of the central node disrupts the operation of the entire system (SPOF – Single Point of Failture)
- Necessary permanent communication with GCS for coordination of all drones,
- Lack of system redundancy
- Coordinates the decision making of all UAVs based on computations and algorithms developed in the GCS
- Susceptible to interference
- Instructions to each drone are developed in the GCS

**Recommender for:**

- Small coverage area
- Small swarm size
- Relatively simple missions

**Requirements:**

- Efficient uplinks and downlinks
- Bidirectional communication link between each UAV and central node

**Decentralized control**

*Cluster-Based Network, Interactive Deployment Strategy*

In many researcher opinion [20,21,24] decentralized control is the most recommended choice for UAV swarm. The main reasons are possibility to reconnect UAV to the network.

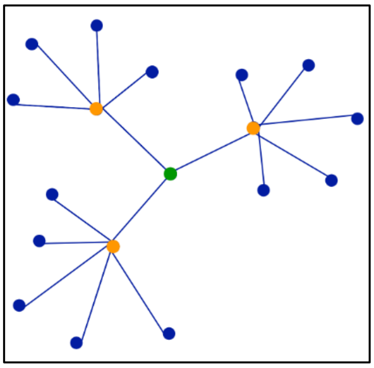


Figure 3 - Decentralized control diagram. [7]

**Advantages:**

- Built in redundancy as the entire swarm is not dependent upon an infrastructure to execute the desired tasks
- Various configurations of ad-hoc communication networks in UAV swarms
- Real time communications between UAVs
- Dynamic reconfiguration of routing for UAV swarm applications
- Cheaper, smaller and lighter communicating devices
- Nodes are dynamically assigned and reassigned based on dynamic routing algorithms
- Real-time communication with ad-hoc manager.
- Cover large areas

**Disadvantages:**

- At least one of the drone in swarm must be connected to the base
- Each UAV in swarm must be equipped with networking hardware,

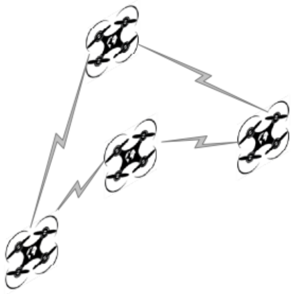
**Applications:**

- managing wildfires,
- disaster monitoring
- Not recommended for applications where accurate telemetry of data between UAVs in crucial

Single-Group Swarm Ad hoc Network
Communication does not depend on the infrastructure The communication between the swarm and the infrastructure is a single point link relying on a specific UAV called gateway. In most papers it mainly concerns UAVs of the same type and size.
UAVs in swarm (nodes) are mutually forwarding data. Gateway UAV need two types od transceivers: (1) low power – short distance for communicating with other UAV and (2) high power- long reach for communicate with central station.

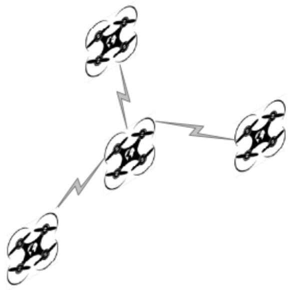
Types of intra-swarm communication architectures [12]:

**Ring architecture**



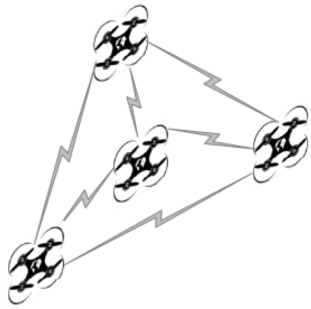
Bidirectional communications
Any UAV as gateway
UAV fail does not affect the loss of communication
Certain stability but lack of scalability

**Star Architecture**



Gateway UAV communicates with control station (infrastructure) and every UAV in swarm. If the gateways node fails, the system goes to fail.

**Meshed architecture**



Combination od ring and star architecture.
Any UAV cab be a gateway

Currently the most popular in applications.

**Advantages:**

- real-time collaborative control optimize and improve efficiency
- mutual communication between the gateway UAV and infrastructure also enables the upload and download of swarm information, including instructional information
- UAV’s ( excluding Gateway UAV) carry low-cost and lightweight transceivers.
- Long range coverage
- Small payloads on UAVs

**Disadvantages**:

- Gateway UAV with integrated two types of transceivers
- Typical *single-group swarm Ad hoc network* requires alike flight parameters (speed, heading)

### Multi-Group Ad hoc Network and multi – layer Ad hoc network

This architectures is significantly advanced. Integrated centralized architecture and single-group or multi layer swarm ad hoc network architecture. The architectures are organized in a centralized manner.

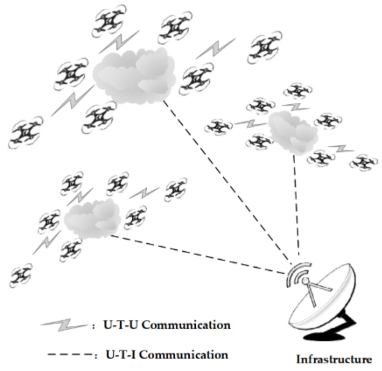



Figure 4 Multi - group Ad-hoc network illustration. [12]

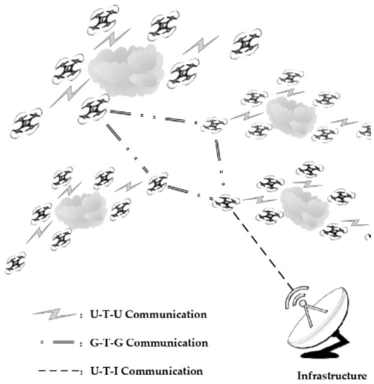



Figure 6 - Multi layer Ad-hoc network.[12]

**Advantages:**

- Increase or decrease of UAV nodes and quickly implement network reconstruction.
- Support different types of UAVs

**Recommender for:**

- complicated mission scenarios
- huge number of UAVs
- mission where network topology is desired
- operation thar require frequent communication between UAVs

**Applications:**

- public safety
- search and resuce
- delivery
- precision agriculture

## 5. Conclusion

In this review paper the fundamentals information about drone swarm and the command and control architectures were presented. The study summarizes the current state of knowledge on swarms of unmanned aerial vehicles.Each architectures was categorized under the two major headings of centralized or decentralized. A UAV swarm as a System of a System was proposed and was explained why a drone swarm must meet autonomous system requirements. An extensive literature analysis was presented and illustrated. The literature analysis shows that the topic is the architecture of drone swarm control systems is a frequent topic of publications. Authors describes architectures whose main functionalities are similar but they call them differently. This introduces a little information noise for people getting acquainted with the topic for the first time.

It is certainly part of the future work to attempt to simulate specific communication architectures and implementation of task queuing services for the selected UAV in example mission (e.g. remote sensing).

## 6. Contact Author Email Address

Karol Bęben, mailto: karol.beben@ilot.lukasiewicz.gov.pl
Robert Głębocki: mailto: rgleb@meil.pw.edu.pl

## 7. Copyright Statement

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