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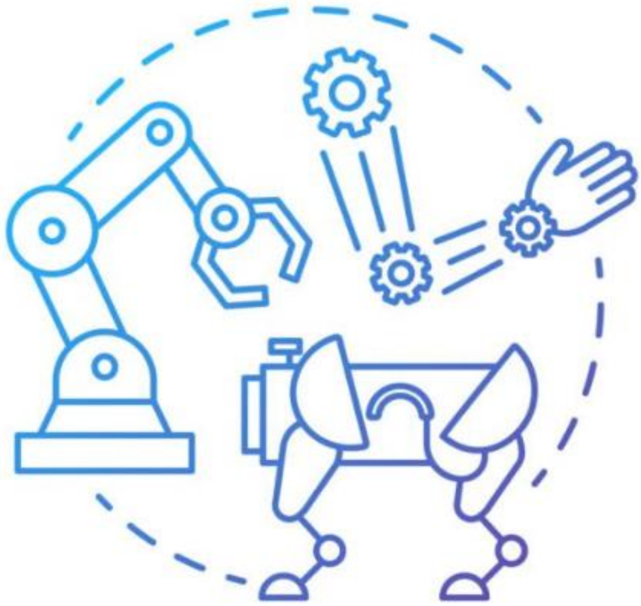

МАТЕРІАЛИ

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У збірник включені тези доповідей, які присвячені сучасним автоматизованим технологіям Industry 4.0 та їх впровадження; інформаційні управляючі системи технологічного призначення; математичні методи в системах автоматизації; розробка та програмування в робототехніці; штучний інтелект та машинне навчання в автоматизації; інтеграція технологій у виробництві та промисловості; сенсорні технології та взаємодія людини з роботами в Industry 5.0; ефективність використання роботизованих систем у виробництві; етика та правові аспекти в робототехніці; Інтернет речей та Інтегровані системи в комп’ютерно-інтегрованих технологіях, автоматизації та робототехніки; технологічні виклики та інновації у світі робототехніки.

Computer-integrated technologies, automation and robotics 2026: Proceedings of III st All-Ukrainian Conference, Kharkiv, May 14-15, 2026: Thesises of Reports / [Ed. I.Sh. Nevlyudov (chief editor).] .-Kharkiv .: [electronic version], 2026. - 97 p.

The collection includes abstracts devoted to modern automated technologies of Industry 4.0 and their implementation; information control systems for technological purposes; mathematical methods in automation systems; development and programming in robotics; artificial intelligence and machine learning in automation; integration of technologies in production and industry; sensor technologies and human interaction with robots in Industry 5.0; efficiency of using robotic systems in production; ethics and legal aspects in robotics; Internet of Things.

ЗМІСТ

ANALYSIS OF AUTONOMOUS NAVIGATION METHODS FOR DRONE SWARMS: CENTRALIZED AND DECENTRALIZED APPROACHES

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Abstract: The work is dedicated to a comprehensive comparative analysis of autonomous navigation methods for swarms of unmanned aerial vehicles. It examines the conceptual differences, technical advantages, and critical disadvantages of centralized and decentralized control approaches in complex environments. Based on aggregated data, key algorithmic foundations (Swarm Intelligence, APF), issues of scalability, fault tolerance, the impact of communication interference, and cybersecurity threats are analyzed. Prospects for the use of adaptive hybrid architectures and Edge Computing to enhance the overall efficiency and autonomy of the swarm are presented. The results of the analysis can be used for the informed selection of swarm control architecture when designing systems for civilian and military applications.

Keywords: autonomous navigation, centralized control, decentralized control, swarm intelligence, artificial potential fields, Edge Computing, cyber resilience.

АНАЛІЗ МЕТОДІВ АВТОНОМНОЇ НАВІГАЦІЇ ДЛЯ РОЮ ДРОНІВ: ЦЕНТРАЛІЗОВАНИЙ ТА ДЕЦЕНТРАЛІЗОВАНИЙ ПІДХОДИ

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Анотація: Робота присвячена комплексному порівняльному аналізу методів автономної навігації для роїв безпілотних літальних апаратів. Розглядаються концептуальні відмінності, технічні переваги та критичні недоліки централізованих і децентралізованих підходів до управління в складних умовах. На основі об'єднаних даних проаналізовано ключові алгоритмічні бази (Swarm Intelligence, APF), питання масштабованості, стійкості до відмов, вплив завад зв'язку та загрози кібербезпеки. Наведено перспективи використання адаптивних гібридних архітектур та Edge Computing для підвищення загальної ефективності та автономності рою. Результати аналізу можуть бути використані для обґрунтованого вибору архітектури управління роєм при проєктуванні систем для цивільних та військових застосувань.

Ключові слова: автономна навігація, централізоване управління, децентралізоване управління, ройовий інтелект, штучні потенційні поля, Edge Computing, кіберстійкість.

The use of group flights of unmanned aerial vehicles (UAVs) in a «swarm» format is one of the most promising areas in the development of automation [1-10], which integrates advancements in the field of distributed computing, sensor miniaturization, and wireless networks to create a unified intelligent system [11, 12]. The interaction of dozens or hundreds of autonomous agents allows for solving tasks that are beyond the capability of individual drones, ranging from large-scale area monitoring to executing coordinated actions in search and rescue operations or in conditions of electronic warfare. The key task for ensuring the effectiveness of such a system is the selection of an optimal autonomous navigation architecture, which determines the principles of information exchange and decision-making within the group.

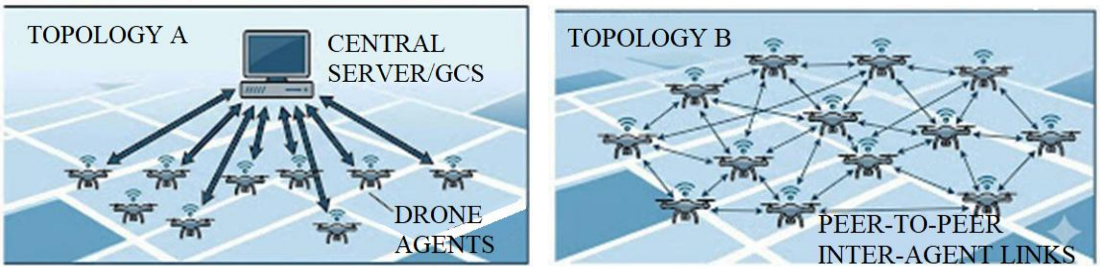
Currently, there are two fundamental approaches to organizing swarm control – centralized and decentralized – each of which has unique advantages and critical limitations, especially in conditions of unstable communication, interference, or the need for rapid scaling. The choice between these approaches determines not only the tactical capabilities of the swarm but also its fault tolerance to the loss of individual elements and its ability to adapt to a dynamic environment.

The rapid development of Edge Computing technologies, swarm intelligence algorithms, and machine learning opens new horizons for the creation of hybrid architectures; however, the lack of generalized criteria for their comparison complicates the design process. Thus, the relevance of this work is determined by the need for systematization and comprehensive comparative analysis of existing autonomous navigation methods for the informed selection of swarm control architecture in accordance with specific operating conditions and target objectives.

MATERIALS AND RESEARCH RESULTS. Let us consider the conceptual foundations of control architectures. The fundamental difference between the approaches lies in the distribution of computational load and the communication network topology:

1. Centralized Control is based on a strict hierarchy, where a single decision-making point (e.g., Ground Control Station, GCS) collects telemetry from all UAVs, builds a global model of the environment, calculates trajectories, and sends individual commands to each agent.

2. Decentralized/Distributed Control assumes that each drone is an autonomous agent with its own computing module. Decisions are made locally based on data from its own sensors and limited information exchange with its nearest neighbors. To visualize these differences, a conceptual diagram (Fig. 1) has been developed, comparing the network topologies.



a) б)

Figure 1 – Conceptual diagram comparing centralized and decentralized control topologies for drone swarms: a) Centralized control with a «single point of failure»; b) Decentralized control based on mesh network topology.

The work presents a comparative analysis of technical advantages and disadvantages.

The analysis of both approaches reveals critical limitations regarding scalability, communication requirements, and resilience to external influences, which directly affect the efficiency of autonomous systems. The centralized approach includes the following advantages: high precision and synchronization (e.g., for complex aerial formations or precision agriculture), and the ability to use sophisticated global optimization algorithms. The disadvantages of the centralized approach include: high vulnerability to communication loss. If the Ground Control Station (GCS) or server fails, the entire swarm becomes uncontrollable. Furthermore, as the number of drones increases, the load on the communication channel and the computing center grows exponentially.

The decentralized approach includes the following advantages: unlimited scalability. A swarm with decentralized control is extremely resilient to the loss of individual agents. Each drone operates autonomously, which reduces response delays to obstacles.

Disadvantages of the decentralized approach include: limited predictability of the swarm's global behavior. High demands on the onboard computing power of each individual drone.

A detailed comparison of both approaches according to key technical parameters, including obstacle response delay and communication requirements, is provided in Table 1.

Considering the issue of navigation algorithmic support, it can be emphasized that centralized systems often employ global path planning algorithms (e.g., A*, Dijkstra), which calculate trajectories for the entire group. In decentralized systems, where each drone must make decisions locally, different approaches are applied: swarm Intelligence algorithms, which are based on observing the behavior of insects (e.g., bees or ants).

Table 1 – Comprehensive comparative analysis of approaches to autonomous navigation

Criterion	Centralized approach	Decentralized approach
Scalability	Low (limited by GCS bandwidth)	**High (virtually unlimited)**
Fault tolerance	Low (single point of failure)	**High (loss of a drone is not critical)**
Requirements for onboard computing	Minimal	**High (Edge Computing)**
Communication requirements	Constant broadband connection to GCS	**Local exchange of short packets (Mesh)**
Delayed reaction to obstacles	High (ping to GCS, calculation time)	**Low (sensor-level response)**

Each drone follows simple rules: avoid collisions, maintain speed and direction with nearest neighbors; the Artificial Potential Fields (APF) method, where each drone, obstacle, and target point generate virtual potential fields. Drones repel each other and obstacles but are attracted to the target, allowing them to autonomously avoid collisions; reinforcement Learning (RL), which utilizes neural networks trained on numerous simulations so that each drone learns optimal navigation decisions in various scenarios.

Despite significant progress in the development of local navigation algorithms that ensure a high level of autonomy for decentralized swarms, the practical implementation of these methods directly depends on the reliability of information exchange channels and the resilience of sensors. It is these components that become the most vulnerable in real-world operating conditions, bringing to the forefront the challenges of cybersecurity and the impact of electronic warfare (EW) means. If swarm intelligence algorithms or reinforcement learning determine how drones should make decisions, the information infrastructure determines whether they will have reliable input data for this and whether they will be able to coordinate their actions under conditions of external destructive influence. Centralized control is vulnerable to cyberattacks, as compromising the Ground Control Station (GCS) provides complete control over the swarm. Decentralized systems are more resilient but are also subject to threats. Interference created by electronic warfare means can completely paralyze a centralized system, while a decentralized swarm will continue to perform its mission by switching to a fully autonomous mode using onboard sensors.

Practical Application and the Future of the Technology. Thus, scenarios for the application of drone swarm control approaches have been considered. Both approaches find their use in various fields. Table 2 shows typical scenarios for each of the autonomous navigation methods.

The future of autonomous navigation lies in the use of hybrid systems. In such systems, the swarm is divided into clusters with local leaders. The leader acts as a central node for its group but communicates with other leaders based on a decentralized principle. This approach allows combining the advantages of both methods: global coordination and local resilience. The implementation of Edge Computing technologies enables drones to process sensor data locally, reducing latency and communication requirements, which is critical for decentralized systems.

Table 2 – Application scenarios of centralized and decentralized solutions

Scope of Application	Best Approach	Reason for Selection
Precision Agriculture	**Centralized / Hybrid**	The need for precise synchronization during processing
Light Shows	**Centralized**	Tight coordination for image generation
Search and Rescue Operations	**Decentralized**	Lack of stable communication, difficult terrain
Military Operations	**Decentralized / Hybrid**	High resistance to electronic warfare, loss of agents

CONCLUSIONS. The primary goal of this study was to create a comprehensive framework for the informed selection of swarm control architecture at the system design stage for civilian and military applications. The obtained results allow developers and researchers not merely to choose between two polar approaches, but to consciously design systems, taking into account the inevitable trade-offs. The work demonstrates that there is no universally better solution – efficiency is ensured only by the correspondence of the architecture to the environmental conditions and task requirements. It is emphasized that future progress in this field will be linked to the development of adaptive hybrid systems capable of dynamically changing their structure and utilizing distributed computing to achieve maximum autonomy and efficiency in real, complex environments. The choice of autonomous navigation architecture for a drone swarm is a complex trade-off that must consider the mission objective, environmental conditions, and resilience requirements. While the centralized approach offers high precision and global optimization, decentralized control provides the scalability and resilience that are critical for operation in real, complex conditions. The future development of autonomous drone swarm control systems lies in the transition to adaptive hybrid architectures that leverage advanced swarm intelligence algorithms, machine learning, and distributed onboard computing to ensure maximum efficiency and autonomy.

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