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Improved unmanned aerial vehicle control for efficient obstacle detection and data protection

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ABSTRACT

The article centers on the research objectives and tasks associated with developing a swarm control system for unmanned aerial vehicles (UAVs) utilizing artificial intelligence (AI). A comprehensive literature review was undertaken to assess the effectiveness of the "swarm" method in UAV management and identify key challenges in this domain. Swarm algorithms were implemented in the MATLAB/Simulink environment for modeling and simulation purposes. The study successfully instantiated and simulated a UAV swarm control system adhering to fundamental principles and laws. Each UAV operates autonomously, following target-swarm principles inspired by the collective behavior of bees and ants. The collective movement and behavior of the swarm are controlled by an AI-based program. The system demonstrated effective obstacle detection and avoidance through computer simulations. Results obtained highlight key features contributing to success, including decentralized autonomy, collective intelligence, UAV coordination, scalability, and flexibility. The deployment of a local radio communication system in UAV swarm control and remote object monitoring is also discussed. The research findings hold practical significance as they enable the effective execution of complex tasks and have potential applications in various fields.

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1. INTRODUCTION

In recent years, research in the field of group aviation control systems integrating artificial intelligence and swarm behavior algorithms has become an important and relevant scientific topic. Traditional methodologies based on individual control of each unmanned aerial vehicle (UAV) face limitations in effectively controlling large groups of UAVs [1]–[5]. The principles of swarm intelligence allow each UAV to operate autonomously, interacting seamlessly with other swarm members, which promises revolutionary discoveries in various fields. From advanced analysis of the earth's surface for environmental and geological studies to improved surveillance of fire zones, swarm management systems are opening up new perspectives.

Moreover, precise coordination between drones paves the way for breathtaking cinematic effects and facilitates effective search and rescue operations. These systems also promote automation by reducing human intervention in UAV operations [6]–[10]. However, addressing obstacle detection and avoidance challenges is key to unlocking the full potential of swarm-controlled UAVs (Figure 1).

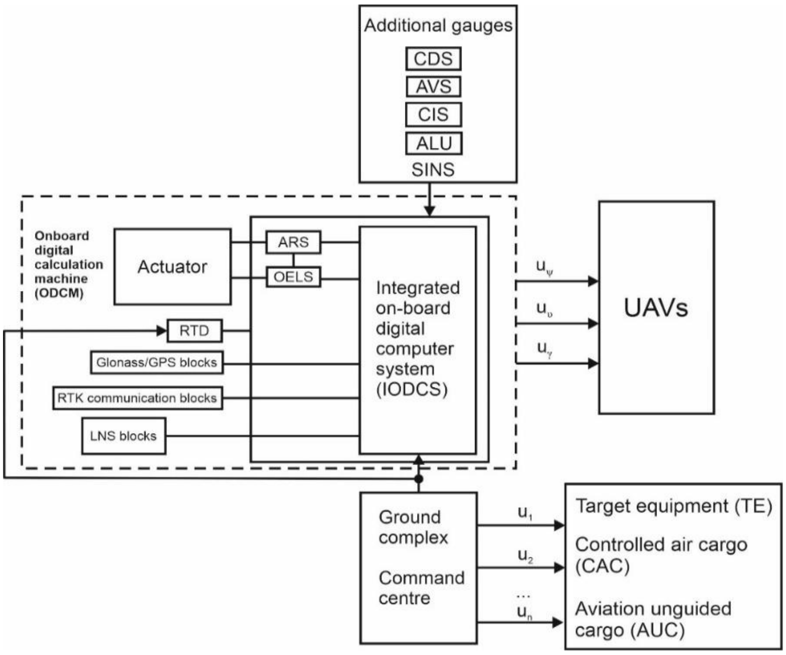


Figure 1. Structure of information-measuring and control systems of UAV

Recent research has focused on developing intelligent automatic control systems for obstacle detection and avoidance to improve the safety and reliability of UAV operation. Although some studies have proposed real-time obstacle detection algorithms [11], adaptive evasion strategies [12], and integration of control systems with sensors [13], challenges remain in achieving optimal obstacle detection and avoidance due to the complexity of the real environment and high costs [14]–[16]. The goal of this work is to develop a swarm control system for UAVs using artificial intelligence and swarm behavior algorithms, improving the performance of UAVs for various applications such as terrain analysis and surveillance. Challenges include developing obstacle detection algorithms, adaptive evasion strategies, sensor integration, and conducting computer simulations to validate algorithms. Successful completion of these missions will significantly improve the safety, reliability and effectiveness of UAV missions in a variety of real-world situations.

2. METHOD

The method for developing a control system for group aviation complexes was based on the theoretical foundations of swarming intelligence, artificial intelligence and control theory. Concepts of swarming intelligence, inspired by collective behavior in nature, have been used to develop algorithms that allow swarms of drones to work in concert. Artificial intelligence techniques, including reinforcement learning and deep learning, have been seamlessly integrated to control swarm behavior and decision making. Control theory principles have been important to ensure stability and optimal control of individual drones and collective swarms [17]–[22].

2.1. Implementation of software and hardware

The proposed control system was implemented in the MATLAB/Simulink environment, which provides modeling and analysis of the behavior of the swarm. Special software modules were created to simulate the behavior of individual UAVs, their communication protocols and a centralized artificial intelligence program. The UAVs have been designed with realistic flight physics and dynamics, carefully considering factors such as thrust, drag and aerodynamics. For hardware, a fleet of commercially available UAVs was used for testing and validation in real-world conditions. These UAVs were equipped with on-board processors, sensors and communication modules that ensure the coordination of the swarm and the execution of commands from the artificial intelligence program.

2.2. Experimental conditions

Simulations were conducted under different climate conditions to evaluate system performance and stability. Variables including changing weather conditions, obstacles in the flight path, and simulated communication disruptions were introduced to evaluate the swarm's adaptability and response to dynamic scenarios. The actual experiments were conducted in controlled open spaces that provided sufficient space for the drones to fly safely. The swarm was assigned predetermined missions and evaluation was made based on mission completion time, efficiency, and overall behavior of the swarm [23]–[27].

2.3. Checking the proposed solutions

Thoroughly tested swarm algorithms and artificial intelligence techniques were subjected to comparative analysis. The performance of the swarm-based control system was compared with traditional methods for controlling individual drones, evaluating the improvements achieved in efficiency and scalability. The adequacy of the proposed models was assessed by comparing the simulation results with real experimental data. The swarm behavior in both environments was analyzed for consistency, ensuring smooth translation of theoretical models into practical applications. In addition, the system's response to disturbances and unexpected scenarios during experiments was analyzed to evaluate the reliability of the proposed solutions [28]–[33].

Specific materials and methods in research on UAV control. As part of the study, specific methods were implemented that corresponded to the objectives of the study: i) UAVs were combined with a requirement of at least four for the study, with an emphasis on the selection and effective modeling of specific UAV models; ii) information and measurement technologies, including GPS devices, cameras, and sensors, were carefully selected and configured for real-time data exchange within the swarm; iii) various machine learning algorithms, such as enhanced learning, have been applied to optimize the performance and decision making of UAVs, with the choice of algorithm depending on the research objectives and available data; iv) UAV swarm simulation software facilitated virtual testing of the proposed control system, evaluating performance in different scenarios; v) virtual experiments were conducted under real-life conditions, deploying the UAV and performing various tasks to test the proposed system, including creating a prototype model; and vi) collected data from experiments, whether through data mining and analysis or simulation, was studied to evaluate system performance, taking into account metrics such as task completion time, coordination efficiency, and resource utilization. It is important to note that the materials and methods implemented in the work were adapted to achieve the specific objectives of the study, and mathematical calculations and images of computer simulations were presented in tables and graphs in the article. To ensure clarity and completeness of the description of the research methodology presented in this section, an image of a simulation of the experimental setup is provided, as well as an accompanying description.

The Figure 2 shows a diagram of the experimental setup for testing the control system for UAVs. The installation consists of a set of platforms on which UAV models and obstacles are located, as well as visualization and data collection tools. UAV models are equipped with sensors and communications to enable real-time interaction and synchronization. The experimental setup provides the opportunity for virtual and real testing of the UAV control system in various conditions, which allows us to evaluate its performance and reliability.

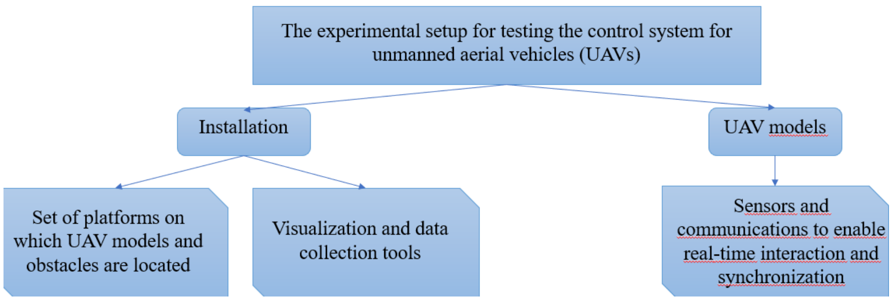


Figure 2. Schematic representation of the experimental setup simulation

3. RESULTS AND DISCUSSION

3.1. Algorithm for detecting obstacles in the operations of group unmanned aerial vehicles

A simulation study showed that the integration of advanced encryption techniques successfully improved data security in a swarm of UAVs. Encrypted communication channels ensure confidentiality and data integrity, which confirms the effectiveness of the system in conditions of instant adaptation in real time. This highlights the potential of advanced encryption for strong data protection in practical UAV applications

[34]–[39]. However, there are certain problems and limitations: High demands on on-board computing resources, the need for specialized control software, integration difficulties, and the need to avoid mutual interference between UAVs pose obstacles to UAV-based swarm operations.

Conclusions and prospects for future research: The review shows significant overlap in UAV operations involving multifunctional integrated avionics systems (IIAS) for both military and civilian applications. The urgent task is to create multifunctional UAVs capable of effectively solving various problems. Research efforts should be focused on refining multifunctional UAV development methodologies, including evaluation methods, models, and development algorithms.

3.2. Improving multispectral imaging of UAV using RF classification and RF spectral characterization

UAV equipped with multispectral cameras offer tunable image resolution based on flight altitude, but interpreting high-resolution images requires machine learning algorithms. Random forest (RF) method using linking or bootstrap aggregation shows superiority in image classification and obtaining spectral estimates through RF method. Simulation results demonstrate improved performance of RF compared to artificial neural networks and support vector machines, especially in quantitative remote sensing data analysis tasks as shown in Figure 3.

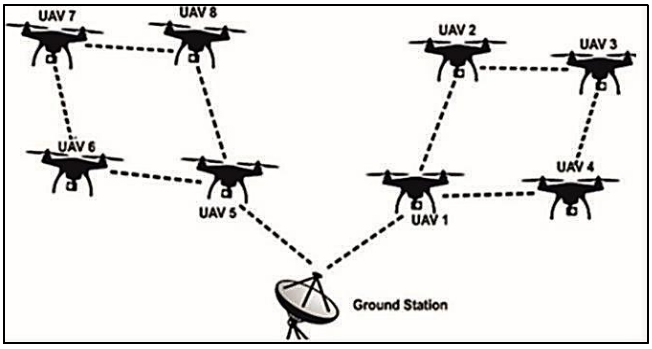


Figure 3. Communication with the UAV group

The integration of machine learning algorithms, advanced sensors and information technology technologies has expanded the applications of UAVs in various sectors, including computers, wireless networks, smart cities, military, communications, agriculture, and mining. One significant application is the creation of local radio communications with intelligent UAV systems. Which is critical for complex communications needs and military operations in closed radio conditions or local communications while moving in difficult terrain as shown in Figure 4.

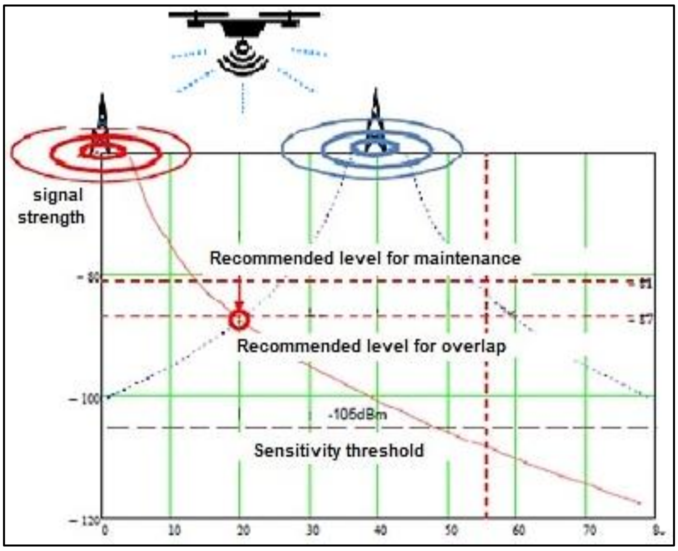


Figure 4. Example of UAV operation for local radio communication

UAVs, also known as drones, come in different types designed for specific purposes, such as light unmanned aerial vehicles with a flight range of up to 25-40 km and a take-off weight of up to 5 kg and heavy UAVs with long flight and a take-off weight of up to 1500 kg and flight range up to 1500 km (see Table 1). UAVs launched in swarms with intelligent control systems are proving highly effective in creating local radio communications. Swarm reconfiguration aims to find trajectories, optimize fuel consumption, avoid collisions, achieve desired shapes, provide optimal control sequences, prevent overthrust, and determine destinations for homogeneous UAVs while minimizing fuel consumption along the resulting trajectories.

Table 1. Types of UAV

UAV type	Take-off weight	Range
Light UAV	Up to 5 kg	25-40 km
Light medium-range UAV	Up to 5-50 kg	10-70 km
Medium class UAV	Up to 50-100 kg	70-150 km
Heavy medium-range UAV	Up to 500 kg	70-300 km
Heavy UAV with long flight	Up to 1500 kg	1500 km

3.3. Improving drone sensor integration for real-time data processing and positioning

UAV are equipped with a variety of sensors, including optical cameras, thermal sensors, lidar sensors for light ranging, lightweight portable radiometers (LPRs), and multispectral cameras as shown in Figure 5. During a group flight, UAVs process information in real time, and to service the system, all devices must determine their coordinates. The standard error (RMS) of control points is a key criterion for the accuracy of determining the coordinates of objects based on photographic material, defined as (1):

$$\Delta XY = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(l_i - \overline{l_i})^2} \quad (1)$$

where ΔXY is the SKO in the plan, n is the number of control points, – the planned coordinates of the control point measured by the total station, – the planned coordinates of the control point measured in the images.

Figure 5. Tetracam multispectral range camera

The group control system relies on independent trajectory and operational control for each UAV. UAVs determine their actions during flight, ensuring efficiency and maximum success while minimizing costs to the team. Artificial intelligence coordinates tasks during group UAV launches. The principles of collective control of UAVs include: i) each team member independently determines their actions based on shared goals, the status of the environment, the current state, and the actions of other team members; ii) optimal actions are aimed at maximizing the functionality of the goal defined in the near future period; and iii) compromise solutions are tolerated and priority is given to actions that benefit the entire team.

This collective control approach is effective in distributed multi-agent systems, providing low computational complexity for fast decision making in dynamic situations. Swarm intelligence techniques such as ant colony, bee, and particle swarm algorithms are considered promising solutions. These algorithms are based on simple rules for the behavior of an individual agent, which ultimately leads to an intelligent multi-agent system within a colony [40]–[45].

3.4. Development of software code for simulating group control of UAVs

In this section, we discuss in detail the development of program code for controlling a group of UAVs based on programming principles. Control and simulation code was created using MATLAB/Simulink. The focus group of UAVs includes three objects flying in the formation. With the arguments p, t, c, we create three UAV objects by setting their initial coordinates. A timeline is added and code is written for their trajectory and movement during flight.

During the flight of a group of UAVs, collisions with obstacles that arise at random points are simulated. This is critical to verify the training and adaptability of our UAV swarm control model to changing trajectories when encountering obstacles in different scenarios. Obstacles in the code are identified by the wallpoint argument and generated at random coordinates using the MATLAB/Simulink rand() function.

The process of creating a UAV control group begins. MATLAB/Simulink serves as a modeling environment, providing a high-level language and interactive software space for numerical calculations and visualization of results. All three UAV objects are added to a list designated uavList. A nested logical for loop is implemented, where the first level selects an object from uavList, and subsequent levels determine the coordinates of obstacles on the path of the UAV group. Using logical if statements, parameters are set to change the flight path when obstacles are detected. The first condition indicates a change in flight along the X-coordinate, and the second along the Y-coordinate. The n parameter determines the distance by which UAV objects will change their trajectory. The final program code is presented in Figure 6.

```
clear

f = figure
ax = axes(f, XLim=[0 10], YLim=[0 10])

al = animatedline(ax, "MaximumNumPoints", 50)
addpoints(al, 0, 0, 0)

hold on

wallpoint = plot(3, 3, 'o')

p=plot(0, 0, 'or')
t=plot(1, 0, 'or')

hold off

clock = 0

while isvalid(f)
    x= 0 + clock
    y= 0 + clock
    p.XData = x
    p.YData = y
    t.XData = x
    t.YData = y + 1

    if p.XData + 0.1 >= 2.75 & p.XData - 0.1 <= 3.7
        p.XData = p.XData + 0.5
    end
    if t.XData + 0.1 >= 2.75 & t.XData - 0.1 <= 3.7
        t.XData = t.XData + 0.5
    end

    clock = clock + 0.01
    drawnow
end
```

Figure 6. Listing of the program

Execution of the program results in a simulation of the flight of a group of UAVs, as shown in Figure 7. The program simulates the flight of a group of UAVs, as shown in Figure 7. In the image, the three red circular objects represent UAVs flying from the lower left corner to the upper right corner. Randomly placed crosses on the field represent obstacles. The simulation demonstrates the ability of a UAV group to maintain formation and control characteristics during navigation. This paper presents a software simulation method [46]–[49].

In Figure 7, the three red circular objects represent UAVs flying from the lower left corner to the upper right corner. Randomly placed crosses on the field represent obstacles. The simulation demonstrates the ability of a UAV group to maintain formation and control characteristics during navigation. This paper presents a software simulation method [46]–[49].

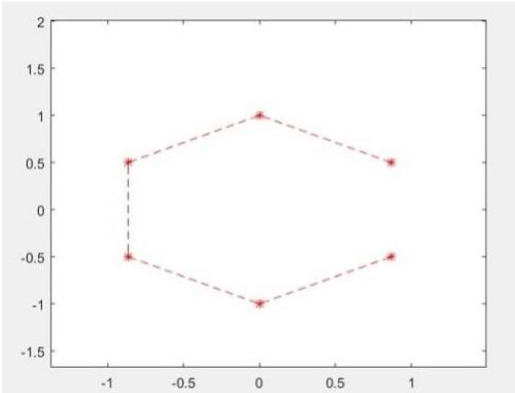
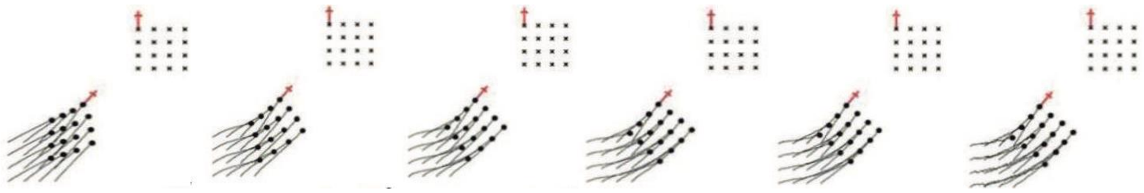


Figure 7. Flight simulation of an UAV system

3.5. Integration of artificial intelligence and swarm algorithms for optimal coordination of groups of UAVs

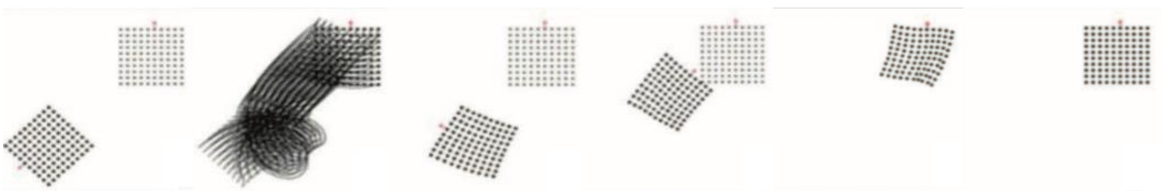
When the formation of a UAV formation encounters obstacles, the lead UAV maneuvers to change its trajectory, avoid the obstacle, and re-enter the formation without any problems. This maneuver is illustrated in detail in Figure 8, which is a graphical representation of obstacles to an UAV based on their distance, denoted by “ak.”. The subs of Figures 8(a) to 8(f) are as: (a) ak=0.1: depicts an obstacle close to the UAV; (b) ak=0.5: shows an obstacle at a distance of 0.5 from the UAV; (c) ak=1.0: illustrates an obstacle located at a distance of 1.0 from the UAV; (d) ak=2.0: displays an obstacle at a distance of 2.0 from the UAV; (e) ak=3.0: shows an obstacle at a distance of 3.0 from the UAV; and (f) ak=5.0: demonstrates an obstacle at a maximum distance of 5.0 from the UAV.



(a) (b) (c) (d) (e) (f)

Figure 8. Obstacles to the creation of an UAV, depending on the degree of remoteness ak: (a) ak=0.1; (b) ak=0.5; (c) ak=1.0; (d) ak=2.0; (e) ak=3.0; and (f) ak=5.0

Figure 8 demonstrates the efficient navigation of UAVs around obstacles at different distances (ak). When a formation of UAVs encounters obstacles, the lead UAV maneuvers to change its trajectory, avoid the obstacle, and return to the formation. This maneuver is illustrated step-by-step in Figure 9, which represents a step-by-step construction of the UAV maneuver to avoid obstacles. The subs of Figure 9 are as: Figure 9(a) the first stage of the maneuver, showing the initial phase of the trajectory change; Figures 9(b) to 9(e): Subsequent intermediate stages of the maneuver, demonstrating the successive steps of changing the UAV's trajectory to avoid obstacles; and Figure 9(f) the final result of the maneuver, where the UAV successfully avoided the obstacle and regained its formation.



(a) (b) (c) (d) (e) (f)

Figure 9. Step-by-step construction of an UAV maneuver for avoiding obstacles: (a) first stage, (b) second stage, (c) third stage, (d) fourth stage, (e) fifth stage, and (f) final result

Groups of UAVs skillfully avoid obstacles, reaching their destination without damaging their formation. The simulation produced successful results, with detailed analyzes presented in Table 2. The results calculated using (1) and presented in Table 2 indicate a technical level coefficient (KTY) of approximately 1.46, highlighting the development prospects for STS [50]. Flight of groups of UAVs autonomously solves emerging obstacles, showing success in 9 cases out of 10 in achieving mission goals compared to a simple automatic control system. This success is attributed to the introduction of advanced technology in the management system for groups of moving objects. The practical use of the group launch system in modern aviation consistently provides highly effective results [51].

Table 2. Analysis of estimated parameters in the IIUS information model for DN UAVs

IIUS parameter	Existing IIUS analogue	New IIUS model (under development)	Well-known world analogue
D (km)	200	300	350
Reliability	80	140	220

3.6. Analysis and reflections on the development and research of simulation of UAV swarm control systems

UAVs equipped with remote control capabilities play a key role in monitoring various locations and reporting potential hazards. This study, described in [52], [53] for signal propagation analysis, introduces a method to evaluate the efficiency of signal propagation. The proposed method stands out for its ability to efficiently estimate distances, which contributes to the reliability of the experimental results, as shown in Figures 8 and 9.

Although the algorithm exhibits optimal performance at a distance of 150% of the size of the unmanned vehicles, the study acknowledges certain limitations that require discussion. Algorithm performance may degrade over shorter distances, creating the risk of damaging the device. Minor damage to the rear of the device and increased maneuver time over shorter distances are observed. Addressing these issues may involve improving the algorithm to improve accuracy and efficiency.

Future research directions could explore advanced mathematical models and methodologies to enhance control system capabilities. However, implementation in the real world may face challenges due to the complex nature of UAV operations. Addressing these challenges has the potential to make significant advances in UAV intelligence, paving the way for safer and more efficient drone applications.

3.7. Description of techniques used

To achieve the set goals, a combination of advanced techniques and methodologies was used to facilitate the development and validation of an intelligent UAV control system. The techniques were involved in the work:

- Simulation in MATLAB/Simulink: MATLAB/Simulink was used to simulate the behavior of a group of UAVs, enabling the development and testing of flight algorithms. This simulation environment facilitated the analysis of different scenarios and evaluation of system performance under different conditions.
- Obstacle detection algorithms: advanced obstacle detection algorithms have been developed to improve the UAV's ability to detect obstacles in real time. These algorithms were designed to process data from multiple sensors, including optical cameras, thermal sensors, lidar sensors, and multispectral cameras, to accurately identify obstacles in the UAV's flight path.
- Adaptive avoidance strategy: an adaptive avoidance strategy has been developed to allow UAVs to dynamically adjust their flight paths in response to detected obstacles. This strategy involved calculating alternative flight paths based on real-time obstacle detection data, allowing the UAV to avoid obstacles while minimizing the risk of collision.
- Seamless sensor integration: a variety of UAV sensors, including optical cameras, thermal sensors, lidar sensors, lightweight handheld radiometers and multispectral cameras, have been seamlessly integrated with the control system. This integration enabled efficient data sharing and communication, providing accurate and timely information to detect and avoid obstacles.
- Computer simulations: comprehensive computer simulations were carried out to validate the developed algorithms and evaluate system performance. These simulations included testing the system in controlled environments with simulated obstacles and complex scenarios, allowing for thorough evaluation and improvement of the system's capabilities.

By using these techniques and methodologies, the research team was able to develop and validate an intelligent UAV control system capable of effectively detecting and avoiding obstacles during flight. These techniques have contributed to improvements in system accuracy, reliability, and efficiency, paving the way for improved safety and efficiency of UAV missions in a variety of applications.

3.7.1. Research review
In this study, a comprehensive work was carried out to develop and validate an intelligent control system for a group of UAVs. The main goals were to improve real-time obstacle detection and avoidance. As well as improve the safety and efficiency of UAV missions in various scenarios.

3.7.2. The discussion of the results
The results obtained allow us to draw the following conclusions. i) the developed algorithms for obstacle detection and adaptive bypass strategy demonstrate high efficiency in solving the assigned tasks. ii) seamless integration of various sensors has improved the accuracy and timeliness of obstacle detection, thereby increasing the reliability of the control system. And iii) computer simulations confirmed the performance and effectiveness of the developed algorithms in various scenarios, which provides further confirmation of the results.

3.7.3. Limitations and prospects for further research
One limitation of this study is the limited set of test scenarios and conditions. Future research should expand the range of test scenarios to include more complex and realistic conditions to further explore the capabilities of the control system. Another direction for future research could be to further improve obstacle detection algorithms and avoidance strategies for more accurate and reliable system operation. The use of new technologies such as deep learning to improve system performance should also be explored. In general, the results of the study confirm the effectiveness of the developed intelligent control system for a group of UAVs in the conditions of detecting and avoiding obstacles. Further research and development can make significant contributions to improving the safety, reliability and efficiency of UAV missions in a wide range of applications.

4. CONCLUSION
MATLAB simulation results have played a key role in the development of flight algorithms for UAV teams, facilitating collaborative efforts to increase mission speed and coverage. These algorithms have demonstrated high accuracy in detecting obstacles, ensuring system safety with a minimum number of false positives. An adaptive avoidance strategy was developed to allow the UAV to maneuver in real time around obstacles, reducing the risk of collisions and increasing operational efficiency. The seamless integration of the UAV's diverse sensors with the control system enabled efficient data exchange, facilitating accurate obstacle detection and avoidance. Comprehensive testing through simulation and real-life scenarios confirmed the reliability and efficiency of the system. This research represents a significant breakthrough in UAV control systems, contributing to improved safety, reliability and efficiency in a variety of applications.

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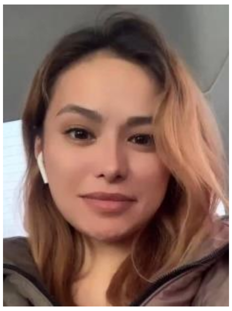

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