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Changing the Formations of Unmanned Aerial Vehicles

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Abstract: The development of hierarchical structures of unmanned aerial vehicles (UAVs) increases the efficiency of unmanned aerial systems. The grouping of UAVs increases the region of recognition or force of assault. Achieving these requirements is possible through a UAV formation. The UAVs in the formation must be controlled and managed by a commander, but the commander cannot control individual UAVs. The UAVs within the formation have assigned specific individual tasks, so is possible to achieve the flight of the formation with minimum collisions between UAVs and maximized equipment utilization. This paper aims to present a method of formation control for multiple UAVs that allows dynamic changes in the constellations of UAVs. The article includes the results of tests and research conducted in real-world conditions involving a formation capable of adapting its configuration. The results are presented as an element of research for the autonomy swarm, which can be controlled by one pilot/operator. The control of a swarm consisting of many UAVs (several hundred) by one person is now a current problem. The article presents a fragment of research work on high-autonomy UAV swarms. Here is presented a field test that focuses on UAV constellation control.

Keywords: unmanned aerial vehicle; mobile robotics; unmanned aerial system; formation; quadrotor

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1. Introduction

An unmanned aerial vehicle does not have a crew on board, but the staff controls the functions of UAVs from a ground station. The number of personnel depends on the size of the UAV. The UAV has a crew whose number ranges from several people to one person. A multi-UAV system has an extensive crew. The widespread use of UAVs by land and aerial forces generates staff demand. Therefore, methods are being sought to control and manage multiple UAVs by reducing the number of staff (if possible, to one person). In such solutions, it is necessary to change the roles of personnel from those handling controls to commanders. Moreover, UAVs must have a high level of autonomy.

Now, UAVs' control and management processes can be divided into three areas. The first is focusing on the UAV classes HALE and MALE. The personnel of the ground station have full control over the UAV. Automatic processes are responsible for monotonous operations (e.g., flight to the operation zone) and routine processes (e.g., take-off or landing). The move parameters, navigation parameters, maintenance parameters, and mission planning are controlled by the staff of the ground station. This kind of UAV does not have a high level of autonomy, so the UAV is at level two of autonomy (on a scale of five levels).

The next area of activity for UAVs refers to a group of UAVs. These UAVs can merge into a group and a few persons must control them together. This kind of activity strives to change the role of a person from a pilot, navigator, etc. to a commander. The construction of a UAV must ensure an autonomy level of three or greater. The UAVs operate as follows:

- The UAVs have independent tasks but operate in a common airspace;
- The UAVs are merged in a formation (constant constellation of UAVs with a hierarchical structure);

- The UAVs are merged as a swarm (the UAVs behave as structures modeled on natural processes taken from nature).

The last area of activity concentrates on collaboration between manned and unmanned vehicles. Future war assumes a saturation with UAVs. However, UAVs can be a threat to manned vehicles. The UAV can change its trajectory under the influence of natural disturbances and the activity of the enemy, which can lead to collisions with the manned vehicle. The problem of collaboration between manned and unmanned vehicles especially applies to manned and unmanned teams (MUTs), which use mini-UAVs. This type of UAV cannot be equipped with a high-precision navigation and communication system. The way to solve this problem is to develop a formation of MUTs with different constellations of manned and unmanned vehicles. The role of each vehicle is distributed by individual task allocation.

Flights in UAV formations represent a groundbreaking innovation in the fields of robotics and aviation technology. Drawing inspiration from nature, such as from the flight of birds, this concept opens up new possibilities in scientific research and commercial applications. This article delves into the technical and operational aspects of drone formation flights, analyzing key challenges such as synchronization, navigation, and collision avoidance.

A UAV system consist of a ground station, communication systems, and unmanned aerial vehicles (UAVs). The ground station can simultaneously monitor the operations of multiple UAVs. Therefore, the management of the airspace, where unmanned aerial vehicles operate, becomes a crucial issue. The form of management depends on the system's purpose or the tasks it is meant to perform. Various examples of tasks performed by UAVs—both civilian and military—can be presented. The system's management style is influenced by the degree of autonomy. A low degree of autonomy assigns superior functions to personnel while increasing autonomy significantly reduces the need for personnel but places high demands on self-organization, learning capabilities, and decision optimization by UAVs. Increasing autonomy requires higher levels of automation, structure-state monitoring, and environmental monitoring. Advanced control systems on board UAVs and the ground station (GS) are crucial elements of the system.

The organization and control of UAV formations are areas of interest for scientific communities. Countries striving to catch up in the technological race in the field of manned aircraft and large UAVs show significant activity in this area. Research focused on the use of small and simple UAVs aims to increase system efficiency through group and swarm operations. A considerable portion of the research revolves around the use of UAVs in formation. Studies have focused on controlling the formations of aircraft [1–4], and multirotor flying platforms [5–7]. The specific nature of formation flight addresses issues such as flight trajectory planning and optimization [3,8], collision avoidance [9,10] and cooperation between the UAVs [11–14], and the organization and maintenance of formations [15,16]. Since maintaining coherence during formation flight is essential, many studies have aimed to develop complex formation control systems [8,17–21].

The article presents practical aspects related to the execution of operations by UAV formations. An algorithm is introduced that enables the adoption of a specific formation and maintains its coherence.

2. Organization of Flights in Shared Airspace

Depending on the purposes of unmanned aerial vehicles (UAVs), flights in a shared airspace can be conducted thus:

- individually by each UAV;
- in formation by a group of UAVs;
- in swarms of UAVs.

2.1. Individual Flight of UAVs

Individual flights in shared airspace do not preclude collaboration between UAVs. Unmanned aircraft systems (UASs) of this type are characterized by the individual assignment of tasks to each UAV. However, there are areas where collisions between UAVs may occur. These areas include the landing zone and task execution zones. In these areas, it is essential to regulate the movement of UAVs to prevent collisions. Task zones can be organized to avoid collisions [22,23], but it is not always possible to arrange the operation of UAVs in such a way. A solution for organizing the operation of UAVs in these zones is to assign priorities to them, which should facilitate decision making in situations of collision (conflicting interests).

In the landing zone, the ground station (GS) assigns priorities to individual UAVs ranging from I to III. Priority I indicates the risk of losing the ability to fly due to depleted energy resources. This priority relates to vital functions associated with sustaining the 'life' of a UAV. The highest value is assigned to this priority because a fully operational UAV can be lost due to energy depletion in batteries or fuel consumption. The system gives absolute priority to such UAVs in the landing phase.

Priority II is assigned to UAVs signaling malfunctions. These UAVs have limited capabilities to perform tasks, including continuing flight. Therefore, all other UAVs yield to these damaged UAVs. Only UAVs with Priority I have precedence because there is always a risk that the damaged UAV may not reach its destination, which could lead to the loss of both the fully operational UAV with depleted fuel and the damaged one. UAVs that do not meet the above priorities have the lowest priority. Individual returning UAVs are queued on the descent path. Priority may change during the process. In the case of collisions in the task zone, the organization is subordinate to task execution. The characteristic features of such a UAS in operation are as follows:

- It performs automatic take-off and landing operations individually by each UAV;
- It performs individual tasks in a specified area by a UAV;
- It operates at different altitudes/areas.

2.2. Flights in UAV Formations

Enhancing the system's efficiency can be achieved by organizing UAVs into formations. Increased striking power or expanded search areas can be obtained through systematic coordination within a formation. Maintaining a formation requires orchestrating collaboration scenarios among UAVs and imposing a cohesive technical specification for each aircraft.

The basis for creating formations is a hierarchical structure that encompasses various levels related to leading/commanding each formation. The formation commander issues orders to subordinate members of the formation, and depending on the levels of autonomy of the UAVs, this information undergoes analysis by the commander. Commanders at different levels and formation members create an arrangement that should be tailored to the specifics of the assigned task. Such an arrangement should be characterized by the following:

- Flexibility during maneuver execution;
- Enabling reconfiguration into various constellations;
- Facilitating the introduction of individual UAVs into operation;
- Preventing collisions between UAVs operating in formation.

It is assumed that the UAV members of the formation are identical while commanders may differ structurally from the formation members. The ground station (GS) communicates with and issues commands only to the commanders. Due to the hierarchical structure, this communication occurs only with the highest-level commander. There is no need to communicate with individual UAVs. Such a solution significantly simplifies and limits radio emissions, which can ensure the covert operation of the system. The downside of this approach is the complex structure of data exchange and the system's dependence on a built chain of actions. Establishing a rigid chain of command without mechanisms for competence transfer can lead to a loss of task execution capabilities.

2.3. Flights in Swarm of Unmanned Aerial Systems (UAS)

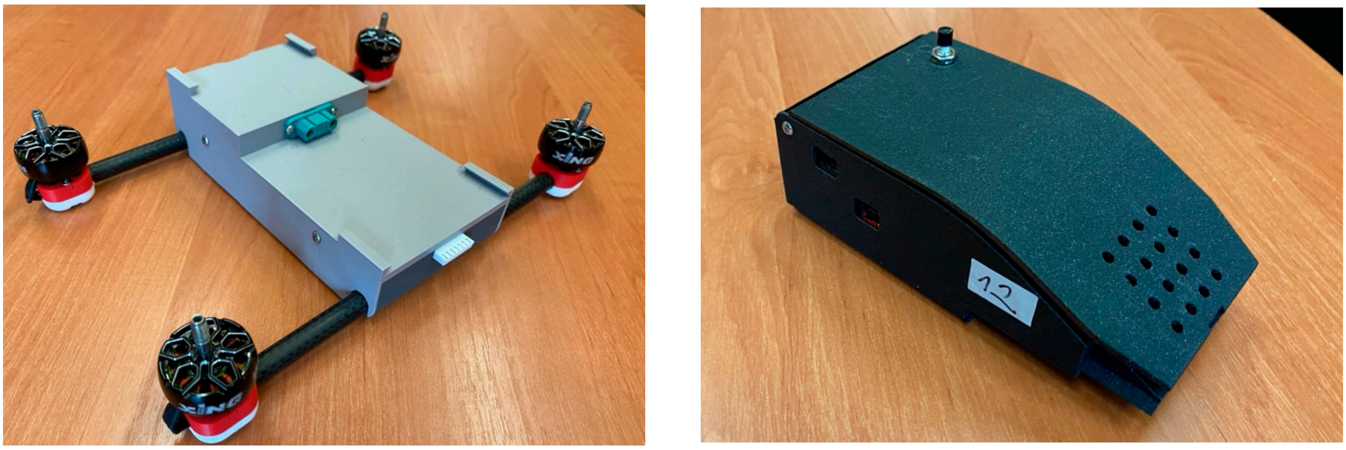
A swarm is a collection of many UAVs whose individual tasks combine to enable the swarm to perform a collective mission. A swarm is characterized by its own 'intelligence'. The principles of organization depend on the algorithm applied. One of the commonly used approaches is the adoption of an algorithm that mimics the behavior of animal flocks, such as the Flocking algorithm or the Boid algorithm (algorithms simulating the behavior of herding animals, birds, or fish). Such an algorithm assumes the natural formations of larger groups of UAVs while also incorporating rules for avoiding obstacles, dispersing the swarm after a predator attack, detecting feeding locations where UAVs stop, and recognizing a leader in the swarm that others follow. The swarm adheres to three rules:

- The alignment of the course and speed of the UAVs;
- Maintaining a minimum distance between UAVs;
- Ensuring that the UAVs attempt to stay in the center of the swarm.

Individual UAVs may leave the swarm if there is a need to restore their capabilities or if circumstances arise that exclude their activity. Since a swarm is composed of several dozen UAVs, the striking power of such a group or the covered area can be significant. Furthermore, the swarm can be formed by UAVs with uniform equipment, allowing the replacement of multi-sensor platforms. Additionally, swarms of flying robots can be spatially deployed.

3. Small Unmanned Aerial Vehicle

A quadcopter, an unmanned aerial vehicle powered by four propellers, is an example of innovative UAV technology. Its basic structure consists of a lightweight but durable frame that integrates key components: four electric motors with propellers, positioned at the ends of arms extending from a central point; an avionic system; and a rechargeable battery. These independently controlled propellers provide an exceptional vertical take-off and landing (VTOL) capability and stability and maneuverability in the air. The construction of the quadcopter is depicted in Figure 1.



(**a**) (**b**)

Figure 1. Construction of the quadrotor: (**a**) the power supply and drive module; (**b**) the control module of the UAV.

The UAV software (UAVbee version 1.8) is a crucial element responsible for its fundamental functionalities, such as its precise control, navigation, and the execution of complex tasks. The avionic system of the UAV includes sensors, a GNSS receiver, and a flight controller [5]. The flying platform enables communication with the user through dedicated applications or interfaces. Figures 2 and 3 illustrate an exemplary design of the UAV utilized in formation flight tests [1,11,20].

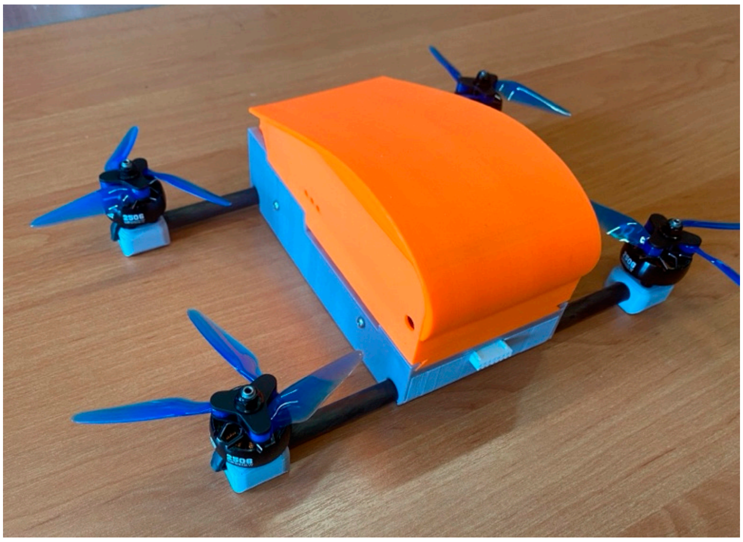


Figure 2. One of the flying platforms used in the research.

Figure 3. The flying platform during tests.

The quadrotor has advantages such as in its maneuverability, hovering, and vertical take-off and landing (VTOL). Unfortunately, it does not have a large payload and flight range. UAV aircraft carry large loads over longer distances at high speeds [24]. Therefore, UAV quadrotors are used in civil and military applications, where VTOL and hovering are important. An example of an autonomous [25] UAV system is the Falcon Drones company's UAV inspection and monitoring system. This system is dedicated to patrolling industrial infrastructure. The industrial zone does not have enough space for the taking off and landing of aircraft. The system has a docking station where the quadrotor lands and takes off. That is why the VTOL function is so important. Hovering allows for the precise inspection of selected waypoints.

Quadrotors are used for reconnaissance and to strike targets up to several kilometers from troops in military applications. Due to their size, they are easy to use and accompany soldiers in many missions. Fixed-wing aircraft and multirotors have many advantages and complement each other, which is evident in military solutions.

3.1. The Mathematical Model of the Quadrotor

The quadrotor structure is presented in Figure 4, including the corresponding forces, torques, and orientation angles (pitch—θ, roll—ϕ, and yaw—ψ). Forces and torques are generated in the body frame ($Ox_by_bz_b$) whereas the orientation angles are described as relations between the body frame and the Earth frame (Oxyz). The quadrotor has six degrees of freedom, so the movement of the quadrotor is rewritten by six equations (three translation motions and three rotation motions) [26].

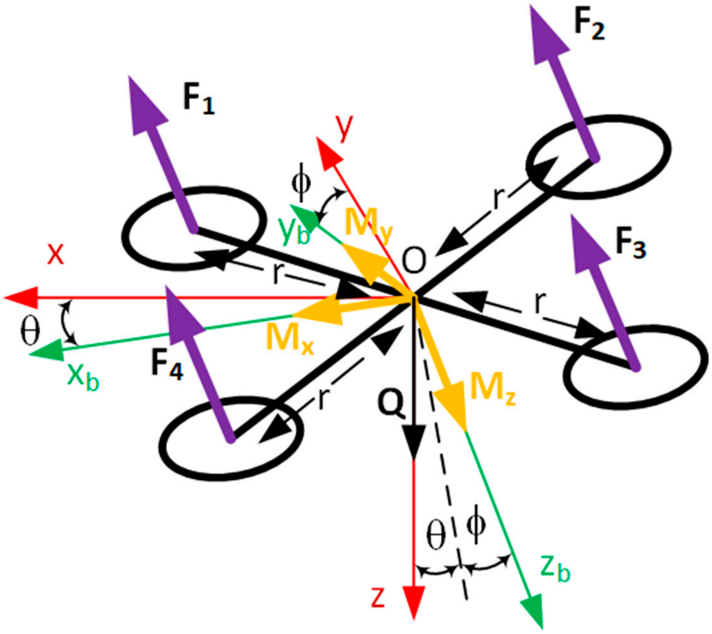


Figure 4. Body frame ($Ox_by_bz_b$) and Earth frame (Oxyz).

The translation motions are rewritten as follows [26,27]:

$$m(\mathbf{V_B} + \boldsymbol{\omega} \times \mathbf{V_B}) = \mathbf{F_b}, \tag{1}$$

Here, m is the mass of the quadrotor, $\mathbf{F_b} = \begin{bmatrix} F_x & F_y & F_z \end{bmatrix}^T$ is the force vector in the body frame, $\boldsymbol{\omega} = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$ denote the angular rates in the body frame, and $\mathbf{V_b} = \begin{bmatrix} v_{xb} & v_{yb} & v_{zb} \end{bmatrix}^T$ is the velocity in the body frame.

The rotation motions are rewritten as follows [26,27]:

$$I\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times I\boldsymbol{\omega} = \mathbf{M_b}, \tag{2}$$

Here, $\mathbf{M_b} = \begin{bmatrix} M_x & M_y & M_z \end{bmatrix}^T$ is the vector of moments in the body frame and I is the matrix moment of inertia:

$$I = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix}.$$

The relationship between the angular velocity $\boldsymbol{\omega}$ and rate of change of Euler angles (pitch, roll, and yaw) $\dot{\eta} = \begin{bmatrix} \dot{\phi} & \dot{\theta} & \dot{\psi} \end{bmatrix}^T$ is depicted below:

$$\dot{\eta} = \mathbf{J}\boldsymbol{\omega}.$$

Here,

$$\mathbf{J} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix}.$$

The resultant thrust is created as a sum of forces generated by the driver units:

$$F_w = \sum_{i=1}^{4} F_i.$$

So, the vector force from Equation (1) is equal to the following:

$$\mathbf{F_b} = \begin{bmatrix} 0 & 0 & F_w \end{bmatrix}^T.$$

The moment vector from Equation (2) is equal to the following:

$$M = \begin{bmatrix} r(F_1 + F_2 - F_3 - F_4) \\ r(F_1 - F_2 - F_3 + F_4) \\ \sum_{i=1}^{4} M_i \end{bmatrix}. \quad (3)$$

Here, r is the radius of the action force and M_i is the torque around the driver unit axis. The last element in Equation (1) is the influence of gravity on the quadrotor.

3.2. The Control System of the Quadrotor

A UAV control system consists of an attitude reference system, an autopilot, and a flight manager system. The attitude reference system is responsible for obtaining the pitch (θ) and roll (ϕ) angles (Figure 4). These angles inform us about the UAV's position in space; they are measured relative to the Earth's surface. The ability to control the pitch and roll angles decides the stable flight of the quadrotor UAV.

The pitch and roll angles are controlled by torques around the Ox axis and Oy. The torques can be controlled by changing the thrust of the drive units. The thrust forces F_1, F_2, F_3, and F_4 generated by the drive units are presented in Figures 4 and 5. Torques M_x and M_y result from asymmetric change forces generated by the driver units (Equation (3)). This is why the inner loop controls UAV space orientation (Figure 5).

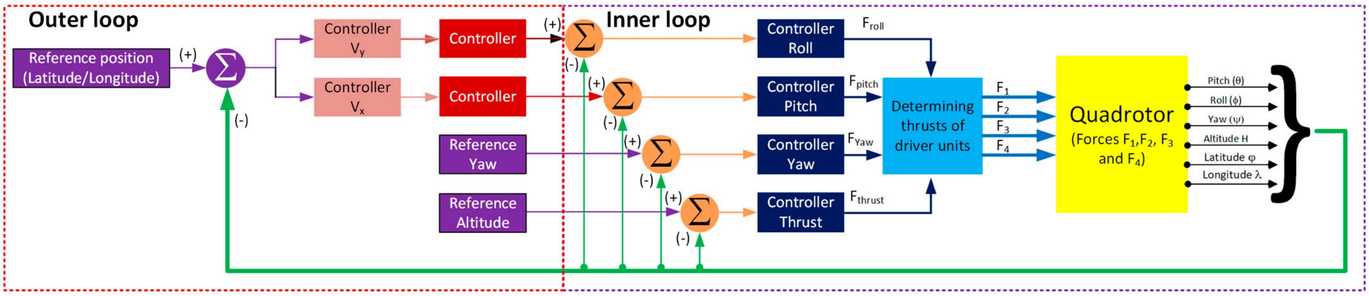


Figure 5. The flight controller.

The next element of UAV control is the autopilot. This element stabilizes the UAV velocity V, altitude H, and course/heading ψ. The autopilot controls the position of the UAV and generates components of velocity V_x and V_y (Figures 4 and 5). Next, the outer loop controllers create the pitch θ and roll ϕ reference value. The outer loop sets the reference value of the altitude and yaw. The course ψ and velocity V depend on the combination of V_x, V_y, and the yaw.

The inner loop has a special block, "Determining thrusts of driver units". This block mixes the components of forces and obtains the values of thrusts (F_1, F_2, F_3, and F_4). The thrusts are equal to the following:

$$F_1 = F_H - F_\phi - F_\theta + kM_\psi;$$

$$F_2 = F_H - F_\phi + F_\theta - kM_\psi;$$

$$F_3 = F_H + F_\phi + F_\theta + kM_\psi;$$

$$F_4 = F_H + F_\phi - F_\theta - kM_\psi;$$

Here, F_h, F_ϕ, and F_θ are the thrust components from the altitude, pitch, and roll; M_ψ is the changing torque of the driver unit; and k is the constant factor.

The flight controller uses six controllers to stabilize the UAV position and movement. Different kinds of controllers control the UAV (fuzzy logic controllers, robust controllers, sliding controllers [28–35]). But the most popular are PID controllers. The control law of the PID has proportional, integration, and differential operations. The control laws in the inner loop [33,34] are as follows:

$$F_{roll} = K_{p_{roll}}(\theta_{ref} - \theta) + K_{i_{roll}} \int (\theta_{ref} - \theta)dt + K_{d_{roll}} \frac{d(\theta_{ref} - \theta)}{dt};$$

$$F_{pitch} = K_{p\_pitch}(\phi_{ref} - \phi) + K_{i\_pitch} \int (\phi_{ref} - \phi)dt + K_{d\_pitch} \frac{d(\phi_{ref} - \phi)}{dt};$$

$$F_{yaw} = K_{p\_yaw}(\psi_{ref} - \psi) + K_{i\_yaw} \int (\psi_{ref} - \psi)dt + K_{d\_yaw} \frac{d(\psi_{ref} - \psi)}{dt};$$

$$F_{thrust} = K_{p\_thrust}(H_{ref} - H) + K_{i\_thrust} \int (H_{ref} - H)dt + K_{d\_thrust} \frac{d(H_{ref} - H)}{dt}.$$

Here, K_{p_xx} is the proportional coefficient, K_{i_xx} is the integration coefficient, and K_{d_xx} is the differential coefficient.

The next part of the UAV control system is the flight manager system (FMS). This system stores information about the flight path, UAV altitudes at the waypoints, UAV velocity, and task allocation (Figure 6). The task allocation assigns a UAV position in the formation. The flight manager system has a radio connecting it with the formation leader. The leader can influence a UAV task.

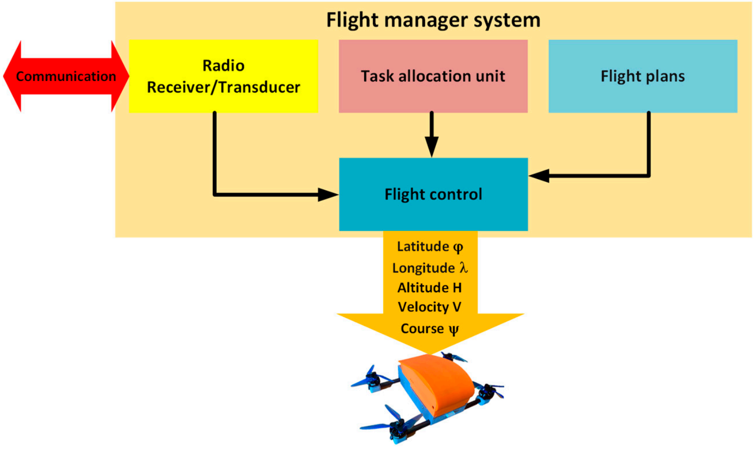


Figure 6. Flight manager system.

The FMS, from the flight plan, task allocation, and leader's orders, creates the desired position, altitude, and velocity. Artificial intelligence algorithms are used to obtain flight parameters (Figure 6). This system is necessary when the UAV performs autonomous flight. The electronic equipment of a UAV is shown in Figure 7.

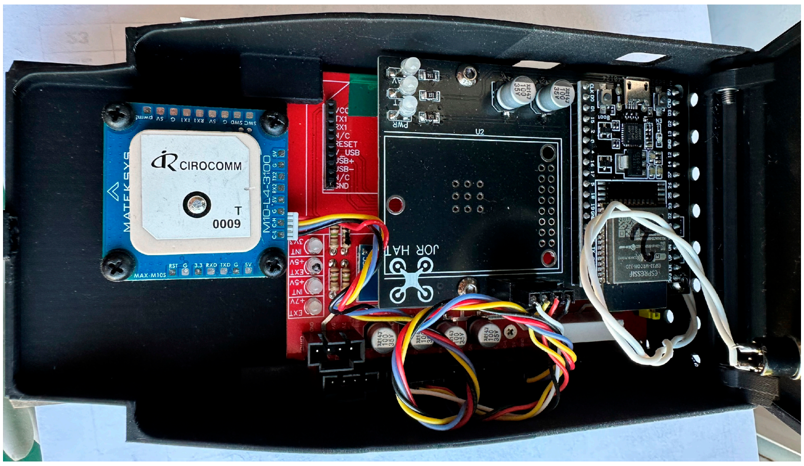


Figure 7. Electronic equipment of the UAV.

3.3. *UAV Experimental Verification*

The platform was tested to confirm the desired parameters. Figure 3 shows the flying platform during tests. The tests were divided into two parts. The first test was focused on confirming vertical move parameters. There was a verified altitude and position stabilization. The flying platform had desired altitudes of 100, 200, 300, and 400 m (Figure 8). The measure was repeated to increase and decrease the altitude of the UAV. The speed was equal to 0 m/s (Figure 9), so the flying platform stabilized the position (longitude and latitude).

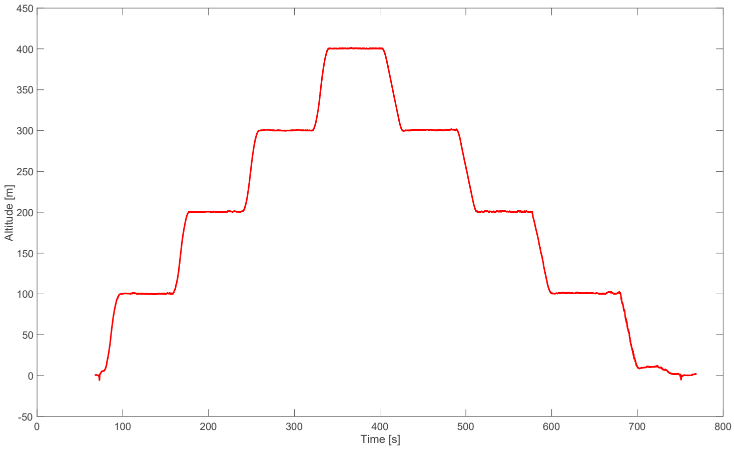


Figure 8. The measured altitude: test of the vertical UAV movement.

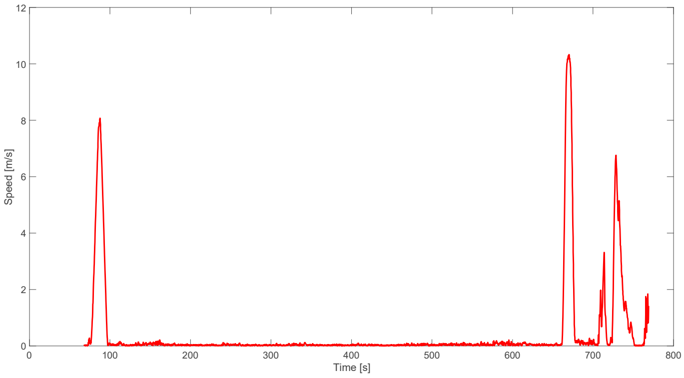


Figure 9. The measured speed: test of the vertical UAV movement.

The next test focused on the stabilization speed and heading. The stabilization of the horizontal movement parameters was tested there. The flying platform, after take-off, flew to the desired point (waypoint). If the UAV achieved a waypoint, it changed course to a counter-course.

Figure 10 presents the speed of the UAV. The desired speed was equal to 10 m/s. The altitude and heading are presented in Figures 11 and 12.

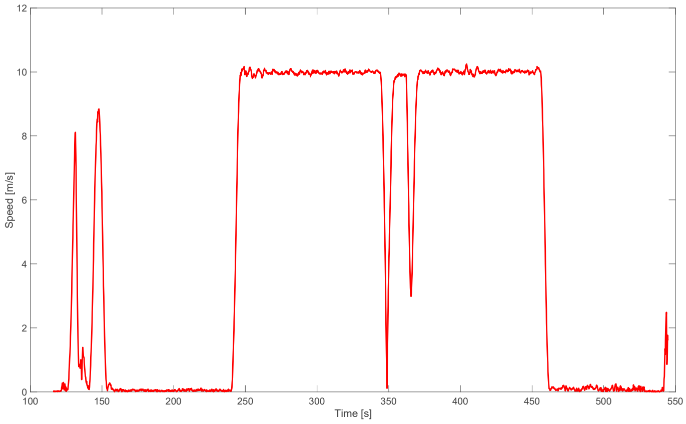


Figure 10. The measured speed: test of the horizontal UAV movement.

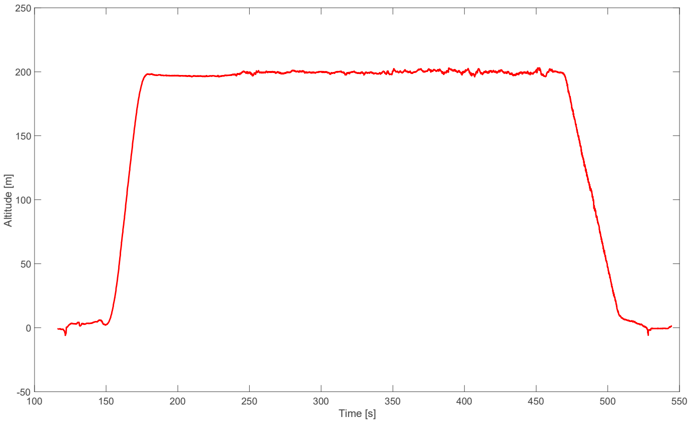


Figure 11. The measured altitude: test of the horizontal UAV movement.

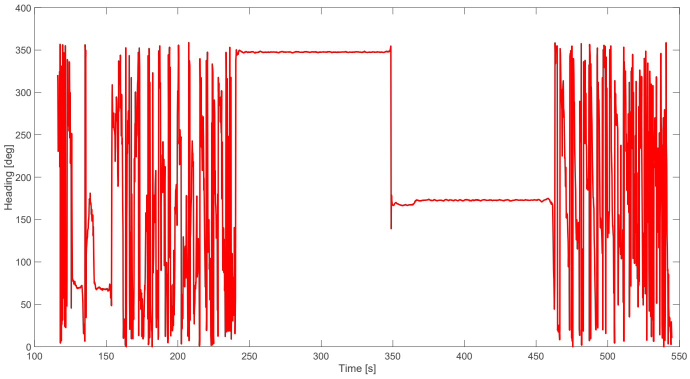
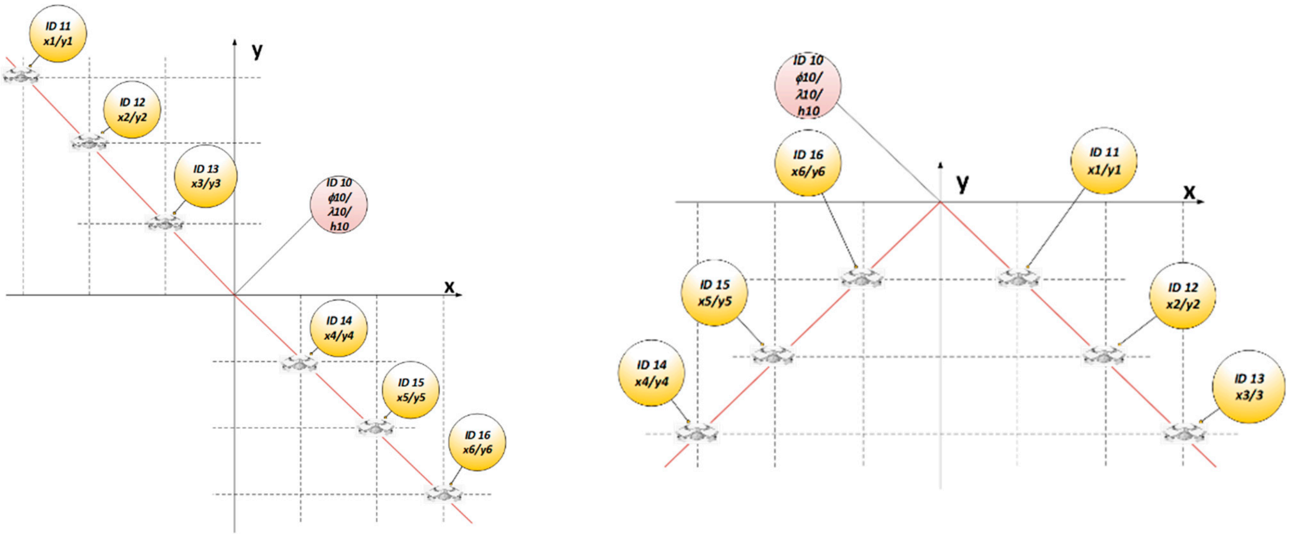


Figure 12. The measured heading: test of the horizontal UAV movement.

4. Organization of UAV Formations

Formations of unmanned aerial vehicles (UAVs) can have various constellations. The simplest constellation involves replicating the shape of a geometric figure such as a line, rectangle, triangle, or hexagon (Figure 13). Each unmanned aerial vehicle has an identifier (ID) that determines the position of the aircraft in the formation (Figure 13).



(**a**) (**b**)

Figure 13. Flight formation configurations: (**a**) the line formation; (**b**) the triangle formation.

The primary task of maintaining the formation is to avoid collisions during the flight of unmanned aerial vehicles (UAVs). Coordinated UAV operation in the same airspace can lead to collisions; therefore, the formation provides separation between UAVs (Figure 9). The separation value is determined by both UAV motion parameters as well as the resolution and precision of navigation sensors. Maintaining separation ensures the safe operation of the formation. This is the main task of the formation control system. The formation commander sends information about the desired position of the formation. UAVs obtain new positions in the formation and move to a new location (UAVs consider information about the memorized separation—Figure 14).

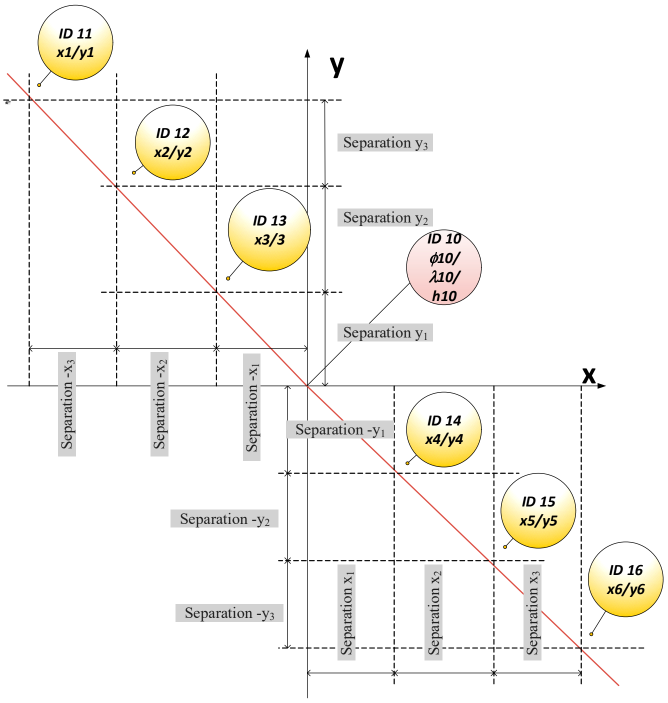


Figure 14. Horizontal separations in formation.

If the formation changes, the team leader sends information about the desired constellation. The UAVs obtain new positions in the formation. After a series of necessary calculations, the appropriate command is sent to the flight controller. The UAVs change altitude before they change positions. This step ensures vertical separation between UAVs and the safe horizontal movement of UAVs during moving to the new positions. The procedure change of the formation finishes when the UAVs come back to the desired altitude.

When the leader sends information about the new position of the formation (frequently, this is the position of the leader), all UAVs obtain the new desired position. After a command from the leader, the formation moves to the new position (Figure 15).

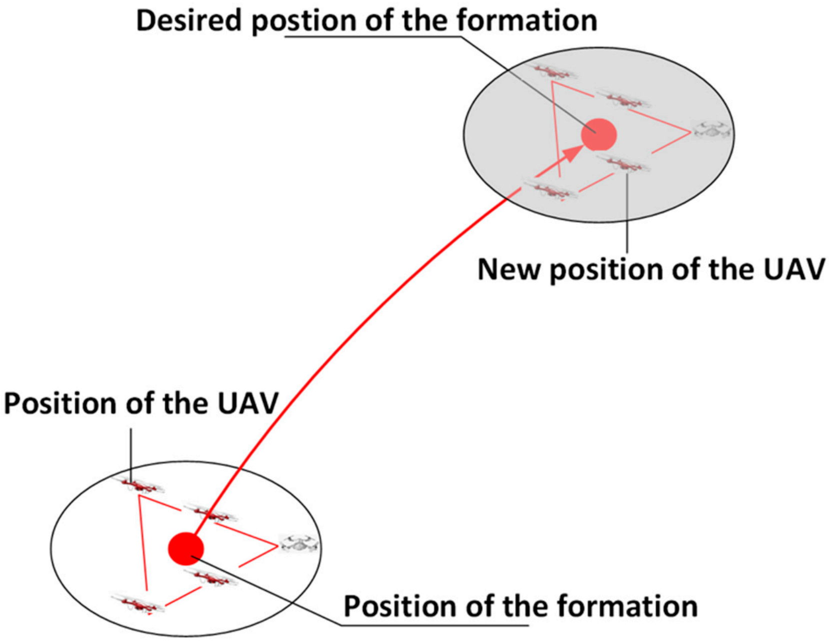


Figure 15. Movement to successive positions in the formation.

5. In-Flight Testing

An essential aspect of performing tasks by UAV formations is adopting a configuration tailored to the task at hand. While the formation is in transit, the adopted arrangement should be characterized by the dispersion of aircraft to avoid collisions between them. Conversely, the take-off and landing maneuver should involve a higher concentration of aircraft, resulting in a limited area for the deployment of the aircraft. Additionally, during search operations, formation flight may require a denser configuration, especially during precise searches at low altitudes. A similar search operation, aimed at roughly covering a large area, may necessitate loosening the formation to increase the area controlled by the formation.

During verification tests, maneuvers were conducted to change the formation from a line to a wedge/triangle and vice versa. A line formation is characterized by the elongation of the formation unlike in a wedge formation.

A line formation is shown in Figure 16. UAV number 1 in Figure 16 is the commander of the formation. The UAVs from numbers 2 to 6 are members of the formation. The triangle formation is depicted in Figure 17. The UAV IDs are the same as in the line formation. The formation commander (ID 1) has not changed position during the reconfiguration of UAVs from the line formation to the triangle formation.

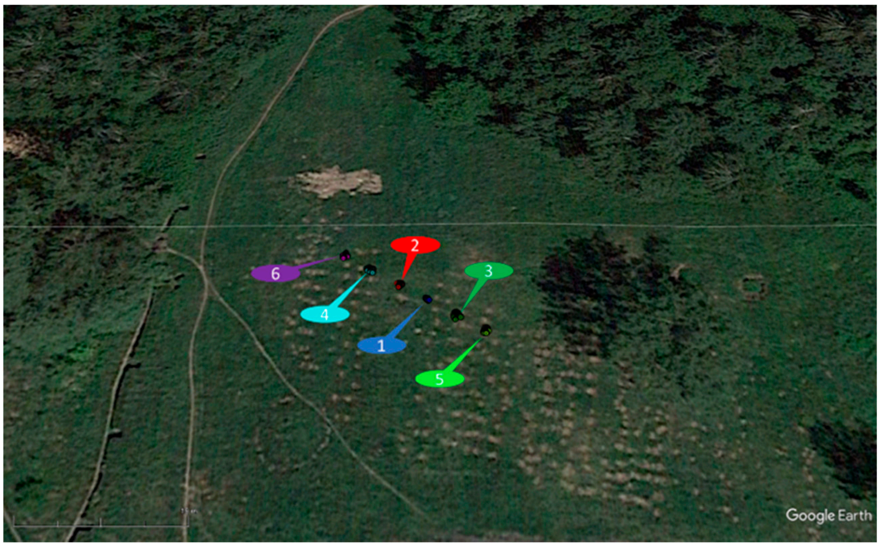


Figure 16. UAVs organized in a line formation.

Figure 17. UAVs organized in a triangle formation.

The transition from a line formation to a triangle formation is illustrated in Figure 18. There is depicted the first step. All UAVs form a line formation, stabilizing their positions and altitudes. Next, the UAVs disperse by changing their flight altitudes (Figure 19). This maneuver ensures the safe operation of the system. The UAVs have different vertical positions, preventing collisions during the transition to the new position. The altitude change is presented in Figure 20 and the vertical speed in Figures 21 and 22. Vertical speed is measured within the NED coordinate system, so negative speed indicates an increase in the altitude (Figure 21).

In the next step, UAVs move to new positions (Figure 23). The airspeeds of the UAVs are shown in Figure 24 When the UAVs reach the desired positions, they return to the operational altitude. Figures 18 and 22 depict the vertical speed and altitude change as the UAVs complete the transition from a line formation to a triangle formation. The outcome of the maneuver is presented in Figure 23.

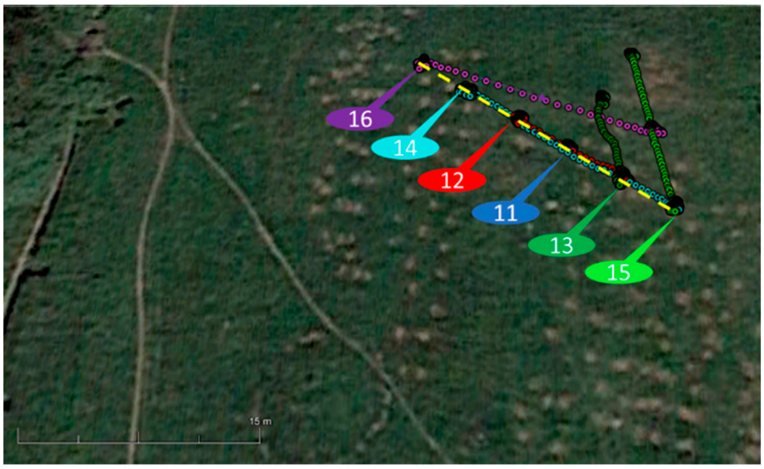


Figure 18. The transition from a line formation to a triangle formation.

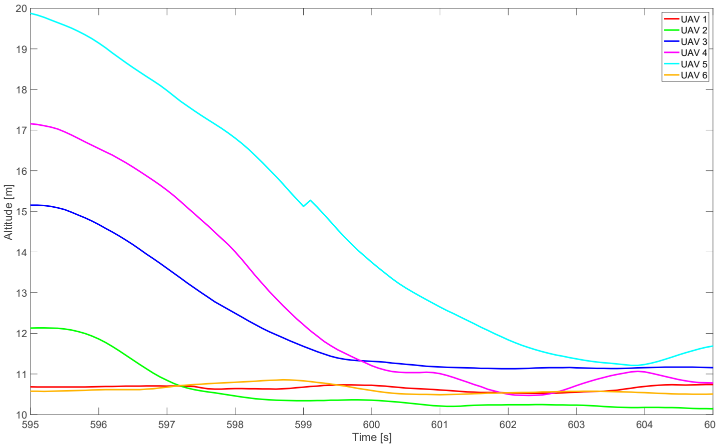


Figure 19. Change in the altitude of UAVs—the last step of reconfiguration from the line to the triangle formation.

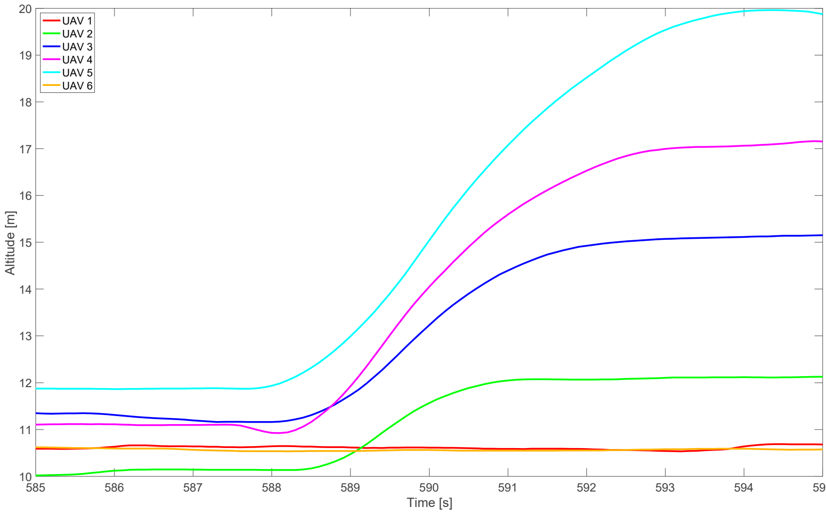


Figure 20. Change in the altitude of UAVs—the first step of reconfiguration from the line to the triangle formation.

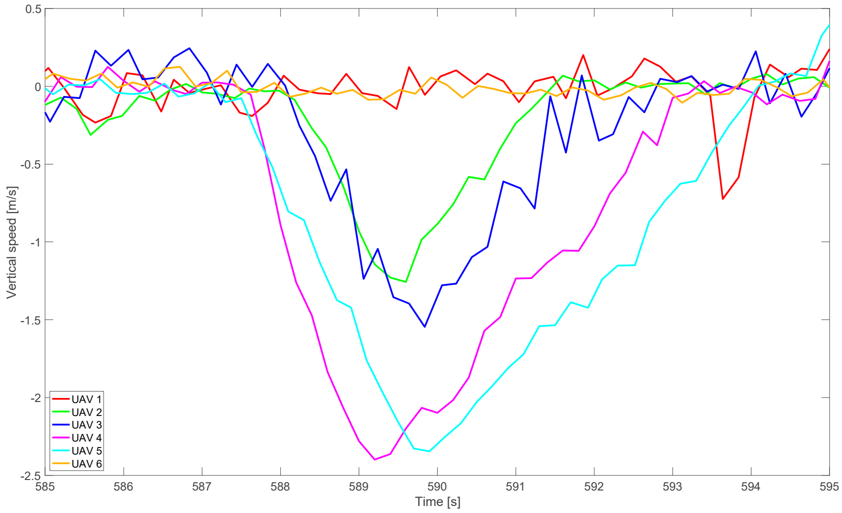


Figure 21. Change in the vertical speed of UAVs during altitude increase.

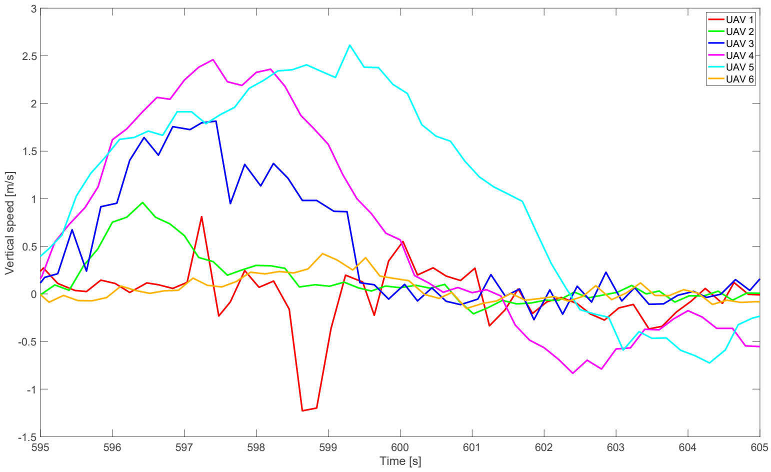


Figure 22. Change in the vertical speed of UAVs during descent.

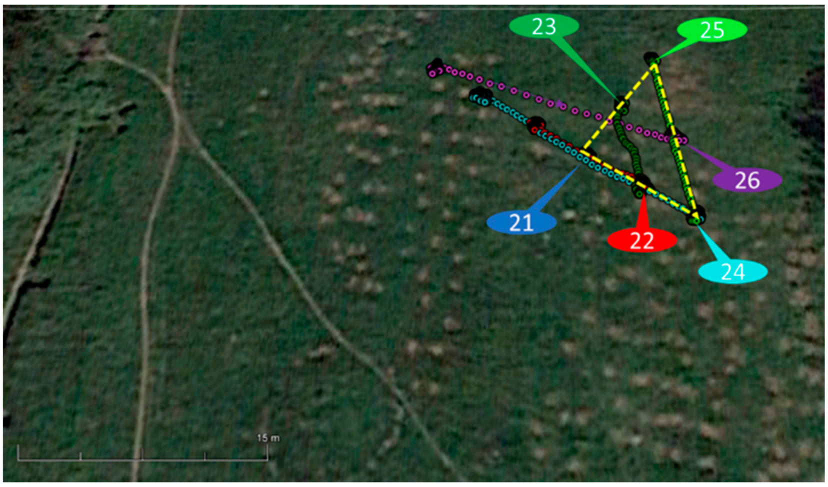


Figure 23. The result of formation reconfiguration from line to triangle.

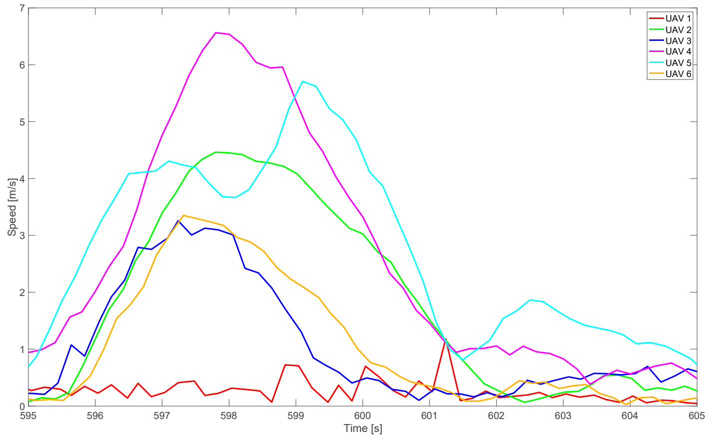


Figure 24. Change in the horizontal speed during the change position (Figure 9)—the second step of reconfiguration from the line to the triangle formation.

Figure 25 presents all altitude changes recorded during the verification tests. To alter the formation's configuration, successive unmanned aerial vehicles were sent to different altitudes. For the sake of software simplification, the changes in altitude were associated with the individual drone numbers. The altitude change related to reconfiguration was calculated such that each drone increased its altitude by two meters relative to the previous one. For example, the UAV with ID 1 increased its altitude by 2 m while the UAV with ID 6 increased it by 10 m. The changes in vertical and horizontal speed recorded during the test are presented in Figures 26 and 27.

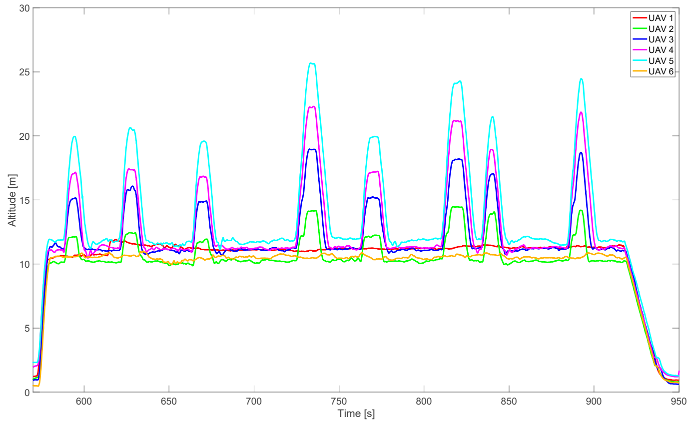


Figure 25. Changes in altitude of UAVs during multiple changes in flight formation.

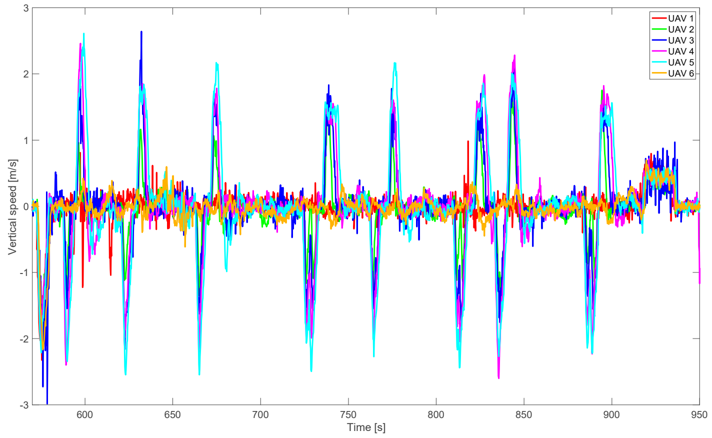


Figure 26. Changes in the vertical speed of UAVs during multiple changes in flight formation.

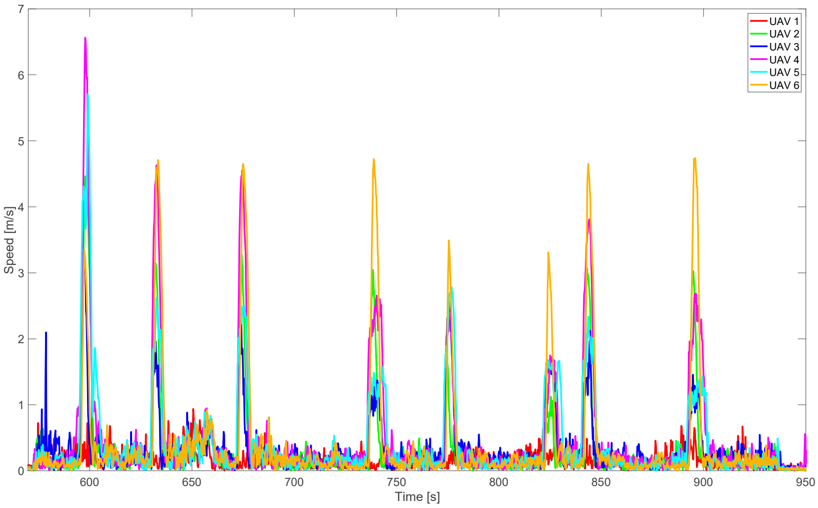


Figure 27. Changes in the horizontal speed of UAVs during multiple changes in flight formation.

The linear and triangular formations are shown in Figure 28. Here, all UAVs hold stable positions. Figures 16 and 17 present the positions recorded from an on-board GPS for linear and triangle formations.


(**a**) (**b**)

Figure 28. Line formation (**a**) and triangle formation (**b**).

6. Conclusions

This article has presented the tests conducted on an autonomous air system. The tests focused on formation changes in UAVs. An autonomous air system consists of UAV quadrotors. This kind of UAV is easy to design and can be tested on a small training ground.

The formation should ensure the safe operation of individual UAVs (collision avoidance) and optimal task execution. Depending on the nature of the task, and environmental conditions, the configuration of the UAV formation changes. The UAV formation is active and adjusts its structure and organization to the factors mentioned above. Therefore, it is crucial to develop scenarios and algorithms for the operation of each formation.

This article has primarily focused on the reconfiguration of formations. The results of the developed UAV reconfiguration algorithm have been presented and executed at the command of the "leaders" forming the command/control chains of UAV teams. Individual UAVs maintain their positions relative to the "leader" of the formation, who does not change position during reconfiguration. Other UAVs, upon the command of the "leader", perform the task of maintaining separation from the reference point (in this case, the "leader"). We have presented two formations: the line and the triangle. The tests focused on creating a formation after take-off, reconfiguring the formation from a line to a triangle, and going back to the line formation.

An algorithm has been developed and implemented in the flight management system for UAVs. The algorithm designed by the authors generates setpoint values for motion parameters transmitted to the UAV's flight control system. This article has not disclosed the details of the flight management algorithm regarding formation, stabilization, and maintenance during flight due to copyright protection.

The algorithm was constructed for the formations of quadrotors. Therefore, it can only be used for this class of UAVs. The basis for its development was position determining. This solution can be used there because the multirotor can fly at a low speed and hover so that multirotors in a formation can wait for each other.

The use of an algorithm to control the formations of fixed-wing aircraft requires the introduction of many changes. The position cannot be the basis for an algorithm of building a formation. The authors of the article are working on fixed-wing formations.

The presented limitations should not be considered defects or limitations. Multirotors and fixed-wing UAVs fulfill different tasks.

The main goal of this research has been to design a system that one person can control. Further research will focus on formation flights while ensuring formation coherence and increasing the number of UAVs in a formation. The authors intend to present the results of flight formation research in subsequent articles.

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