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Enabling Autonomous Formation Flight of Unmanned Aerial Vehicles Using Two-Stage Switching Control

Leszek Ambroziak[1]; Marcin Żukowski[2]; Suryansh Sharma[3]; and Mariusz Bogdan[4]

Abstract: This paper reports on in-flight tests conducted to evaluate a method aimed at controlling the formation of autonomous unmanned aerial vehicles (UAVs) in a leader-follower configuration. The study introduces a two-stage formation flight controller designed to address the challenges encountered in controlling the position and velocity errors inherent in the leader-follower formation flight. In particular, difficulties arise when activating the formation flight mode with considerable distances between the leader and the follower, as well as substantial disparities in their heading angles. The proposed formation flight control scheme comprises two stages: coarse guidance on the leader and precise leader following. The efficacy of this control system was assessed by in-flight testing, in which flight parameters of both the leader and the follower were recorded and scrutinized. The analysis demonstrates that the proposed control algorithm significantly enhances the organization of formation flight. The results obtained from the tests validate the effectiveness of this method, showcasing improvements in formation flight organization and ensuring collision-free conditions. The described algorithm presents a promising approach toward enhancing formation flight control for autonomous UAVs. **DOI: 10.1061/JAEEEZ.ASENG-6128.** *© 2025 American Society of Civil Engineers.*

Introduction

In the last decade, the advancement of unmanned aerial systems (UAS) has been primarily driven by significant progress in robotics, control engineering, telecommunication, and material sciences (Gundlach 2014; Nonami et al. 2010; Valavanis and Vachtsevanos 2015; Sharma et al. 2023a). This surge in innovation within the UAS community has led to emerging research directions focusing on different parts of systems ranging from enhancing communication and data exchange systems (Goddemeier et al. 2012; Zeng et al. 2016; Zhou et al. 2015; Sharma et al. 2021), refining precise localization systems (Rady et al. 2011; Romaniuk et al. 2016) to bolstering propulsion and power systems (Zhou and Prasad 2013; Shiau et al. 2009; Sharma et al. 2023b) and optimizing launchers and take-off systems (Kondratiuk and Ambroziak 2016; Reck 2003; Guruge et al. 2016). These advances have also contributed to the development of novel flight and control algorithms centered on increasing UAS autonomy (Iskandarani et al. 2014; Cummings et al. 2012; Khan et al. 2015; How et al. 2009), exploring manned-unmanned teaming (Schmitt and Schulte 2016), ensuring interoperability (Olson and Burns 2005; Senthilnath et al. 2013; Fahlstrom and Gleason 2012) and synthesis of advanced control laws (Mystkowski 2014; Kownacki 2015; Zhiteckii et al. 2015) among others. In particular, cooperative control, in the form of formation flight, has received substantial attention in recent years (Wang et al. 2024a; Guerrero and Lozano 2012; Rabbath and Léchevin 2010; Gosiewski and Ambroziak 2012). The effectiveness and robustness of formation flight significantly augment the operational potential of UAS (Li et al. 2024; Giulietti et al. 2005, 2000). Applications such as military operations, environmental mapping, heavy cargo transportation, search and rescue missions, aerial refueling, etc., all greatly benefit from having multiple UAVs flying in a formation and collaborating. In addition, such formation flights also work in drag reduction strategies, energy conservation algorithms, and long-distance data transmission approaches. Achieving efficient formation flight necessitates the development and rigorous testing of suitable control laws, especially pertinent in the case of small UAVs that are constrained by a limited payload capacity. The constraints imposed by a smaller payload severely limit the spectrum of onboard sensor suites and impede the potential for elaborate flight computers and communication systems. Consequently, the imperative lies in formulating simple yet reliable control laws tailored to work with these limitations (Wang et al. 2024b). This poses interesting challenges in the domain of formation flight design.

The issue of formation flight control has been extensively documented and explored within the existing literature. Numerous studies have delved into various approaches concerning the formation of flight control systems and their architecture. Notably, investigations have predominantly focused on leader-follower approaches coupled with proportional-integral controllers (Li et al. 2023; Buzogany et al. 1993; Hall and Pachter 2000; Pachter et al. 2012), nonlinear models (Cheng et al. 2008; Kim et al. 2009), switching controllers (Ambroziak and Gosiewski 2015) or fault tolerant (Wu et al. 2024; Du et al. 2024). Additionally, a range of other controller types, including optimal (McCamishj et al. 1996; Du and Yamashita 2007),

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adaptive (Bošković and Mehra 2003; Schumacher and Kumar 2000), predictive (Zhu et al. 2024; Shin and Kim 2009), robust (Su et al. 2023; Li et al. 2006) or ML-based (Xiong and Zhang 2024; Ma et al. 2023) controllers, have undergone analysis and evaluation. Virtual structure and behavior-based methodologies for formation control have also been discussed in separate studies (Li and Liu 2008; Kownacki and Oldziej 2016). Trajectory optimization methods for multiple-agent formation flight have been thoroughly presented and discussed in prior works (Yu et al. 2024b; Raffard et al. 2004; Kuwata and How 2011) while an efficient and optimal path smoother tailored for path planning in UAV formations amid moving obstacle conditions has been proposed (Antony et al. 2024; Radmanesh and Kumar 2016).

All of the aforementioned control systems predominantly rely on position or displacement-based approaches to formation control, wherein objects measure their absolute or relative positions within a global coordinate system. However, an alternative formation control system has been proposed that takes advantage of only the lines of sight with respect to the nearby agents and does not require a communication link for data exchange between vehicles. Another approach, outlined in (Betser et al. 2005), focuses on controlling the formation of flying robots without determining the relative position of each vehicle, employing a detective-deviated pursuit rule to regulate distances between vehicles.

Among the existing literature on formation flying and swarming, several studies propose innovative approaches to the control and coordination of unmanned aerial vehicles (UAVs) and micro aerial vehicles (MAVs). These works explore advanced methodologies, including bionic control strategies, aimed at improving the efficiency and effectiveness of swarm operations (Zhang et al. 2023). (Yu et al. 2022) propose a bionic tracking-containment control method that utilizes smooth communication transitions, allowing UAVs to maintain formation while adapting to dynamic environments. Another study (Yu et al. 2024a) introduces a second-order communication topology for swarm control, enhancing the responsiveness and stability of the formation through improved information sharing among UAVs.

Vision-based techniques represent another actively studied category of formation flight control strategies. Various methods utilizing vision information to achieve formation flight of multiple aircraft, even in the presence of obstacles, have been presented (Johnson et al. 2004). In (Lin et al. 2014), a control system is presented that employs a monocular camera to measure the relative distance between a leader and follower without artificial markers.

Another cluster of formation flight control approaches involves using artificial potential fields. These forms of control typically rely on potential fields to steer clear of collisions (Chen et al. 2015) and guide a UAV to a desired position. However, the derivation, handling, and application of artificial potential fields vary across different studies. For instance, in (Suzuki et al. 2009; Sharma et al. 2021; Kokume and Uchiyama 2010), a bifurcating potential field was utilized to establish the desired airspeed and heading for fixed-wing UAVs, emphasizing the challenge of maintaining the aircraft on a predefined trajectory—a circle with a constant radius or a straight line. These studies explore decentralized control methodologies without the presence of a leader. Another approach (Paul et al. 2008) involves the virtual leader concept in tandem with an extended local potential field, primarily designed for small unmanned helicopters but limited to holonomic mobile objects. Notably, the aforementioned works primarily explore formation flight theoretically, emphasizing the necessity of validating proposed algorithms through flight testing.

This paper investigates the in-flight assessment of UAV formation flight control. The proposed control scheme consists of a dual-stage approach encompassing guidance on a leader and the precise tracking of the mentioned leader. Extensive in-flight testing was conducted to assess and validate the proposed control system. The flight parameters of both the leader and the follower were presented and subjected to comprehensive analysis. The proposed control algorithm demonstrates a notable enhancement in the organization of formation flight. The results obtained from these tests serve to validate the efficacy and effectiveness of this method in controlling formation flight. Moreover, the described algorithm improves formation flight organization and plays a pivotal role in ensuring collision-free conditions during operations.

Methodology

UAV Under Test—The Bullit 60

The Micro air vehicle (MAV) called Bullit 60 (Topmodel 2024) (Fig. 1) was examined and used in the studies. This MAV is a fixed-wing aircraft with a flying wing configuration. The control surfaces for a flying wing are commonly called elevons. Bullit 60 is made of balsa wood covered with foil and is powered by an electric motor located on the front. The MAV's wing is a single-delta configuration with a symmetrical, bi-convex profile BELL 540 (modification of NACA0012). The main Bullit 60 mechanical and aerodynamic parameters are presented in Table 1.

The Bullit 60 Flight Control and Communication Equipment

The Bullit was equipped with a Kestrel autopilot produced by Procerus Technologies Lockheed Martin L.C. Kestrel autopilot is a small-scale device designed for autonomous flight control that provides UAV stabilization on three axes. In addition to this, the GPS antenna and radio modems for communication with the ground control station (GCS) and between UAVs during formation flight were also mounted. Furthermore, the UAV was provided with a Gumstix computer module, and its function was to enable communication between the UAVs and execute the formation flight control algorithm. All of the onboard equipment used on the MAV is presented as a block diagram in Fig. 1.

Configuring the autopilot onboard a microaircraft is a challenging and time-consuming task that requires significant expertise. During the integration and configuration process of the autopilot with the delta microaircraft platform, appropriate mixing of all control channels, servo directions, and deflection ranges of control surfaces were set. The range of operation for the RC equipment sticks in manual control mode, the power of the communication radio modem, and many other parameters were also configured. It was also crucial to determine parameters such as minimum and maximum speed and the angle of attack during the level flight. All these elements were defined during the first flight in manual control mode after the model trimming process. The delta microaircrafts prepared for flight tests are shown in Fig 1. The most critical stage in the autopilot configuration process with the aircraft platform was selecting the gains for the various control loops (both stabilization and navigation). This task was performed using the Pilot In The Loop technique, where the RC pilot assisted in adjusting individual control parameters. Correctly setting all gains and parameters to ensure a specified control quality requires conducting numerous test flights under various conditions. The values of the controller gains for selected control loops of the delta microaircraft are presented in Table 2. This section elaborates on the complex and detailed procedure necessary to integrate and calibrate the autopilot system within a UAV effectively. The involvement of a skilled pilot

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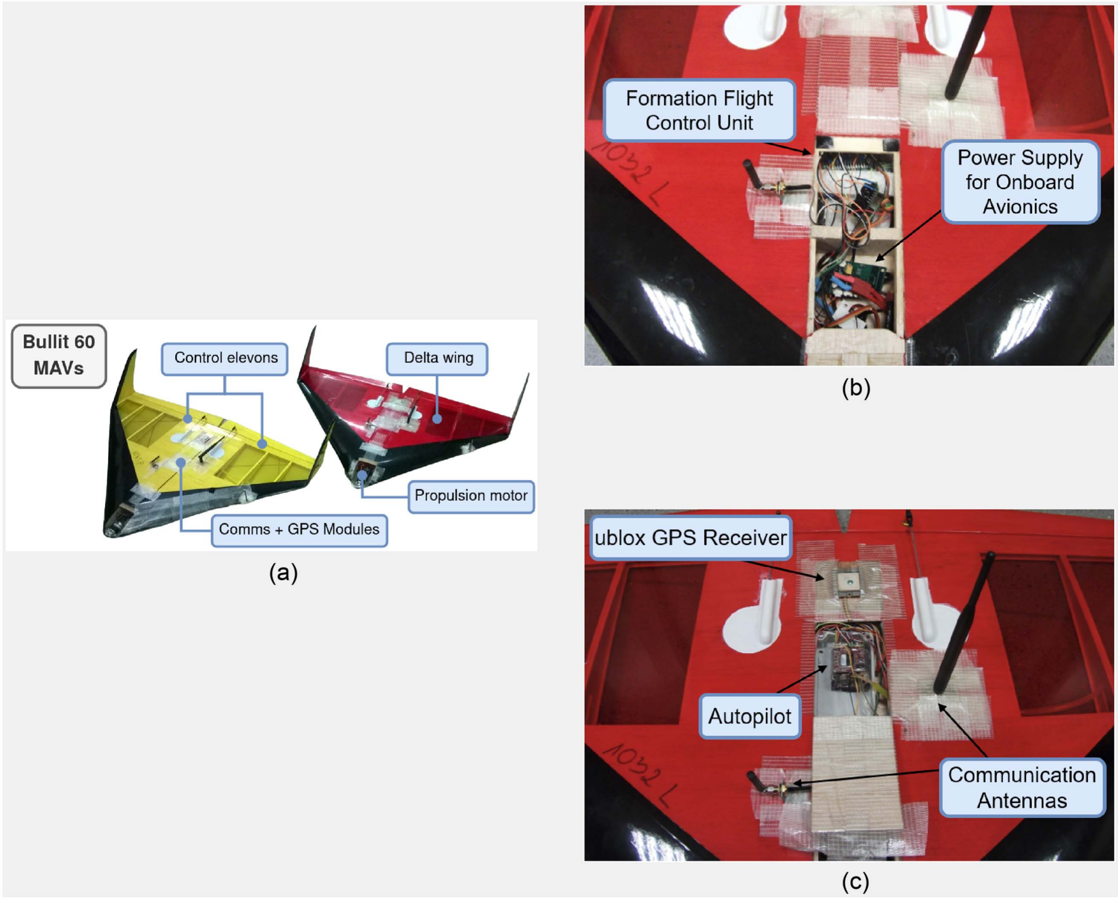

Fig. 1. Bullit 60 UAVs: (a) The Bullit 60 UAVs with different control and system features; (b) close-up view of the Formation Flight Control unit and power supply subsystem; and (c) close-up view of the autopilot subsystem and antennas.

in the loop during this process underscores the hybrid approach of manual expertise and automated control, which is critical to fine-tuning the system to respond accurately to both pilot inputs and autonomous mission demands. This detailed adjustment process ensures that the UAV can perform optimally across a spectrum of operational scenarios, significantly enhancing its reliability and performance under actual flight conditions.

Table 1. Bullit 60's main mechanical and aerodynamic parameters

Parameter	Value
Wing span (b)	1.095 (m)
Total length (l)	0.770 (m)
Total mass ready to flight (m)	1.8 (kg)
Wing area (S)	49.7 (dm^2)
Mean chord (c)	0.660 (m)
Tip chord (c_t)	0.170 (m)
Propeller	$14'' \times 8''$
Propeller area (S_p)	0.0031 (m^2)
I_x	0.091108 (kgm^2)
I_y	0.076144 (kgm^2)
I_z	0.165955 (kgm^2)
I_{xz}	0.0011547 (kgm^2)
Angle of attack (α)	3°
Trimmed airspeed (V_{trim})	14 (m/s)
Maximum airspeed ($V_{\max}$)	34 (m/s)
Minimum airspeed ($V_{\min}$)	11 (m/s)

Two-Stage Switching Control for Autonomous Formation Flight

The formation flight control system constitutes a higher-level control loop relative to the control loops associated with the autopilot,

Table 2. Gain values of the main control loops in the autopilot

Control loop	Gain	Value	Unit
PID roll rate–>aileron	k_p	0.048	[rad/(rad/s)]
	k_i	0	(rad/rad)
	k_d	0	$[\mathrm{rad}/(\mathrm{rad}/s^2)]$
PID pitch rate–>elevator	k_p	0.049	[rad/(rad/s)]
	k_i	0	(rad/rad)
	k_d	0	$[\mathrm{rad}/(\mathrm{rad}/\mathrm{s}^2)]$
PID roll–> ileron	k_p	0.61	(rad/rad)
	k_i	0.01	[rad/(rad s)]
	k_d	0	[rad/(rad/s)]
PID Pitch–>elevator	k_p	0.44	(rad/rad)
	k_i	0.01	[rad/(rad s)]
	k_d	0	[rad/(rad/s)]
PID airspeed–>pitch	k_p	0.078	[rad/(m/s)]
	k_i	0.035	(rad/m)
	k_d	0.01	$[\mathrm{rad}/(\mathrm{m}/\mathrm{s}^2)]$
PID heading–>roll	k_p	1.5	(rad/rad)
	k_i	0.01	[rad/(rad s)]

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such as stabilization and navigation controllers. The control signals generated in the group flight control system serve as input signals to the lower-level control loops (both navigational and stabilization loops, depending on the adopted concept/method of group flight control). In this approach, the formation flight control system is based on the leader-follower scheme. In this control architecture, an important component of the control system is the communication system, which allows data exchange between the objects flying in the group. In addition, the process of organizing a mission carried out by a group of unmanned aerial vehicles is a troublesome issue, requiring certain solutions to ensure the reliability and safety of operations involving unmanned aerial vehicles. The control system is based on two control algorithms, coarse and precise, which are activated depending on the distance between the leader and the follower.

Formation Flight Geometry

The formation of a flight control system is based on a leader-follower control strategy. The case analyzed concerns two UAVs, one acting as the leader and the other as the follower. This was chosen to perform in-flight testing of the proposed formation flight algorithm with available hardware resource constraints (autopilots, airframes, base stations, etc.). The control laws are based on the position errors between the leader and the follower [Eqs. (1) and (2)]. The follower generates control signals locally based on the data received from the leader. The generated control signals are sent to the local control system of the unmanned aerial vehicle. This simple formation geometry of two UAVs is presented in Fig. 2, (Ambroziak et al. 2022). The leader and follower positions can be denoted as follows:

$$L_{\text{pos}} = \begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix},$$

$$F_{\text{pos}} = \begin{bmatrix} x_F \\ y_F \\ z_F \end{bmatrix} \tag{1}$$

The position errors between the leader and the follower can be defined as follows:

$$\begin{aligned} e_x &= x_L - x_F = \mathbf{R_v}, \\ e_y &= y_L - y_F = \mathbf{R_\psi}, \\ e_z &= z_L - z_F \end{aligned} \tag{2}$$

where e_x = error in the north direction (latitude), e_y = error in the east direction (longitude), and e_z = altitude difference between the leader and the follower.

To derive the proposed group flight control laws, the distance $\mathbf{R}$, representing the shortest path between the leader and the follower, must also be defined:

$$\|\mathbf{R}\| = \sqrt{\|\mathbf{R_\psi}\| + \|\mathbf{R_v}\|} \tag{3}$$

The formation flight control system uses three basic navigational parameters—speed, heading, and altitude—as control signals. These three parameters, representing the control vector (desired flight trajectory) of the follower in the formation flight frame, can be presented as:

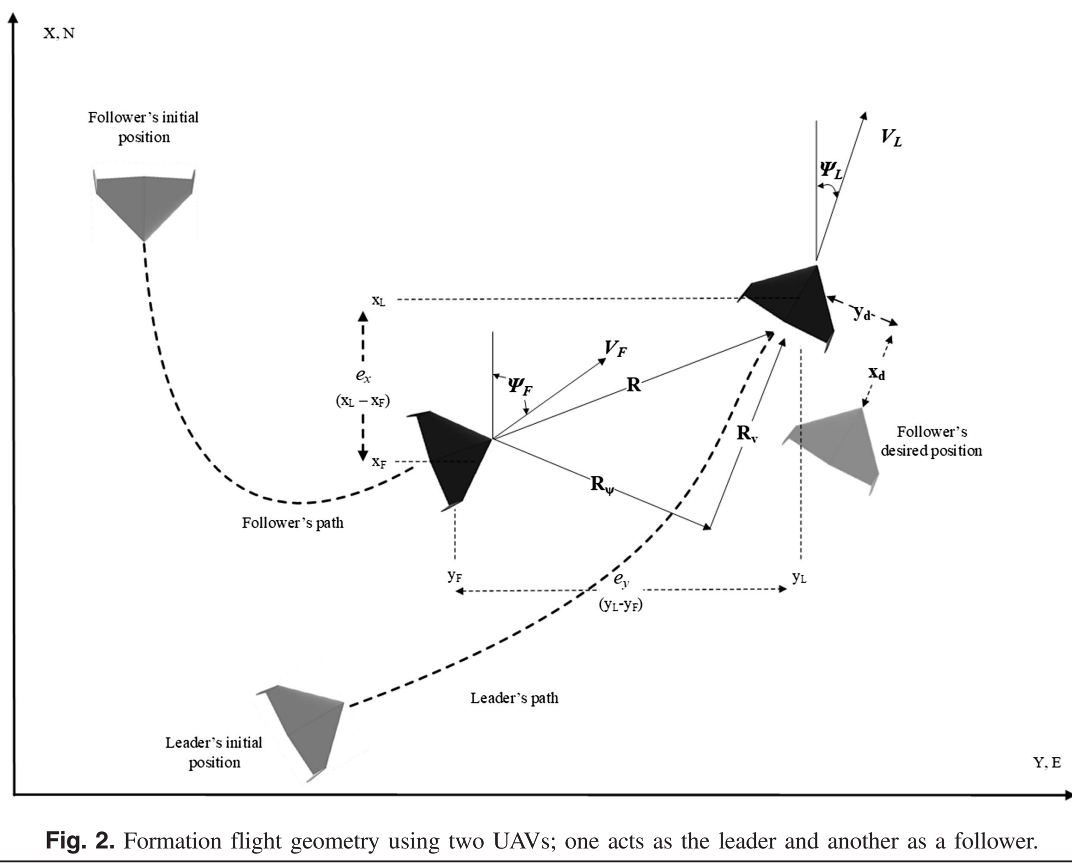

Fig. 2. Formation flight geometry using two UAVs; one acts as the leader and another as a follower.

$$T_F^c = \begin{bmatrix} V_F^c \\ \psi_F^c \\ A_F^c \end{bmatrix} \quad (4)$$

where V_F^c = the desired airspeed of the follower, ψ_F^c = the desired heading of the follower, and A_F^c = the desired altitude of the follower.

The main task of the formation flight control system is to minimize position errors between the leader and the follower. The proposed group flight control system is based on a two-stage algorithm. The first part of the algorithm (first phase/stage of control) is responsible for guiding the second aircraft (the follower) to a virtual point located behind the leader. The virtual point represents a shifted position of the leader in the x-direction by a specified distance. This shift is introduced for safety reasons (to eliminate the possibility of a collision). Additionally, the two aircraft are at different set flight altitudes in the first phase for safety reasons. This approach also allows for the control of a larger number of unmanned aerial vehicles. The second part of the algorithm consists of the precise control system (second phase/stage of control). When the follower reaches a sufficiently small distance from the leader [calculated with Eq. (3)], and the difference in flight headings is minimal, the second part of the control algorithm is activated.

Coarse Leader-Following Algorithm

The purpose of the coarse leader-following algorithm is to position the follower aircraft at a certain distance behind the leader. Activating the group flight control system when the distance between the aircraft is significant using a single-stage algorithm (where the control signal is obtained by adding a correction generated by the controller to the desired signal that the leader currently possesses) did not meet the required quality criteria (it could not position the follower at a specified distance from the leader). The coarse control algorithm eliminates this effect and significantly simplifies the organization of flight for multiple unmanned aerial vehicles. The initial stage of forming a group of unmanned aerial vehicles has been somewhat automated. Coarse leader-following allows the activation of the group flight control function at any moment (regardless of the distance between the flying objects and regardless of the difference in headings of the aircraft intended to follow the leader). An important feature of the leader-following algorithm is also the fact that it can be applied to flying objects of various classes without the need to tune its parameters (only the second precise control algorithm is subject to parameter tuning). This is an important advantage that greatly simplifies the implementation of this control system on different objects (of different sizes and dynamics). The coarse control algorithm is created on simple trigonometric relationships. Based on the calculated position difference between the leader and the follower, and the parameter **R** [Eq. (3)], an open-loop signal is generated that contains the desired heading value for the follower. This algorithm in block form is shown in Fig. 3.

The desired flight speed in the leader-following phase is calculated according to the following formula:

$$V_{F_Z} = V_{L_Z} + k_p^v(e_x \sin\chi_L + e_y \cos\chi_L) \quad (5)$$

where k_p^v = the controller gain, and V_{L_Z} = the desired Leader's airspeed.

Precise Formation Flight Control System

After the leader-follower phase with the coarse controller, the system switches to the precise control algorithm. To execute this stage of control, the position errors calculated in Eq. (2) must be determined in the leader's coordinate system. This is achieved using a rotation matrix by the angle χ_L. The position errors in the new coordinate system can be expressed as

$$e_{x_{rot}} = \boldsymbol{R_v} = \sin\psi_L e_x + \cos\psi_L e_y \quad (6)$$

$$e_{y_{rot}} = \boldsymbol{R_\psi} = \cos\psi_L e_x - \sin\psi_L e_y \quad (7)$$

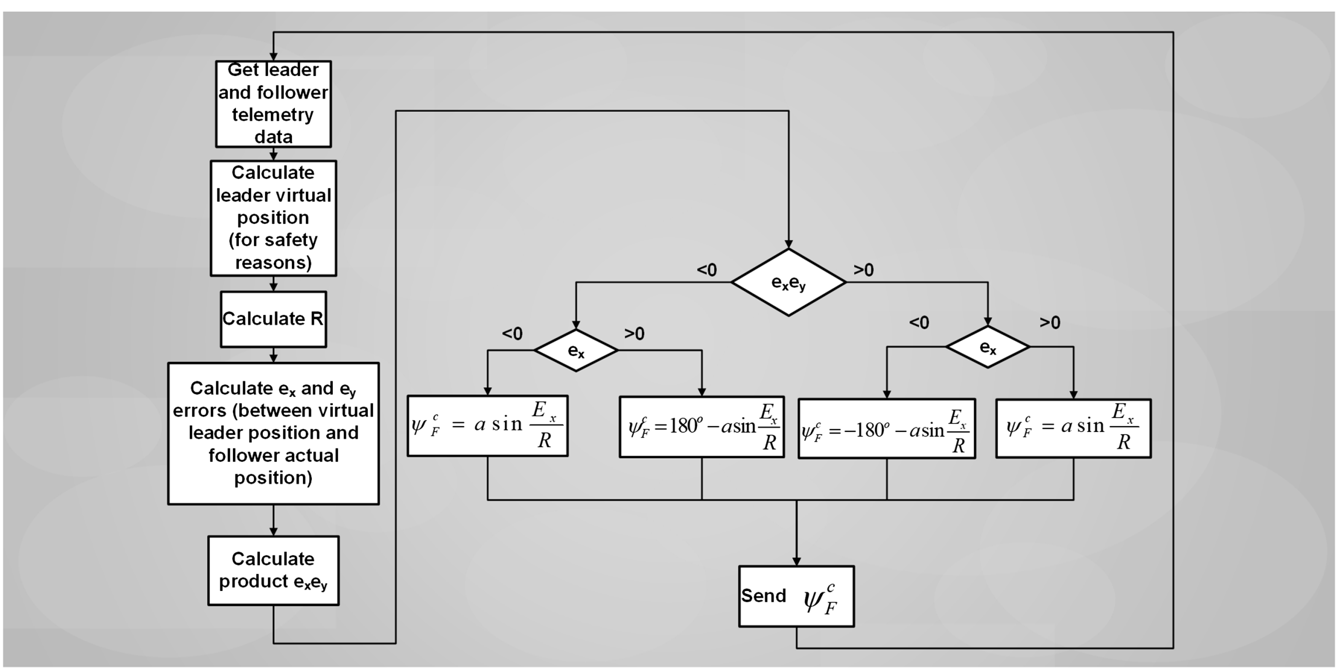

Fig. 3. Initial leader control and guidance algorithm used in formation flight.

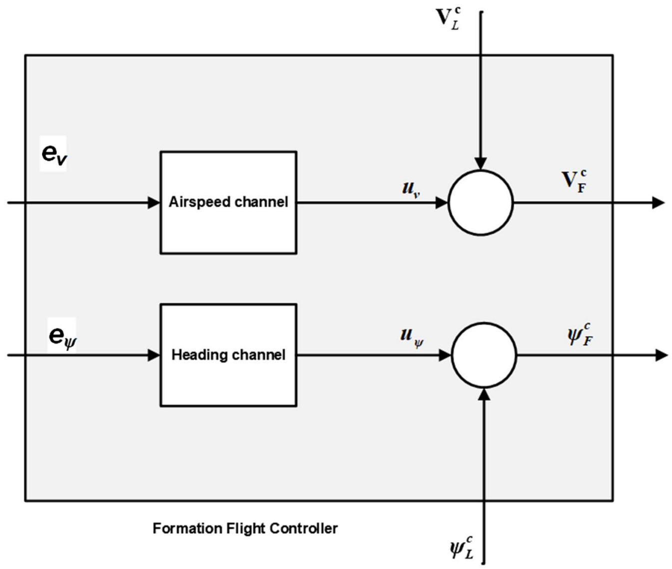

Fig. 4. Formation flight controller block diagram detailing input and output signal generation.

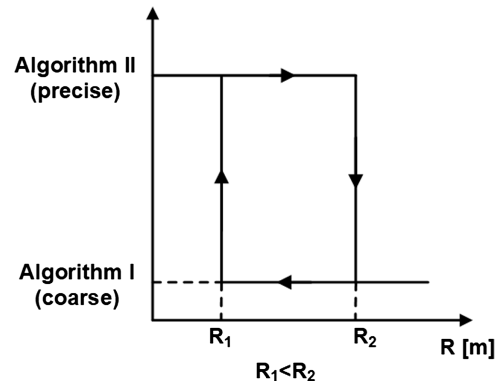

Fig. 5. Switching function between formation flight control algorithms, where R1 and R2 represent defined distances between the leader and the follower.

Position errors [Eqs. (6) and (7)] before being fed to the controller should also consider the desired distances in the x and y directions. They can be expressed in the following form:

$$e_v = e_{x_{rot}} - x_d = [\sin\psi_L e_x + \cos\psi_L e_y] - x_d \tag{8}$$

$$e_\psi = e_{y_{rot}} - y_d = [\cos\psi_L e_x - \sin\psi_L e_y] - y_d \tag{9}$$

where x_d = the desired distance in the x-direction between the leader and the follower, y_d = the set distance in the y-direction between the leader and the follower, e_v = the position error in the formation frame with respect to the desired distance in the x-direction (input signal to the controller generating the correction for the desired flight speed of the follower), and e_ψ = the position error in the formation frame with respect to the desired distance in the y-direction (input signal to the controller generating the correction for the desired course of the follower).

The position errors [Eqs. (8) and (9)] determined in the formation control system are input values to the formation flight control system as shown in Fig. 4.

The implemented controller generating the correction in discrete form can be presented as

$$u_{v/\psi} = k_p + k_i \frac{T_s}{2}\frac{z+1}{z-1} + k_d\left[-\frac{25}{12} + 4z^{-1} - 3z^{-2} + \frac{4}{3}z^{-3} - \frac{1}{4}z^{-4}\right] \tag{10}$$

where k_p = the proportional gain, k_i = the integral gain, k_d = the derivative gain, and T_s = the sampling time.

Switching between the leader-following algorithm and the precise control algorithm is performed according to the designed function. This function is shown in Fig. 5. Such a switching solution prevents excessive and unnecessary switching between algorithms and improves the stability of the entire control system.

Results

Multiple in-flight tests of the proposed formation flight control algorithm were performed using the Bullit 60 MAVs described previously. The research began by testing a single UAV in flight to verify all components of the local control system. Subsequently, the coarse algorithm was tested, and finally, a series of tests of the full two-stage switching formation control system were conducted. Two UAVs were used, one acting as the leader and the other as its follower. The UAV leader had information about the desired trajectory. The follower UAV was tasked with following the leader UAV with a potential field algorithm. The tests were carried out using a loiter function, which makes a UAV follow a circular path with a specified radius.

Single UAV Test

At the beginning of the experimental research, studies were carried out on the flight of individual UAV models. The aim of these trials was to determine the properties and behavior of microaircraft in various phases of flight and to assess their utility in further research on group flight control algorithms. The behavior of the test models was executed and checked during the following flight phases:

1. Automatic takeoff,
2. Desired path following and desired path reaching,
3. Waypoint following,
4. Loitering,
5. Failsafe functions, and
6. Automatic landing.

The results of flight tests for a single UAV are presented in the form of path charts during the task of following a specified circular path (Fig. 6), altitude profile (Fig. 7), and time plots of fundamental navigational parameters such as airspeed (Fig. 8), commanded and measured heading (Fig. 9).

The results obtained from the single UAV flight tests show that the delta micro UAV correctly followed the desired path and maintained the set flight altitude and airspeed. This indicates the correct configuration of the autopilot and the selection of all control parameters. An important aspect of the conducted studies was to verify the accuracy of the autopilot's fail-safe functions in case of a failure of a specific system component. The aircraft correctly switched to emergency mode and undertook appropriately programmed actions (e.g., returning to the home position or starting a loitering task at the point of communication signal loss from the ground station). Additionally, the delta micro UAVs were prepared to perform automatic take-off and landing, which is an important element in increasing system reliability and safety during flight tests of the full formation flight algorithm.

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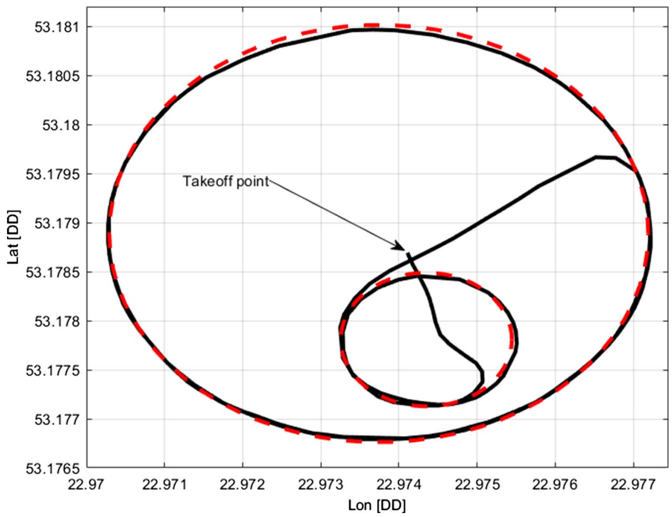

Fig. 6. Exemplary flight of tracking a desired path during loitering (circle radius 70 m and 200 m).

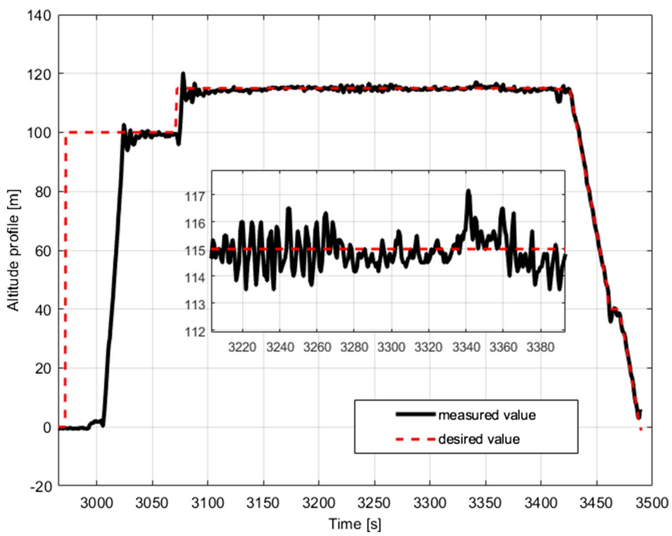

Fig. 7. Exemplary flight altitude profile during flight tests.

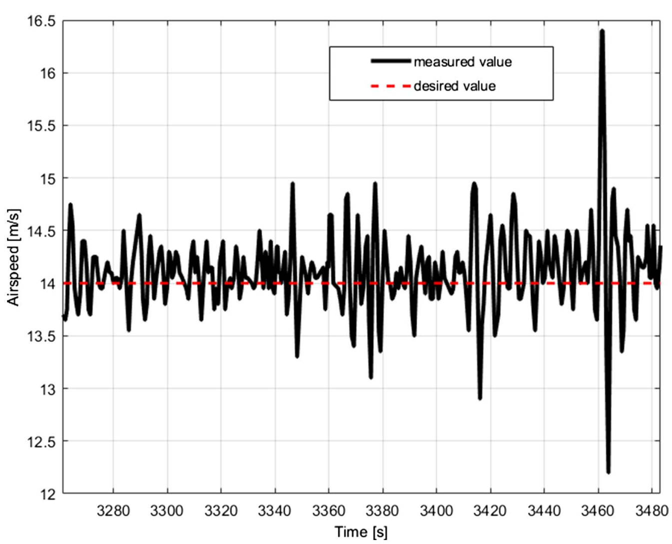

Fig. 8. Airspeed during flight tests.

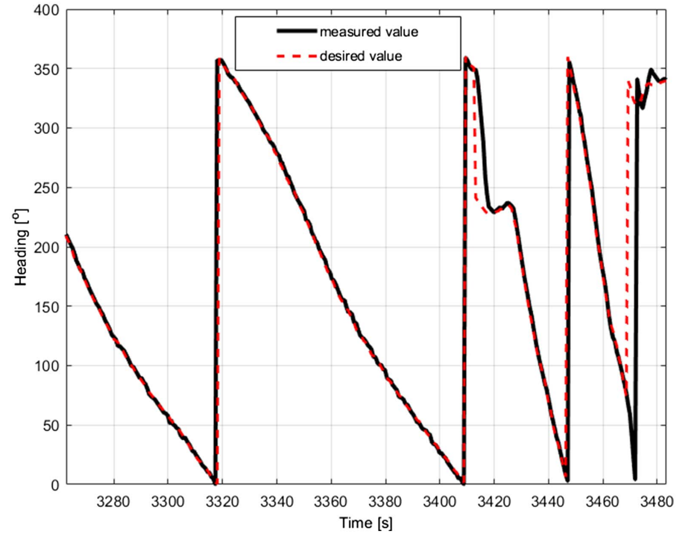

Fig. 9. Heading during flight tests.

Coarse Algorithm Tests

After successful flight tests of the single delta UAV, studies on the group flight algorithm were initiated. These studies began with the correct configuration of communication radio modems to eliminate the phenomenon of communication channels being overwhelmed by data packets flowing to and from the ground station from two micro UAVs. Only after correctly setting transmission speed, broadcasting mode and transmitter power was it possible to establish correct and fast communication with two UAVs simultaneously. Both the communication system with the ground station and the direct data exchange system between the UAVs were thoroughly tested during in-flight trials. The exchanged data packets were recorded and logged, and the quality of the communication signal with the ground station was also recorded. Ensuring the correct exchange of telemetry data allowed for the initiation of flight tests of the group flight control algorithm. The initial flight tests focused on the leader-following algorithm (without switching to the precise algorithm). The test procedure was as follows:

1. Automatic start with the leader UAV,
2. Switching the leader to NAV mode and setting the loitering function at an altitude of 100 m,
3. Switching RC control to the follower UAV (to supervise its automatic start process),
4. Start by the follower in automatic mode,
5. Activation of the leader-following function,
6. Following the leader with a 15 m difference in altitude,
7. Deactivation of the leader-following function,
8. Landing by the follower in automatic mode, and
9. Landing by the leader in automatic mode.

The result of the flight test of the initial/coarse-only leader-following algorithm is shown in Fig. 10. In exploring autonomous aerial vehicle formations, implementing a rudimentary coarse algorithm has demonstrated significant efficacy, particularly in scenarios requiring synchronization and positioning of a follower UAV relative to a leader. Despite the inherent simplicity and the associated lack of precision of the coarse algorithm, its practical effectiveness is noteworthy, especially in long-range operations where the follower needs to initiate engagement from significant distances. This coarse algorithm operates on a basic set of control laws that are less computationally intensive, making it highly suitable for rapid deployment in situations where computational resources are limited

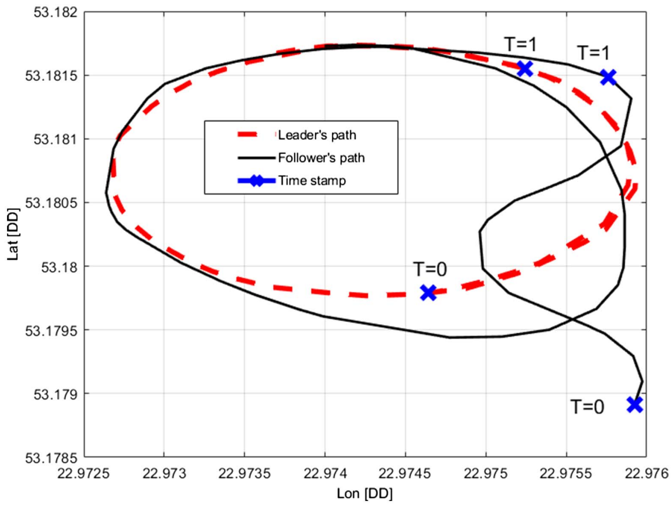

Fig. 10. Leader's and follower's path during the test (only initial algorithm).

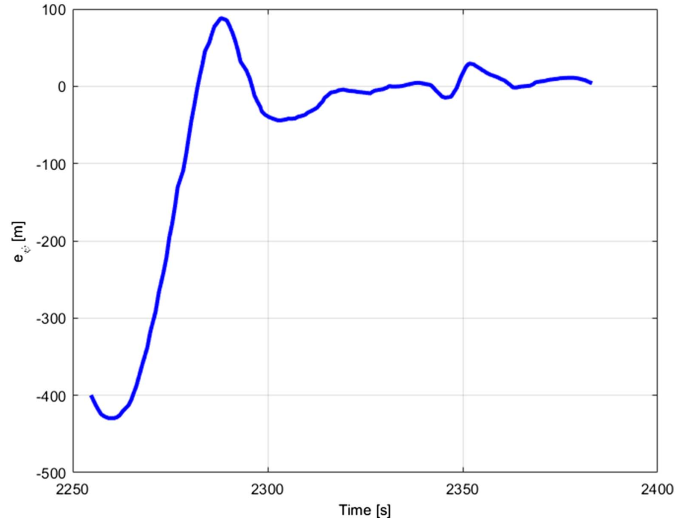

Fig. 11. e_ψ error during test.

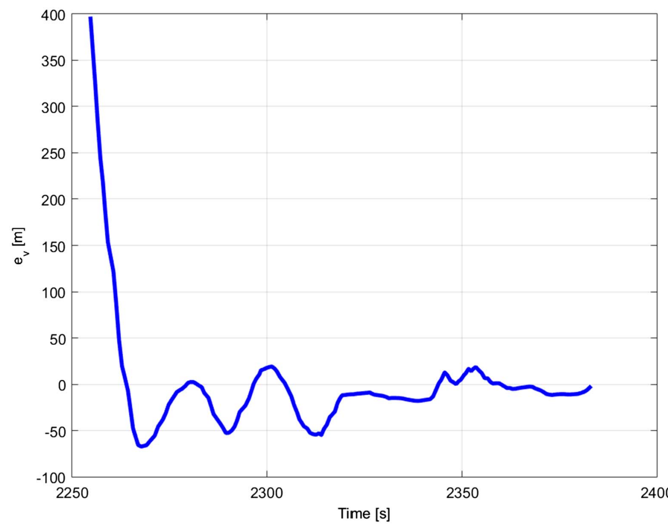

Fig. 12. e_v error during test.

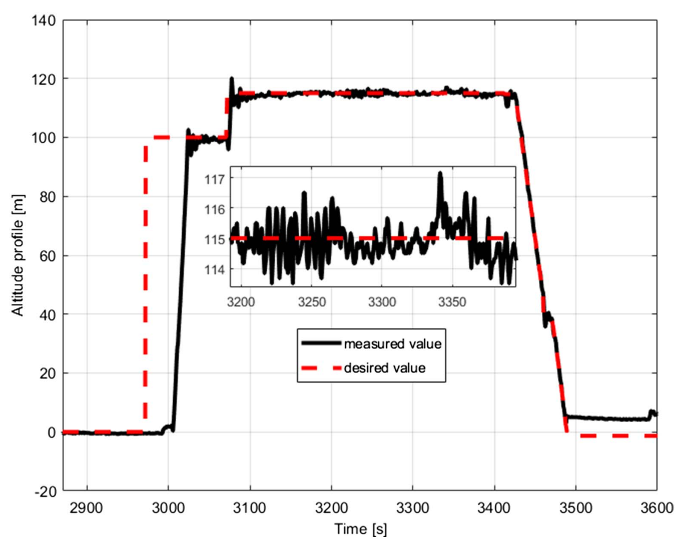

Fig. 13. Altitude profile of the leader UAV.

or when quick responsiveness is paramount. The algorithm utilizes a series of simple navigational commands that, while not providing high accuracy, allow the follower UAV to approximate the leader's trajectory sufficiently to maintain a functional formation. The experimental results have shown that the follower UAV, guided solely by the coarse algorithm, is able to effectively minimize positional error over time and align itself behind the leader in a stable manner. This alignment is maintained even as the leader performs various maneuvers, demonstrating the robustness of the algorithm under dynamic conditions. Furthermore, the utility of such a coarse algorithm extends beyond the mere alignment of followers. It facilitates a foundational layer upon which more sophisticated layers of command and control can be superimposed. This tiered approach to algorithmic control allows for scalability and adaptation, depending on the specific requirements of the mission and the operational environment.

Two-Stage Formation Flight Algorithm Test

The comprehensive investigation of the full formation control system was executed methodically across a spectrum of meteorological scenarios, notably during strong wind conditions, where the wind speed exceeded half the UAV's cruising velocity, as well as under calm conditions with minimal wind interference. This strategic approach was employed to rigorously assess the robustness and adaptability of the control system under diverse environmental stressors. Initially, the study focused on evaluating the efficacy of the system in adverse weather conditions to establish a baseline for its performance. This phase involved closely monitoring the UAV's responsiveness and stability, examining how well the control system could maintain formation integrity and navigate effectively despite the significant aerodynamic challenges presented by the strong winds. The insights gained from these tests were critical to understanding the limits and capabilities of the control system, providing valuable data to refine and optimize the algorithm for better performance.

Figs. 11 and 12 show the heading and airspeed signal inputs that were provided to the controller in the y and x direction, respectively. The controller used these for heading and velocity control of the follower UAV. It can be easily observed that both error signals in the two control channels (airspeed and heading) converge to zero. Figs. 13 and 14 illustrate the altitude profiles of the leader and

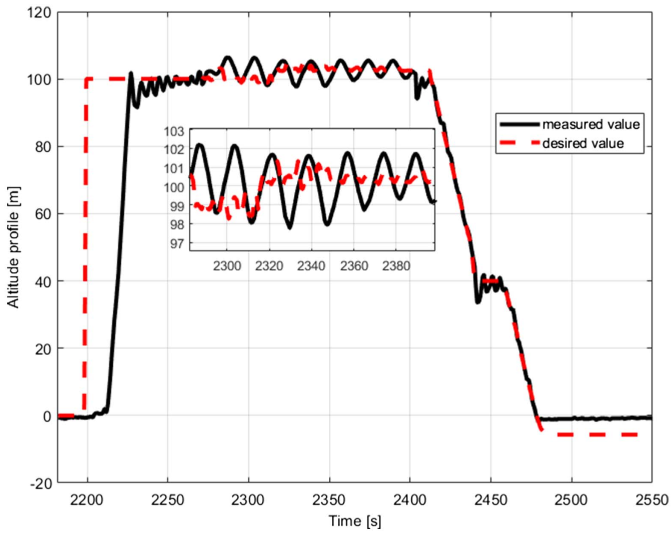

Fig. 14. Altitude profile of the follower UAV.

the follower. The plots reveal oscillations in maintaining altitude, with those observed in the follower being slightly more pronounced. Upon observing this behavior, a decision was made to subtly reduce the gains coefficients in the formation flight speed control channel and in the local airspeed to the altitude control channel. It is also important to remember that the follower tracks the leader's trajectory based on the data received from them. Weather conditions and wind gust disturbances (Fig. 16) should also be considered, as they can significantly impact the performance and accuracy of the altitude control system. These environmental factors must be factored into the system calibration and operational strategies to enhance stability and ensure a more consistent following behavior.

The trajectories followed by the leader and follower UAV are shown in Fig. 15. It can be seen that the follower UAV (shown in blue) could, after an initialization period, follow the leader UAV (shown in red) in formation flight. The flight test was conducted outdoors, and the UAVs had to fly under windy conditions, which affected the performance of the algorithm. The recorded wind speed can be seen in Fig. 16. Wind speed varied between 7.25 to 7.75 m/s during the flight test.

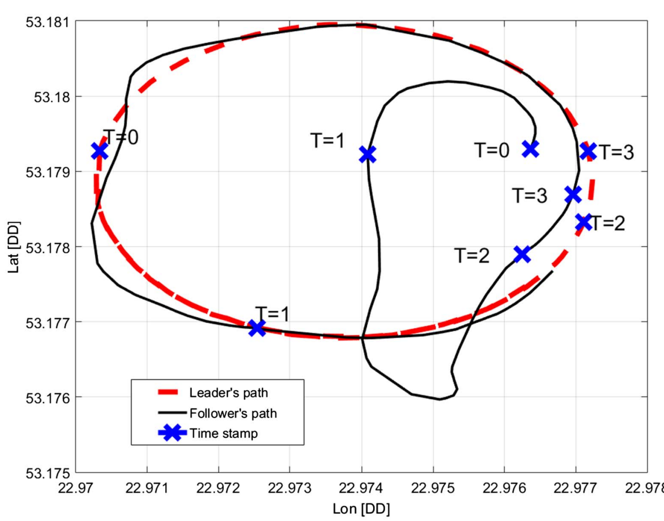

Fig. 15. Leader and follower UAV trajectories during an outdoor flight test under strong wind conditions.

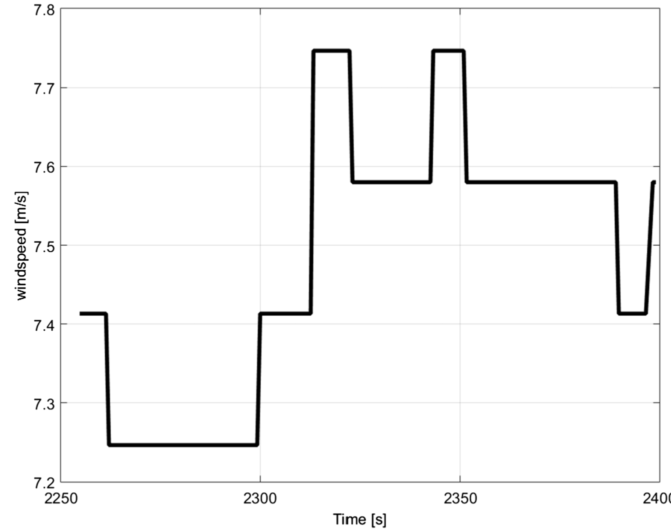

Fig. 16. Measured wind speed during outdoor flight test under strong wind conditions.

In our study, we conducted a series of flight tests under no-wind conditions to rigorously evaluate the effectiveness of the proposed control system for UAV formation flying. These tests were specifically designed to assess the precision and responsiveness of a two-stage switching control approach. The trajectories executed by both the leader and the follower UAVs during these tests are illustrated in Figs. 17 and 18. Observational data from these tests revealed that the follower UAV could maintain a close formation with the leader UAV, adhering to the designated flight path with minimal lag. This performance is particularly noteworthy, as it demonstrates the system's ability to effectively synchronize follower movements with the leader. It is critical in formation flying, where timing and positional accuracy are paramount. The two-stage switching control approach employed in these tests involves an initial coarse adjustment phase, where the follower UAV

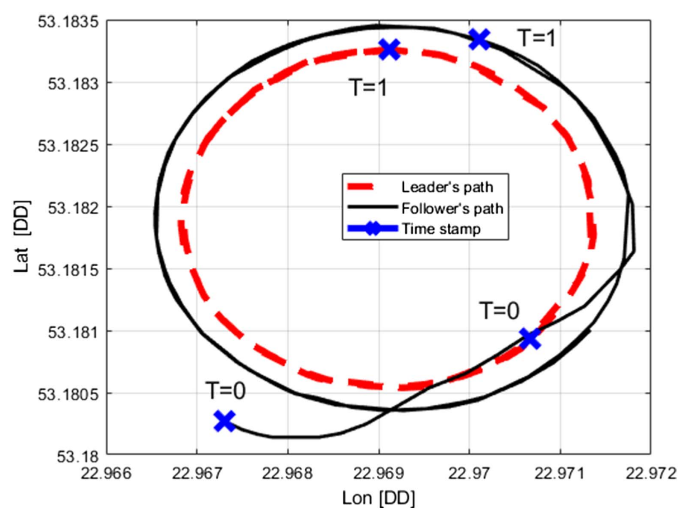

Fig. 17. Leader and follower UAV trajectories during an outdoor flight test (smooth activation and deactivation of the leader following function).

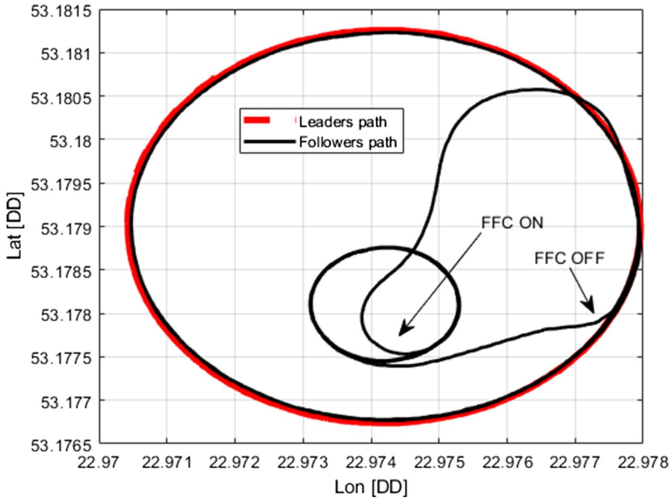

Fig. 18. Leader and follower UAV trajectories during an outdoor flight test under no wind condition.

quickly aligns itself with the leader's trajectory, and a fine-tuning phase that handles more precise adjustments to maintain the formation. This method allows for efficient handling of the formation dynamics, providing rapid alignment initially and refined control subsequently.

The effectiveness of this approach was quantified by analyzing the deviation of the follower from the leader's trajectory, measuring the time delay in follower response, and assessing the stability of the formation throughout various maneuvers. The results indicate that the follower UAV consistently maintained a trajectory closely aligned with that of the leader, with deviations well within acceptable limits, thereby validating the efficacy of the control system. These findings suggest that the two-stage switching control strategy is viable and robust for managing UAV formations. This approach could be particularly advantageous in scenarios where UAVs are required to quickly form up and then maintain tight formations, such as aerial surveillance, environmental monitoring, or complex cinematography. Further research could explore the integration of adaptive control elements into this two-stage approach, allowing the system to adjust dynamically to changing environmental conditions such as wind or varying payload weights.

To better illustrate the conducted tests and in-flight experiments, Fig. 19 presents several images captured during the tests. Additionally, a prepared video showcasing the research has been made available via the following link: https://youtu.be/kO-VUSkAAzE.

Furthermore, implementing machine learning techniques could enhance the system's predictive capabilities, potentially leading to even tighter control over formation dynamics. In conclusion, flight tests under controlled conditions have provided substantial evidence supporting the reliability and effectiveness of the proposed two-stage switching control system for UAV formation flying. This control strategy not only meets the basic requirements of formation integrity but also introduces a level of flexibility and precision that could be tailored to a wide range of applications in both civil and military aviation domains.

Practical Applications

The research presented in this paper offers significant practical implications for industries and applications that rely on autonomous unmanned aerial vehicles (UAVs) operating in formation flight.

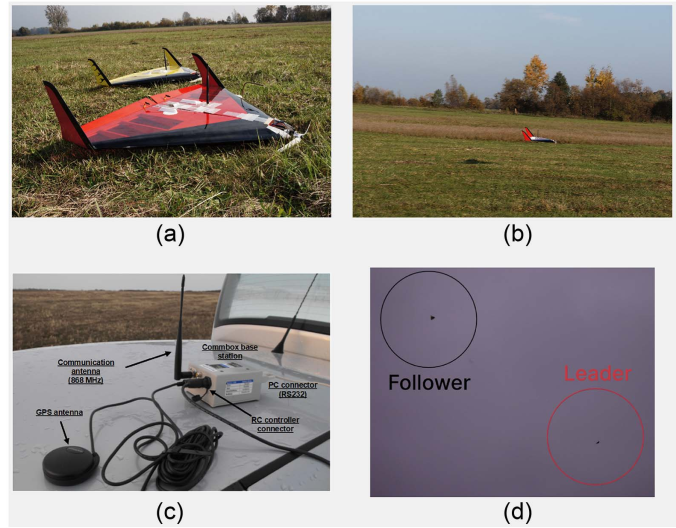

Fig. 19. Representative images from experimental tests demonstrating the UAV formation control algorithm in action: (a) The Bullit 60 UAVs on the airfield during testing; (b) The Bullit 60 UAV during automatic landing; (c) UAV base station; and (d) Leader and Follower UAVs in a formation flight.

The proposed two-stage control algorithm provides a robust and reliable solution for managing leader-follower UAV configurations, effectively addressing challenges such as large initial distances and significant misalignments in heading angles between UAVs. Notably, the coarse control algorithm simplifies the management of multiple UAVs, eliminating the need for extensive parameter tuning.

Key applications and benefits:

- Logistics and delivery systems—precise UAV formation control can optimize air delivery routes, reduce energy consumption, and enhance the overall operational efficiency of package transport systems.
- Disaster response and environmental monitoring—coordinated UAV formations enable efficient coverage of large areas, making them ideal for tasks such as wildfire monitoring, search and rescue operations, and surveying disaster-affected regions.
- Agriculture—in precision agriculture, formation flight control facilitates synchronized UAV operations for crop monitoring, fertilizer application, and data collection over extensive agricultural areas.
- Military and defense—reliable formation flight is essential for UAV swarms in defense applications, including surveillance, reconnaissance, and tactical missions, ensuring accurate coordination and operational effectiveness.

By ensuring collision-free operation and improving the organization of formation flights, this research provides a strong foundation for the broader adoption of autonomous UAVs across various practical, real-world applications. The proposed methodology represents a substantial step forward in enhancing the efficiency, scalability, and adaptability of UAV operations in complex scenarios.

Conclusions

The conclusions drawn from the in-flight tests of the new method for controlling the formation flight of Unmanned Aerial Vehicles (UAVs) presented in this work highlight the efficacy of the two-stage switching controller. This controller has proven to be a robust method for managing autonomous formation flights. The first stage of the controller, the leader guidance algorithm, offers a straightforward approach to reducing positional and heading discrepancies between the leader and follower UAVs. Its ease of implementation across various UAV models, regardless of their distinct flight dynamics, without the need for parameter tuning, marks a significant advancement in UAV control strategies. In addition, implementing the first stage algorithm helps simplify the PID controller configuration process. By reducing the initial distance between the leader and the follower, the first stage algorithm allows the PID controller to operate within a narrower control band, enhancing the overall stability and responsiveness of the formation control system. This benefit is particularly crucial under varying operational conditions, such as different wind scenarios, where control systems typically face greater challenges. Experimental validations conducted under windy and no-wind conditions have demonstrated that this two-stage switching approach not only maintains formation integrity but also adapts efficiently to environmental changes. These tests underscore the practical applicability and resilience of the proposed control method in real-world scenarios, paving the way for its broader adoption in UAV operations. Looking ahead, the integration of this two-stage switching controller could significantly enhance the operational flexibility and safety of UAV formations, particularly in complex environments such as urban airspace or during emergency response operations where reliable and precise formation flying is critical. Moreover, the scalability of this approach suggests its potential utility in larger fleets of UAVs, offering promising avenues for future research and development in swarm intelligence and coordinated multi-UAV operations. Future studies will focus on refining the algorithm to enhance its precision under strong wind conditions without significantly impacting its agility and computational efficiency. Additional layers could incorporate real-time environmental data and adaptive learning mechanisms to dynamically adjust the control parameters, thereby optimizing the formation flying capabilities under varying operational conditions.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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References

Ambroziak, L., and Z. Gosiewski. 2015. "Two stage switching control for autonomous formation flight of unmanned aerial vehicles." *Aerosp. Sci. Technol.* 46 (Oct): 221–226. https://doi.org/10.1016/j.ast.2015.07.015.

Ambroziak, L., C. Kownacki, and A. Simha. 2022. "Switched control strategy for robust formation flight with HIL and in-flight validation." In *Proc., IEEE Int. Conf. on Communications*. New York: IEEE.

Antony, A., S. R. Kumar, and D. Mukherjee. 2024. "Artificial potential fields based formation control for fixed wing UAVs with obstacle avoidance." *IFAC-PapersOnLine* 57 (Jan): 19–24. https://doi.org/10.1016/j.ifacol.2024.05.004.

Betser, A., P. A. Vela, G. Pryor, and A. Tannenbaum. 2005. "Flying in formation using a pursuit guidance algorithm." In Vol. 7 of *Proc., American Control Conf.*, 5085–5090. New York: IEEE.

Bošković, J. D., and R. K. Mehra. 2003. "An adaptive reconfigurable formation flight control design." In Vol. 1 of *Proc., American Control Conf.*, 284–289. New York: IEEE.

Buzogany, L. E., M. Pachter, and J. J. D'Azzo. 1993. "Automated control of -aircraft in formation flight." In Vol. 7 of *Proc., Guidance, Navigation and Control Conf.*, 1349–1370. Reston, VA: American Institute of Aeronautics and Astronautics.

Chen, Y. B., J. Q. Yu, X. L. Su, and G. C. Luo. 2015. "Path planning for multi-UAV formation." *J. Intell. Rob. Syst.* 77 (1): 229–246. https://doi.org/10.1007/s10846-014-0077-y.

Cheng, Z., D. Necsulescu, B. Kim, and J. Sasiadek. 2008. "Nonlinear control for UAV formation flying." *IFAC Proc. Vol.* 41 (2): 791–796. https://doi.org/10.3182/20080706-5-KR-1001.00136.

Cummings, M. L., J. P. How, A. Whitten, and O. Toupet. 2012. "The impact of human-automation collaboration in decentralized multiple unmanned vehicle control." *Proc. IEEE* 100 (3): 660–671. https://doi.org/10.1109/JPROC.2011.2174104.

Du, M., and Y. Yamashita. 2007. "Optimal control of formation flight based on MLD systems." In *Proc., IEEE Int. Conf. on Control Applications*, 904–909. Amsterdam, Netherlands: Elsevier.

Du, Z., X. Qu, J. Shi, and J. Lu. 2024. "Formation control of fixed-wing UAVs with communication delay." *ISA Trans.* 146 (Mar): 154–164. https://doi.org/10.1016/j.isatra.2023.12.036.

Fahlstrom, P., and T. Gleason. 2012. *Introduction to UAV systems*. 4th ed. Hoboken, NJ: Wiley.

Giulietti, F., M. Innocenti, M. Napolitano, and L. Pollini. 2005. "Dynamic and control issues of formation flight." *Aerosp. Sci. Technol.* 9 (1): 65–71. https://doi.org/10.1016/j.ast.2004.06.011.

Giulietti, F., L. Pollini, and M. Innocenti. 2000. "Autonomous formation flight." *IEEE Control Syst.* 20 (6): 34–44. https://doi.org/10.1109/37.887447.

Goddemeier, N., K. Daniel, and C. Wietfeld. 2012. "Role-based connectivity management with realistic air-to-ground channels for cooperative UAVs." *IEEE J. Sel. Areas Commun.* 30 (5): 951–963. https://doi.org/10.1109/JSAC.2012.120610.

Gosiewski, Z., and L. Ambroziak. 2012. "Formation flight control scheme for unmanned aerial vehicles." In *Control and Information Sciences*, 331–340. London: Springer.

Guerrero, J. A., and R. Lozano. 2012. *Flight formation control*. Hoboken, NJ: Wiley.

Gundlach, J. 2014. *Designing unmanned aircraft systems: A comprehensive approach*. 2nd ed. Reston, VA: American Institute of Aeronautics and Astronautics.

Guruge, P., B. B. Kocer, and E. Kayacan. 2016. "A novel automatic UAV launcher design by using bluetooth low energy integrated electromagnetic releasing system." In *Proc., IEEE Region 10 Humanitarian Technology Conf., R10-HTC 2015—Co-located with 8th Int. Conf. on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management, HNICEM 2015*, 7391861. New York: IEEE.

Hall, J. K., and M. Pachter. 2000. "Formation maneuvers in three dimensions." In Vol. 1 of *Proc., IEEE Conf. on Decision and Control*, 364–369. New York: IEEE.

How, J. P., C. Fraser, K. C. Kulling, L. F. Bertuccelli, O. Toupet, L. Brunet, and N. Roy. 2009. "Increasing autonomy of UAVs: Decentralized CSAT mission management algorithm." *IEEE Rob. Autom. Mag.* 16 (2): 43–51. https://doi.org/10.1109/MRA.2009.932530.

Iskandarani, M., S. N. Givigi, G. Fusina, and A. Beaulieu. 2014. "Unmanned aerial vehicle formation flying using linear model predictive control." In *Proc., 8th Annual IEEE Int. Systems Conf., SysCon 2014*, 18–23. New York: IEEE.

Johnson, E. N., A. J. Calise, R. Sattigeri, Y. Watanabe, and V. Madyastha. 2004. "Approaches to vision-based formation control." In Vol. 2 of *Proc., IEEE Conf. on Decision and Control*, 1643–1648. New York: IEEE.

Khan, A., B. Rinner, and A. Cavallaro. 2015. "Multiscale observation of multiple moving targets using micro aerial vehicles." In Vol. 2 of *Proc.,* Int. Conf. on Intelligent Robots and Systems, 4642–4649. New York: IEEE.

Kim, D. M., S. Park, S. Nam, and J. Suk. 2009. “A modified nonlinear guidance logic for a leader-follower formation flight of two UAVs.” In Vol. 15 of *Proc., 2009 ICCAS-SICE*, 8–14. New York: IEEE.

Kokume, M., and K. Uchiyama. 2010. “Guidance law based on bifurcating velocity field for formation flight.” In *Proc., AIAA Guidance, Navigation, and Control Conf.* Reston, VA: American Institute of Aeronautics and Astronautics.

Kondratiuk, M., and L. Ambroziak. 2016. “Concept of the magnetic launcher for medium class unmanned aerial vehicles designed on the basis of numerical calculations.” *J. Theor. Appl. Mech.* 54 (1): 163–177. https://doi.org/10.15632/jtam-pl.54.1.163.

Kownacki, C. 2015. “Design of an adaptive Kalman filter to eliminate measurement faults of a laser rangefinder used in the UAV system.” *Aerosp. Sci. Technol.* 41 (Feb): 81–89. https://doi.org/10.1016/j.ast.2014.12.008.

Kownacki, C., and D. Oldziej. 2016. “Fixed-wing UAVs flock control through cohesion and repulsion behaviours combined with a leadership.” *Int. J. Adv. Rob. Syst.* 13 (1): 36. https://doi.org/10.5772/62249.

Kuwata, Y., and J. P. How. 2011. “Cooperative distributed robust trajectory optimization using receding horizon MILP.” *IEEE Trans. Control Syst. Technol.* 19 (2): 423–431. https://doi.org/10.1109/TCST.2010.2045501.

Li, B., X. H. Liao, Z. Sun, Y. H. Li, and Y. D. Song. 2006. “Robust autopilot for close formation flight of multi-UAVs.” In Vol. 2006 of *Proc., 38th Southeastern Symp. on System Theory*, 294–298. New York: IEEE.

Li, J., J. Liu, S. Huangfu, G. Cao, and D. Yu. 2023. “Leader-follower formation of light-weight UAVs with novel active disturbance rejection control.” *Appl. Math. Modell.* 117 (May): 577–591. https://doi.org/10.1016/j.apm.2022.12.032.

Li, J., J. J. Liu, P. Cheng, C. Liu, Y. Zhang, and B. Chen. 2024. “Event-based obstacle avoidance control for time-varying UAV formation under cyber-attacks.” *J. Franklin Inst.* 361 (13): 107019. https://doi.org/10.1016/j.jfranklin.2024.107019.

Li, N. H., and H. H. Liu. 2008. “Formation UAV flight control using virtual structure and motion synchronization.” In *Proc., American Control Conf.*, 1782–1787. New York: IEEE.

Lin, F., K. Peng, X. Dong, S. Zhao, and B. M. Chen. 2014. “Vision-based formation for UAVs.” In *Proc., IEEE Int. Conf. on Control and Automation, ICCA*, 1375–1380. New York: IEEE.

Ma, B., Z. Liu, F. Jiang, W. Zhao, D. Qingqing, X. Wang, J. Zhang, and L. Wang. 2023. “Reinforcement learning based UAV formation control in GPS-denied environment.” *Chin. J. Aeronaut.* 36 (11): 281–296. https://doi.org/10.1016/j.cja.2023.07.006.

McCamishj, S., M. Pachter, and J. J. D’Azzo. 1996. “Optimal formation flight control.” In *Proc., 1996 Guidance, Navigation, and Control Conf. and Exhibit*, 1–18. Reston, VA: American Institute of Aeronautics and Astronautics.

Mystkowski, A. 2014. “Implementation and investigation of a robust control algorithm for an unmanned micro-aerial vehicle.” *Rob. Auton. Syst.* 62 (8): 1187–1196. https://doi.org/10.1016/j.robot.2014.04.002.

Nonami, K., F. Kendoul, S. Suzuki, W. Wang, and D. Nakazawa. 2010. *Autonomous flying robots: Unmanned aerial vehicles and micro aerial vehicles*. Berlin: Springer.

Olson, L., and L. Burns. 2005. “A common architecture prototype for army tactical and FCS UAVS.” In Vol. 2 of *Proc., Digital Avionics Systems Conf.* New York: IEEE.

Pachter, M., J. J. D’azzo, and J. L. Dargan. 2012. “Automatic formation flight control.” *J. Guidance Control Dyn.* 17 (6): 1380–1383. https://doi.org/10.2514/3.21364.

Paul, T., T. R. Krogstad, and J. T. Gravdahl. 2008. “Modelling of UAV formation flight using 3D potential field.” *Simul. Modell. Pract. Theory* 16 (9): 1453–1462. https://doi.org/10.1016/j.simpat.2008.08.005.

Rabbath, C. A., and N. Léchevin. 2010. *Safety and reliability in cooperating unmanned aerial systems*. Singapore: World Scientific Publishing.

Radmanesh, M., and M. Kumar. 2016. “Flight formation of UAVs in presence of moving obstacles using fast-dynamic mixed integer linear programming.” *Aerosp. Sci. Technol.* 50 (Mar): 149–160. https://doi.org/10.1016/j.ast.2015.12.021.

Rady, S., A. A. Kandil, and E. Badreddin. 2011. “A hybrid localization approach for UAV in GPS denied areas.” In *Proc., IEEE/SICE Int. Symp. on System Integration*, 1269–1274. New York: IEEE.

Raffard, R. L., C. J. Tomlin, and S. P. Boyd. 2004. “Distributed optimization for cooperative agents: Application to formation flight.” In Vol. 3 of *Proc., IEEE Conf. on Decision and Control*, 2453–2459. New York: IEEE.

Reck, B. 2003. “First design study of an electrical catapult for unmanned air vehicles in the several hundred kilogram range.” *IEEE Trans. Magn.* 39 (1): 310–313. https://doi.org/10.1109/TMAG.2002.805921.

Romaniuk, S., L. Ambroziak, Z. Gosiewski, and P. Isto. 2016. “Real time localization system with Extended Kalman Filter for indoor applications.” In *Proc., Int. Conf. on Methods & Models in Automation & Robotics*, 42–47. New York: IEEE.

Schmitt, F., and A. Schulte. 2016. “Mixed-initiative mission planning using planning strategy models in military manned-unmanned teaming missions.” In *Proc., 2015 IEEE Int. Conf. on Systems, Man, and Cybernetics, SMC 2015*, 1391–1396. New York: IEEE.

Schumacher, C. J., and R. Kumar. 2000. “Adaptive control of UAVs in close-coupled formation flight.” In Vol. 2 of *Proc., American Control Conf.*, 849–853. New York: IEEE.

Senthilnath, J., S. N. Omkar, V. Mani, and A. R. Katti. 2013. “Cooperative communication of UAV to perform multi-task using nature inspired techniques.” In *Proc., 2013 IEEE Symp. on Computational Intelligence for Security and Defense Applications, CISDA 2013-2013 IEEE Symp. Series on Computational Intelligence, SSCI 2013*, 45–50. New York: IEEE.

Sharma, S., T. Dijkstra, and R. V. Prasad. 2023a. “Open gimbal: A 3 degrees of freedom open source sensing and testing platform for nano and micro UAVs.” *IEEE Sens. Lett.* 7 (9): 1–4. https://doi.org/10.1109/LSENS.2023.3307121.

Sharma, S., A. Simha, V. Prasad, S. Deshmukh, K. B. Saravanan, R. Ramesh, and L. Mottola. 2023b. “BEAVIS: Balloon enabled aerial vehicle for IoT and sensing.” In *Proc., Annual Int. Conf. on Mobile Computing and Networking, MOBICOM*, 488–502. Reston, VA: American Institute of Aeronautics and Astronautics.

Sharma, S., A. Simha, R. Venkatesha, V. Gokhale, and S. Narayana. 2021. “Hermes—Wind energy harvesting wireless system for sensing aoa and wind speed.” *IEEE Rob. Autom. Lett.* 6 (4): 7097–7104. https://doi.org/10.1109/LRA.2021.3097499.

Shiau, J. K., D. M. Ma, P. Y. Yang, G. F. Wang, and J. H. Gong. 2009. “Design of a Solar power management system for an experimental UAV.” *IEEE Trans. Aerosp. Electron. Syst.* 45 (4): 1350. https://doi.org/10.1109/TAES.2009.5310303.

Shin, J., and H. J. Kim. 2009. “Nonlinear model predictive formation flight.” *IEEE Trans. Syst. Man Cybern. Part A Syst. Hum.* 39 (5): 1116–1125. https://doi.org/10.1109/TSMCA.2009.2021935.

Su, Y. H., P. Bhowmick, and A. Lanzon. 2023. “A robust adaptive formation control methodology for networked multi-UAV systems with applications to cooperative payload transportation.” *Control Eng. Pract.* 138 (Sep): 105608. https://doi.org/10.1016/j.conengprac.2023.105608.

Suzuki, M., K. Uchiyama, D. J. Bennet, and C. R. McInnes. 2009. “Three-dimensional formation flying using bifurcating potential fields.” In *Proc., AIAA Guidance, Navigation, and Control Conf. and Exhibit*. Reston, VA: American Institute of Aeronautics and Astronautics.

Topmodel, C. Z. 2024. “Wireless communications with unmanned aerial vehicles: Opportunities and challenges.” Accessed September 12, 2024. www.topmodelcz.cz.

Valavanis, K. P., and G. J. Vachtsevanos. 2015. *Handbook of unmanned aerial vehicles*. Dordrecht, Netherlands: Springer.

Wang, J., K. Li, and K. Xia. 2024a. “Distributed formation control of multi-UAV systems using relative information.” *J. Franklin Inst.* 361 (10): 106945. https://doi.org/10.1016/j.jfranklin.2024.106945.

Wang, Z., T. Wang, T. Li, and Z. Mao. 2024b. “Distributed observer-based close formation control for UAV swarm under outside disturbances and wake interferences.” *J. Franklin Inst.* 361 (5): 106651. https://doi.org/10.1016/j.jfranklin.2024.106651.

Wu, Y., H. Liang, S. Xuan, and X. Zhang. 2024. "Extended state observer based finite-time fault-tolerant formation control for multi-UAVs." *J. Franklin Inst.* 361 (16): 107158. https://doi.org/10.1016/j.jfranklin.2024.107158.

Xiong, H., and Y. Zhang. 2024. "Reinforcement learning-based formation-surrounding control for multiple quadrotor UAVs pursuit-evasion games." *ISA Trans.* 145 (Feb): 205–224. https://doi.org/10.1016/j.isatra.2023.12.006.

Yu, D., J. Long, C. L. Philip Chen, and Z. Wang. 2022. "Bionic tracking-containment control based on smooth transition in communication." *Inf. Sci.* 587 (Mar): 393–407. https://doi.org/10.1016/j.ins.2021.12.060.

Yu, D., H. Xu, X. Jin, Q. Yin, Z. Wang, C. L. Chen, and X. Li. 2024a. "bionic swarm control based on second-order communication topology." *IEEE Trans. Neural Networks Learn. Syst.* 35 (6): 8373–8385. https://doi.org/10.1109/TNNLS.2022.3227292.

Yu, N., J. Feng, and H. Zhao. 2024b. "A proximal policy optimization method in UAV swarm formation control." *Alexandria Eng. J.* 100 (Aug): 268–276. https://doi.org/10.1016/j.aej.2024.05.029.

Zeng, Y., R. Zhang, and T. J. Lim. 2016. "Wireless communications with unmanned aerial vehicles: Opportunities and challenges." *IEEE Commun. Mag.* 54 (5): 36–42. https://doi.org/10.1109/MCOM.2016.7470933.

Zhang, T., D. Dong, Z. Du, J. Long, D. Yu, Z. Wang, and C. L. Chen. 2023. "Swarm control based on artificial potential field method with predicted state and input threshold." *Eng. Appl. Artif. Intell.* 125 (Oct): 106567. https://doi.org/10.1016/j.engappai.2023.106567.

Zhiteckii, L. S., A. Y. Pilchevsky, A. O. Kravchenko, and B. V. Bykov. 2015. "Modern control theory for designing lateral autopilot systems of UAV." In *Proc., 2015 IEEE 3rd Int. Conf. Actual Problems of Unmanned Aerial Vehicles Developments, APUAVD 2015*, 160–164. New York: IEEE.

Zhou, M., and J. V. Prasad. 2013. "Transient characteristics of a fuel cell powered UAV propulsion system." In *Proc., Int. Conf. on Unmanned Aircraft Systems, ICUAS 2013—Conf, Proc.*, 114–123. New York: IEEE.

Zhou, Y., N. Cheng, N. Lu, and X. S. Shen. 2015. "Multi-UAV-aided networks: Aerial-ground cooperative vehicular networking architecture." *IEEE Veh. Technol. Mag.* 10 (4): 36–44. https://doi.org/10.1109/MVT.2015.2481560.

Zhu, Y., S. Li, G. Guo, P. Yuan, and J. Bai. 2024. "Formation control of UAV–USV based on distributed event-triggered adaptive MPC with virtual trajectory restriction." *Ocean Eng.* 294 (Feb): 116850. https://doi.org/10.1016/j.oceaneng.2024.116850.