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Dynamic Simulation, Flight Control and Guidance Synthesis for Fixed-Wing UAV Swarms

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Abstract
Autonomous unmanned flight based on fixed-wing aircraft constitutes a practical and economical solution for transport missions to remote destinations or disadvantaged communities, for which payload and range represent interesting figures of merit. In those scenarios, the employment of UAV swarms appears as a promising way to pursue a scale effect on payload. Considering the military market, the deployment of swarms of smaller aircraft may enable logistic modularity, mitigating the risk of losing the entire mission cargo or war-load by flying over hostile areas. This paper is concerned with several aspects of fixed-wing UAV swarm flight: 6-DOF flight dynamics modeling, aircraft stabilization, path tracking for autonomous guidance, intra-swarm formation control, overall performance assessment and disturbance rejection are topics touched in the work. The methodologies and study-cases herein illustrate the design and coordination of a swarm, obtained through reliable control techniques, and demonstrated within a complete non-linear simulation environment.

1. Introduction

The always-increasing interest in the employment of autonomously-flying assets in aerospace is supported primarily by the versatility and safety that these solutions can provide in rescue and reconnaissance missions for both civilian and military applications. Unmanned aerial vehicles (UAVs) have many advantages over manned aircraft that help explain their effectiveness. These include reduced operational cost and detectability, relaxed limitation to acceleration tolerance, and flexibility especially with respect to deployment and recovery platforms.

The new frontier in this field of application is certainly represented by rotary-wing UAVs, which are a rather flexible alternative especially because of hovering capability, and lighter-than-air platforms.[7] However, fixed-wing aircraft still represent arguably the best solution in terms of mission range, fuel consumption and payload.[9]

While, on the one hand, the literature reports an extensive documentation on dynamics and control of fixed-wing UAVs, based on both classical and modern control techniques for stabilization and guidance,[1,3,5] the same cannot be said for the dynamic characterization and control of a cooperating formation. The problem of fixed-wing UAVs swarms synthesis is often approached in the literature from the perspective of mission management, with a focus on swarm coordination and communication logic, more than on rigorous dynamic modeling and on the accurate physical description of the problem.[2,4,12] Actually, aircraft dynamics is typically modeled in 2D by associating each element in the swarm with three states (two displacements and one rotation within the longitudinal plane), sometimes neglecting state and control input constraints, mainly related to the aircraft minimum airspeed for sustained flight (stall), and more generally, to aerodynamic effects.

This gap in documented research motivates this paper, which is focused on analyzing the problem of UAV swarm formation flight without simplifying aircraft dynamics, and putting in place control strategies applicable in the field, taking into account the non-linearities inherent to the problem at hand.

The current study relies on a non-linear simulation framework developed employing an object-oriented library in `Matlab (R2022b)`®, called `SILCROAD` (*Si*mulation *L*ibrary for *Cr*aft *O*bject *A*dvanced *D*ynamics),[8] and developed at the Department of Aerospace Science and Technology, Politecnico di Milano. This environment provides enhanced flexibility for adding or removing units from the formation, with each unit having its own control system, and being implemented as a separate object within the inter-agent simulation environment. As a result, this approach significantly streamlines and expedites the simulation environment generation process, by circumventing the inherent rigidity of simulation programs such as `SIMULINK (R2022b)`®. Connecting the multitude of states and inputs originating from

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each formation component in SIMULINK (R2022b)® would require a substantial effort, which is alleviated by the proposed approach.

An additional advantage of this approach lies in the ability to easily modify the swarm by integrating it with different types of aircraft, simply by adjusting the properties of the corresponding unit.

In the present research, the test-bed considered as a constituting unit within the swarm has been selected as a small reconnaissance drone, the AAI RQ-2 Pioneer (see Figure 1 and Table 1), featuring a compact size and ensuing good maneuverability, and a conventional configuration, easy to capture with good accuracy without deploying highly sophisticated aerodynamic models.

The envisioned formation is capable of coordinating through a distributed control algorithm, i.e. each aircraft within the formation acts autonomously and makes decisions based on local information without relying on a central control. Distributed control algorithms enable aircraft to communicate with each other and adopt predefined rules to maintain the desired formation. This implies:

- improved resilience and fault tolerance, as each aircraft can continue operating autonomously even when others in the formation are unavailable.
- reduced computational complexity, as each aircraft processes only local information and interacts with neighboring aircraft.
- increased scalability, as aircraft can be added or removed from the formation without reconfiguring the entire control system.

The methodological workflow adopted for illustrating this architecture involves an initial modeling of the individual aircraft, followed by a stability analysis assessing the performance of the purpose-designed stability augmentation system. Subsequently, an algorithm for autonomous guidance along a multi-checkpoint path is studied, applicable to a single aircraft or to a swarm during the cruise phase. Lastly, a distributed control strategy is investigated for coordinating several aircraft flying along a designated trajectory, also in presence in disturbance like localized wind streams.

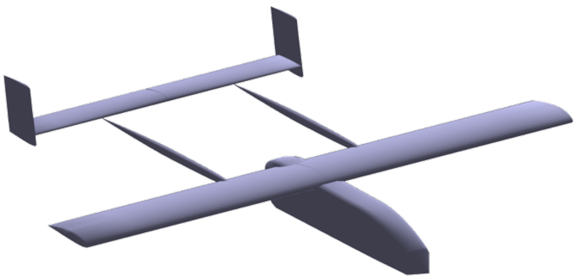

Figure 1: AAI RQ-2 Pioneer, 3D view

Parameter	
Mass (kg)	205
Overall length (m)	4.3
Wingspan	5.15
Number of thrusters	1
Nominal Power (kW)	28.3
Range (km)	185
Service ceiling (m)	4 600

Table 1: AAI RQ-2 Pioneer parameters

2. Stability augmentation system

The stability augmentation system (SAS) scheme proposed herein is based on a model-based approach and an optimal control law, specifically the Linear Quadratic Regulator (LQR) technique. This control strategy allows to optimally minimize a quadratic cost function. It achieves this goal by employing state feedback, where the control gains are calculated based on the dynamic model of the aircraft, and on user-defined weight matrices that capture the trade-off between state-tracking performance and control effort.[10] In other terms, the controller aims to stabilize the system while achieving a balanced control employment performance.

Following this approach, for control design and stability analysis purposes it is first necessary to linearize the system dynamics around a specific trim condition. The stabilization strategy involves closing the loop on the canonical state variables of an aircraft in a linear framework, namely perturbations of speed/aerodynamic angles, rotational rates and attitude angles, or analytically $\{u, \Delta\beta, \Delta\alpha, \Delta p, \Delta q, \Delta r, \Delta\phi, \Delta\theta, \Delta\psi\}$, properly filtered to ensure the elimination of high-frequency spurious signals in feedback and, consequently, on the inputs transmitted by the controller to the actuation system of the aircraft. Washout filters are applied on the pitch and yaw rate signals to ensure that the guidance controller has enough bandwidth to operate effectively.

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The state vector associated with the linearized dynamic model has been augmented with the states of the four actuators (elevator, aileron, rudder, throttle), which have been modeled as first-order dynamic systems characterized by specific response time constants, as well as low-pass filters and washout filters. As a result, the aircraft exhibits a slight time delay in the response to the input command (generally composed of elevator δ_e, rudder δ_r, aileron δ_a, throttle δ_t), reflecting the inherent behavior of a system with non-ideal actuators and filters.

No thrust control has been considered for stabilization.

The general SAS scheme is shown in Figure 2.

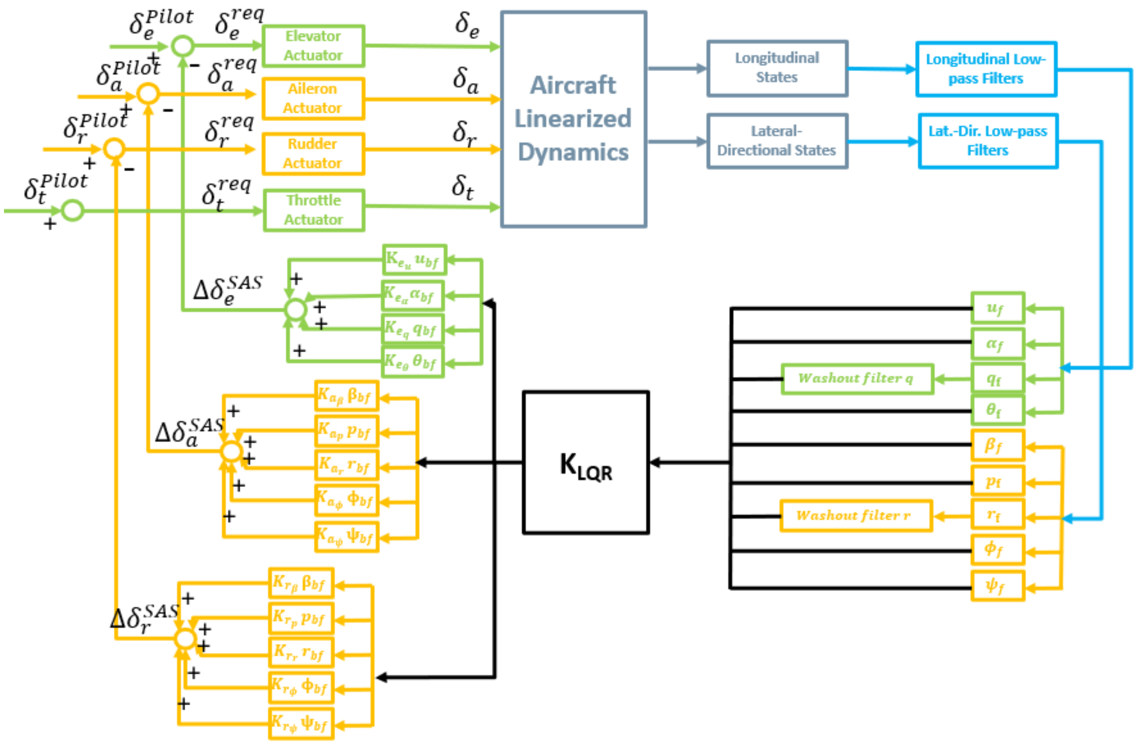

Figure 2: Proposed stabilization control. Green: Longitudinal dynamics. Yellow: Lateral-directional dynamics. Cyan: Low-pass filters.

In the LQR gain-tuning process, each row of the gain matrix corresponds to a specific command input. The values in each row, when multiplied by the filtered state vector, contribute to the overall feedback signal applied to the corresponding command. The subscript $(\cdot)_{bf}$ for signals in the feedback branch stands for *b*andwidth *f*iltered.

Since the controller design was carried out in a linear framework, it is important to ensure and assess its effectiveness in non-linear conditions. This typically involves the application of a gain scheduling procedure, where the gain matrix K is re-tuned for several sampled flight conditions within the operating envelope of the aircraft. Look-up tables and interpolation techniques are then employed online to select the most effective pre-computed gain matrix for stabilizing the aircraft under each specific flight condition.

In Figure 3, the evolution of the longitudinal and lateral-directional states (respectively) is shown in response to an initial perturbation of $\Delta\beta = 5°$ on the side-slip angle, starting from a steady horizontal flight condition.

Considering a linearized and decoupled model (as typical in flight dynamics and control[6]), this perturbation typically affects the lateral-directional dynamics only. Conversely, in the coupled non-linear case, the longitudinal dynamics is also affected. Consequently, all branches of the control system respond to dampen the oscillations.

3. Single-aircraft guidance algorithm

The guidance algorithm is inspired by prior work carried out on airship guidance.[8] It essentially employs beam tracking, similar to that used for VOR navigation or ILS approach.

The core strategy, based on available GPS measurements, is a proportional control logic which aims to minimize the differences between the actual and desired velocity, as well as the vertical and lateral position errors with respect to

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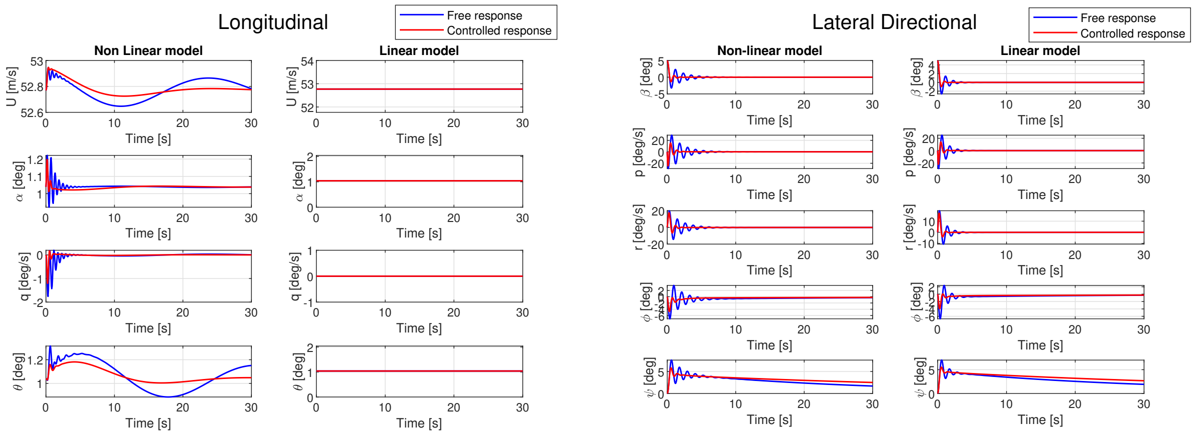

Figure 3: Evolution of longitudinal and lateral-directional states, for a steady horizontal flight condition and an initial perturbation $\Delta\beta = 5°$. Comparison of linear and non-linear simulation model, free and artificially stabilized systems.

the beam.

Besides the velocity magnitude (modulus) regulation, which is managed by the throttle, the elevator is also employed to manage the vertical speed of the aircraft. It would be impractical to solely rely on position error control. Such an approach would result in a highly reactive control action as the aircraft would lack information on the direction of motion, leading to significant control action even for small position errors. For this reason, the elevator is responsible for controlling the vertical position error, which is calculated in a local plane normal to the horizon plane, and additionally, for tracking a target rate of climb, determined based on the vertical position error. The so-determined target rate of climb is intended to be positive when the aircraft is below the reference beam position, or negative when the aircraft is above it. This approach allows for precise vertical control and ensures the aircraft keeps on the beam, or at a prescribed vertical distance from it.

Concerning lateral guidance, the aileron control input is used to adjust roll, and minimize any lateral deviation from the intended beam course. Unlike vertical guidance, where a set-point for the vertical rate is targeted, the aileron control aims to eliminate the difference between the track angle χ (which corresponds to the horizontal azimuth heading ψ in still air) and the designated ground course. This approach, rather than directly tracking a lateral rate set-point, has been found to be empirically more effective, especially during course change maneuvers where the lateral rate gradient is significant. Tracking the lateral rate set-point directly in such situations would result in intense control action, which would require reducing the lateral control gains to avoid tracking divergence. By controlling the course error instead, a smoother control response can be achieved while still incorporating information about the direction of motion. This approach ensures an effective trajectory blending along a complex target flight plan with required turns.

Finally, a feedback branch is employed for turn coordination, introducing a rudder deflection proportional to the side-slip angle.

The general guidance control scheme is reported in Figure 4. Low-pass filters have been added to prevent high-frequency noise interference in the control loops (e.g. turbulence).

An illustrative scenario is depicted in Figure 5, where a hexagonal target pattern with multiple staggered checkpoints at different altitudes is assigned. The black spheres represent proximity volumes around each checkpoint. When the aircraft enters a position within the space defined by the proximity sphere, as determined by GPS coordinates comparison, the control system initiates the re-aligning maneuver and directs the aircraft towards the next way-point.

4. Swarm modeling and control

As stated in the introduction, the present work aims at achieving a mutual independence of the units in a swarm, to the extent required to avoid loss of control of the swarm in case of disturbance or loss of a leading unit. This feature is especially interesting for the leg in the swarm mission where precision with respect to the track is of primary relevance, typically when flying over target (for a photographic or cargo-dropping run). However, classical formation flight, implementing a basic leader-follower philosophy, remains of interest for those parts of the mission where mutual separation in a compact formation is neede, keeping each unit in an aerodynamically advantageous position, i.e. typically in cruise, or prior to approaching the over-target phase of the mission.

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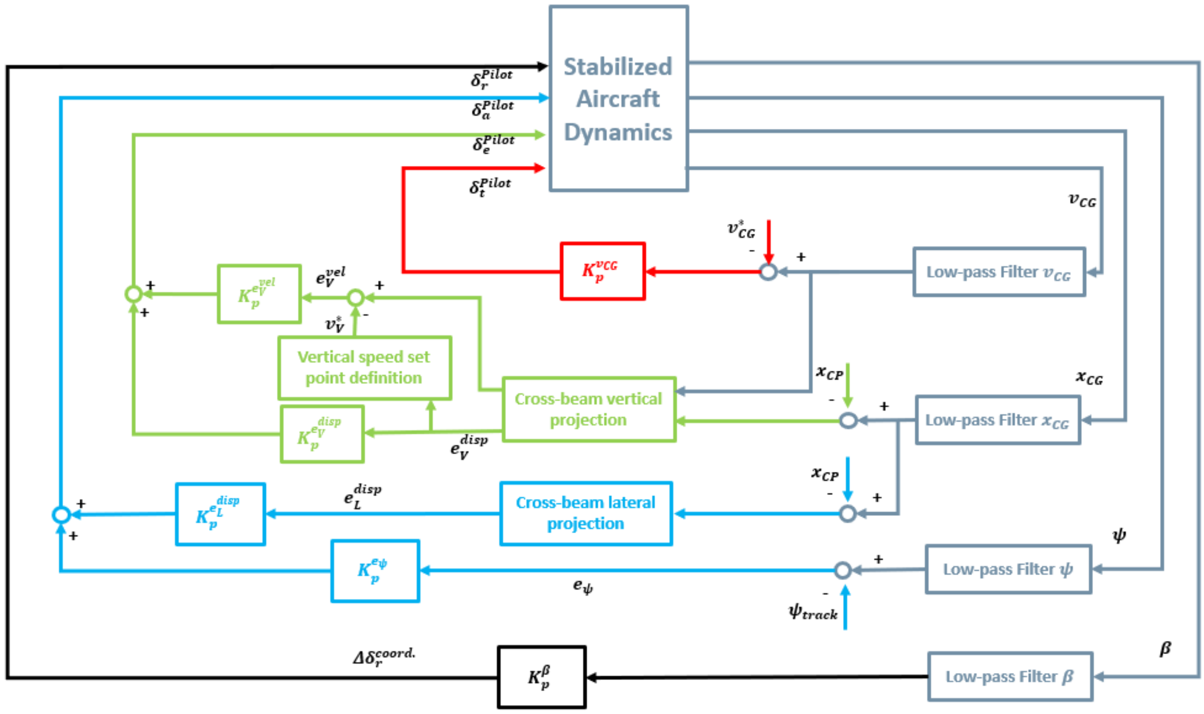

Figure 4: Guidance control scheme. Red: airspeed tracking. Green: longitudinal beam-tracking. Cyan: lateral beam-tracking. Black: turn coordination.

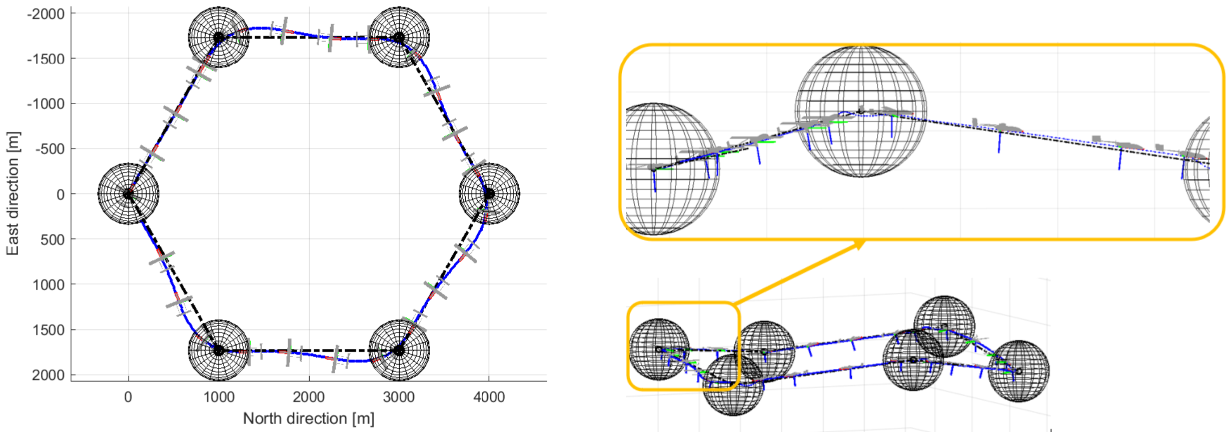

Figure 5: Guidance control: hexagonal pattern, top and lateral views (from east, with zoom).

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4.1 Formation control: flight in cruise mode

To achieve formation flight, the relationship between a leader and a follower aircraft is considered and studied. In that scenario, the control logic of the follower aircraft is rather straightforward, and it involves maintaining a fixed relative position with respect to the leader, determined in the leader's body components based on its center of gravity position. The primary objective of the controller is to minimize the distance between the follower and the target position, by defining three position errors that correspond to the projections of this distance in a reference frame aligned with the leader's body frame, and with the origin located at the target position.

An explanatory sketch of these three position errors is depicted in Figure 6.

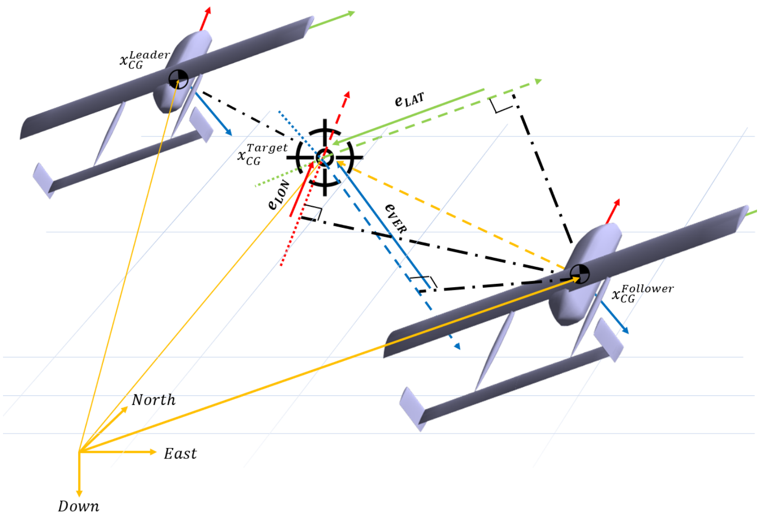

Figure 6: Formation control: definition of target point for the follower, and of the follower position errors.

In this autonomous flight mode coordination control is carried out using feedback variables made available through the onboard GPS system. The relative positions are elaborated by the follower, knowing the global coordinates of its own position and the target position. However, it would be impractical to execute the leader-follower coordination using only position errors as control variables. Therefore, the control system is provided with information about the direction of motion and evolution of attitude of the leader, so that a related control action adjusting the control inputs of the follower both in the longitudinal and lateral-directional body plane is enabled. Altogether, in the proposed control design, the control inputs for the follower are generated combining three factors:

- a position error (as previously described),
- a path error (measured with respect to the course angle χ and climb angle γ of the leader, respectively),
- an attitude error (measured with respect to the roll angle ϕ and pitch angle θ of the leader respectively).

By combining the path and attitude errors with respect to the leader, the control system of the follower can achieve accurate and stable tracking of the target position, maintaining a good sensitivity to the unfolding of the leader's dynamics. This approach enables for a precise and smooth control action of the ailerons and elevator, in turn ensuring accurate aircraft mutual positioning.

The longitudinal position control is primarily handled by the throttle, which operates through a control law based on position and velocity errors along the leader's longitudinal (i.e. x) body axis.

A proportional control law is employed to mitigate the side-slip angle through rudder deflection, ensuring turn coordination.

A detailed diagram illustrating the control logic for formation control in cruise mode is shown in Figure 7.

4.2 Flying over target: beam tracking vs. formation keeping

An autopilot mode has been designed to manage both formation control in a leader-follower logic (see section 4.1), and guidance, with the control logic described in section 3. As said, this dual functionality of the autopilot has been

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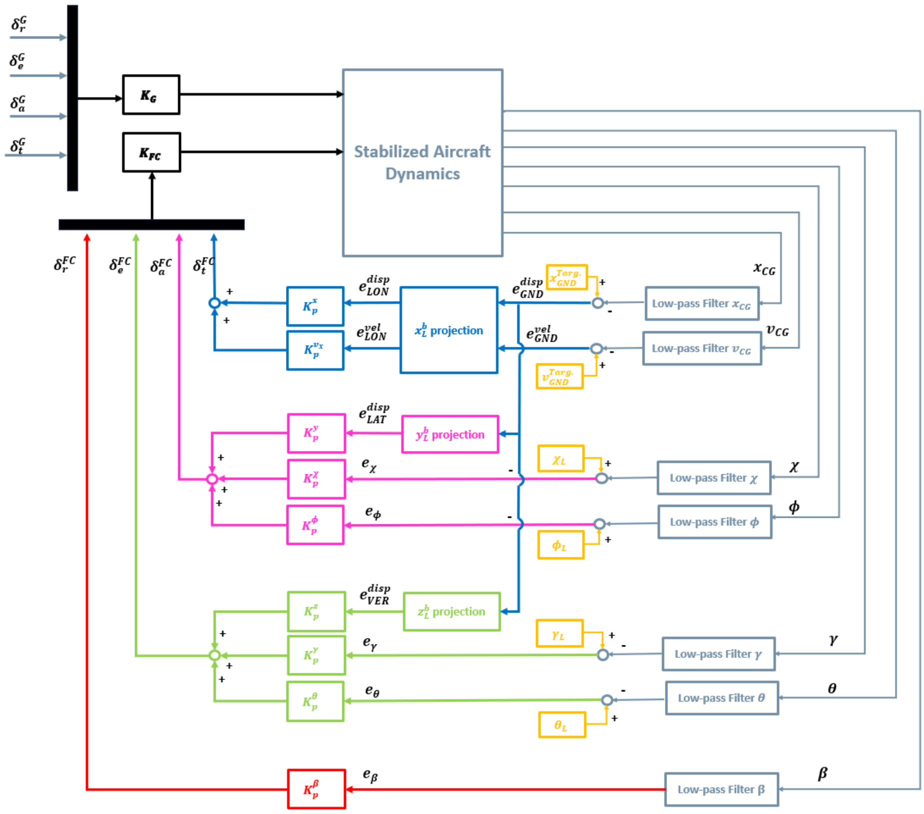

Figure 7: Control scheme for follower aircraft in formation flight (cruise mode).

devised to serve the various purposes of a typical reconnaissance mission. During the navigation phase, the main objective is to maintain tight formation around the leader, leveraging the relative positioning of the swarm elements to exploit an aerodynamically advantageous position (*sweet spot*). The sweet spot can be identified as an area near the wingtip of the leading aircraft that offers beneficial aerodynamic effects to a follower. By positioning themselves in this region, follower aircraft can take advantage of the upwash generated by the leader's wing, resulting in reduced drag and improved fuel efficiency (see 4.3). During the on-target phase instead, the primary goal is to accurately survey/overfly the area below, while mitigating potential disturbances such as wind or signal loss from the preceding aircraft (in particular, due to hits in a hostile scenario). In this situation, each unit within the formation is capable of fulfilling the mission task by adhering to a designated path, according to the guidance mode introduced in section 3.

Accordingly, the two autopilot modes are regulated by two respective gains (K_G and K_{FC}), modulated via a supervisory multiplier ranging from 0 to 1, which can be adjusted based on a certain error parameter (e.g. the leader's cross-track error). As the leader's cross-track error increases, for instance due to wind disturbance, the weighting of the navigation (i.e. on-target) mode is increased compared to the formation control (i.e. cruise) mode. Alternatively, the control laws can be implemented so as to work in a mutually exclusive fashion, allowing the former or the latter to take priority.

4.3 Wake interference modeling

Aerodynamic wake interference plays a critical role in swarm architecture design, when it comes to define a 3D structure of the formation, and cannot be disregarded. The vortex flow field generated by the wingtips of a leading aircraft affects the following aircraft by subjecting them to a non-uniform induced velocity field. This field features an upwind region on the outer portion of the wake and a downwind region on the inner portion (see Figure 8). The induced velocity effect results in either a positive or negative change in the angle of attack of the trailing aircraft, depending on its sidewards displacement relative to the leading aircraft.

As shown in Figure 9, in the upwind region, the increase in induced angle of attack causes the resultant aerodynamic forces to tilt forward. Consequently, the aircraft experiences an increase in lift, accompanied by a reduction in drag. Conversely, in the downwind region, the opposite effect occurs. The decreased angle of attack leads to a

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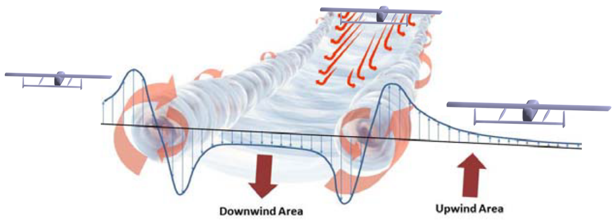

Figure 8: Vortex flow field behind a leading aircraft, investing trailing units in the formation.

reduction in lift and an increase in drag, which results in higher fuel consumption and degraded flight performance.

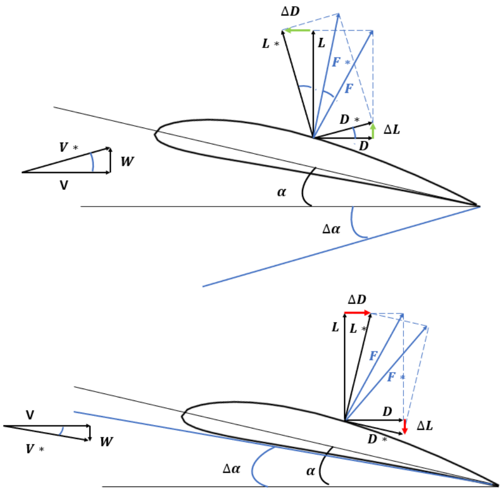

Figure 9: Upwind (top) and downwind (bottom) effects on lift coefficient (C_L) and drag coefficient (C_D).

To investigate the wake effects, a simplified approach employing the vortex lattice method (VLM) was employed, with leading and trailing lifting surfaces. Although the VLM provides a simplified representation of flow physics, it is widely accepted and adopted for studying and analyzing aircraft dynamics in formation flight. Initially, the aerodynamic force and moment coefficients of the isolated wing are calculated. Subsequently, the changes ΔC_i to be applied to all coefficients and associated with the trailing wing are determined, based on the lateral and vertical separation between the two wings. These coefficients are then compiled into a database, to compute within a time-marching simulation the wake interaction effects felt by the trailing aircraft, by interpolating the database at the current relative position between the leader and follower aircraft.[11]

For a better visualization of the phenomenon, surface plots were constructed, as shown in Figure 10, illustrating the increase in aerodynamic coefficients as a function of lateral and vertical separation. The region where peaks in lift coefficient change (ΔC_L) and valleys in drag coefficient change (ΔC_D) are observed correspond to the sweet spot mentioned previously.

5. Example Applications

In order to illustrate the functions of the proposed control suite, some examples will be shown in the following paragraphs, adopting the AAI RQ-2 Pioneer as a test-bed. Similar to the stability analysis presented previously, the model is fully non-linear in terms of mechanics and aerodynamics. In particular, the change in the aerodynamic coefficients resulting from the wake interaction effects are accounted for in formation flight (see section 4.3). Furthermore, all aircraft are always artificially stabilized by means of the stability augmentation systems described previously (see section 2).

5.1 Testing in still air

In a first scenario, no disturbance due to the wind is considered, and formation flight is tested on assigned linear tracks, composed to form paths of increasing complexity, and considering two or three units in the swarm.

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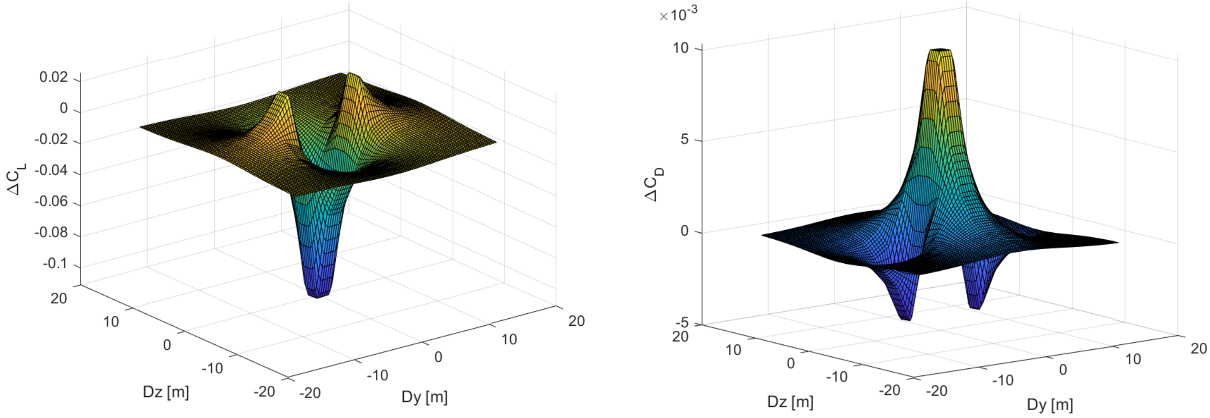

Figure 10: Pictorial representation of the database of change to lift coefficient ΔC_L (left) and drag coefficient ΔC_D (right), as functions of lateral (Dy) and vertical (Dz) distance between leading and trailing wings.

5.1.1 Two-aircraft formation: single leg trajectory path

A preliminary testing phase is conducted considering two aircraft, assigning a single straight and climbing flight path to the leader, while the follower is instructed to maintain a 7 m distance from leader along all three reference axes, starting from a non-zero (i.e. perturbed) positional error (Figure 6). In addition, an initial misalignment of 10° from the desired course is imposed, to test both beam-tracking guidance and formation control systems capability to counteract a sudden lateral disturbance.

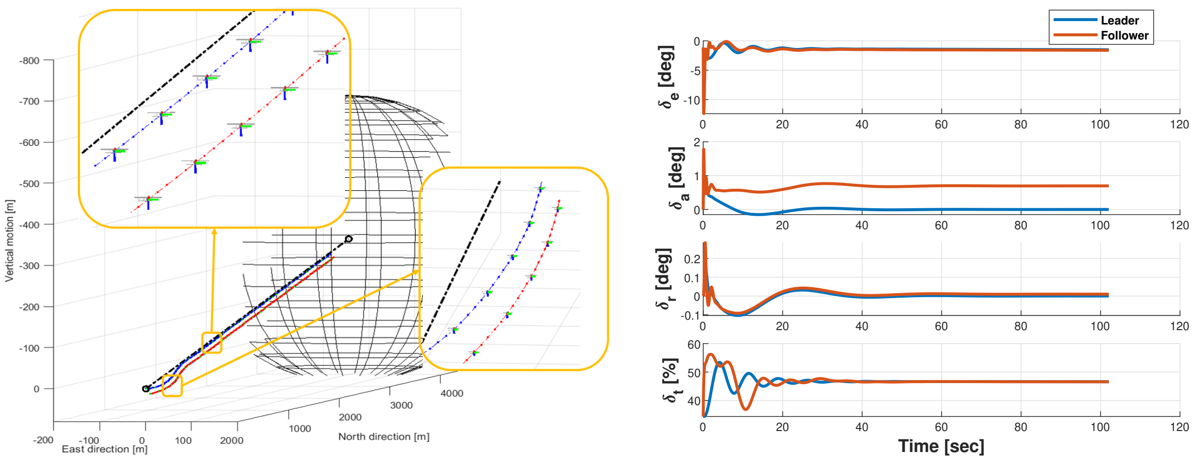

Figure 11: Straight climbing path with initial 10° misalignment. Two-aircraft formation. Left plot. Visualization of trajectory. Blue: leader. Red: follower. Right plot. Time histories of controls for leader and follower.

As reported in Figure 11, the follower responds to the initial disturbance in a more abrupt manner, aiming to quickly catch up not only with the target position but also with the leader's attitude. However, none of the four control commands reaches saturation, thereby ensuring a wide maneuvering margin for the follower aircraft. It is noteworthy that while the elevator, rudder, and throttle tend to converge to the leader's values after the realignment maneuver, the aileron retains a residual value different from zero. This is expected, since the aileron compensates for the rolling moment induced by the wake interference.

The overall assessment of formation performance can be carried out evaluating the three characteristic errors targeted by the formation control system in cruise mode, namely e_{Lat}, e_{Vert} and e_{VMod}, as well as the three positional errors for the formation control (Figure 12).

In Figure 12 the terms e_{Lat}, e_{Vert} and e_{VMod} denote the positional and velocity modulus errors relative to the leader's current position and ground speed in relation to the designated path, and are therefore employed for beam-tracking by the leader. Conversely, e_1, e_2, and e_3 represent the longitudinal, lateral, and vertical position errors of

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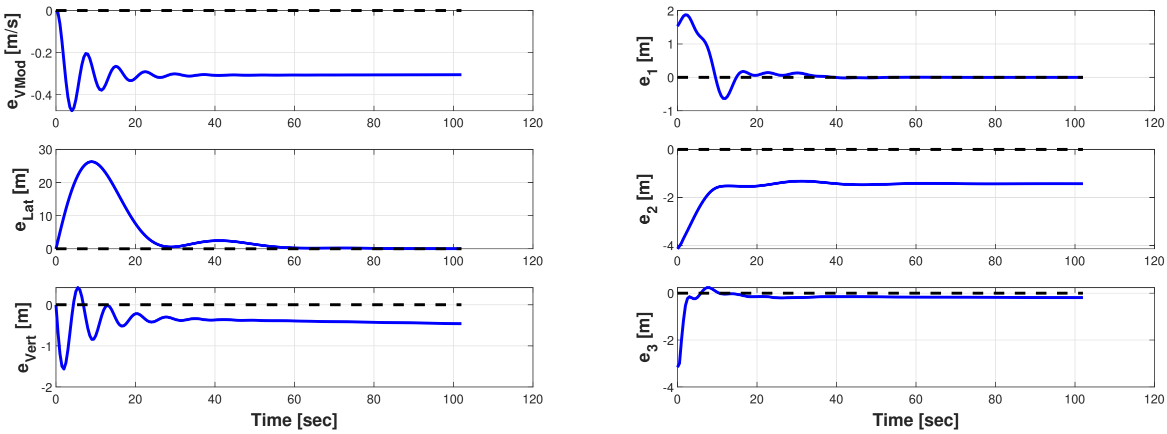

Figure 12: Target errors for beam-tracking (left) and for formation control (right).

the follower with respect to the target relative distance from the leader, as outlined in section 4 (in other words, these positional errors correspond to e_{LON}, e_{LAT} and e_{VER} respectively in Fig. 6).

All positional errors converge to a constant value within a tolerance band of ±2 m. The residual static error observed in e_{Vert} (left plot in Figure 12) can be attributed to the specific tuning of the guidance system gains, which leads to the baseline controller closing the error gap on the vertical rate set point (see section 4) faster than on the vertical position itself. Moreover, although the error in the speed modulus is small and acceptable (less than 1% of the target velocity), it could be further reduced by incorporating an integrative contribution into the baseline controller. The formation control system also demonstrates a satisfactory performance, reducing both vertical and longitudinal position errors to zero in physically acceptable time windows. The persistent lateral error e_2 (right plot in Fig. 12) can be attributed to the equilibrium condition established by the aircraft to compensate for the wake-induced rolling moment.

5.1.2 Three-aircraft formation: hexagonal pattern

Without any special arrangement or modification to the control architecture, a third aircraft can be added to the swarm. The latter aircraft is assigned a target position to the left of the leader, symmetrically with respect to the position of the right-hand-side follower, thus generating a V-shaped formation. Here, an hexagonal path is assigned, alternating climbs to a 100 m altitude and descents to 0 m, on the first four legs of the route (see Figure 13).

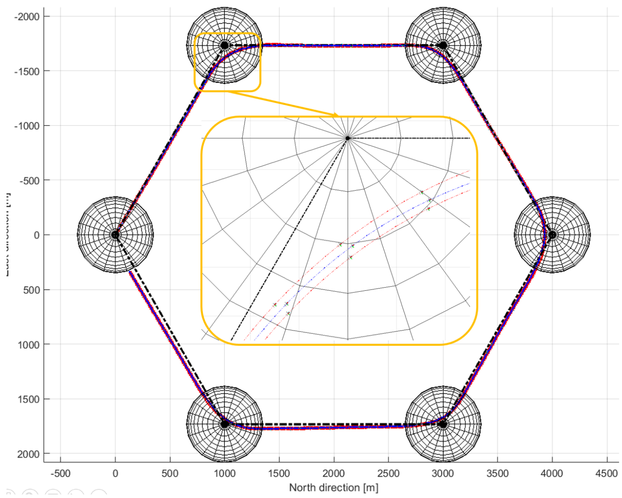

Figure 13: Three-aircraft swarm in V-shaped formation on a hexagonal pattern with climbs/descents.

The behavior of the errors of the beam-tracking guidance system of the leader and of the relative position tracking systems of the two followers is shown in Figure 14.

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The vertical profile of the route includes four altitude changes over the first four legs, where it is observed that the guidance system of the leader struggles to perfectly adapt the speed to the required one, while still remaining within a tolerance of 1.1% error (center plot). Lateral and vertical errors, on the other hand, are effectively reduced to zero at the end of each turning maneuver and subsequent realignment with the current beam.

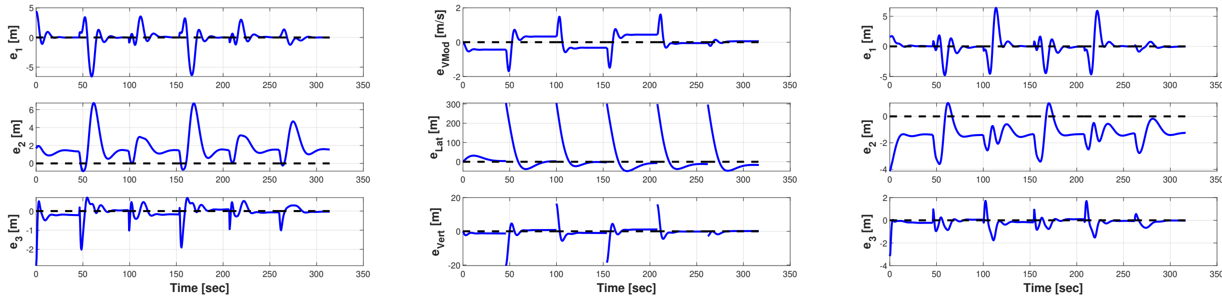

Figure 14: Time histories of errors for three-units formation flight along a hexagonal pattern. Left: left-hand side follower position errors. Center: leader's guidance errors. Right: right-hand side follower position errors.

The position errors of both followers (left and right plots in Figure 14) remain bounded within a tolerance of ±5 m for e_1, and ±2 m for e_3 respectively, with peaks occurring only at the turning points. It can be noticed that the lateral position error is mirror-symmetric between the right and left followers, given the symmetry of the formation.

Similar to the two-units formation flight in section 5.1.1, also in this case, the formation controller does not reduce the error e_2 to zero. However, overall, this offset proves beneficial as it ensures an adequate lateral separation margin to avoid dangerous trajectory crossings during turning maneuvers.

5.2 Testing in windy condition

Specific tests were conducted considering wind disturbances. Deterministic wind has been modeled incorporating both time-dependent variations, by specifying start and end times of the disturbance, and spatial distributions, defining a wind-affected region. Example visualizations of the wind disturbance are shown in Figure 15.

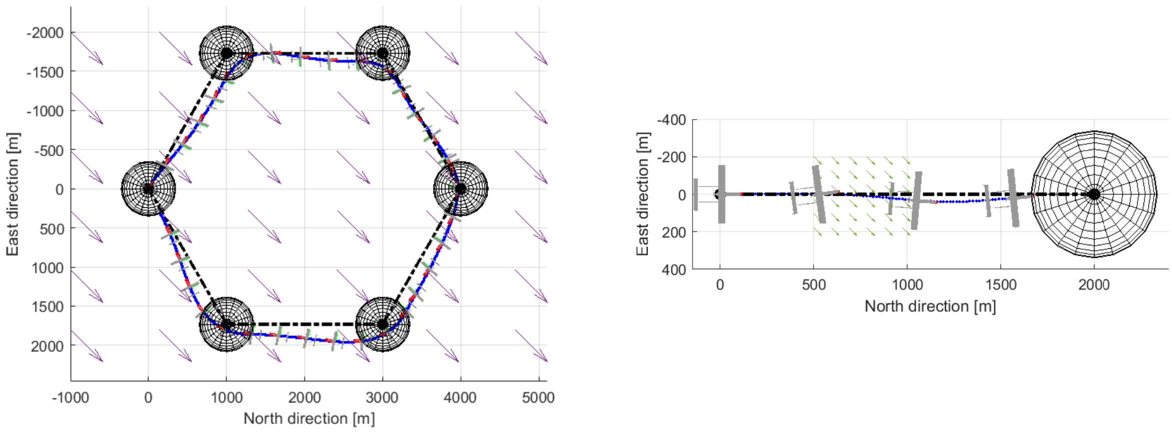

Figure 15: Example visualizations of constant-in-time wind disturbance. Left: homogeneous disturbance. Right: localized disturbance (wind-stream tube).

An interesting scenario involves subjecting the formation to a wind-stream tube featuring altitude bounds, in such a way that only the leader experiences an airspeed variation, whereas the followers do not enter the tube. This allows evaluating two possible formation behaviors:

1. in a complete leader-follower subordination logic, the followers chase the leader's trajectory, disregarding any information on the intended track. The leader's reaction to the disturbance causes the entire formation to experience an increase in cross-track error. However, mutual distances are kept within the formation.

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2. when encountering a disturbance that deviates the leader from the route, the guidance mode takes priority, steering the followers back onto the established path and waiting for the disturbance to subside. Formation is momentarily lost, but most of the swarm keeps on accurately tracking the intended path.

Consider a setting where the formation is flying along a leg in a northerly direction and encounters a moderate-intensity (6 m/s, 90 ° direction) wind disturbance, that extends over a 500 m path. It is interesting to analyze the two possible scenarios just introduced.

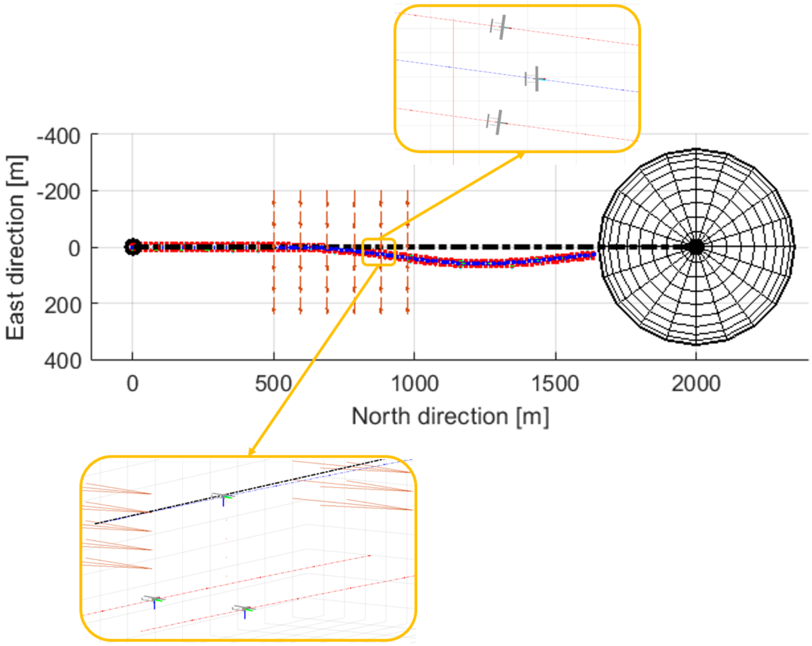

Figure 16: Leader flying through constant wind disturbance tube, followers with cruise mode engaged, accurately targeting formation flight and disregarding navigation information.

In the first case (Figure 16), as typical to the cruising phases of the mission, when it is advantageous to maintain a tight formation (for instance for optimal aerodynamic performance, as explained in section 4.3), the leader's entry into the wind-stream tube causes a sudden variation in the cross-track error. However, the autopilot formation control ability (cruise mode) keeps on accurately tracking the position with respect to the leader, even though the two followers are not subjected to a wind-induced airspeed change.

In the second case (Figure 17), which could be associated for example with an on-target phase of a reconnaissance mission, any disturbances encountered along the path are rejected without compromising the mission task. In this context, as soon as the leader enters the wind-stream tube, an increase in cross-track error triggers the disengagement of the formation control (cruise mode) of the autopilot, and the take over of the guidance mode (beam-tracking), which keeps the rest of the formation on the intended flight path. The formation is then reestablished by switching back to the cruise formation control mode once the disturbance has ceased.

6. Conclusions and outlook

Various aspects of formation flight have been investigated within this paper. The intention of this work is not to replace the existing documentation on the control and coordination of a fixed-wing multi-unit UAV system, but rather to propose a viable alternative for a more in-depth modeling of the problem from the perspective of flight dynamics, rather than pure control architecture.

The dynamic modeling in a fully non-linear environment has allowed highlighting specific aspects of the problem, such as the stability of individual aircraft subjected to state disturbances, the challenges of interfacing with non-ideal actuation systems subjected to bandwidth limitation and signal saturation, the effects induced by aerodynamic interaction, the criticality of maneuvering at angles of attack close to stall, while avoiding exceeding the constraints on minimum sustaining airspeed, as well as managing a limited available engine power, resulting in a constrained flight envelope.

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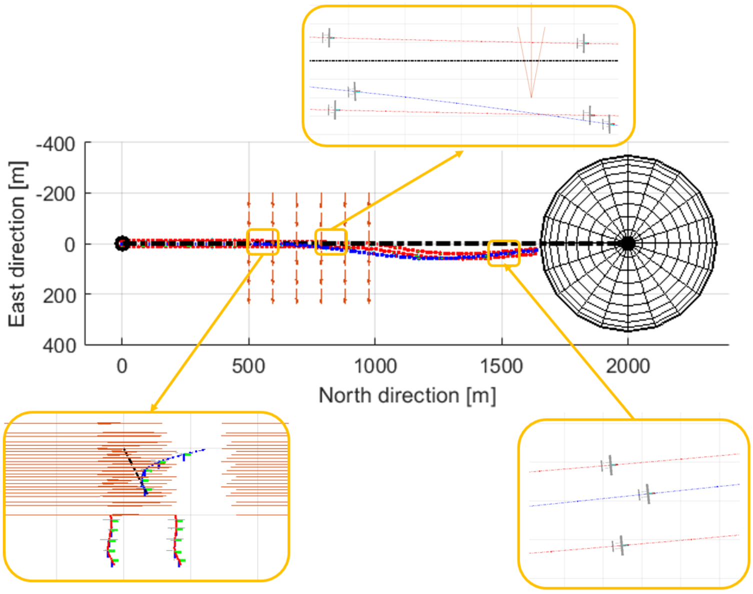

Figure 17: Leader flying through constant wind disturbance tube, followers with on-target guidance mode engaged, keeping on the prescribed track and momentarily disregarding accuracy on mutual distances from the leader.

The problem of stabilization was addressed by employing a stability augmentation system (SAS), designed following a model-based approach and tuned according to an LQR (Linear Quadratic Regulator) procedure.This approach resulted in a satisfactory three-axes stabilization, ensuring the required flying qualities for the specific aircraft class, and leaving sufficient bandwidth for the higher layers of the controller, responsible for guidance.

A guidance system was studied to ensure the ability to follow a path with multiple checkpoints in 3D space, adjusting the aircraft heading and altitude coping with a required complex trajectory. The chosen control logic and tuning ensure adequate guidance system performance, tested on an hexagonal pattern, where the cross-track error is effectively reduced to zero for each leg. Additionally, the system is able to avoid trajectory overshoots thanks to the blending technique employed.

For the formation coordination, a control architecture based on the leader-follower hierarchy was employed. A decentralized control approach was adopted, where each aircraft (follower) is assigned a target position to chase, relative to the preceding aircraft (leader). This is achieved by comparing position, attitude, and trajectory information exchanged between the two involved formation elements. This communication mode ensures a limited amount of exchanged data, thereby reducing computational complexity, required communication bandwidth, and consequently ensuring swarm scalability. The outcome of performed testing reported an effective and promising formation coordination. The follower aircraft were able to maintain a stable (within proper tolerances) and aligned position relative to the leader aircraft, responding appropriately to variations in the leader's position and trajectory.

Additional tests were performed to prove the formation behaviour in presence of a constant wind disturbance, ensuring both tight formation through relative position tracking within the swarm, or triggering formation reconfiguration, with followers flying along a designated route when properly switching their autopilot mode.

There are several perspectives for further development of this work currently under consideration: firstly, the possibility of significantly increasing the number of aircraft units within the swarm while establishing a proper hierarchy to ensure stability and robustness. Secondly, an analysis of possible swarm reconfiguration methods in the event of signal loss. In this regard, for future work, a coordination logic based on local distance measurements using laser distance measurement instead of relying on GPS data could be explored.

Lastly, an optimal tuning of the control systems can be pursued to enhance performance across a wide range of deployment scenarios. This could involve conducting extensive simulations to identify the optimal control settings and refine the control algorithms with the aim to maximize the effectiveness, efficiency, and adaptability of the control systems in different mission scenarios.

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