POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

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

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

Author: Marco Tomasoni

Advisor: Prof. Carlo E. D. Riboldi

Academic year: 2022-2023

Abstract

Autonomous unmanned flight based on fixed-wing aircraft offers a practical and cost-effective solution for transportation missions to remote or underserved areas, particularly when payload capacity and range are critical factors. In such contexts, the use of UAV swarms presents an attractive approach to leverage payload capabilities. Additionally, within the military domain, deploying swarms of smaller aircraft could enhance logistic modularity, reducing the risk of losing the entire mission's cargo or weaponry when traversing hostile territories.

This thesis comprehensively addresses various aspects of fixed-wing UAV swarm flight, encompassing 6-degree-of-freedom flight dynamics modeling, aircraft stabilization through Linear Quadratic Regulator approach, path tracking for autonomous guidance, intra-swarm formation control, overall performance evaluation, and disturbance management.

One of the notable features of this research is the implementation of several guidance algorithms designed to serve different purposes of a typical reconnaissance mission. These algorithms are tailored to ensure effective navigation, target identification, and data collection, enhancing the swarm's capability to perform complex reconnaissance tasks.

Concerning swarm management, the research is grounded in predefined hierarchical structures based on the leader-follower paradigm, and simulates swarm dynamics, accounting for the complete nonlinear motion of each involved UAV.

A distributed coordination law is chosen and synthesized based on different available strategies for information conveyance, such as relative position/velocity versus absolute position/velocity, among others. The swarm assembly commences with a simple two-element formation and gradually scales up in complexity by incorporating additional elements in a comprehensive complete reconnaissance mission simulation.

The methodologies and case studies presented in this work exemplify the design and coordination of a UAV swarm, facilitated by robust control techniques, and rigorously demonstrated within a comprehensive nonlinear simulation environment.

Examples based on the actual aerodynamic and inertial characteristics of an existing military UAV are presented, shedding light on both the potential benefits and challenges associated with its integration into a swarm.

1. Fixed-Wing UAV modeling

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. However, fixed-wing aircraft still represent arguably the best solution in terms of mission range, fuel consumption, and payload. While, on the one hand, the literature reports extensive documentation on the dynamics and control of fixed-wing UAVs, based on both classical and modern control techniques for stabilization and guidance [1–3], the same cannot be said for the dynamic characterization and control of a cooperating formation. The problem of fixed-wing UAV 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 [4]. 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's minimum airspeed for sustained flight (stall) and more generally, to aerodynamic effects.
The proposed dynamic model, within this work, is based on the generalized balance equation:

$$\boldsymbol{M}_{CG}\dot{\boldsymbol{w}}_{CG} + \boldsymbol{w}_{CG} \times \boldsymbol{M}_{CG}\boldsymbol{w}_{CG} = r_{\mathbf{CG}} \ , \qquad (1)$$

encompassing six non-linear scalar equations describing rigid body dynamics. Six additional nonlinear equations are incorporated into the model, completing the dynamic description. These include three equations that establish the kinematic relationships between the body angular rates and the attitudes definition according to the Euler angle set (ϕ, θ, ψ), as well as three equations specifying the rates of displacement in the North-East-Down (NED) inertial reference frame.

1.1. Testbed Aircraft

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

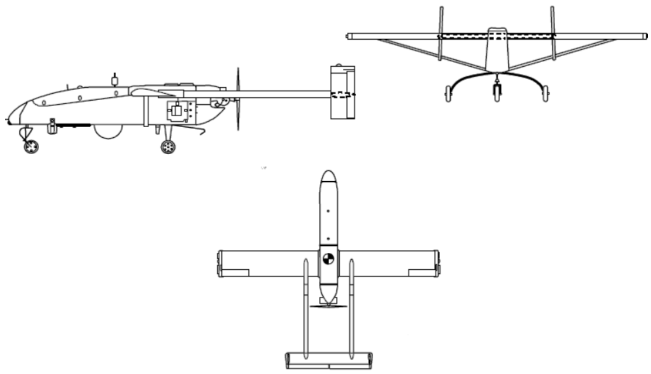

Figure 1: AAI RQ-2 Pioneer 2D views.

2. Stability Augmentation System (SAS)

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.
Following this approach, for control design and stability analysis purposes it is first necessary to linearize the system dynamics around a specific trim condition. Several trim conditions, sampled from within the aircraft's operational envelope, have been analyzed through eigenanalysis. A root locus analysis has been conducted to examine the impact of increased altitude and decreased airspeed on aircraft stability behavior, as illustrated in Figure 2 and 3.

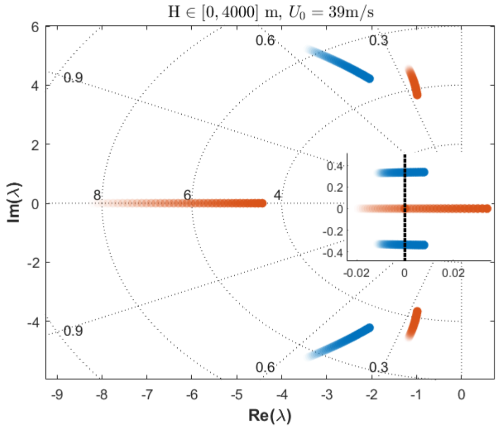

Figure 2: Complete system root locus for increasing altitude.

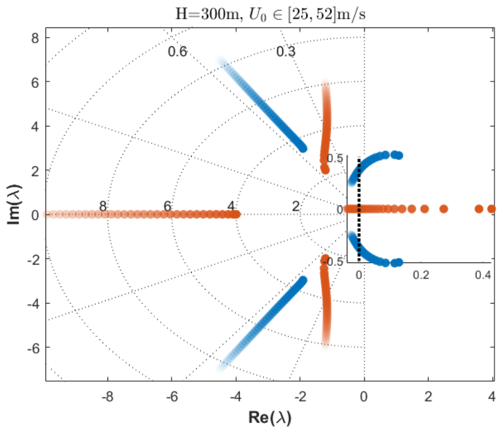

Figure 3: Complete system root locus for decreasing airspeed.

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 $\{u, \Delta\alpha, \Delta\beta, \Delta p, \Delta q, \Delta r, \Delta\phi, \Delta\theta, \Delta\psi\}$ 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.
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, 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 4.

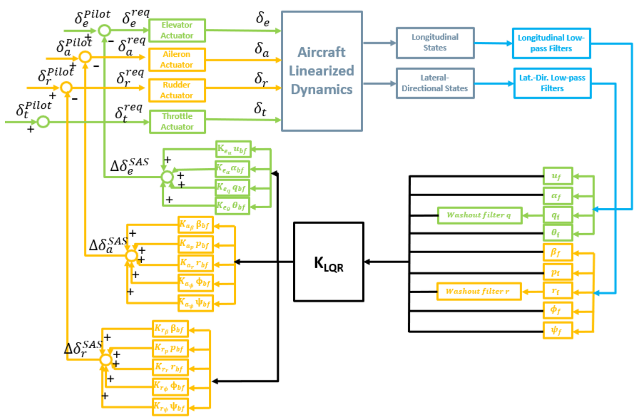

Figure 4: Proposed stabilization control. Green: Longitudinal dynamics. Yellow: Lateral-directional dynamics. Cyan: Low-pass filters.

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 $()_{bf}$ for signals in the feedback branch stands for bandwidth filtered. Since the controller design was carried out in a linear framework, it is important to ensure and assess its effectiveness in nonlinear 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 5 and 6, the time evolution of longitudinal and lateral-directional states is depicted. It compares open-loop (on the left) and closed-loop (on the right) responses, assuming the aircraft is flying with level wings at an altitude of 300 m and a ground speed of 140 km/h. The perturbed initial condition is specified by:$u \simeq$

$0.05\ m/s, \quad \Delta\alpha \simeq 3\ deg, \quad \Delta\beta \simeq 3\ deg.$

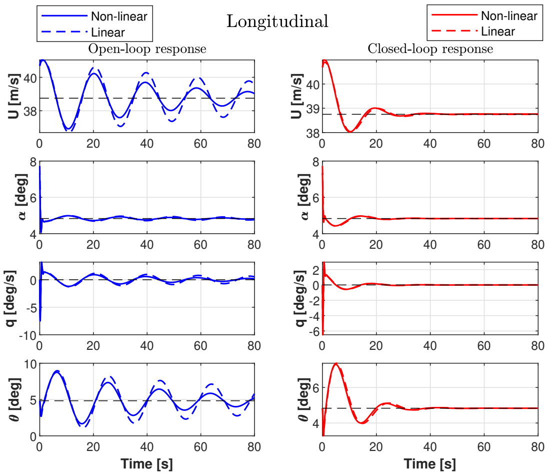

Figure 5: Longitudinal states evolution around trim condition 1. Open-loop (left) vs. closed-loop (right). Linear (dotted) vs. non-linear model.

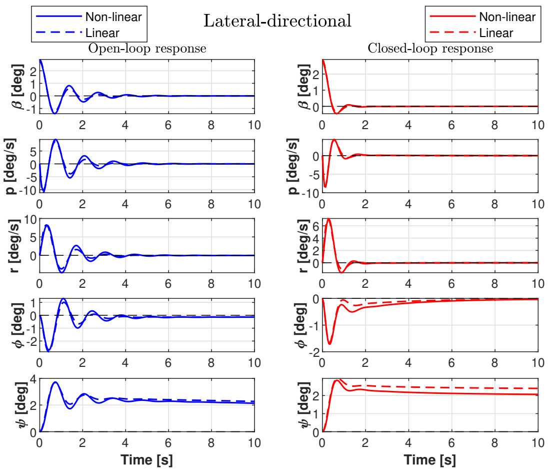

Figure 6: Lateral-directional states evolution around trim condition 1. Open-loop (left) vs. closed-loop (right). Linear (dotted) vs. non-linear model.

3. Single-Aircraft Guidance Algorithms

The integration of three distinct guidance algorithms is incorporated into the aircraft's Automatic Flight Control System (AFCS) to address various stages of a reconnaissance mission. These algorithms include:

1. **Beam Tracking Control:** This algorithm is utilized for waypoint navigation, ensuring the aircraft accurately follows predefined paths.
2. **Circular Trajectory Tracking:** During loitering phases, this algorithm allows the aircraft to maintain a circular trajectory around a specific point of interest.
3. **Rendezvous and Formation Rejoining:** A dedicated procedure is employed for the rendezvous and formation rejoining.

These algorithms collectively enhance the mission's capabilities by providing specialized control strategies for different mission phases.

3.1. Beam Traking

Following a pre-assigned set of checkpoints in 3D space, connected by straight legs, is the problem at hand, which is essentially a means to achieve way-point navigation. The purposeful guidance algorithm is inspired by prior work carried out on airship guidance [5]. It essentially relies upon beam tracking logic for both longitudinal and lateral-directional guidance, similar to that used for VOR navigation or ILS systems.
This approach encompasses self-contained motion control along longitudinal and horizontal beam planes, defined contingent upon its orientation. This is achieved by introducing a coordinate system fixed on the beam, composed of mutually orthogonal unit vectors, centered at the departure checkpoint. The coordinate system is defined such that: the unit vector $\boldsymbol{d_S}$ aligns with the beam and directs towards the destination checkpoint, the unit vector $\boldsymbol{d_V}$ is orthogonal to $\boldsymbol{d_S}$ pointing positively upwards, and $\boldsymbol{d_L}$ completes the triad, indicating rightward direction from above. The core strategy, based on available GPS measurements, is a proportional control logic that aims to minimize the differences between the actual and desired ground speed as well as the vertical (Figure 7) and lateral (Figure 8) positioning errors with respect to the intended path, by targeting as feedback variables, the position error itself and a velocity error with respect to an imposed re-alignment rate set point commanded as a function of vertical/lateral cross-track error. It would be indeed 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 intervention even for small

deviations.

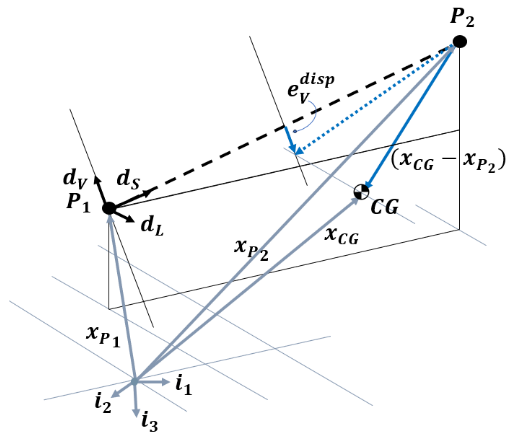

Figure 7: Sketch of beam tracking measurement in the longitudinal plane. Definition of e_V^{disp}. Illustration inspired by [5].

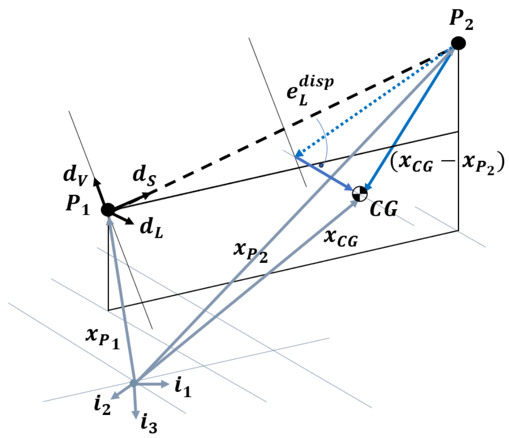

Figure 8: Sketch of beam tracking measurement in the beam horizontal plane. Definition of e_L^{disp}. Illustration inspired by [5].

3.2. Circular Trajectory Tracking

For the execution of circular trajectories, inspiration was drawn from several previous works centered around the employment of a vector field-based guidance method [1].
Essentially, the proposed approach aims to asymptotically bring the cross-track error to zero by means of course error e_χ as the only feedback variable for lateral guidance. Consequently, regardless of the UAV's relative position with respect to the required path, the commanded course angle χ_{cmd} must prompt the UAV to move toward the path itself. The ensemble of commanded course angles constitutes what is termed a vector field. This designation is apt as it represents an array of vectors comprising unit course vectors that indicate the desired travel direction
The vector field describing function:

$$\chi_{cmd} = \gamma + \lambda \left(\frac{\pi}{2} + \tan^{-1}(k_0 \ \hat{d}) \right) \ , \qquad (2)$$

should operate in such a way that when the cross-track error $\hat{d}$ is large, it guides the aircraft toward the center of the orbit. Conversely, when the aircraft approaches the perimeter of the orbit, the function should curve the trajectory by $\frac{\pi}{2}$ with respect to the current phase angle γ. This curvature forces the aircraft to follow the tangential direction to the orbit perimeter, according to the orbit travel direction (λ).

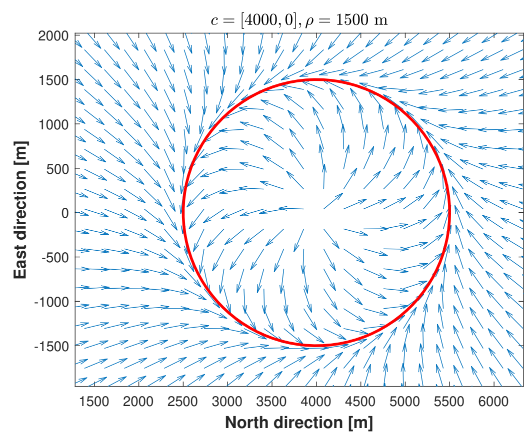

Figure 9: Vector field for circular trajectory tracking.

3.3. Rendezvous

In addressing the complex challenge of in-flight rendezvous for real-world missions, two primary techniques have been considered: linear and circular rendezvous. The latter has been chosen sin it offers advantages such as redundancy in communication, enhanced situational awareness, and the ability to assemble without the risk of encroachment or collisions. Nevertheless, it requires more advanced navigation algorithms and generally takes more time to complete.
In this approach, a leader positions itself on a stable circular trajectory, awaiting incoming followers. The followers employ coordination maneuvers to enter the circular path and chasing the leader. Phasing techniques are employed to quickly reduce the phase shift from the leader. The proposed procedure combines two distinct

guidance techniques: circular trajectory tracking, as detailed in Section 3.2, and leader chasing [6], pursued by imposing additional lateral acceleration proportional to the side-bearing angle η and phase shift σ, according to Equation (3):

$$a_n = \frac{V^2}{R_{ref}}(1 + K_\eta \sin\eta + K_\sigma\ \sigma)\ . \tag{3}$$

The procedure ensures gradual convergence of aircraft to a moving point (the leader) on a designated circular path, as detailed in Figure 10.

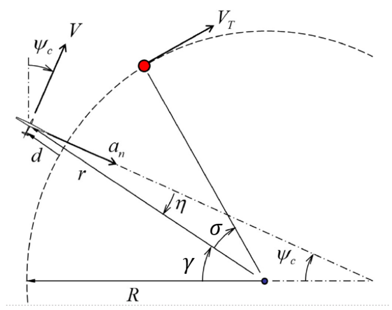

Figure 10: Geometric scheme for leader chasing [6].

3.4. Guidance Testing

An illustrative scenario is depicted in Figure 11 for beam tracking guidance, 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.

A brief insight into circular trajectory tracking is presented in Figure 12 with the assignment of an orbit with a radius of $R = 300$ m.

Lastly, an illustrative rendezvous procedure is presented in Figure 13, with two followers (in red) approaching the orbit from different directions. As they near entry into the circuit, the rendezvous procedure is engaged, guiding the followers onto a tighter circular path until they completely recover the phase shift with the leader. An event function is employed to halt the simulation once both followers are within 50 m of the leader.

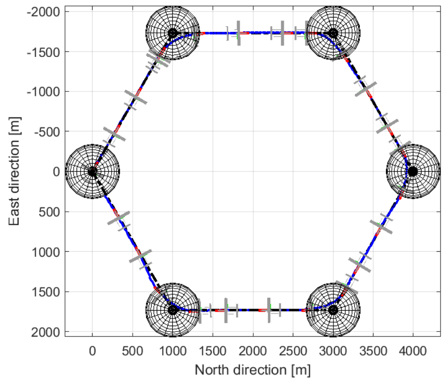

Figure 11: Aircraft trajectory for the hexagonal path.

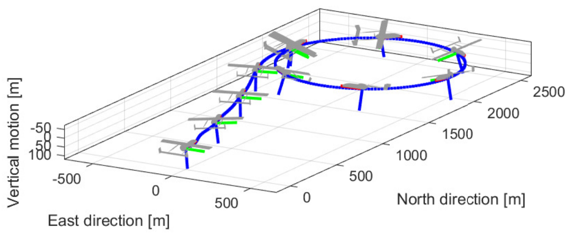

Figure 12: 3D trajectory view for circular path with $R = 300$ m and center coordinates $\mathbf{c} = [1800, 0]$.

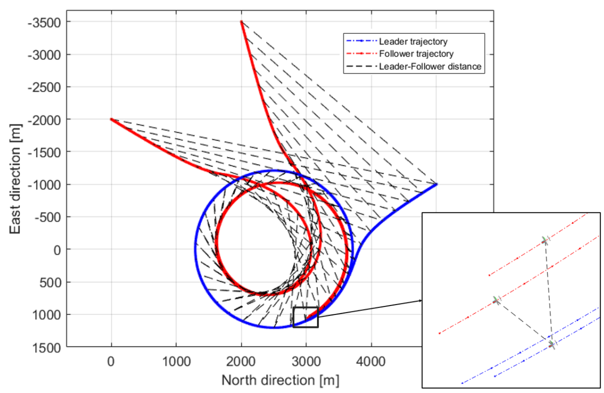

Figure 13: Leader and followers trajectories during rendezvous procedure.

4. Formation 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.

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 14.
Coordination control is carried out using feedback variables made available through the on-board 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 by combining three factors:

1. a **position error**,
2. a **path error** (measured with respect to the course angle χ and climb angle γ of the leader, respectively),
3. 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.

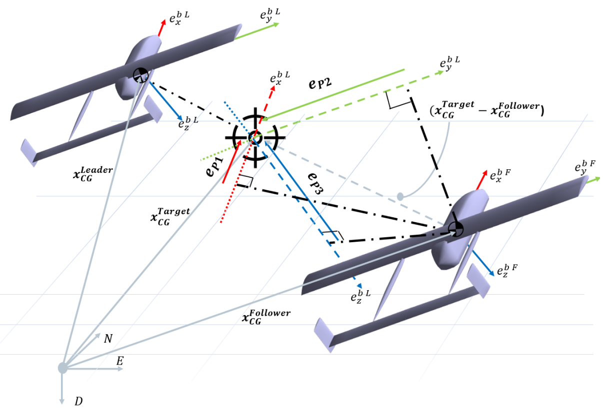

Figure 14: Formation control: definition of target point for the follower, and of the follower position errors $\boldsymbol{e_{P1}}, \boldsymbol{e_{P2}}$ and $\boldsymbol{e_{P3}}$.

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 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. 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_{GM} and K_{FCM}), 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. The induced velocity effect results in either a positive or negative change in the angle of attack of the trailing aircraft, depending on its sideward, vertical, and streamwise stagger relative to the leading aircraft.
An empirical procedure has been implemented to model the wake effects resulting from the proximity of the lifting surfaces within the formation. This procedure relies on a VLM code, which calculates changes in aerodynamic force and moment coefficients as a function of the relative distance between leading and trailing aircraft. The program outputs 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 available data at the current relative position between leading and trailing aircraft [7]. For a better visualization of the phenomenon, surface plots were constructed, as shown in , 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.

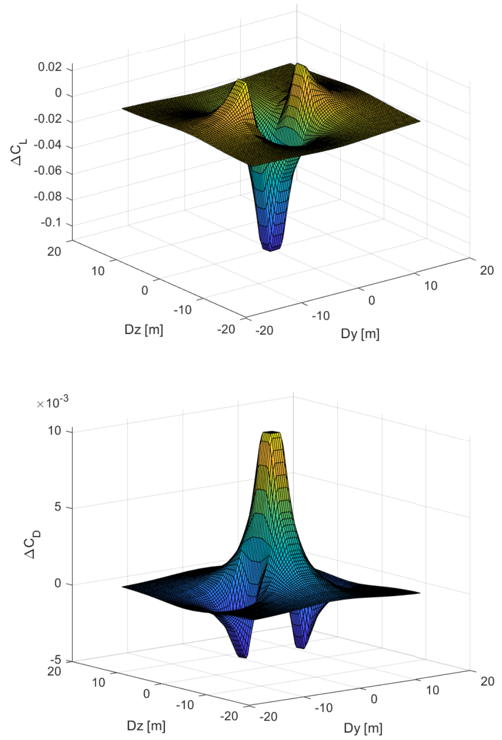

Figure 15: Representation of the database compiled for ΔC_L (left) and ΔC_D (right), as functions of lateral (Dy) and vertical (Dz) distance between leading and trailing wings.

5. Mission Simulation

A realistic scenario has been envisaged in order to test the synthesized controllers dropped into an operational context typical of a ground reconnaissance mission.
The mission includes an initial altitude rendezvous, followed by waypoint navigation to a target, wind disturbance testing, a circular flight over a second target, and concludes with navigation out of the operational scenario.

A crucial aspect of the mission is to test the scalability of the formation, involving a swarm of 9 UAVs flying in coordinated fashion throughout all phases, pursuing an assigned target position. The primary objective is to assess the reliability and feasibility of coordination within a scaled swarm, both in terms of the number of units and complexity, while identifying potential challenges in maintaining the desired formation geometry.

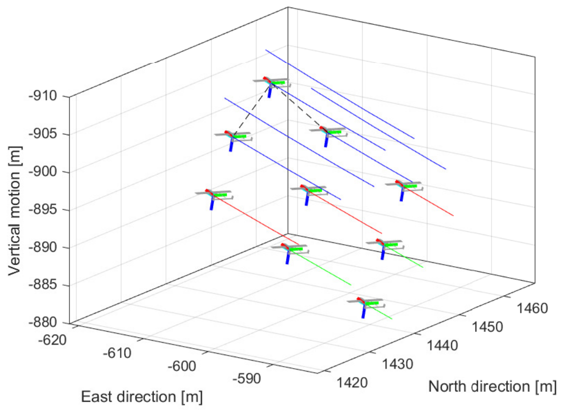

Figure 16: Formation assembled in diamond shape.

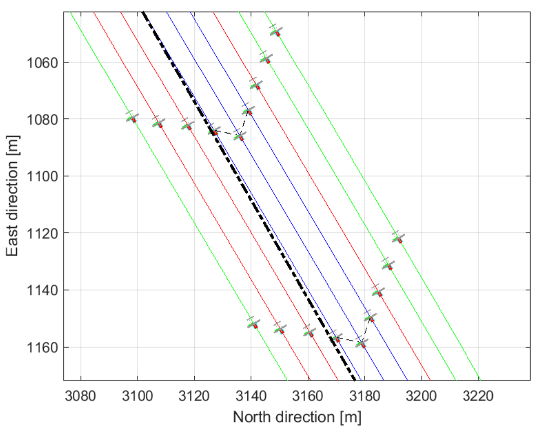

Figure 17: Formation assembled in V-shape.

6. Conclusions

This thesis extensively explored various aspects of formation flight in multi-unit UAV swarms, with a focus on flight dynamics modeling. It aimed to provide a complementary perspective to existing control architectures. Dynamic modeling in a fully nonlinear environment revealed critical insights, including individual aircraft stability, actuation challenges, aerodynamic interactions, and maneuvering constraints.

Stabilization was effectively achieved through a model-based Stability Augmentation System (SAS) and Linear Quadratic Regulator (LQR) tuning, ensuring adequate three-axis stability while preserving bandwidth for higher-level guidance controllers.

A robust guidance system enabled precise 3D path following, reducing cross-track errors to zero during waypoint navigation and avoiding trajectory overshoots through blending techniques. Integration with a vector field-based guidance procedure facilitated loitering and formation regrouping within confined spaces, addressing speed limitations.

Formation coordination employed a decentralized leader-follower hierarchy, allowing swarm scalability with minimal data exchange and computational complexity. Extensive testing confirmed effective and promising formation coordination, with followers maintaining stable positions relative to the leader. Wind disturbance tests validated tight formation and reconfiguration capabilities.

Realistic mission scenarios tested the control algorithms in a ground reconnaissance context, demonstrating feasibility and reliability across various mission phases. Future research prospects include increasing swarm size with hierarchical stability measures, signal loss mitigation through local measurements, collision avoidance, and the controllers optimal tuning.

References

[1] S. Farì, "Guidance and control for a fixed-wing uav," Master's thesis, Politecnico di Milano, 7 2016.

[2] N. T. Dat, T. N. Son, and D. A. Tra, "Development of a flight dynamics model for fixed wing aircraft," pp. 202–205, Association for Computing Machinery, 1 2018.

[3] E. N. Mobarez, A. Sarhan, and M. M. Ashry, "Modeling of fixed wing UAV and design of multivariable flight controller using PID tuned by local optimal control," in *18th International Conference on Aerospace Sciences & Aviation Technology, Cairo, Egypt, 9-11 April*, 2019.

[4] H. Chen, X. Wang, L. Shen, and Y. Cong, "Formation flight of fixed-wing uav swarms: A group-based hierarchical approach," *Chinese Journal of Aeronautics*, vol. 34, pp. 504–515, 2 2021.

[5] C. E. Riboldi and A. Rolando, "Thrust-based stabilization and guidance for airships without thrust-vectoring," *Aerospace*, vol. 10, 4 2023.

[6] S. Park, "Rendezvous guidance on circular path for fixed-wing uav," *International Journal of Aeronautical and Space Sciences*, vol. 22, pp. 129–139, 2 2021.

[7] D. Singh, A. F. Antoniadis, P. Tsoutsanis, H. S. Shin, A. Tsourdos, S. Mathekga, and K. W. Jenkins, "A multi-fidelity approach for aerodynamic performance computations of formation flight," *Aerospace*, vol. 5, 6 2018.