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Thrust-Based Flight Stabilization and Guidance for Autonomous Airships

Carlo E.D. Riboldi[1†] *and Alberto Rolando*[2]
[1]*Department of Aerospace Science and Technology, Politecnico di Milano*
20156 MILANO, Italy
[2]*PACE Aerospace & IT GmbH*
14059 BERLIN, Germany
carlo.riboldi@polimi.it · alberto.rolando@pace.de
[†]Corresponding author

Abstract
The problem of three-axis stabilization and beam-tracking guidance of a thrust-controlled airship without thrust vectoring is analyzed. A comparison is carried out throughout the work, introducing at first stability-augmentation and guidance controllers for an existing reference airship, featuring traditional aerodynamic surfaces for control. Then a four-thrusters airship with no aerodynamic controls is presented, and flight controllers for this platform are designed and implemented. The performance of both airships in autonomous flight is assessed in a realistic non-linear dynamics simulator, showing interesting tradeoffs of the two configurations in complex virtual scenarios, in still air or steady wind conditions.

1. Introduction

Lighter-than-air (LTA) platforms allow to obtain longer endurance and good near-hover maneuverability, in this sense merging the advantages typically provided by fixed-wing and rotary-wing aircraft.[5–9,19] However, thinking of a classical airship configuration, the large envelope (besides obviously enabling buoyant flight) is responsible for poor aerodynamic behavior, often resulting in disturbance-prone flight, and in complex controllability issues. More in depth, the significant mass and aerodynamic inertia, found on slender airships especially around the pitch and yaw axes,[10,11] together with the large wet area tend to amplify the dynamic reaction to disturbances in the airstream.[17] Similarly, the lack of a wing limits damping-in-roll, and impacts the execution of maneuvers, such as turns. Finally, the positioning of the thrusters and control surfaces, both typically placed close to the stern of the airship, and the lack of ailerons significantly far from the roll axis, tend to produce a more complex dynamic response to controls, compared to either rotary- or fixed-wing aircraft configurations.[11,12]

Ways to deal with these peculiar controllability features, impacting both stabilization[3,14] and guidance[1,16] on airships, include adopting alternative propulsive configurations, typically optimizing the flying platform for some part of the mission profile (such as hover, or constant-airspeed cruise).[15] Effective ways of controlling airships may be easily associated with the employment of thrust vector control (TVC), adopted on larger manned designs as well as on smaller, tail-less layouts.[4,13]

These solutions, despite technically viable, invariably tend to increase complexity and reduce weight effectiveness, by having on-board a significant number of actuators (e.g. for thruster-pivoting in the case of TVC) and related cables and electronics, or thrusters which are activated only during specific maneuvers, and representing a dead-weight and a source of drag for the rest of the mission.

To the aim of reducing complexity while exploiting the installed thrusters in a smarter way, the deletion of flight control surfaces and the de-localization of thrusters, which shall be now employed for simultaneously achieving a desired flight speed and controlling the airship, are clearly interesting concepts.

A previous study by the authors has investigated a feasible layout and the chance to artificially increase the stability of a solely thrust-based airship design, defining a procedure for the optimal arrangement of the thrusters onboard, and showing that a basic stabilization control can effectively condition the free dynamics of the LTA, making it pitch- and yaw-stable without either TVC or controllable aerodynamic surfaces.[17]

In the present research, this concept is further extended. Concentrating on control, a realistic stability conditioning control suite is deployed,[2] showing a good performance on a four-thrusters, thrust-controlled airship layout (emerging from[17]). Then the problem of guidance is analyzed, and realistic beam-tracking directional and vertical controllers

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are introduced.[2,22] The results, obtained in a virtual environment on a fully non-linear simulator for flight dynamics named SILCROAD,[18] developed at the Department of Aerospace Science and Technology, Politecnico di Milano, cover several maneuvers in forward flight, with small changes in altitude. They show that migrating from a standard configuration based on aerodynamic surfaces to a purely thrust-based control with no thrust-vectoring, where the thrusters act simultaneously for stabilization, navigation, and speed-tracking, allows for comparable or better maneuverability.

Thrust-based control can be therefore considered to be a viable design alternative to standard aerodynamics-based control in terms of flight dynamics performance, bringing in also the mentioned advantage of a greater simplicity, and the ability to exploit the reduced size and prompter response of de-localized small electric motors. These features in turn may constitute primers for the down-scaling of airship size, and the ensuing wider adoption of LTAs also in the low-weight category of the UAV market.

2. Stabilization algorithms

As known from the analysis of slender airship configurations with a back-tail, marginally stable or unstable modes are typically featured in the eigendynamics of these flying craft over the entire span of operative airspeeds.[11] Therefore, especially in scenarios where autonomous flight is of interest, deploying an inner stabilization layer is recommendable to make the airship easily steerable by means of an external guidance system.

Three loops for pitch, roll and yaw stabilization have been envisaged in the present work. The corresponding concepts have been studied at first for a standard aerodynamic-controlled configuration featuring elevons and a rudder as tail control surfaces. Then the architecture has been ported on a four-thrusters thrust-controlled machine, retrieved from an optimal design example[17] and considered as a conceptual example of a thrust-based configuration throughout the present work.

2.1 Airship three-axis stabilization for an aerodynamically-controlled back-tailed configuration

The logic behind stability augmentation systems around the pitch and yaw axes is similar on an airship featuring movable aerodynamic surfaces and on a standard winged aircraft. An increase in pitch damping is obtained through the elevator function of the elevons, whereas the rudder produces a stabilizing action around the yawing axis. On the other hand, Since the airship is lacking a wing, compared to winged aircraft a significant damping in roll needs to be added. This is obtained through the differential motion of the elevons.

The logic implemented for the three stabilizing loops is presented in Figure 1. The signal-conditioning suite includes low-pass filters to suppress noise in the measurements, and washout filters required to allow a sufficient residual low-frequency bandwidth for the guidance system to work. However, since the behavior in turns has proven satisfactory adopting flat turns as a standard strategy, i.e. without involving roll, a washout was not implemented on the corresponding branch.

In Figure 1, the superscript $(\cdot)^{bf}$ stands for bandwith-filtered, and the corresponding signals have undergone low-pass and (for pitch- and yaw-rate) washout filtering.

According to the logics in Figure 1, a purely proportional controller has been implemented on the yaw axis stabilization system, whereas proportional-integral controllers have been envisaged for the pitch and roll axis. The adoption of small integral components in the feedback loop, based on $\int q^{bf}$ and $\int p^{bf}$ signals, has been found empirically to produce better stabilization results than the proportional control alone.

In the baseline configuration featuring aerodynamic surfaces, no thrust control has been considered for stabilization.

2.2 Stabilization on a thrust-controlled airship

The considered conceptual layout of a four-thrusters airship is shown in Figure 2. The thrusters are numbered from #1 to #4, looking at the airship from astern, starting from #1 at the bottom-starboard, and proceeding in a clockwise direction. No thrust-vectoring is considered, i.e. no change in attitude is possible between the direction of the thrust lines and the airship.

In the layout considered in Figure 2, a positive thrust would suffice to obtain control around all three axes. However, reversible thrust is more technically viable when considering electric motors driving purpose-designed propellers, or ion thrusters. Therefore, the ability of the thruster to produce also negative thrust (despite with a limited efficiency with respect to a corresponding positive thrust setting) has been hypothesized.

The process of porting a control law on an airship with aerodynamic control surfaces to a thrust-controlled one is based on the use of thruster combinations to obtain a response similar to that of the baseline airship. The definition

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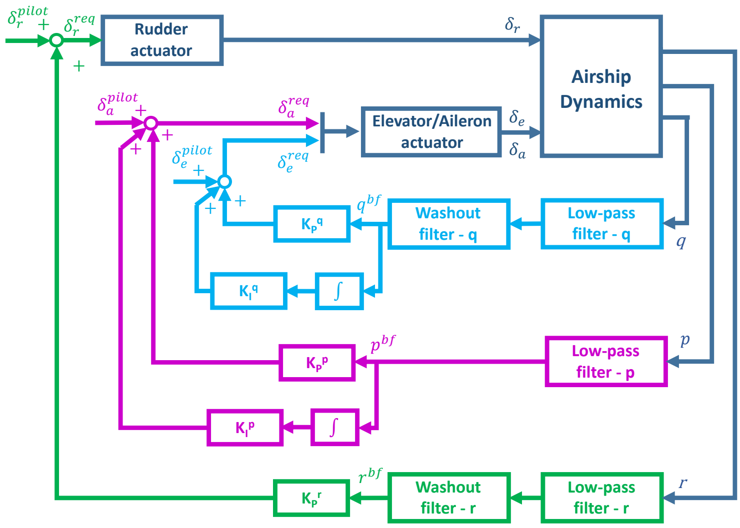

Figure 1: Proposed stabilization control for an airship with aerodynamic control surfaces on the tail. Cyan: pitch-rate damper. Purple: roll-rate damper. Green: yaw-rate damper.

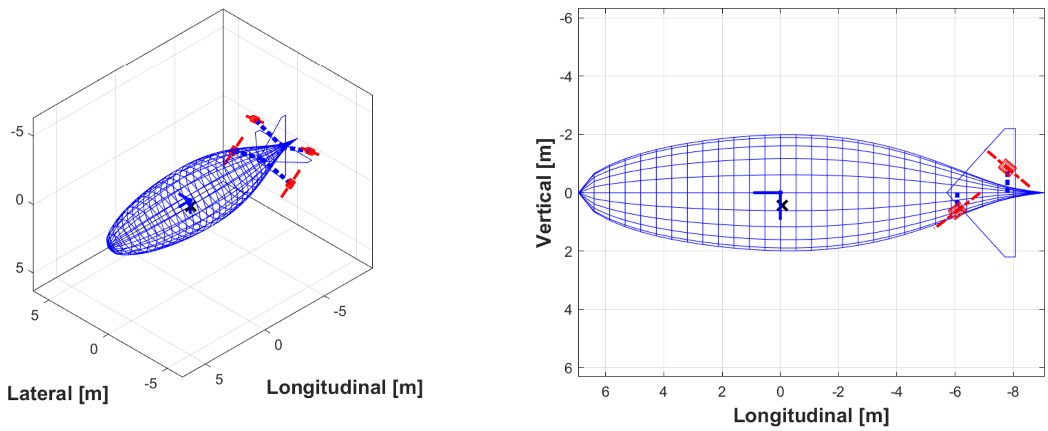

Figure 2: Conceptual layout of a four-thrusters airship with no movable surfaces and no thrust vector control. Left: three-quarters view. Right: view from the port side of the airship.

DOI: 10.13009/EUCASS2023-025

of these specific combinations is intimately related to the adopted thruster layout (i.e., the number of thrusters, their positioning on board, and the direction of the thrust lines).

Considering the specific thruster configuration adopter in Figure 2, porting the controller introduced in section 2.1 to the thrust-controlled airship can be obtained as follows:

- a rotation around the pitch axis can be obtained by changing the thrust of bottom thrusters (#1 and #2) and top thrusters (#3 and #4) in an opposing way, i.e., bottom thrusters pushing forward and top thrusters pulling back for a positive pitch-rate, and vice versa.
- a rotation around the yaw axis can be obtained with the starboard thrusters (#1 and #4) and port thrusters (#2 and #3) operating in an opposing way, i.e., port thrusters pushing forward and starboard thrusters pulling back for a positive yaw-rate, and vice versa.
- a rotation around the roll axis can be obtained by having thrusters #1 and #3 pushing and #2 and #4 pulling for a positive roll rate, and vice versa.

The scheme of the proposed thrust-based controller is presented in Figure 3.

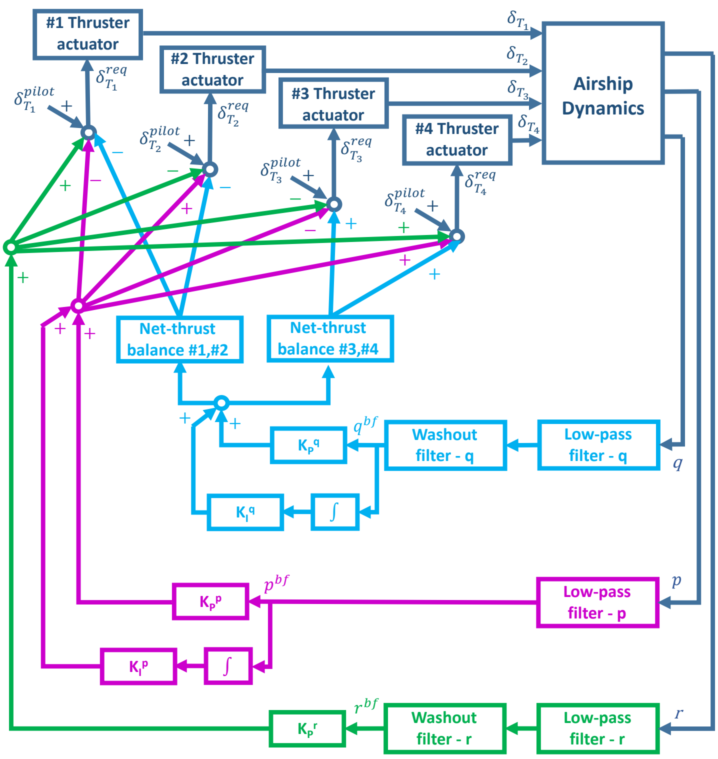

Figure 3: Stability augmentation scheme proposed for the four-thrusters layout concept introduced in Figure 2. Same color scheme as for Figure 1.

Together with an attitude control action, the thrusters input are set so as to produce the thrust required for motion in forward flight.

The net thrust balance blocks in Figure 3 have been implemented for a better-balanced control around the pitch axis, such to avoid introducing a non-null net thrust contribution in the direction of the longitudinal axis of the airship.

3. Guidance algorithms

Similar to the conceptual scheme followed in section 2, an aerodynamic-based control for guidance will be introduced first, so as to more easily capture the logic behind the proposed control law on a more standard case. The porting of the guidance law in the case of a thrust-controlled airship will be presented next.

The structure of the guidance controller follows the beam-tracking philosophy, typically adopted for VOR-to-VOR navigation or ILS/GS following problems in fixed-wing aviation practice. Given the inherently poor stability

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characteristics of airships, guidance laws are conceptually applied to an artificially stabilized machine, exploiting the residual low-frequency bandwidth where stability augmentation is not acting.

3.1 Guidance logic for an aerodynamically-controlled airship

The longitudinal and lateral-directional guidance problems are treated in a decoupled fashion.

Considering the aerodynamically-controlled reference airship, longitudinal guidance is carried out by the simultaneous employment of elevator and thrust. Similar to winged aircraft, beam-tracking in the longitudinal plane is not achievable without simultaneously controlling airspeed along the trajectory and the rate of climb. In particular, referring to Figure 4, a control loop based on the tracking of a reference speed set-point is closed with the motor thrust setting. Elevator control is employed to simultaneously target two errors,

- a position error with respect to the intended beam, measured in a local plane normal to the horizon plane
- a rate of climb error, between the current rate of climb and a target value, itself a function of the vertical position error. The latter set-point is such to be positive (i.e. ascending) when the airship is below the target beam, or conversely negative (i.e. descending) when the airship is above the intended beam.

Looking at Figure 4, notably low-pass filters are included on potentially noisy measures, to allow the system to deal with a turbulent atmosphere scenario.

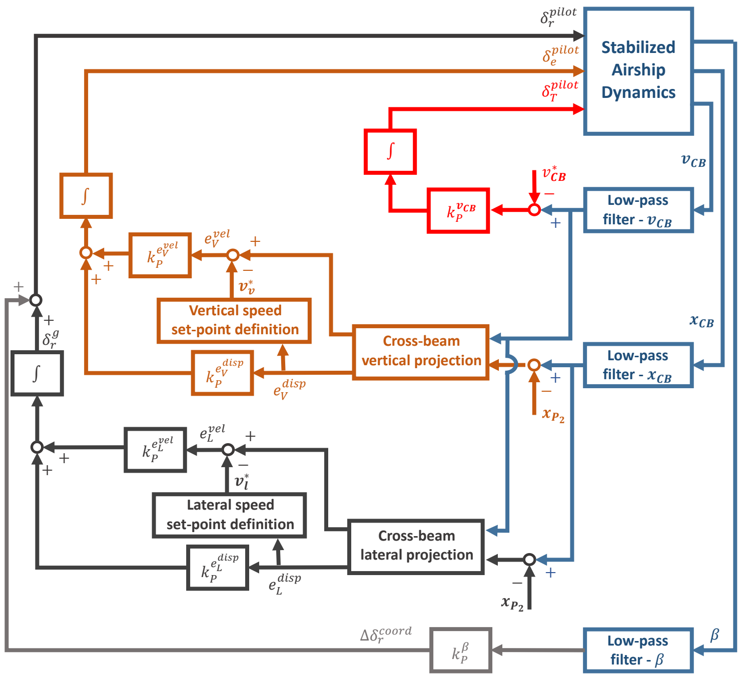

Figure 4: Guidance control for the aerodynamically-controlled airship. Red: airspeed tracking. Brown: longitudinal beam-tracking. Grey: lateral beam-tracking with turn coordination.

Guidance in the horizontal plane has been designed based on two cooperating loops, namely for turn coordination and for beam-tracking.

Turn coordination has been implemented targeting the sideslip angle in the body frame, which is pushed toward zero by an action of the rudder.

Lateral beam-tracking is performed in according to the same philosophy of longitudinal beam-tracking. This implies targeting by rudder control both a lateral position error and a lateral speed error. The former is measured on a local horizontal plane between the current position and the direction of the target beam, whereas the latter is obtained as a difference between the projection of the current airship speed vector along a line normal to the target beam (on the horizon plane) and a set-point. The lateral speed set-point is a function of the lateral position error. Notably, aileron (i.e. differential elevon) control is not employed for steering the airship. This approach is typical to airships, where course-changing can be effectively performed through flat turns (since buoyancy, unlike lift, cannot be banked, resulting in poor effectiveness of a banking maneuver in reducing turn radius, unlike on winged aircraft).

DOI: 10.13009/EUCASS2023-025

3.2 Thrust-based guidance for a four-thrusters airship

Porting the guidance logic envisaged for an aerodynamically-controlled airship to the case of a thrust-controlled one without thrust vectoring follows the same scheme outlined in section 2.2 for stabilization, where the action of the aerodynamic control surfaces is reproduced through the proper use of thrust control settings.

In addition, the collective control of all four thrusters at once allows to track the speed set-point along the trajectory of the airship (with the top and bottom thruster command scaled according to their tilt angles, in such a way to avoid the insurgence of a non-longitudinal thrust component when collective control is operated).

For longitudinal beam-tracking, differential use of the top and bottom thrusters is employed to steer the airship in the vertical plane of a local horizon frame, thus pursuing vertical position error annihilation, and following rate of climb set-point values. Employing both the top and bottom thrusters at the same time to obtain a rotation around the pitch axis has been found to produce an excessive control authority, in turns making gain tuning more complex. Consequently, only positive thrust is employed in longitudinal guidance, e.g. increasing thrust on the #1 and #2 (bottom) thrusters to achieve a positive pitch-rate, while leaving the thrust of #3 and #4 (top) thrusters unchanged. This solution is forcibly producing a change in the thrust along the longitudinal body axis of the airship when longitudinal guidance is acting. However, the ensuing control-induced disturbance was found to be well managed by the speed tracking control.

For lateral guidance, beam-tracking is obtained through the differential use of starboard (#1, #4) and port (#2, #3) thrusters. Negative thrust on the former couple and positive on the latter is employed to obtain a positive yawing motion, for instance. A lateral position error and a lateral speed error identical to those introduced for the aerodynamically-controlled airship are both tracked by employing differential thrust as just explained.

The corresponding scheme for guidance control for the four-thrusters thrust-controlled concept is represented in Figure 5.

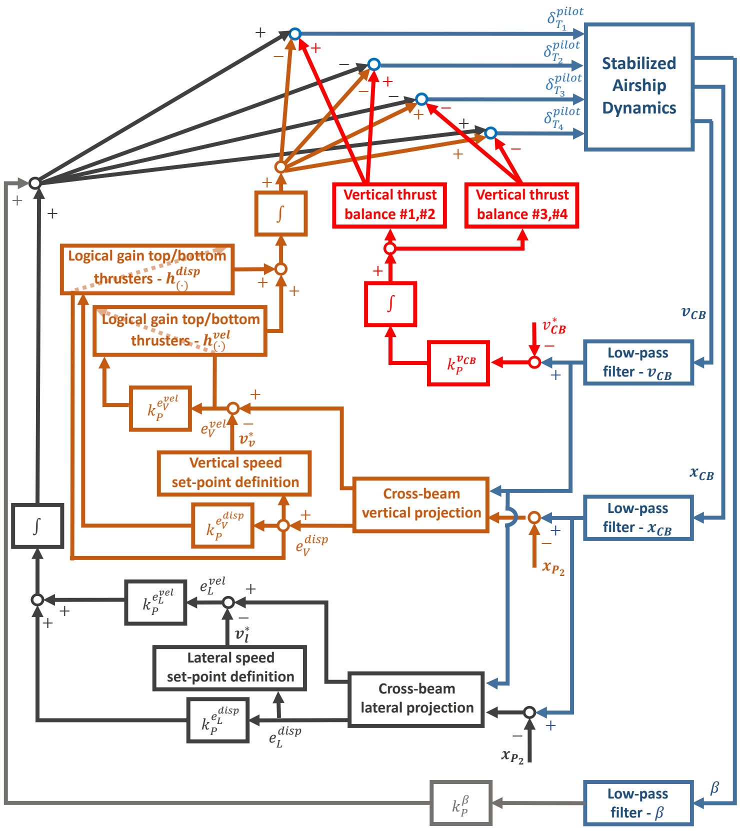

Figure 5: Guidance control for the four-thrusters concept. Same color codes as for Figure 4.

DOI: 10.13009/EUCASS2023-025

4. Example applications

To show the capability of the proposed controllers, example results will be shown for both an aerodynamically-controlled reference and a four-thrusters concept.

The selected reference test bed is that of the Lotte airship.[11,12] Already considered to be a test-case in previous studies,[17] a virtual model of the airship was implemented for the present research in `SILCROAD`[18] (*Si*mulation *L*ibrary for *Cr*aft-*O*bject *A*dvanced *D*ynamics), a novel object-oriented library developed in `Matlab (R2019b)`® at the Department of Aerospace Science and Technology (DAER), Politecnico di Milano, to accurately simulate or co-simulate (in the case of interacting objects in the same scenario) the non-linear response of several machine types (generically named *craft*), subject to aerodynamic, gravity, buoyancy, and thrust forcing terms. Among the sub-classes in the library is the airship class, which was employed for the fully non-linear simulations presented in this work. This highly customizable library lends itself to multiple uses, including the systematic design, implementation, and testing of control laws applied for instance to the dynamic models of winged aircraft and airships (as well as submarines or torpedoes, etc.).

Previously considered in the methodological part of this text as a baseline, the Lotte experimental airship features a single engine astern of the envelope and a cruciform tail with vertical stabilizer and rudder, horizontal stabilizer, and elevons.[12]

The four-thrusters concept, implemented in this work again employing the `SILCROAD` library, reproduces the layout obtained from a previous study,[17] which emerged from an optimal approach in the arrangement of thrusters on board, based on an energy measure of performance, including control use and response to disturbance. Concerning aerodynamics, the envelope shape and size are the same as the Lotte airship, whereas the entire area of the tail surfaces has been considered fixed, thus removing the control degrees of freedom for elevons or rudder motion. The rear thruster of the baseline airship has been removed as well, and replaced by four thrusters arranged as in Figure 2. The mass of the actuation systems and rear thruster has been estimated and removed, whereas the mass for the four new thrusters has been added. Correspondingly, a slight forward shift of the center of gravity (by 5.9 mm) was observed, as well as an increase in mass of 3 kg,[17] with respect to the original Lotte design.

The basic data of the two airships are reported in Table 1.

Table 1: Reference data for the considered airship test beds.

Parameter	Aero.-controlled airship	Thrust-controlled airship
Mass (kg)	134.28	137.28
Envelope volume (m^3)	107.42	107.42
Overall length (m)	16.0	16.0
Hor. disp. c. of gravity from c. of buoyancy (mm)	0	5.9
Ver. disp. c. of gravity from c. of buoyancy (mm)	455.0	455.0
Number of thrusters	1	4
Nominal thrust (each unit) (N)	500	250
Aerodynamic control	Rudder, elevons	(no aerodynamic control)

In the next subsections, examples of the performance obtained from stabilization and guidance controllers are presented for both the reference aerodynamically-controlled airship and the thrust-controlled concept.

At a modeling level, the actuators for the control surfaces and the electric motors are considered as first-order systems (with time constants of 0.03 s and 0.001 s respectively). Deflections of the aerodynamic surfaces are limited to +/-25 deg at most, whereas thrust settings are limited between +/-100%. However, the top reverse thrust intensity is half of the nominal value, on account of the non-symmetry of the propeller and its expected lower thrust performance in reverse thrust conditions. Low-pass and washout filters have been implemented as first-order dynamic systems, with time constants of 0.005 s and 5 s respectively.

4.1 Stabilization performance

The time histories of states and controls for the standard aerodynamically-controlled airship, resulting from a perturbation in the initial condition of 0.5 m/s in vertical and lateral velocity components (W and V respectively in the plots), and starting from a trimmed horizontal flight at 6 m/s, are presented in Figure 6. The black dash-dotted lines represent the trimmed values of states and controls. The guidance system is switched off in this test. In these and the following plots, the customary notation of flight dynamics is adopted (U, V, W are body velocity components, p, q, r are body

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components of the rotational speed, φ, ϑ, ψ are attitude angles, δ_e, δ_a, δ_r, δ_T are elevator, aileron, rudder and thrust controls).

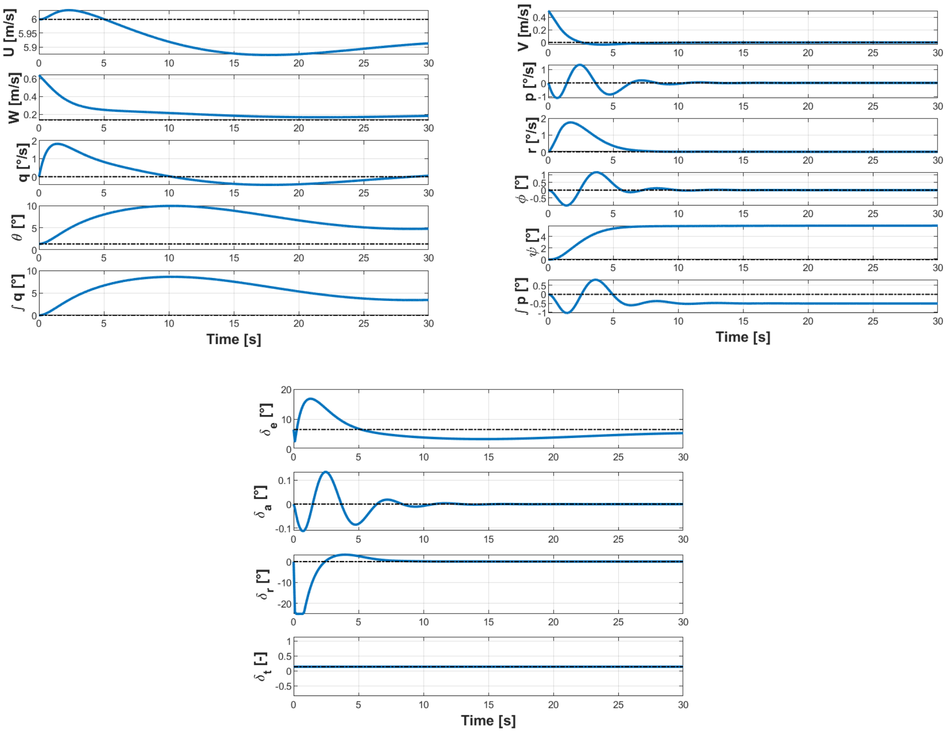

Figure 6: Time response of aerodynamically-controlled airship in trimmed horizontal flight at a ground speed of 6 m/s, to an initial perturbation of W and V of 0.5 m/s. Top-left and top-right: longitudinal and lateral-directional states. Bottom: controls. Black dash-dotted lines: trimmed value.

Observing the evolution of control in Figure 6, it is apparent that the perturbation is contrasted by the controller within the considered time frame, i.e., the control setting returns to the trimmed values by the end of the simulation. Correspondingly, the rotational rates q, p, and r are reduced to zero or a near-zero condition, whereas residual unbalances to the speed components (especially U) are still visible.

The integral terms on q and p (as well as the steady-state value of ϑ), are interestingly left to non-null values, due to the limited control action of the controller (i.e. limited gain) on these integrals. However, even a mild control action on these quantities proves beneficial in guidance problems. Correspondingly, the non-adherence of post-perturbation steady-state values to the pre-perturbation trim condition is expected, since the stability augmentation system is acting on rotational rates, and not significantly on their integrals. Furthermore, this feature of the stabilization controller leaves a sufficient bandwidth for the guidance controller to operate.

In Figure 7 the same scenario of Figure 6 is analyzed for the four-thrusters concept.

Looking at the pitch-rate signal q, it is apparent that its evolution is not significantly contrasted within the time frame of the simulation, due to the washout filtering effect. Correspondingly, a slow departure from the trimmed reference is observed especially in terms of the pitch attitude ϑ in the response in Figure 7. As observed for the baseline airship and controller, this is expected from the proposed stabilization system, which is tasked with increasing the damping around the body axes of the airship, leaving the task of steering or trimming the airship, as well as the control margin to carry out this task at a lower frequency, to the guidance system. In a similar fashion, the value of the roll angle φ is not returned to its null trimmed value. Instead, a non-null roll-rate p in the initial phase, even though damped over time, still produces a non-null steady-state value of this attitude angle, and is associated to a non-converging integral of the $\int p$, which as said is not unexpected.

4.2 Guidance along a multi-checkpoint trajectory

The satisfactory performance of the damping loops, shown in section 4.1, allows to effectively stabilize both the aerodynamically-controlled and thrust-controlled airships, in turns enabling guidance testing in realistic guidance sce-

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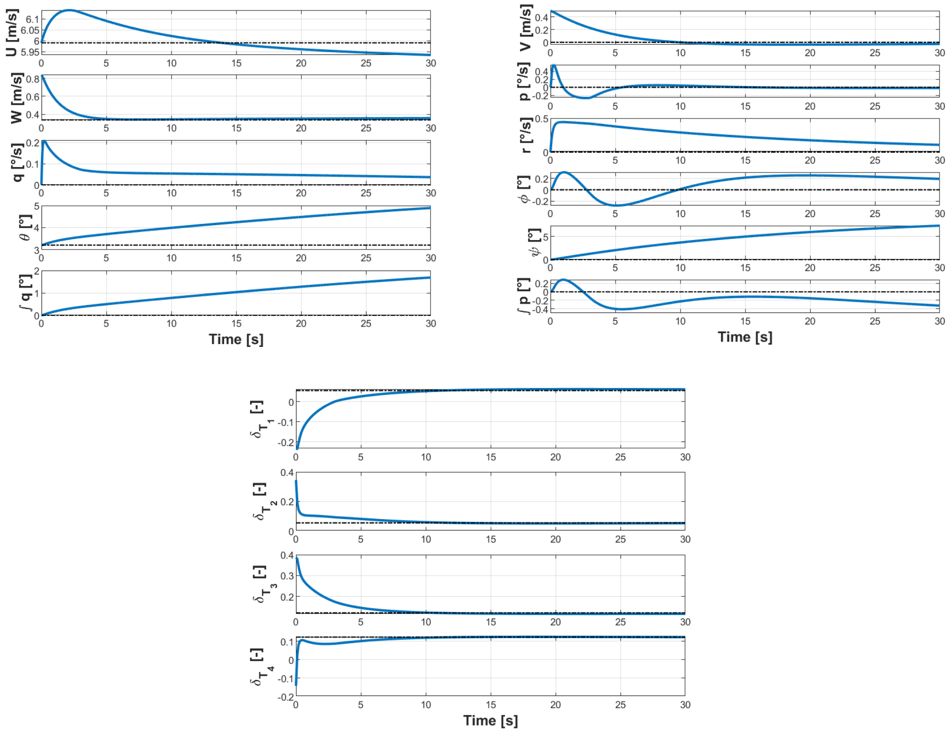

Figure 7: Time response of four-thrusters airship with thrust-based stabilizing control, in trimmed horizontal flight at a ground speed of 6 m/s, to an initial perturbation of W and V of 0.5 m/s. Top-left and top-right: longitudinal and lateral-directional states. Bottom: controls. Black dash-dotted lines: trimmed value.

narios. In particular, in this paper the results obtained covering a six-checkpoint path are shown, with checkpoints forming a regular hexagon viewed from top (60 degree angles, side length of 200 m), and with an altitude of alternatively 0 m or 10 m above ground, starting from 0 m at the beginning of the circuit.

4.2.1 Testing in still air conditions

Guidance testing is carried out in SILCROAD,[18] considering the airship on the initial checkpoint at the beginning of the simulation (i.e. zero coordinates in the following trajectory plots), in a trimmed horizontal flight condition and aligned on a northern course. This implies that the airship at start is misaligned with respect to the intended target beam, and the first segment requires a climb to 10 m and a turn to port of 60 degree. In a first testing scenario, no wind is considered.

Checkpoint capture is defined as entering a spherical space around the checkpoint, with a radius of 10 m. To ease navigation on the long run, the guidance system automatically switches to the next checkpoint in the flight plan on reaching a plane normal to the current desired track and including the current target checkpoint. This happens irrespective of the successful capture of the current target checkpoint.

Figure 8 shows top-views and three-quarters views of the trajectory flown by the reference, aerodynamically-controlled airship (top plots), and the thrust-controlled four-thrusters concept (bottom plots), considering a ground speed set-point of 6 m/s.

From Figure 8 it can be observed that both airships manage to capture all checkpoints. Considering the aerodynamically controlled reference, the steep turn to port required by the initial misalignment successfully takes the airship to the checkpoint concluding the first leg. However, as a result of the trajectory flown along the first track, the airship enters the second track with a misalignment of nearly 90 degree (i.e., on a western course, instead of a northern course as required). Nonetheless, this requiring condition does not lead to a miss of the next checkpoint, showing adequate accuracy of the control system in capturing the checkpoint position, at the price of a certain elongation of the trajectory with respect to the expected track.

In this regard, in analyzing this and other similar cases for the present research, it was found that due to the limited authority of the controls (as required for a realistic simulation), constrained between hard limits of the actuator dead ends, a trade-off scenario is configured between the accuracy along the track and in the capture of checkpoints. In

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other words, when trying to increase control gains to achieve better accuracy along the tracks, control saturation is more often encountered, and this in turns produces a detrimental effect on both track and checkpoint capture accuracy. By reducing control gains, thus limiting the reactivity of control to feedback variables (errors with respect to set-points), significant elongations with respect to the trajectory are encountered (as in the top plots in Figure 8), but a smoother overall trajectory and control time history are obtained, which produce as a welcome side-effect a better ability to capture checkpoints. Better track-keeping performance is generally encountered for lower speeds or longer tracks.

Considering the outcome of the four-thrusters airship concept (bottom plots in Figure 8), the accuracy in both track-following and checkpoint capture is generally better than for the baseline airship (top plots), with smaller top elongation at least in terms of lateral guidance. However, a more intense higher-frequency oscillation is encountered in the flight trajectory for the four-thrusters airship, which is especially visible in the three-quarters view, and witnesses some difficulty in steadily keeping the (mildly) ascending or descending tracks. A spillover of oscillation from the lateral to the vertical flight trajectory is a result of the higher degree of control coupling, expected with thrust-based control compared to standard aerodynamics-based control. It should be recalled that the same four thrust inputs are responsible for both beam-tracking and speed-tracking, whereas the thrust control on the baseline airship is basically responsible for speed-tracking only, leaving attitude control and navigation to the aerodynamic surfaces. In combination with the increased gains, this is also reflected in the more intense rotation around the roll axis, with bank angles φ between $+/-20$ degree (not shown), much greater than for the baseline airship (which turns through almost-flat maneuvers).

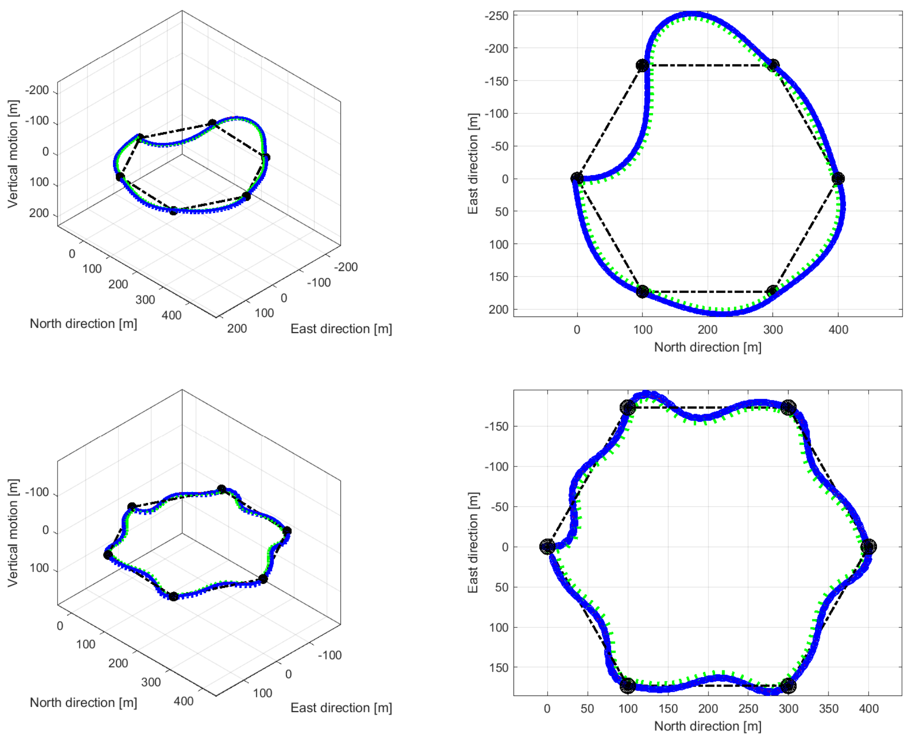

Figure 8: Trajectory on a six-checkpoints circuit, flown with a ground speed set-point of 6 m/s. Top row: reference aerodynamic-controlled airship. Bottom row: thrust-controlled four-thrusters airship. Left column: three-quarters view of the trajectory. Right column: view from top. Black dash-dotted lines: target track. Black spheres: target checkpoint capture volume.

4.2.2 Flight in steady wind conditions

Sample results showing the effect of a constant wind of 3 m/s from the west will be shown here, considering the same six-checkpoint scenario described above. Figure 9 shows the flight trajectories flown by both airship test beds, with a ground speed set-point of 8 m/s.

As a general comment to Figure 9, the baseline airship and the four-thrusters concept behave in a qualitatively similar way as in a still air condition (section 4.2.1). In particular, the reference airship features a less oscillating,

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smoother trajectory, with some elongation in terms of beam-tracking, whereas the four-thrusters concept displays a more oscillating trajectory, but with a lower top elongation. Oscillation for the four-thrusters airship is especially visible at altitude, and, as observed, roll motion is more intense for this airship, due to the higher degree of lateral-directional vs. vertical coupling induced by thrust-based control.

Concerning accuracy in the capture of check-points, the baseline airship misses the third and fourth checkpoints (at the end of the third track) due to lateral elongation (top-right plot in Figure 9). Looking at the third checkpoint miss, following the capture of the second checkpoint the target track, going northeast, forces the airship in an almost tailwind condition, which tends to increase its ground speed. As a result of that, the engine control δ_T is reduced to almost zero (not shown), reducing the airspeed to cope with the requirement on ground speed (constant at 8 m/s for all tracks), in turn decreasing the effectiveness of the aerodynamic control surfaces and producing a sluggish response to the controls.

On the other hand, the thrust-controlled airship does not miss any checkpoint (bottom plots in Figure 9). On the return legs, following the northernmost checkpoint, the reaction of the guidance controller to the changing relative direction of the wind (from back-port to back-starboard) is generally very intense, despite remaining out of saturation (not shown), and markedly around the rolling axis. The ensuing motion also produces a spillover of oscillation in the vertical plane, which triggers an additional control component from the vertical guidance. The complex response of the thrust-controlled layout results in an excessively oscillating maneuver, which despite not missing excessively the track, may turn annoying for the payload.

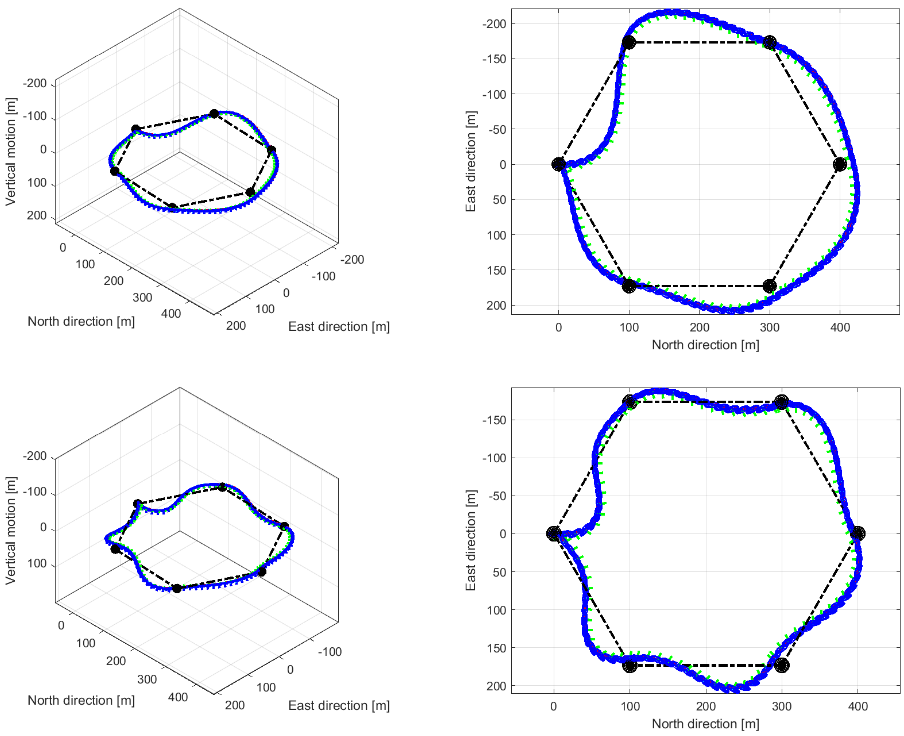

Figure 9: Six-checkpoints flight trajectory in presence of a 3 m/s wind from the west (i.e. from top to bottom in the right plots), and a ground speed set-point of 8 m/s. Top row: reference aerodynamic-controlled airship. Bottom row: thrust-controlled four-thrusters airship. Left column: three-quarters view of the trajectory. Right column: view from top. Black dash-dotted lines: target track. Black spheres: target checkpoint capture volume.

5. Conclusions and outlook

In this paper, the problem of control and navigation of airships in forward flight is treated. A three-axis stabilizing control is designed for increasing damping around the body axis, leaving sufficient bandwidth for a guidance control layer, implemented to autonomously pilot the airship along a pre-defined track.

In order to carry out a comparative analysis, two test-beds are considered. A reference one has been chosen as an

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existing aerodynamically-controlled airship. Its performance is compared to that of a four-thrusters, thrust-controlled airship with no thrust vectoring.

Testing has been carried out in a fully non-linear simulation environment (employing the novel `SILCROAD` library and simulation tool). Satisfactory controllability characteristics have been obtained on both airships, and the respective controllers perform realistically in terms of control use, with good accuracy in the required navigation tasks.

Critical points emerge in terms of control-induced coupling on the four-thrusters configuration, which tends to produce unnecessary oscillations in the flight trajectory, due to the spillover of the control action from the three branches of the navigation system (i.e., speed-tracking, and longitudinal- and lateral-beam-tracking).

Major points in favor of the thrust-based layout and control with respect to the reference airship include generally better proximity to the target track, even in complex navigation scenarios, and the preserved authority of controls in windy conditions, which conversely, as expected tends to decrease for aerodynamic surfaces in tailwind conditions corresponding to lower airspeed values.

The present analysis supports that a control suite not substantially dissimilar from that found on standard winged aircraft produces adequate stabilization and navigation results for aerodynamically governed airships. Furthermore, it suggests that a thrust-based and thrust-controlled layout with no thrust vectoring is an achievable and interesting possibility, with advantages and disadvantages with respect to the aerodynamics-based baseline, but generally reliable and not unbearably difficult to design.

Following suit from the latest observations, future research will explore the transition to hovering flight, and the management of hover and near-hover maneuvers, of great relevance besides forward flight, on a thrust-controlled airship without thrust-vectoring, thus extending the analysis of this flying platform to a broad range of maneuvers and flight conditions of practical interest. In particular, both automatic and semi-automatic maneuvers will be studied, benefitting from the employment of a guidance suite already developed by the authors (currently applied to rotorcraft[20,21]), and suitably adapted for obstacle avoidance in terminal maneuvers.

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