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Development of a Flying Platform to Study Three-Surface Configurations with Redundant Longitudinal Control

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Abstract. Improvements in aviation are typically driven by innovative propulsion systems and unconventional configurations. However, since these novel technologies often require a significant leap to become industrially viable, less demanding alternatives can be profitably explored through intelligent adaptations of existing configurations. Three-surface airplanes can be considered as a realistic alternative to conventional back-tailed airplanes, particularly because this configuration allows for trim optimization to minimize drag, provided both the canard and tail are equipped with movable surfaces enabling redundant longitudinal control. The focus of this paper is twofold. First, it aims to provide the first field demonstration of the possible benefits of the three-surface configurations with redundant longitudinal control over equivalent back-tailed airplanes. Second, it presents a preliminary comparison between test data and numerical results obtained from a CFD simulation campaign.

Introduction

Improvements in aviation are typically driven by innovative propulsion systems and unconventional configurations. However, these novel technologies require significant changes in the way we design, build, and operate aircraft. Just consider the substantial modifications to the supply chain and storage systems at airports that may be required by a massive use of hydrogen as aircraft propellent. In this context, interesting and less demanding alternatives can be found by intelligent adaptations of conventional configurations [1, 2, 3].

Among all, three-surface airplanes can be considered as a realistic alternative to conventional back-tailed airplanes. Recently (see Ref.[4] and [5]), a three-surface configuration was employed to demonstrate the potential benefit of the redundant longitudinal control: when both the canard and tail have a movable part, the longitudinal trim, i.e. the equilibrium of vertical forces and moments about the pitch axis, becomes overdetermined: there is an infinite possible combination of canard and elevator deflections which can trim the airplane. This allows one to select the couple of elevator and canard deflections associated with an optimum of a particular merit function, such as for example the overall drag. As reported in preliminary works [4, 5], a comparison between a standard back-tailed four-seat propeller-driven aircraft and an equivalent three-surface aircraft with redundant longitudinal control predicted that the latter configuration exhibits a 4% improvement in the maximum lift-to-drag ratio, potentially leading to comparable fuel savings. It is noteworthy that such an improvement could be achieved through a relatively minor change to the airframe design, especially if compared to more impactful alternatives such as box-wing or blended-wing airplanes.

Building on this promising analysis, we are developing a flying prototype to demonstrate the effectiveness of three-surface configuration with redundant longitudinal control through a dedicated flight experimentation. To achieve this, we first designed a reference back-tailed prototype optimized for a standard mission of a scaled remote-controlled airplane. Next, we turned the reference aircraft into an equivalent three-surface aircraft, featuring the same wing, fuselage, static margin, and empennage volume. For a given canard of a specific surface, the tail area must be reduced to maintain the same empennage volume and the wing shifted backward to keep the static margin unaltered. Both canard and tail are equipped with movable surfaces, yielding the desired redundancy in the longitudinal trim.

A parallel study was also performed based on Computational Fluid Dynamics (CFD) analyses. In particular, both airplane configurations (two- and three-surface) were modeled through a panel method-based tool, FlightStream [6], to compute the aerodynamic steady coefficients, C_L, C_D and $C_{\mathcal{M}_G}$, as functions of the angle of attack and the deflections of both control surfaces. The obtained aerodynamic database was then used to perform the comparison between the simulated data and the measured quantities obtained through the testing campaign of both airplanes.

Both the experimental and numerical studies on the scaled demonstrator provided evidence that the three-surface configuration with redundant longitudinal control is associated with a significant increase in the maximum lift-to-drag ratio over an equivalent back-tailed airplane, quantified in about 20%. The reasons for this improvement, still to be better understood, are manifold. First, by appropriately configuring the area and location of the lifting surfaces, it is possible to trim the aircraft such that all wings (main wing, tail and canard) generate positive lift. This leads to lower angles of attack and to a corresponding reduction in the overall airplane drag. Second, there could be a beneficial aerodynamic interaction between the canard and the wing, because the outer sections of the main wing experience upwash flow components entailed by the tip vortices of the forward surface. Third, redundant control allows one to optimize the aircraft trim across all flight conditions by directly setting the lift of all surfaces, as also reported in [4, 5, 7]. The study presented in this paper represents the extension of the work object of [8].

Experimental and numerical study on three-surface configurations with redundant control

In the present section, the procedure to design and build the equivalent two- and three-surface airplanes with redundant longitudinal control is first presented. Next, the process of modeling the aircraft in FlightStream is described.

First, it is necessary to define how the equivalence between a three-surface and reference back-tail airplane is established. Among all possible criteria, static margin and tail volume represent two parameters expected to strongly influence equilibrium, stability and maneuverability. Hence, in a preliminary design context, one may envision that airplanes with the same stability margin and tail volume should meet the same mission and design requirements. Accordingly, we first design a conventional aft-tailed aircraft and then convert it into an equivalent three-surface configuration, following the criteria, previously mentioned.

The design process for both prototypes utilized Digital Datcom [9] coupled with downwash/upwash models [10, 11] to render the aerodynamics of the reference and equivalent three-surface aircraft. The reference back-tail airplane was designed to perform a usual mission for remote-controlled demonstrators, as reported in [8]. In order to design the three-surface airplane, one has to find suitable values for the canard area S_C, the tail area S_T, the incidence of the canard i_C, and the location of the aerodynamic center of the wing x_{AC^w}. In doing so, one may consider that in the case of redundant longitudinal control lift C_L and pitch moment $C_{\mathcal{M}_G}$ coefficients are both functions of the angle of attack α, the elevator deflection δ_E and the canard deflection δ_C, as

$$\begin{cases} C_L = C_{L_\alpha}\alpha + C_{L_{\delta_E}}\delta_E + C_{L_{\delta_C}}\delta_C + C_{L_0}, \\ C_{\mathcal{M}_G} = C_{\mathcal{M}_{G_\alpha}}\alpha + C_{\mathcal{M}_{G_{\delta_E}}}\delta_E + C_{\mathcal{M}_{G_{\delta_C}}}\delta_C + C_{\mathcal{M}_{G_0}}. \end{cases} \quad (1)$$

When it comes to evaluating the vertical and pitch moment equilibrium, one immediately recognizes that there are infinite possible solutions for α, δ_E and δ_C. Each combination of these trim variables is associated with a drag coefficient $C_D = C_D(\alpha, \delta_E, \delta_C)$, that can be computed again using Datcom. The redundancy in the trim is leveraged to minimize drag across all speeds, resulting in quasi-linear relationships between the angle of attack, the canard and elevator deflections as function of the overall lift coefficients C_L^*, indicated as $\alpha = \alpha^*(C_L^*)$, $\delta_E = {\delta_E}^*(C_L^*)$ and $\delta_C = {\delta_E}^*(C_L^*)$ [4, 8]. The trimmed polar is than computed as,

$$C_D = C_D\big(\alpha^*(C_L^*), \delta_E^*(C_L^*), \delta_C^*(C_L^*)\big). \quad (2)$$

The design of the three-surface model, i.e. the selection of the values for canard area S_C, tail area S_T, canard incidence i_C and wing location x_{AC^w}, is carried out by maximizing the maximum lift-to-drag ratio of the trimmed polar, constrained by the reference static margin and tail volume.

Fig. 1 shows a picture of the two equivalent designs and reports the expected increase in the maximum lift-to-drag ratio of the trimmed polar as function of the canard surface, demonstrating that the three-surface prototype could feature an increment of almost 3%. The demonstrators were then built to allow for an experimental campaign aimed at providing evidence of the goodness of the proposed configuration. The flying platform was also given a name: Aether (Airplane in Three-Surface Configuration with Redundant Longitudinal Control). The Aether features a wingspan of 1.5 m and weighs 3.5 kg. Fig. 2 displays two pictures of the two airplanes during flight tests.

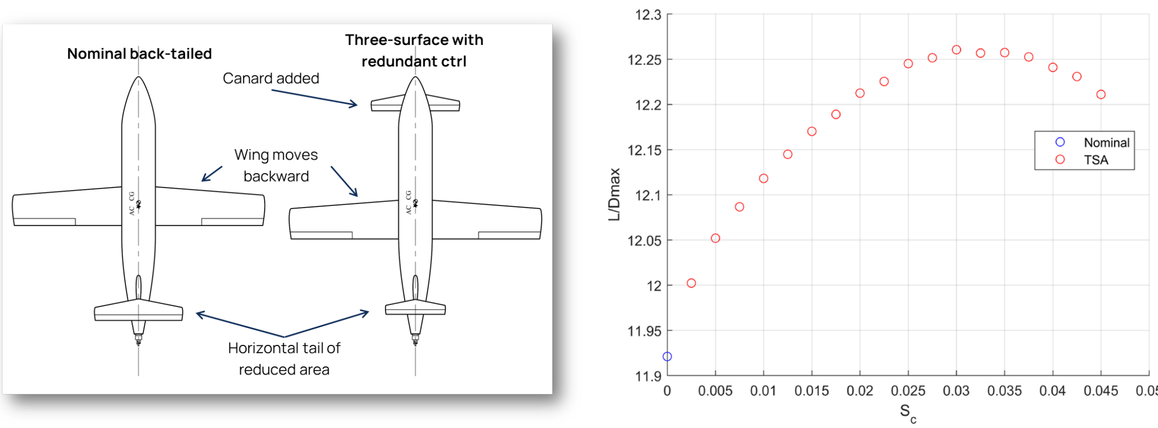

Figure 1: View of reference back-tailed (Nominal) and equivalent three-surface (TSA) airplanes (left). The three-surface airplane features a canard surface of 0.03 m2, associated with the optimal lift-to-drag ratio.

Figure 2: The Aether platform in two- (left) and three-surface (right) configuration, during flight tests.

The external shape of the aircraft is 3D-printed and connected to some carbon-fiber-made structural elements which provide stiffness to the system. The control of the platform is managed by the Pixhawk device and PX4 autopilot software. The system also integrates retractable landing gears, off-the-shelf motors for the deflection of control surfaces and an electric motor linked to a propeller. A nose-mounted pitot tube, an inertial measurement unit (accelerometers and gyros) and GPS enable the measurement of the key flight mechanics variables. Telemetry, batteries and the remote-control unit complete the hardware setup.

The test campaign, aimed at determining and comparing the polars of both aircraft, was performed between March 2025 and June 2025. It initially focused on estimating the neutral point of the two-surface reference aircraft so as to impose a static margin of 12% through the introduction of an appropriate ballast. Finally, a series of gliding flights at varying speeds was conducted to allow the quantification of the polar. The same procedure was applied to the three-surface aircraft; however, in this case, gliding flights were also performed for several canard deflections chosen a priori. This resulted in multiple trimmed drag polars, each parameterized by the corresponding canard deflection. During each gliding flight, the aircraft speed and position were recorded using the pitot tube and GPS, respectively, enabling the estimation of glide angle. The glide angle and the speed measurements easily provided the lift-to-drag ratio and the lift coefficients (and consequently the drag coefficients), through the standard flight mechanics model of steady gliding flight to enable the estimation of the trimmed aerodynamic polar.

In parallel with the execution of flight tests, the software FlightStream was also used to model both demonstrators, with the goal of supporting the interpretation of the flight testing results. FlightStream is described as a modernized panel method that includes enhancements over other vortex lattice techniques associated with an increased accuracy in the results. For this reason and for its capability to model in a simple way the control surface motion, it was chosen in this study. With its reduced computational expense compared to traditional Navier-Stokes solvers, panel methods offer a good trade-off between fidelity and solver runtime.

FlightStream was then used to derive a complete aerodynamic dataset encompassing the lift, drag and pitch moment coefficients as functions of all trim variables, i.e. the couple α and δ_E for the reference airplane, and the triplet α, δ_E and δ_C in the case of redundant longitudinal control. Afterwards, the aerodynamic dataset was used to compute the equilibrium of the airplane for the same speed and static margin recorded in the experimentation. Although the adopted procedure could produce less accurate results than just running the simulations for the experimentally recorded trim variables, it was considered preferable due to, first, the inherent mismatches between the demonstrator and the numerical model and, second, to some uncertainties in the recorded angles of attack and control deflections during the experimental campaign.

Results

Experimental data were filtered and thoroughly analyzed to yield the polars of both airplanes. Similarly, numerical data were analyzed to ensure convergence of the solutions and used to derive the numerical trimmed polars for comparison with the experimental data.

Fig. 3 displays the experimental polar data of the two-surface reference airplane (thick dashed black line) and the three-surface one for three different canard deflections (thin solid lines). Each marker represents the flight data while the lines show the corresponding quadratic fittings. From this plot, it can be observed that the three-surface airplane with redundant longitudinal control exhibits lower drag within a lift coefficient range of 0.25 to 0.7, resulting in an increase in the maximum lift-to-drag ratio of approximately 19%, significantly higher than the one predicted by the flight mechanics models developed in the design phases.

To assess the accuracy of the two numerical methods against the flight data, Tab. 1 presents the induced drag coefficients k_2 of a parabolic polar approximation, fitted to both real and simulated dataset. The results indicate that Datcom tends to better capture the parasitic drag, while FlightStream performs more accurately in estimating the lift-induced component.

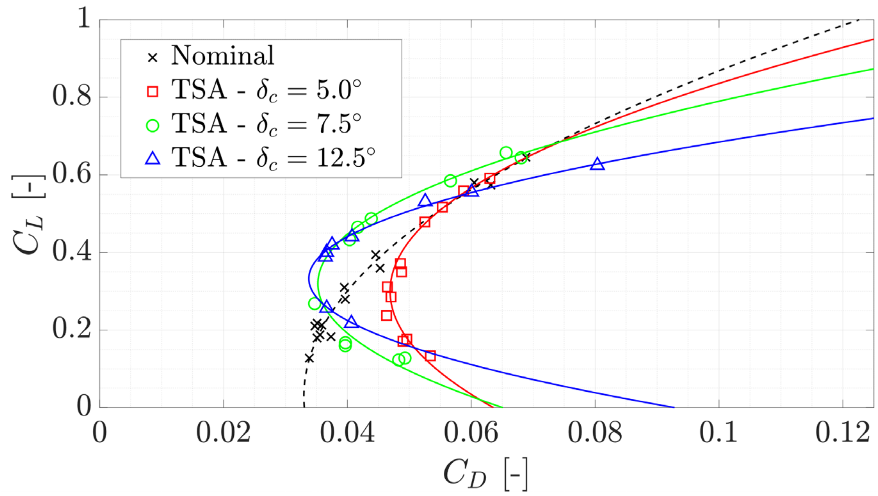

Figure 3: Polar data obtained from flight tests for the for two-surface (black dashed line) and three-surface airplane (solid lines and markers) for different canard deflections.

Table 1: Experimental and numerical polar comparison in terms of fitting coefficients.

	Two-surface	**Three-surface** ($\delta_c = 7.5$ deg)
	k_2	k_2
Experimental data	0.095	0.293
Datcom	0.049	0.055
FlightStream	0.132	0.172

Conclusions and outlook

This study provides the first experimental evidence that a three-surface configuration with redundant longitudinal control can deliver improved aerodynamic performance over equivalent standard back-tailed airplanes. Complementary CFD simulations using FlightStream also estimated higher lift-to-drag ratios, supporting the experimental findings. There are still some non-negligible discrepancies in the matching between numerical and simulation data, particularly evident in the three-surface case. Such a mismatch can be due to multiple sources: incorrect treatment of the wake interaction among the wings in the numerical tools, geometric deviation between the modeled airplanes and the manufactured ones or deterministic biases in the outputs of the sensors used during the experiments. The continuation of this work will aim to address these modeling gaps, possibly through a new set of experimental data and a refinement of the numerical simulations.

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