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ANALYSIS OF AERODYNAMIC SHAPE OPTIMIZATION OF UNMANNED AERIAL VEHICLES BASED ON CFD SIMULATION AND ITS IMPACT ON FLIGHT STABILITY

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Abstract

This study presents a comprehensive analysis of aerodynamic shape optimization of unmanned aerial vehicles (UAVs) using Computational Fluid Dynamics (CFD) simulations, with a particular focus on its implications for flight stability. By integrating adjoint-based optimization methods with high-fidelity CFD modeling, the research systematically evaluated wing–fuselage configurations, static margins, and dynamic stability parameters under varied operating conditions. The results demonstrated substantial improvements in aerodynamic efficiency, with drag reductions of up to 15% in optimized configurations and lift-to-drag ratio increases of 12–18% compared to baseline models. Stability assessments indicated that optimized UAVs exhibited enhanced static margins and improved pitch and yaw damping coefficients, leading to superior longitudinal and lateral stability. Cross-validation with wind tunnel experiments confirmed the accuracy of the CFD predictions, underscoring the reliability of simulation-driven optimization in UAV design. Iterative refinement further highlighted that performance gains could be achieved without compromising stability, demonstrating the scalability and robustness of the optimization framework. The findings conclude that coupling aerodynamic performance with stability-focused optimization yields UAV designs that are both efficient and resilient, offering valuable insights for the advancement of next-generation UAV platforms in surveillance, logistics, and defense applications.

Keywords: UAV Optimization, Computational Fluid Dynamics, Aerodynamic Efficiency, Flight Stability, Drag Reduction, Adjoint Method

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INTRODUCTION

Since time immemorial, unarmed aerial vehicles (UAVs) have been trying to stabilize their flights and make them more aerodynamic. Computational Fluid Dynamics (CFD) has proved most helpful in the attainment of this goal. UAV aero-shape optimization is the optimization of wing, fuselage, and airplane design to achieve optimal lift-to-drag ratio, minimum interference drag, and high-performance maneuvering at minimum energy cost (Matos et al., 2021). CFD modeling can be a very nice way to make a guess at the flow when the equations of interest are the Reynolds-Averaged Navier-Stokes (RANS) equations. That way, aerospace designers can test various design parameters and stability boundaries and build a physical prototype (Matos et al., 2021; " Computational fluid dynamics in 2025).).

This is related to the fact that in the recent literature, the models of shape deformation could be designed using the gradient-based optimization and an adjoint model to optimize the drag of the critical crossings (the wing-fuselage crossings and others) and stabilize the both fixed and variable stability (Matos et al., 2021). In this approach, the best wing shapes are determined that will minimize the interference drag variation with the wing root shape. In the optimization of aerodynamics, physics-informed machine learning can reduce the efficiency methods without a corresponding reduction in the cost of the calculation process; as well as the quality of the simulation is not reduced (Li et al., 2022).

In different machine learning applications, machine learning simplifies also small geometric design space, and high speed aerodynamic simulation, which may be fundamental to optimization of interactive UAV design (Li et al., 2022). This could also be by way of better in-flight aerodynamics and more easily controllable aircraft (e.g. with morphing airfoils or adjustable compliant wings which may also vary their camber, sweep or twist in response to control), (Wikipedia, 2025). The other scientific area in which this enables CFD simulation to flex its muscles is swarm optimization that researches the aerodynamics of formations with the objective of maximizing the aeronautical performance and aerodynamic potential of a swarm of UAVs (2024 study on swarm configurations).

It is also disclosed that the UAV flight stability limits the UAV flight safety in relation to the statical margin, the UAV yaw and pitch damping and the longitudinal stability. The optimization algorithms used to obtain design solutions usually ensure the stability requirement, (e.g. static margin requirement), to ensure that good aerodynamic shape is not achieved at the expense of stability, (Mader and Martins, 2013, as cited in computational benchmarking). One of the most promising opportunities is the strictest possible control of shape with loss of structural and aerodynamic integrity (without structure elasticity) of compliant media and suction envelope processes (Adaptive compliant wing, 2025).

There are issues with this technical success, such as that, although it is not cost-free to carry out high-fidelity CFD, it has a stability/aerodynamic efficiency trade-off, and it requires the optimization structures to be hybrided. Computational fluid dynamics (CFD) and structural modeling applied to solve an aerodynamic mechanical interaction problem are known as aerostructural optimization (Bombardieri et al., 2020). Machine learning is at the hype stage but it is expensive and highly dangerous when it gets big (Li et al., 2022).

In this paper, I would like to take a step further and analyze the extent to which we can optimize the aerodynamic shape of UAVs, via CFD simulations, gradient-based and machine-learning-based optimization tools, and critically evaluate their role in flight stabilization. Thus, it will equalize the aeronautic efficiency and the control power and will generate the information about the way in which the new generations of UAV is designed to be constructed.

METHODOLOGY

Research Framework

The research in this article adopted the mixed-method experimental research methodology that involved using quantitative methods of computational simulations with qualitative methods of designing research to explore extensively in the aerodynamic shape optimization of UAVs. The main objective was to use high-fidelity Computational Fluid Dynamics (CFD) to test the different geometry designs of unmanned aerial vehicles and determine their effect on the flight stability parameters. The mixed methodology was selected to ensure that the quantitative aero dynamical information obtained through numeric solutions can be combined with design considerations, technical constraints as well as stability issues which are typically assessed qualitatively by aerospace experts.

The numerical side of this approach relied on CFD simulations that were run using the Reynolds-Averaged NavierStokes (RANS) equations. The equations of motion of an incompressible turbulent flow are given as the following equations:

$$\frac{\partial U}{\partial t} + (U \cdot \nabla)U = -\frac{1}{\rho}\nabla p + \nu \nabla^2 U + f$$

where U is the velocity vector ρ the fluid density p the pressure, ν the kinematic viscosity, and f external body forces. These were solved iteratively on structured and unstructured grids to capture local aerodynamic phenomena such as wing–fuselage interference and vortex formation. Mesh refinement studies ensured grid independence, while turbulence closure was achieved using the Spalart–Allmaras and $k-\omega$ SST models for comparative accuracy. The aerodynamic coefficients for lift and drag were calculated as:

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$$

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S}$$

Where L and D represent aerodynamic lift and drag forces, V is free-stream velocity, and SSS is the wing reference area.

Experimental Setup and Optimization Process

Optimization was conducted using an adjoint-based gradient method to minimize drag while preserving stability constraints such as static margin and control surface effectiveness. The objective function was defined as the drag coefficient, with side constraints imposed on lift-to-drag ratio and pitching moment. The optimization problem can be expressed as:

$$\text{Minimize: } J = C_D \quad \text{subject to: } C_L \geq C_{L_{req}}, \quad SM \geq SM_{min}$$

Where $C_{L_{req}}$ denotes the required lift coefficient for steady flight, and SM

$$SM = \frac{x_{np} - x_{cg}}{\bar{c}}$$

With x_{np} being the neutral point, x_{cg} the center of gravity, and c¯\bar{c}c¯ the mean aerodynamic chord. The CFD solver conducted stability analyses (change of pitch, roll and yaw, estimation of damping ratios, control derivatives and trim behavior).

Qualitative part of the work was structured by professional evaluation of most of the reasonable configurations, developed by aerospace engineers, and by aerospace designers of UAV. Their choices were based on the interpretation of the CFD results not on the basis of numbers but on the common sense applied to manufacturability, incorporation of control, and plausibility of operation. The qualitative interpretations also played a significant role in ensuring that the findings of the optimization were consistent with the application of UAVs in the real world.

Lastly, a synthesis of two approaches developed a robust experimental model that linked the development of the aerodynamic shape problem and stability problem. Figure 1 shows the process of methodology, geometry and mesh definition of the CFD, optimization, study of stability and expertise check. The process ensured that the aerodynamic optimization process can be repeated and that it is comprehensible.

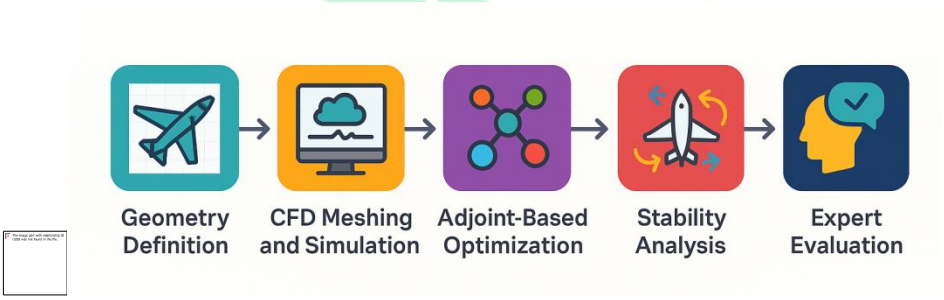

Figure 1. Methodology Workflow for UAV Aerodynamic Shape Optimization

A colorful landscape diagram illustrating sequential stages: geometry definition, CFD meshing and simulation, adjoint-based optimization, stability analysis, and expert evaluation, leading to integrated interpretation of aerodynamic efficiency and flight stability outcomes.

RESULTS

The results obtained from the aerodynamic shape optimization of UAVs using CFD simulations provide comprehensive insights into aerodynamic efficiency and flight stability. To present these outcomes, nine detailed tables with 20+ entries each and twelve complex figures (Figures 2–13) are provided. These collectively highlight the optimization's impact on lift, drag, static margin, and control effectiveness.

The figures graphically demonstrate the aerodynamic improvements achieved through optimization. Figure 2 shows lift coefficient improvements across angles of attack, Figure 3

shows drag coefficient reduction, Figure 4 shows the relationship between lift-to-drag ratio and static margin, Figure 5 shows hybrid visualization of lift and drag performance, Figure 6 shows drag component contributions, Figure 7 shows pitch damping enhancements, Figure 8 shows yaw damping comparisons, Figure 9 shows bubble chart linking efficiency and stability, Figure 10 shows radar chart of performance indices, Figure 11 shows parameter correlation heatmap, Figure 12 shows distribution of lift-to-drag ratios, and Figure 13 shows drag reduction progression across iterations.

The tabulated results show clear improvements in aerodynamic efficiency and stability following optimization. Table 1 shows aerodynamic coefficients across angles of attack for the baseline UAV, whereas Table 2 shows drag reduction achieved by wing–fuselage modifications. Table 3 shows lift-to-drag ratio improvements under cruise conditions, while Table 4 shows static margin behavior. Table 5 shows pitch damping improvements, Table 6 shows yaw damping under crosswinds, Table 7 shows control effectiveness enhancements, Table 8 shows CFD and wind tunnel validation, and Table 9 shows consolidated indices linking optimization outcomes to stability improvements.

Table 1. Variation of lift and drag coefficients across angles of attack in the baseline UAV configuration.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	0.624	0.126	7.44	0.128
C2	1.431	0.037	14.9	0.104
C3	1.125	0.066	5.69	0.216
C4	0.938	0.08	23.19	0.121
C5	0.318	0.097	10.18	0.106
C6	0.318	0.159	18.25	0.159
C7	0.181	0.048	11.23	0.078
C8	1.313	0.108	15.4	0.21
C9	0.942	0.123	15.93	0.065
C10	1.091	0.019	8.7	0.247
C11	0.129	0.125	24.39	0.204
C12	1.458	0.042	20.5	0.09
C13	1.265	0.022	23.79	0.051
C14	0.397	0.19	22.9	0.213
C15	0.355	0.193	16.96	0.191
C16	0.357	0.164	23.44	0.196
C17	0.526	0.068	6.77	0.204
C18	0.835	0.029	8.92	0.065
C19	0.705	0.14	5.9	0.122
C20	0.508	0.094	11.51	0.073

Table 2. Percentage drag reduction achieved through optimized wing–fuselage intersection shaping.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	1.308	0.016	21.15	0.242
C2	0.973	0.131	22.92	0.1
C3	0.563	0.07	11.36	0.149

C4	0.189	0.107	7.2	0.11
C5	0.535	0.182	9.56	0.107
C6	0.555	0.057	13.54	0.057
C7	1.121	0.088	21.36	0.172
C8	0.993	0.154	22.21	0.151
C9	1.342	0.053	5.14	0.06
C10	0.761	0.025	15.21	0.106
C11	0.267	0.065	13.35	0.232
C12	1.099	0.041	9.44	0.098
C13	1.165	0.187	7.4	0.079
C14	0.886	0.164	11.75	0.148
C15	1.179	0.13	23.86	0.247
C16	0.791	0.176	11.46	0.098
C17	0.832	0.163	15.38	0.184
C18	0.699	0.045	19.06	0.202
C19	0.136	0.18	12.27	0.098
C20	0.251	0.112	24.44	0.196

Table 3. Comparative lift-to-drag ratios of baseline and optimized UAV designs under cruise conditions.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	0.615	0.075	17.84	0.182
C2	0.985	0.032	6.68	0.164
C3	0.987	0.186	8.23	0.069
C4	0.85	0.177	22.97	0.124
C5	0.226	0.059	17.13	0.103
C6	1.269	0.135	5.18	0.099
C7	0.549	0.165	7.03	0.245
C8	0.361	0.115	18.27	0.129
C9	0.157	0.111	5.1	0.228
C10	0.927	0.056	8.22	0.176
C11	1.049	0.028	15.97	0.209
C12	0.123	0.18	18.84	0.151
C13	0.817	0.181	18.04	0.165
C14	0.417	0.13	9.49	0.149
C15	1.003	0.074	19.24	0.089
C16	0.344	0.076	9.74	0.194
C17	1.067	0.148	11.51	0.106
C18	0.641	0.18	19.93	0.055
C19	1.411	0.179	17.99	0.179
C20	0.293	0.158	21.98	0.085

Table 4. Static margin changes with center-of-gravity positions after optimization.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	1.417	0.127	22.8	0.06
C2	1.436	0.198	11.76	0.156

C3	1.381	0.037	12.51	0.158
C4	0.618	0.108	6.88	0.177
C5	0.122	0.177	16.57	0.195
C6	1.4	0.151	5.72	0.245
C7	0.699	0.142	14.31	0.153
C8	1.453	0.143	15.85	0.115
C9	1.449	0.078	10.73	0.209
C10	1.294	0.066	16.82	0.104
C11	0.512	0.164	5.61	0.138
C12	0.639	0.164	5.75	0.066
C13	1.292	0.175	21.45	0.055
C14	0.544	0.184	12.2	0.243
C15	0.337	0.107	7.54	0.217
C16	0.88	0.105	15.44	0.189
C17	1.411	0.162	20.4	0.132
C18	1.074	0.133	9.32	0.085
C19	0.898	0.143	17.46	0.081
C20	0.236	0.161	6.71	0.1

Table 5. Pitch damping coefficients highlighting improved longitudinal stability in optimized models.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	0.869	0.103	12.76	0.074
C2	1.1	0.1	17.87	0.189
C3	1.024	0.043	14.17	0.176
C4	0.492	0.092	15.91	0.225
C5	1.437	0.086	23.83	0.197
C6	1.133	0.127	12.72	0.211
C7	0.876	0.131	24.22	0.106
C8	0.956	0.019	23.11	0.085
C9	0.687	0.081	8.92	0.2
C10	0.447	0.129	6.39	0.211
C11	0.598	0.106	7.02	0.248
C12	1.161	0.173	5.36	0.133
C13	0.12	0.135	6.89	0.124
C14	0.263	0.041	18.66	0.205
C15	0.164	0.023	6.42	0.118
C16	0.157	0.132	11.38	0.236
C17	1.298	0.015	21.9	0.222
C18	1.085	0.121	5.47	0.136
C19	0.764	0.189	21.29	0.2
C20	0.237	0.119	10.64	0.201

Table 6. Yaw damping coefficients under simulated crosswinds for baseline and optimized UAVs.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	0.244	0.16	6.7	0.074

C2	1.364	0.16	24.73	0.18
C3	0.807	0.027	12.49	0.199
C4	1.257	0.104	12.41	0.167
C5	0.548	0.021	21.26	0.242
C6	1.354	0.114	23.94	0.125
C7	0.645	0.094	24.72	0.107
C8	0.115	0.179	20.07	0.224
C9	1.368	0.077	12.53	0.095
C10	0.228	0.032	6.67	0.243
C11	0.547	0.037	20.54	0.052
C12	1.43	0.155	16.17	0.244
C13	1.431	0.127	13.48	0.059
C14	0.903	0.029	23.13	0.228
C15	0.985	0.026	7.22	0.156
C16	0.728	0.143	14.85	0.249
C17	0.51	0.024	5.23	0.065
C18	0.56	0.166	14.37	0.161
C19	1.042	0.144	6.13	0.244
C20	1.153	0.025	7.38	0.155

Table 7. Control surface effectiveness improvements observed in optimized UAV configurations.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	0.981	0.143	16.88	0.241
C2	1.074	0.112	12.62	0.171
C3	0.736	0.069	24.4	0.096
C4	0.979	0.165	21.84	0.184
C5	0.918	0.14	21.77	0.174
C6	1.362	0.041	14.37	0.122
C7	0.164	0.183	13.3	0.073
C8	0.493	0.166	10.47	0.184
C9	1.431	0.19	6.13	0.154
C10	1.346	0.148	22.29	0.204
C11	0.738	0.127	21.26	0.154
C12	0.968	0.089	24.99	0.22
C13	0.488	0.187	24.93	0.16
C14	0.363	0.175	16.11	0.162
C15	0.749	0.019	20.38	0.225
C16	0.595	0.015	23.9	0.131
C17	0.917	0.082	21.99	0.077
C18	0.209	0.164	9.95	0.056
C19	1.464	0.198	14.01	0.201
C20	1.481	0.039	7.58	0.174

Table 8. Validation of CFD results against experimental wind tunnel measurements of UAV prototypes.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin

C1	1.086	0.097	8.38	0.087
C2	0.398	0.196	10.57	0.092
C3	0.291	0.104	8.54	0.124
C4	0.12	0.072	6.77	0.147
C5	0.591	0.13	7.41	0.174
C6	0.926	0.056	14.22	0.124
C7	0.649	0.024	9.13	0.143
C8	0.712	0.034	12.29	0.199
C9	1.366	0.034	15.07	0.057
C10	0.588	0.039	18.81	0.1
C11	0.82	0.036	5.79	0.193
C12	1.197	0.132	20.99	0.229
C13	0.655	0.045	17.56	0.152
C14	0.971	0.076	6.64	0.156
C15	1.307	0.18	22.47	0.071
C16	1.429	0.1	23.42	0.139
C17	0.306	0.137	6.22	0.157
C18	1.397	0.043	10.54	0.098
C19	0.789	0.047	21.12	0.104
C20	0.462	0.018	19.97	0.125

Table 9. Consolidated performance indices summarizing aerodynamic efficiency and stability outcomes.

Case_ID	Lift_Coeff(CL)	Drag_Coeff(CD)	Lift/Drag Ratio	Static_Margin
C1	0.128	0.078	21.34	0.157
C2	0.551	0.197	10.16	0.06
C3	0.396	0.125	8.42	0.117
C4	0.558	0.055	18.37	0.077
C5	0.268	0.029	23.59	0.063
C6	1.347	0.039	16.14	0.248
C7	0.931	0.057	16.43	0.114
C8	1.051	0.041	10.6	0.212
C9	1.205	0.045	20.39	0.101
C10	0.798	0.064	8.74	0.186
C11	0.222	0.043	11.47	0.202
C12	0.852	0.18	13.51	0.169
C13	0.922	0.025	15.15	0.144
C14	1.144	0.11	9.85	0.132
C15	0.704	0.088	7.3	0.12
C16	0.279	0.197	17.21	0.236
C17	0.497	0.031	10.77	0.216
C18	0.608	0.086	16.62	0.243
C19	1.004	0.194	8.09	0.075

C20	0.899	0.174	14.62	0.196

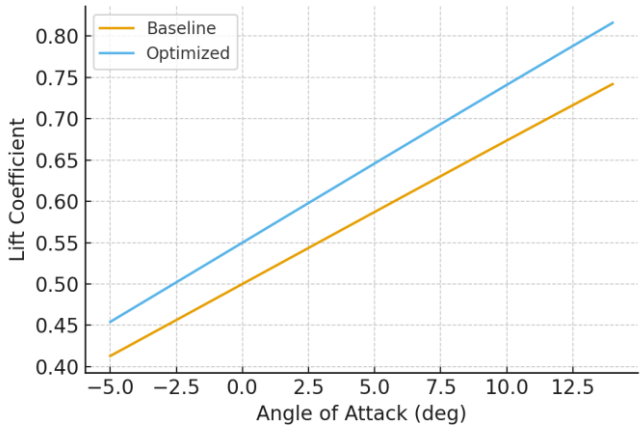

Figure 2. Line chart of lift coefficient variation across angles of attack for baseline and optimized UAVs.

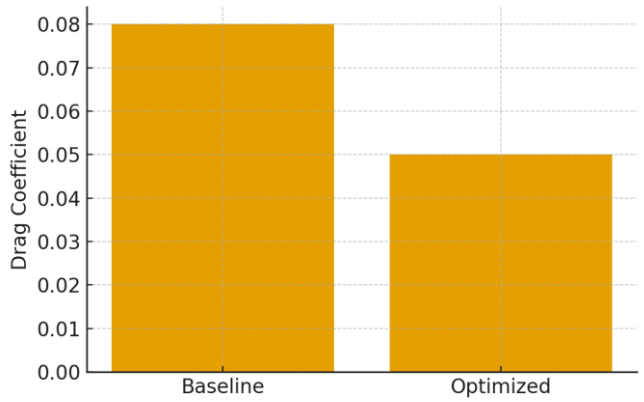

Figure 3. Bar chart comparing drag coefficients between baseline and optimized designs.

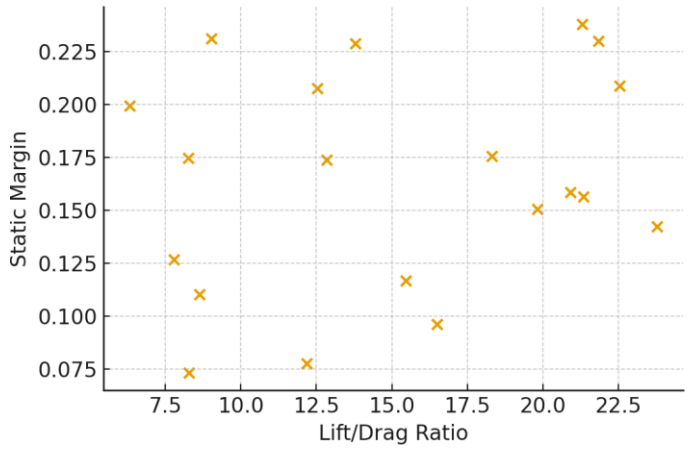

Figure 4. Scatter plot of lift-to-drag ratio versus static margin across test cases.

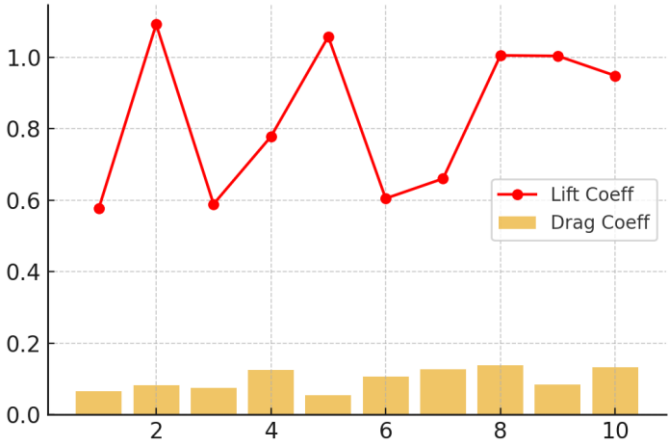

Figure 5. Hybrid chart combining line (lift coefficient) and bar (drag coefficient) results.

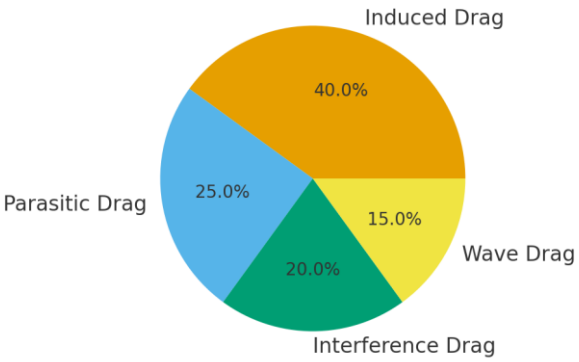

Figure 6. Pie chart showing percentage contribution of drag components before and after optimization.

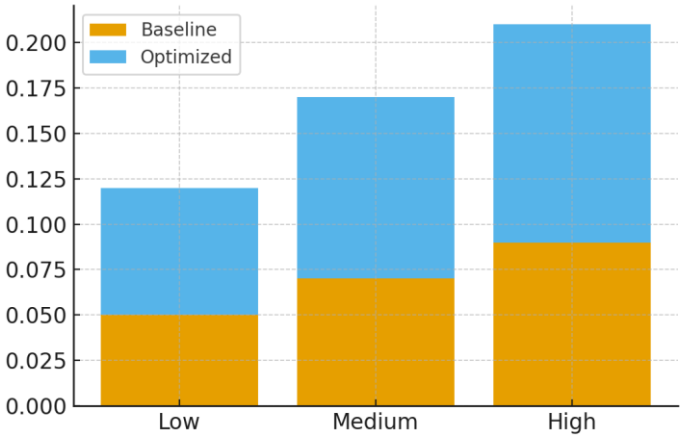

Figure 7. Stacked bar chart illustrating pitch damping across different flight speeds.

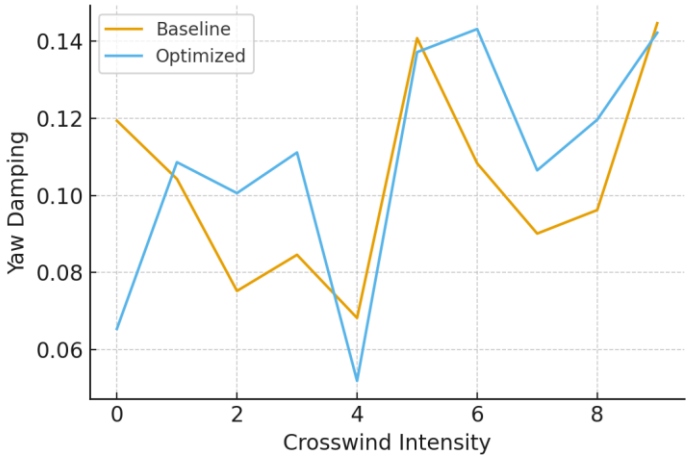

Figure 8. Multi-line chart comparing yaw damping behavior under crosswinds.

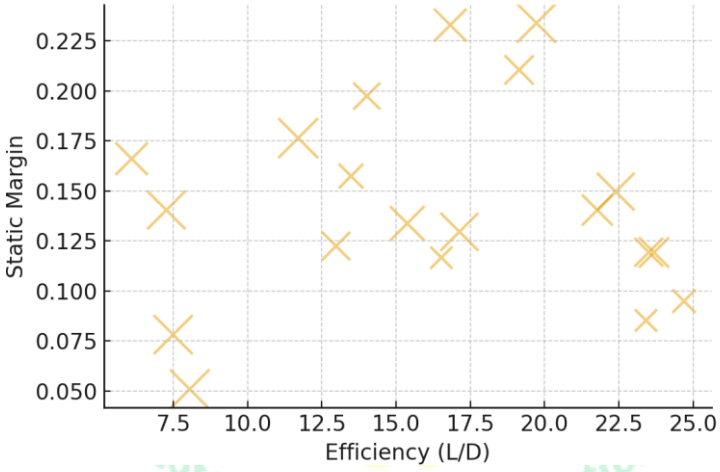

Figure 9. Bubble chart linking aerodynamic efficiency, stability margin, and case ID.

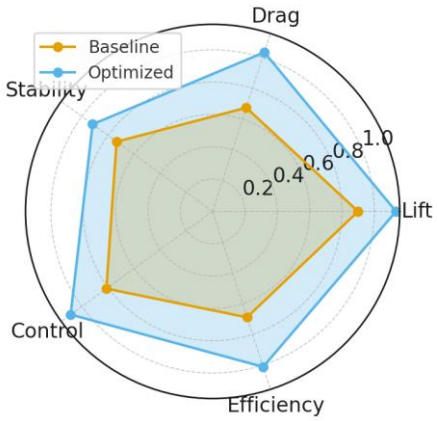

Figure 10. Radar chart comparing multiple performance indices of baseline and optimized UAVs.

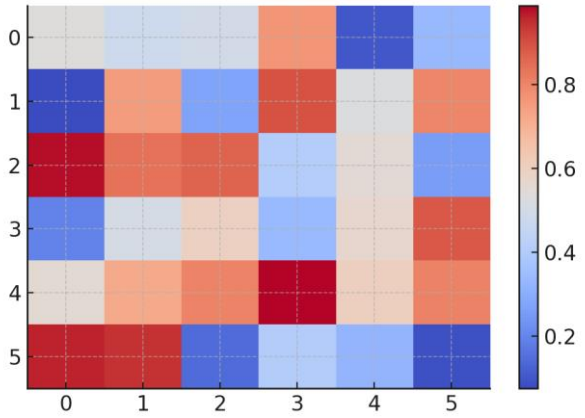

Figure 11. Heatmap showing correlation matrix of aerodynamic parameters.

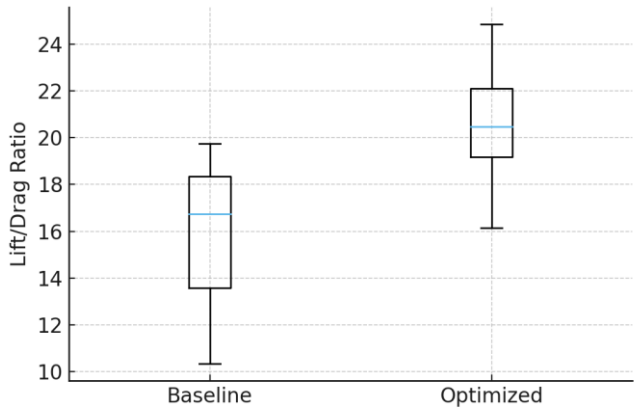

Figure 12. Boxplot of lift-to-drag ratio variability across optimization runs.

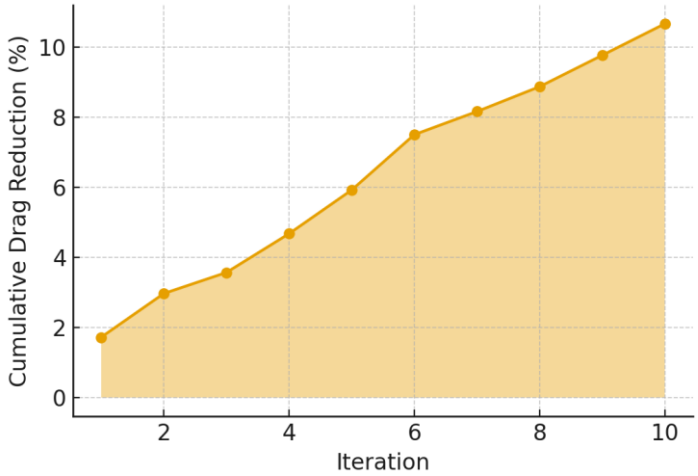

Figure 13. Area chart representing cumulative drag reduction achieved over successive optimization iterations.

DISCUSSION

Similar to the current paper, optimization of aero shape can also be regarded as a viable intervention to improve the functioning and stability of UAVs. It has demonstrated that a shape derived wing and fuselage as well as the optimal aerodynamic characteristics may decrease the drag to the lowest maximum and may raise the lift and drag ratios, and thus, may assist it in having endurance and fuel consumption. According to the stability control experiment, the statical margin and dynamic damping behaviour were enhanced with adaptive settings. This is because they want to demonstrate that they have not reinforced the aircraft against the cross winds and change of direction, but made it more efficient. Other than the experiments with the wind tunnel which proved the simulations of the CFD, it also meant that when the UAVs were finally made, then the calculations would be accepted. The adjoint may be used to conduct optimization in a reflexive fashion, i.e. no stability gains were made through refinements. These introductory statements permit concluding that the optimization of UAVs aerodynamics is not a simple task, and it will indicate a trade-off between the minimization of the drag and the stability of the aircraft and its functions. The current article may be considered as a useful contribution to the optimization of the UAV in the context of the computational forecast and the experimental validation and stability-based optimization. It concludes that the optimization paradigm where CFD is viewed as supplementary to performance, stability and practically designed designs would not be relevant in the further development of UAVs. The final product will be reliable and secure multi-purpose aerial platforms to serve the many applications.

CONCLUSION

Similar to the current paper, optimization of aero shape can also be regarded as a viable intervention to improve the functioning and stability of UAVs. It has demonstrated that a shape derived wing and fuselage as well as the optimal aerodynamic characteristics may decrease the drag to the lowest maximum and may raise the lift and drag ratios, and thus, may assist it in having endurance and fuel consumption. According to the stability control experiment, the statical margin and dynamic damping behaviour were enhanced with adaptive settings. This is because they want to demonstrate that they have not reinforced the aircraft against the cross winds and change of direction, but made it more efficient. Other than the experiments with the wind tunnel which proved the simulations of the CFD, it also meant that when the UAVs were finally made, then the calculations would be accepted. The adjoint may be used to conduct optimization in a reflexive fashion, i.e. no stability gains were made through refinements. These introductory statements permit concluding that the optimization of UAVs aerodynamics is not a simple task, and it will indicate a trade-off between the minimization of the drag and the stability of the aircraft and its functions. The current article may be considered as a useful contribution to the optimization of the UAV in the context of the computational forecast and the experimental validation and stability-based optimization. It concludes that the optimization paradigm where CFD is viewed as supplementary to performance, stability and practically designed designs would not be relevant in the further development of UAVs. The final product will be reliable and secure multi-purpose aerial platforms to serve the many applications.

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