nature portfolio

Peer Review File

Wing-tail coordination balances efficient cruising and maneuvering flight in an avian-inspired flapping robot

Corresponding Author: Professor Ang Chen

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This work is a rather through experimental analysis of morphing tail flapping wing robot design. The authors did a great job profiling the performance of this platform. However the scope and impact of this work feels limited. Here are some of my concerns:

1. As a bio-inspired design, the manuscript lacks meaningful connection with the animal counterpart: the authors should try to provide more details about the oriolus oriolus mentioned (including typical wing span, weight, reynolds number, flapping frequency, etc.), does this design achieves similar acceleration/deceleration, pitch moment, body kinematics etc. It is understandable with limited actuation the performance will not be truly on-par with avian flight, but the authors should make an effort to make this connection.

2. Continuing from the above point, as a design/platform paper, this work lacks any modeling/design optimization and theoretical analysis, and it's purely experimental. This limites the potential impact of this work. How is the platform designed, how is the wing morphology selected, does changing these morphological parameters affects the finds presented in this work?

3. I'm suprised that tail pitch is not controlled, as birds do both tail pitching and spread/furl. If the tail incidence is controlled, the platform could achieve high manuverability, stability and effeiciency at the same time.

Overall I think this work is exploring a promising direction, but what's presented in this manuscript feels incomplete and lacks impact for this venue.

Minor points:
1. Consider citing this prior work on morphing tail:
@article{murayama2023aerodynamic,
title={Aerodynamic performance of a bird-inspired morphing tail},
author={Murayama, Yuta and Nakata, Toshiyuki and Liu, Hao},
journal={Journal of Biomechanical Science and Engineering},
volume={18},
number={1},
pages={22--00340},
year={2023},
publisher={The Japan Society of Mechanical Engineers}
}

2. Figure 6A will be easier to read if trajectories are projected on to all three planes

Reviewer #2

(Remarks to the Author)
This paper presents a bird-inspired flapping-wing robot (NPU-Sparrow) featuring a reconfigurable tail and coordinated wing

angle-of-attack control. Through the combined control of tail span morphing and wing pitch modulation, the system achieves a balance between energy-efficient cruising and highly agile flight. The work demonstrates significant innovation in both mechanical design and control strategy, especially in the in-depth exploration of tail functionality. Overall, the study is innovative but needs additional comparisons and robust experimental validation.

1. Bird tails combine spreading and deflection mechanisms, while most fixed-wing aircraft use elevators for maneuverable flight. This article opts for a extending mechanism instead of a deflection mechanism. How can it be proven that the spreading mechanism offers a more significant advantage over the deflection mechanism?

2. One of the core conclusions of this paper is that the negative-lift tail configuration constitutes a superior engineering solution because it provides static stability. However, the authors also acknowledge in the Discussion that bird tails typically generate positive lift during flight. This suggests that birds—as biological prototypes—commonly operate under statically unstable conditions. Could the authors further elaborate on this discrepancy? Why have birds evolved to adopt this more challenging (statically unstable) flight mode, whereas the NPU-Sparrow design favors a safer (statically stable) configuration? Does this imply that the proposed design represents a bio-inspired engineering optimization rather than a strict biomimetic replication? The trade-offs between biological fidelity and engineering practicality merit deeper discussion.

3. The title and abstract emphasize "energy-efficient," but the main text lacks corresponding experimental validation and quantitative analysis. he key evidence supporting this claim mainly derives from Fig. 6E, which shows a theoretical available thrust curve extrapolated from wind-tunnel data, rather than direct measurements of in-flight power consumption. To strengthen the reliability of this conclusion, the authors are advised to include real-time power data from actual flight tests comparing the conventional fixed-tail configuration and the morphing-tail configuration, to empirically demonstrate that tail retraction indeed reduces energy consumption during high-speed cruise.

4. According to Fig. 5B, the positive-lift tail configuration is marked as “unstable” at both 0° and 20° angles of attack. Does this indicate that this configuration—even with the assistance of wing angle-of-attack control—cannot maintain stable flight throughout the entire flight envelope? This limitation appears critical and should be more explicitly stated and discussed in the manuscript, including whether it represents the primary reason why this configuration was ultimately discarded.

5. The paper notes that tail deployment leads to a significant rearward shift of the aerodynamic center, but it does not sufficiently explain how this change affects flight stability in practice, or how such movement is compensated during flight to maintain steady conditions. The authors should provide additional analysis or clarification on this point.

6. Conventional aircraft achieve smaller turning radii by increasing roll angles or elevator deflection angles. The article's claim of a "steady turning radius reduced by 18.5%" is based solely on theoretical calculations. It is recommended that the authors provide flight experiment data to enhance persuasiveness.

7. The paper mentions that flight control is implemented using a “simple PID algorithm.” However, the NPU-Sparrow is a highly coupled multi-input–multi-output (MIMO) system: tail area variation affects the overall aerodynamic center, while wing angle-of-attack control simultaneously influences pitch and roll. It is questionable whether a single “simple PID” controller can effectively stabilize such a complex dynamic system.

Minor：
1. The arrangement and layout of subfigures in Fig. 1 could be further optimized to improve logical coherence.

2. The arrows in Fig. 3D do not clearly reflect the specific meanings of "supinating" and "pronating." Is there a clearer way to annotate them?

3. The color and shading of the curves in Fig. 4D are easily confused with those in Fig. 4A. It is suggested to improve their distinguishability.

Reviewer #3

(Remarks to the Author)
-Summary

This manuscript introduces NUS-Sparrow, a flapping-wing aerial robot featuring a morphable tail and controllable wing-pitching mechanism. The platform is claimed to decouple roll and pitch control and to allow a trade-off between agility (tail deployed) and reduced drag (tail compact). The paper provides experimental characterization (including wind-tunnel tests) and flight experiments

After careful reading, I find the manuscript contains interesting engineering work and simple experimental validation, but — in its current form — it is not recommended for publication in Nature Communications. The major reasons are concerns about motivation, unquantified claims of improvement, unclear novelty relative to prior art, and issues with clarity, presentation, and missing technical details. Below I list major and minor issues for editors and authors reference.

-Major concerns

Motivation and Contribution:
1) The manuscript reads largely like an engineering demonstration rather than a clear conceptual advance in flapping-wing aerodynamics or control.
2) Key claimed benefits (improved agility vs. cruise efficiency trade-off) are qualitative. Important quantified comparisons (with baseline / ablated configurations and/or to representative prior works) are lack, such as
A. Flight agility (measurable metrics such as maximum angular acceleration, turn rate, rise time to command, etc.).
B. Cruising efficiency (flight power, power loading W/kg or g/W, and power consumption vs speed).
C. Net system-level trade-offs.

Novelty and Relation to Prior Works:
Morphable tails / morphing control surfaces and their benefits have been explored in propeller-based MAVs and other small aircraft. The manuscript does not clearly explain what is genuinely new here: Is the novelty in the mechanism design, the way it is applied to a flapping-wing vehicle, a control strategy, or new aerodynamics measurements for flapping platforms? A concise, pointed "novelty statement" in the Introduction that explicitly contrasts this work with the most relevant prior studies should be included.
Or detail the unique challenges of adapting morphable tails to flapping wings (e.g., unsteady aerodynamics, coupling with wing flapping, control latency due to low bandwidth) and show how the current design addresses them. The Introduction part should include more related reference for comparision and highlight the uniqueness and contribution of the proposed study.

Readability and Quality:
The manuscript requires substantial improvement in organization and writing quality to ensure readability. Numerous issues related to language, clarity, and technical presentation make the paper difficult to follow (particularly in the Result sections). In particular, there are frequent instances of incorrect or imprecise vocabulary, inconsistent use of technical terminology, and missing definitions for important concepts and parameters. Many paragraphs lack logical flow, and the narrative often feels fragmented, making it challenging for readers to understand the authors' intended meaning. A thorough restructuring and careful rewriting are strongly recommended to meet the high standards of clarity and precision expected for Nature Communications. This includes improving logical transitions, standardizing terminology, and providing clear explanations for all key ideas, variables, and experimental procedures.

-Detailed Comments
1) Misuse of "angle of attack" throughout the manuscript. The authors repeatedly use "angle of attack" to describe the geometric posture or installation angle of the tail. However, angle of attack refers specifically to the angle between the incoming airflow and an airfoil, which is distinct from a body-frame installation angle. This terminology is misleading and technically incorrect.
Please replace these instances with more appropriate terms such as tail installation angle, tail pitch angle, or tail configuration angle.
For example, in Line 93, the so-called "wing angle-of-attack control mechanism" appears to adjust the wing's angle in the body frame, not its aerodynamic angle of attack (which is not measured).
Similarly, in Line 97, the meaning of "13°" is unclear—this seems to refer to the vehicle pitch angle rather than an angle of attack. Please clarify.
2) It is not evident what information Figure 2C is intended to convey or how it contributes to the main text. A clearer explanation or justification for its inclusion is needed.
3) Line 121: unclear biological reference and naming rationale. The authors cite morphometric data of Oriolus oriolus to justify a wingspan of 0.45 m. The relevance of this species to the design is not explained. Furthermore, if the design is based on Oriolus, why is the robot named "NPU-Sparrow" instead of a name tied to Oriolus? This is confusing and should be clarified.
4) Lines 139–140 lack clarity. The meaning of this sentence is difficult to follow. It should be rewritten for clarity and logical flow.
5) Line 164, Eq. (1) appears unnecessary. Equation (1) does not seem to play a role in the subsequent analysis or discussion of flight stability. Unless it directly supports later derivations, it may be unnecessary.
6) Line 168: wind tunnel setup unclear and overly complex description. A figure illustrating the wind-tunnel experimental setup and vehicle mounting would greatly improve clarity. The text in Lines 168–171 is overly dense and difficult to follow. It is also unclear how the authors determined the two installation angles of 7° and −10°. Please explain the selection process and provide supporting data.
7) Line 178: MAC undefined and paragraph structure problematic. The term "MAC" is introduced without definition (it should be explained at the first time it appears). The paragraph consists of only three long, complex sentences that are difficult to read. Breaking them into shorter, clearer statements is recommended.
8) Line 199: unclear origin of numerical values. The values 17.3 and 17.5 are introduced without explanation. Are these measured values or results from calculation? Please specify the method and context.
9) Line 301: negative-lift tail raises contradictions in cruise-power claims. The optimized configuration appears to require the tail to generate negative lift, which increases takeoff weight burden and reduces net aerodynamic lift. Under such conditions, it is unclear how tail morphing directly reduces cruise power consumption.
A more appropriate interpretation may be that morphing helps mitigate additional drag induced by the tail, rather than reducing the absolute cruise power requirement. The text should be revised accordingly.
10) Section 2.5 lacks quantitative analysis of tail-induced power cost. The manuscript does not provide sufficient information on how the tail configuration (installation angle, area) affects total power consumption during cruise flight. A quantitative analysis of the tail's aerodynamic and energetic impact is recommended.
11) Line 315 and Section 2.6: missing experimental setup and unclear cross-referencing. Section 2.6 should clearly

describe the experimental measurement setup—sensor types, sampling rate, data processing, and how each plotted quantity was obtained. (Please also give direct reference if those information are provided in future sections)
The analysis and conclusions should be directly tied to Figure 6 through explicit cross-references.
For instance, Line 321 refers to "horizontal accelerations (Fig. 6A)," yet Figure 6A shows only trajectory and speed. Reviewers and readers expect clear, direct correspondence between text and figures.
12) Lines 350–360 appear misplaced. This paragraph reiterates the rationale for using a negative-lift tail, which has already been addressed earlier. It does not connect logically to the flight experiments and seems out of place in this section.
13) Flight experiments lack direct evidence supporting claimed trade-off. The Introduction claims a trade-off between agility and cruising power consumption, but the flight experiments do not provide direct quantitative evidence for this claim. Measuring total power consumption under different flight speeds and tail configurations should be straightforward and is essential to support the central contribution. The whole flight experiment section need insightful analysis and conclusion.
14) Section 3 (Discussion) lacks depth and appropriate structure. The current Discussion reads largely as a short Conclusion rather than a true discussion. It should include more information like what is the unique advantage and limitation of the current design. How does this work inpire future directions.

Comments on Figures

15) Figure 1:
Panels C and D do not appear to be referenced or discussed in the main text. If these subfigures are not essential to the scientific narrative, it is recommended to remove them to avoid unnecessary distraction.
16) Figure 3:
Additional clarification is required for Panel B and C. For example:
- What does the x-axis represent? Is it the "angle of attack" of the vehicle or of the tail?
- What does the y-axis represent? Is it the lift generated by the tail alone, or the total lift of the whole vehicle?
- What is the wind speed used in the test?
- Please clearly define the "lift coefficient." Is it the conventional Cl defined same as in Blade element thoery?
- Does this Cl correspond to the tail or the entire vehicle?
- Why was 20° chosen as the maximum testing angle? Is this related to the expected stall angle of the tail? If so, this should be explained.
17) Figure 6:
Several issues require clarification and correction:
- The meaning of "overload" in Panel B is unclear. Is it equivalent to the load factor?
- Is the "angle of attack" in this figure identical to the measured pitch angle? Why is there a consistent error between the pitch command and the measured angle of attack?
- In Panel B, the second and third plots contain three legends but four curves, which must be corrected or better clarified.
- Panel C is never referenced in the manuscript. If it does not contribute to the analysis, consider removing it.
- Panel D contains a line that is not explained in the legend. This needs clarification.
- Panel D shows that when the tail becomes smaller, the airspeed increases while the angle of attack decreases. This raises several concerns: How does the altitude change during this period? A decreasing angle of attack should lead to reduced lift. Is additional wing pitching angle applied to compensate for lift loss? Does the total power consumption increase when the wing angle changes to maintain flight equilibrium?
None of these questions are addressed in the current manuscript and must be clarified.
- Panel E lacks sufficient organization, description, and explanation. A detailed interpretation should accompany the figure, including how the plotted data were measured and how they support the claims in the text.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Summary

The authors have made substantial and commendable efforts in the rebuttal. The manuscript is significantly improved in terms of writing quality, and included biological connection (Table 1, flight envelope validation), improved experimental rigor (baseline comparisons, empirical power data). Again, I commend the authors on the detailed experimental results. However, my fundamental concerns remains as regards to theoretical contribution and generalizability of this work.

Major concerns:

1. Lack of theoretical framework and modeling. This remains my primary concern. Despite improvements, the work is fundamentally an experimental engineering demonstration without predictive aerodynamic models, design principles or optimization framework, oparametric studies, or theoretical analysis of stability margins and control coupling.

The authors state design parameters are based on "passerine birds" and "fixed-wing aircraft standards," but do not show the design process of how these were actually chosen. As a design it's perfectly acceptable to pick certain parameters, but what is the guiding design principle/objective function? The auhtors calaims this work as "efficient avian-inspired control configuration". But was the design optimized for efficiency? The authors did not provide much analysis otherthan comparison to baseline, providing limited contribution.

Even with simple modeling, the authors could have provided guiding design principles/insights. As you move the design along the pareto front, perhaps the morphological parameter trends, potential negative/positive lift shift could have been revealed. These are the key insights the author should provide.

2. Limited novelty and scope. Prior work established morphing tails on fixed-wing MAVs (Ajanic 2020, 2022), wing morphing for roll (Di Luca 2017, Chang 2020), and tail morphing effectiveness (Murayama 2023). This validates tail morphing works on flapping-wing platform with specific implementation. Question: Is cross-platform validation sufficient novelty without theoretical framework explaining why it transfers?

Reviewer #2

(Remarks to the Author)
The revised version clarified the relationship between tail fin deployment and main wing angle of attack for pitch control. In fact, changes in the main wing angle of attack and tail fin deflection produce a similar effect, which does indeed help with pitch control.

A minor issue: in Figure 1D, the longitudinal static stability layout contradicts the tail fin lift direction, and the center of gravity position is not indicated. The center of gravity position is crucial for determining longitudinal stability.

Reviewer #3

(Remarks to the Author)
I appreciate the authors' detailed responses and the revisions made based on my previous comments. The manuscript has improved in clarity and presentation.

Summary of the Work:
1, This study presents a bird-inspired flapping-wing drone (NPU-Sparrow) featuring independently variable wing pitching angles and a size-morphable tail to enhance flight authority.
2, The primary motivation is to achieve bird-like flight capabilities, including aggressive maneuvering and efficient cruising.
3, Specifically, the manuscript:
(A) introduces the overall design of NPU-Sparrow and claims to address maneuverability challenges in flapping-wing systems through a relatively simple and engineering-feasible platform;
(B) analyzes how the proposed wing configuration influences maneuverability;
(C) investigates how tail size affects power consumption;
(D) validates the design through outdoor flight experiments.

Comments and Suggestions:

1) Novelty. I personally concern the novelty of the proposed design, is it the first implementation of size-morphable on a flapping wing drone? if it is, please highlight. If not, maybe the proposed configuration (variable wing together with the morphable tail) is a new strategy (I guess so).
In the response letter, the authors state:
"Directly transplanting complex morphing mechanisms onto flapping wings would significantly compromise the aeroelastic response upon which they depend for generating lift and thrust, while also imposing unacceptable weight and inertial penalties."
However, in the current design, the morphable structure appears to be applied only to the tail, not to the wings. Therefore, this argument does not seem fully aligned with the actual implementation. Furthermore, introducing additional actuators for independent variable wing pitching would also increase system weight and extra power consumption.
The authors are encouraged to clarify this novelty-related statement more directly and consistently. Specifically, they should explain how their design avoids the stated drawbacks while still achieving meaningful functional improvement, and clearly define what constitutes the core innovation of the proposed platform.

2) Another concern relates to the level of scientific contribution. Incremental improvements in engineering feasibility alone may not be sufficient for publication in its current form. To strengthen the manuscript, the authors are encouraged to provide deeper scientific insights—such as more rigorous flight control development, quantitative performance evaluation, or systematic comparisons—that clearly demonstrate the advancement beyond an engineering prototype.

Although the authors have not fully addressed my concerns (still on novelty and scientific contribution), I do not believe it is necessary for me to recommend rejection of the revised manuscript, as the other reviewers and the editor have already requested major revisions on this issue (I will follow the majority view). In addition, the revised version has introduced new problems. I recommend that these issues must be properly addressed before the manuscript can be considered for publication.

3) While the overall paper quality has improved, several figures still suffer from low resolution and suboptimal organization (e.g., Figure 6). The figures should be revised to meet publication standards.

4) Sections 2.3 (“Influence on Flight Stability”) and 2.4 (“Influence on Maneuverability”) would benefit from clearer organization and greater concision. There appears to be some overlap between these sections. In addition, I suggest reconsidering the use of the term “stability” in Section 2.3. In control and dynamical systems, “stability” typically refers to the input–output or equilibrium behavior of a system, whereas the discussion in this section seems to address a different concept (sounds like torque generation capability or control authority, etc). A more precise term would improve clarity.

Version 2:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Summary

I thank the authors for a substantial and thoughtful revision. They have restructured the paper and repositioned the central claim from "a morphing tail on a flapping robot" to a model-guided wing-tail coordination design framework, revising the title accordingly. This directly targets my primary concern from the previous rounds. Great to see the new predictive model and the Pareto front (Fig. 3C), which formalize the cruise-efficiency / maneuverability trade-off and are used to motivate the design choices, materially strengthens the contribution.

Major concerns:

1. On whether the "predictive model" is genuinely predictive. I appreciate the effort the authors put into building the model and the Pareto map -- this is a real improvement and largely addresses my earlier request for design principles. I would, however, still like to see this qualified honestly in the text. As implemented, the model is an empirical response-surface fit to this specific robot's own wind-tunnel data; it interpolates within the tested envelope (and the authors note it breaks down beyond ~25 degrees AoA) rather than providing a scale-transferable framework a reader could use to design a different robot. So explicitly calling out this caveat is important.

Related to this, the model appears to overestimate the magnitude of aerodynamic-center migration relative to the wind-tunnel measurements. Comparing the source data for Fig. 3B and Fig. 4D, the predicted AC shift exceeds the measured shift by roughly a factor of 2-3 across all three control strategies (e.g., tail-morphing-only: 43% predicted vs. 17.5% measured). Since the stability boundary (M_AC < 0), the selected tail angle, and the breadth of the exploitable Pareto region all depend on AC position, I would ask the authors simply to (a) state explicitly that the model is a robot-specific empirical fit valid within the tested range, and (b) briefly comment on how sensitive the Pareto front and the -10 degree design point are to this quantitative discrepancy. Please explicitly discuss this in the manuscript.

2. Figure 3 is hard to interpret. The caption defines the axes of panel C but never identifies the three colored curves, the marker shapes (lambda_t = 0 / 0.5 / 1), the color scale (i_t), or the "x" symbol; the reader must reconstruct the legend from three separate paragraphs of body text or legends from later figures (pronation vs supination). Please consider adding some text to guide the reader on how to read and interpret the figure (where the final design sits, and how the lines move as the morphological parameters change, etc.).

Minor points:

1. Pareto-front axis convention. By convention a Pareto front is plotted so that both competing objectives improve along their axes, placing the jointly-optimal (hard-to-reach) region in the top-right corner. Here the vertical axis (load factor) increases upward, but the horizontal axis is minimum flapping frequency, where lower is better. I suggest reversing the frequency axis (or plotting an efficiency proxy that increases rightward) and stating explicitly that lower flapping frequency corresponds to higher cruise efficiency, so the desirable region sits in the top-right as readers expect.

2. Inconsistent flight-envelope numbers. The Introduction states a "193% expansion of the flight speed envelope," whereas the Results report the envelope is "extended by 22.5% compared to the baseline." These describe the same quantity two different ways -- the 193% appears to be the speed range relative to its own minimum (e.g., (13.2-4.5)/4.5), not an expansion versus the baseline. Please reconcile these and use a single consistent framing; as written, the 193% in the Introduction reads as inflated.

3. Fig. 7B comparison. The comparison against birds and other robots mixes points reported on a single metric with different definitions of load factor (instantaneous vs. steady-state). This makes the "clear advantage over existing flapping-wing vehicles" claim somewhat apples-to-oranges. I am not asking for additional experiments -- please either annotate these differences in the figure/caption or soften the claim accordingly.

Reviewer #2

(Remarks to the Author)
The author has addressed all my comments. Great work!

Reviewer #3

(Remarks to the Author)
The revised manuscript presents a clearer contribution, centered on the NPU-Sparrow platform, which integrates a linkage-driven morphing tail into a flapping-wing vehicle to balance flight agility and cruise efficiency.
The remainder of the paper provides a clear description of the system, along with appropriate validation and methodology to support this central idea.
Overall, my main concerns regarding this work have been adequately addressed.

Responses to the Reviewers' Comments on the Manuscript

ID NCOMMS-25-70548

Dear reviewers,

On behalf of my co-authors, we sincerely appreciate the efforts you have dedicated to assisting in the improvement of this manuscript. We are deeply grateful to the reviewers for the positive and constructive comments and suggestions regarding our manuscript entitled "**Avian-inspired tail morphing enables balanced energy-efficient and agile flight for a flapping robot**" **(ID NCOMMS-25-70548)**. These comments highlighted shortcomings in our original draft concerning biomimetic relevance, experimental quantification, and writing quality. Consequently, in this major revision, we have implemented the following core improvements:

1. We have deepened the bio-inspired connection and clearly elucidated the design philosophy of the robot. Through the newly added Table 1, we provide a detailed correlation between the morphological data of medium-sized passerine birds and the design parameters of NPU-Sparrow. Furthermore, we elaborate on the selection of the robot's design parameters, including the design details and specific considerations for the flapping wings and control mechanisms. Additionally, we have supplemented a comparison of the level flight speed range between NPU-Sparrow and Sturnus vulgaris, further validating its bio-similarity in terms of the flight envelope.

2. Further strengthened experimental verification and data presentation. In the flight test section, we supplemented comparative data between NPU-Sparrow and the baseline model regarding flight speed range, empirical power consumption (Fig. 6B), and steady turn radius (Fig. 6G). Supported by experimental data, we conducted an in-depth analysis of the advantages of NPU-Sparrow's control configuration. Additionally, we refined the details and presentation style of certain figure panels.

3. Standardized terminology and enhanced overall writing quality. We corrected terminology usage throughout the text to ensure rigorous and accurate definitions. The structure and logical flow of the Introduction were optimized to make the argumentation more coherent and fluid. The Discussion section was reorganized and meticulously rewritten to deeply analyze the distinctions between the biological prototype and engineering optimization, significantly enhancing the depth and professionalism of the content.

Below is a point-by-point response to the reviewers' comments. We have marked the revisions in the manuscript using red underlines and have removed some content.

Sincerely,

The authors

Response to Reviewer 1's comments:

This work is a rather through experimental analysis of morphing tail flapping wing robot design. The authors did a great job profiling the performance of this platform. However the scope and impact of this work feels limited. Here are some of my concerns:

Thank you so much for reviewing our manuscript and providing helpful comments.

1. As a bio-inspired design, the manuscript lacks meaningful connection with the animal counterpart: the authors should try to provide more details about the oriolus oriolus mentioned (including typical wing span, weight, reynolds number, flapping frequency, etc.), does this design achieves similar acceleration/deceleration, pitch moment, body kinematics etc. It is understandable with limited actuation the performance will not be truly on-par with avian flight, but the authors should make an effort to make this connection.

We thank the reviewer for their valuable comments. This study aims to propose an efficient bio-inspired control configuration grounded in the simplification of avian flight mechanisms, endowing a flapping-wing robot with both agile maneuvering and efficient cruise capabilities. Renowned for their exceptional agility and long-distance migratory abilities, passerine birds serve as ideal biomimetic models for performance optimization in this research. Consequently, the design of the NPU-Sparrow is explicitly referenced against morphological data from medium-sized passerines.

To clarify the biomimetic comparison, we have supplemented Table 1 in the main text with data on weight, wingspan, and theoretical minimum-power flight speed for three representative medium-sized passerines: Oriolus chinensis, Turdus viscivorus, and Sturnus vulgaris. The weight (90 g), wingspan (0.45 m), and design cruise speed (7 m/s) of the NPU-Sparrow were selected based on the natural parameter distribution ranges of the aforementioned birds, ensuring biological plausibility in terms of physical scaling.

Table 1. Morphological and flight data of medium-sized passerine birds and NPU-Sparrow.[1–5]

	Oriolus chinensis	Turdus viscivorus	Sturnus vulgaris	NPU-Sparrow
weight (g)	46.2-104	83-140	75-100	90
Wingspan (m)	0.44-0.47	0.42-0.48	0.31-0.415	0.45
Theoretical minimum-power flight speed (m/s)	6.8	7.1	6.8	

In Section 2.6 (Flight Experiments), we have added a comparison of the flight speed envelope between NPU-Sparrow and the baseline model. Experimental results indicate that, enabled by active tail morphing, NPU-Sparrow achieves a level flight speed range of 4.5 m/s to 13.2 m/s, representing a 22.5% expansion compared to the baseline model with a fixed tail area (Fig.6B). Referencing passerines of similar body mass (e.g., the European Starling, with a level flight speed range of approximately 6 – 14 m/s[6]and a takeoff speed of approximately 4.1–4.2 m/s[7]), NPU-Sparrow has essentially attained the flight speed levels of similarly sized birds, verifying its kinematic performance proximity to the biological prototype.

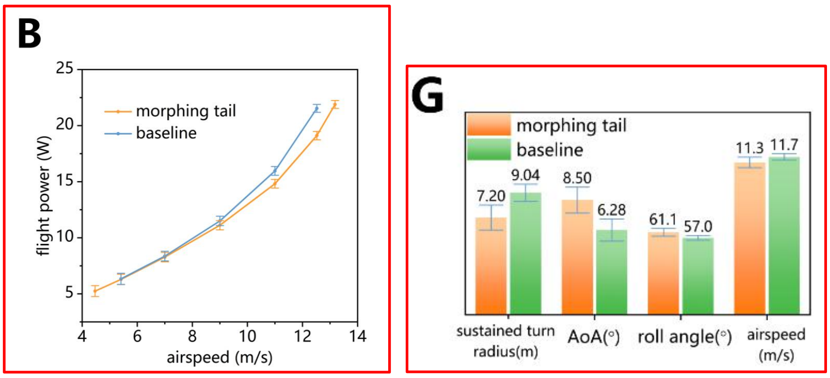


Fig.6B. Comparison of the flight speed envelope and power consumption between NPU-Sparrow with a morphing tail and the baseline model. G.Comparison of average turn radius, angle of attack, roll angle, and flight speed between NPU-Sparrow with a morphing tail and the baseline model during a complete steady turn. Error bands represent the standard deviation across data from one complete turn.

Due to the limited availability of specific quantitative data regarding the maneuverability and agility of similarly sized passerines in the existing literature (e.g., angular acceleration, minimum turn radius), we assessed the biomimetic advantages by comparing the NPU-Sparrow to its baseline model. The experiments demonstrate that the morphing tail reduces the steady turn radius by 20.4%(Fig. 6G). Furthermore, during barrel roll maneuvers, the peak filtered roll rate reaches 375°/s(Fig. 6F), indicating a significant enhancement in maneuverability. These results validate the effectiveness of the bio-inspired design in expanding the flight envelope from an engineering feasibility perspective.

We sincerely appreciate the reviewer's suggestions. The supplementary explanations mentioned have been incorporated into the revised manuscript to more clearly establish the performance correlation and design logic between this study and the biological prototype.

Reference:

[1]. Farner, D. S. Dimensional Relationships for Flying Animals. *Auk* **78**, 653–654 (1961).

[2]. Dimaki, M., Alivizatos, H. & Kokkini, P. Ringing studies of the Golden Oriole Oriolus oriolus (Aves: Oriolidae) during passage through Antikythira Island, southwestern Greece. *Ringing & Migration* **34**, 113–119 (2019).

[3]. Jr, J. B. D. CRC Handbook of Avian Body Masses.

[4]. Blem, C. R. Geographic Variation in Mid-Winter Body Composition of Starlings. *The*

Condor **83**, 370 (1981).

[5]. Bruderer, B. & Boldt, A. Flight characteristics of birds: *Ibis* **143**, 178–204 (2001).

[6]. Ward, S. *et al.* Metabolic power of European starlings *Sturnus vulgaris* during flight in a wind tunnel, estimated from heat transfer modelling, doubly labelled water and mask respirometry. *Journal of Experimental Biology* **207**, 4291–4298 (2004).

[7]. O'Hagan, D., Andrews, C. P., Bedford, T., Bateson, M. & Nettle, D. Early life disadvantage strengthens flight performance trade-offs in European starlings, Sturnus vulgaris. *Animal Behaviour* **102**, 141–148 (2015).

2. Continuing from the above point, as a design/platform paper, this work lacks any modeling/design optimization and theoretical analysis, and it's purely experimental. This limites the potential impact of this work. How is the platform designed, how is the wing morphology selected, does changing these morphological parameters affects the finds presented in this work?

We appreciate you pointing this out. We fully agree on the importance of theoretical analysis. In this revision, we have supplemented the design considerations in the text to address the previous omission in description. As previously stated, passerine birds, which NPU-Sparrow mimics, served as a primary source of inspiration for the robot's design due to their superior flight capabilities. We have made the following modifications in Section 2.1(Avian-inspired flapping-wing robot) of the revised manuscript:

> Based on passerine morphometric data, NPU-Sparrow was designed with a takeoff weight of 90 g, a wingspan of 0.45 m, and a cruise speed of 7 m/s (Table 1). Referring to general parameters of similar-scale fixed-wing aircraft, the wing loading was established at 0.23 N/m² and the aspect ratio at 5, with remaining parameters derived from these initial conditions. Using the cruise state as the design baseline, the flapping-wing system is refined through iterative wind tunnel tests. The wings flap at a frequency of 8 Hz with a stroke amplitude of 80°. Under maneuvering conditions, the flapping frequency can increase to 16 Hz. The wings are constructed from a carbon fiber skeleton bonded to a polyurethane film. To mimic avian wing cross-sections, the two ribs proximal to the root feature the upper surface of a GOE225 airfoil (corresponding to the arm wing), while the distal three ribs employ a flat-plate airfoil (corresponding to the hand wing). To replicate the streamlined and

Addressing key factors affecting flight performance, the range of tail area variation and the control range of the flapping wing incidence angle were both designed based on aircraft performance requirements. Specifically, the median value of the tail area variation—which corresponds to the tail area of the baseline model in the performance comparison—was determined based on the requirement of a horizontal tail volume coefficient of 0.45 for fixed-wing aircraft. During the tail extension process, the center of pressure remains virtually invariant. Referencing the tail volume requirements for avian cruise flight, we established a minimum tail volume coefficient of 0.3, corresponding to a tail spread angle of 30° and a planform area of 0.00813 m²; the maximum tail volume coefficient was set to 0.6, corresponding to a spread angle of 107° and a planform area of 0.01775 m².

Design considerations for the flapping wing incidence angle control mechanism have been supplemented in the Materials and Methods section of the revised manuscript:

Facilitated by the control mechanism, the flapping wings achieve a ±5° incidence angle control, which is kinematically decoupled from the flapping motion. This range was determined based on the requirements for roll agility. For a constant moment of inertia, the roll angular acceleration of the robot is governed by the differential lift between the left and right wings:

$$\dot{p} = \frac{\Delta L \cdot l}{I_x}$$

where l denotes the moment arm length from the center of pressure of the flapping wing to the robot's x-axis, and ΔL represens the lift difference between the left and right wings. Assuming a constant wing planform and small angles of attack, the lift curve slope remains constant. Consequently, under static conditions, the relationship between the robot's maximum roll angular acceleration and the maximum differential incidence angle is given by:

$$\dot{p} = \frac{q S_{wing} a \Delta\alpha \cdot l}{I_x}$$

where q is the dynamic pressure, S_{wing} is the flapping-wing area, a is the lift curve slope, and $\Delta\alpha$ is the differential incidence angle.

This study aims to propose a concise and efficient avian-inspired control configuration. By employing a low-complexity structure, it significantly enhances maneuvering performance while ensuring cruise efficiency, thereby realizing a transition from biological imitation to bio-inspired mechanism optimization and providing a viable path for efficient bio-inspired engineering implementation. The aforementioned design process provides a foundational platform for the realization of this control configuration. While adjustments to specific parameters may exert some influence on the final flight performance, they do not alter the inherent performance enhancement effect that this control configuration imparts to the foundational platform.

3. I'm suprised that tail pitch is not controlled, as birds do both tail pitching and spread/furl. If the tail incidence is controlled, the platform could achieve high manuverability, stability and effeiciency at the same time.

Thank you for your insightful comments. You correctly pointed out that introducing pitch deflection capability alongside tail morphing would enhance control redundancy and pitch agility, which aligns closely with the actual morphology and functions of birds.

In the Introduction of the revised manuscript, we have further emphasized that the avian flight system possesses a high degree of kinematic redundancy. Its pitch control is achieved through the coupling of various methods, including wing sweeping, twisting, camber variation, and tail pitching and morphing[1,2]. For artificial flapping-wing robots, fully replicating this complex multi-degree-of-freedom synergistic mechanism would inevitably increase mechanical complexity, weight, and control difficulty, potentially leading to a loss of overall efficiency. Therefore, one of the core challenges and objectives of this study is to seek an optimal balance between retaining key biomimetic functions and ensuring engineering feasibility, thereby exploring a pathway to achieve high-performance control through simplified design.

In the specific design of NPU-Sparrow, active tail morphing serves not only as a means of pitch control but also as a critical mechanism for flexibly adjusting tail volume and the overall overload capacity of the body, thereby extending the flight speed envelope. Simultaneously, the synergistic control of the flapping wing incidence angle can generate effective pitch moments. Functionally, the combination of these two methods substitutes for the traditional global deflection of the tail, achieving an engineering simplification of pitch control. The primary aim of this study is to systematically verify the feasibility and unique value of this simplified configuration of "tail area adjustment combined with flapping wing incidence angle control." Consequently, we ultimately selected a design scheme employing only tail morphing for pitch control, aiming to maintain structural simplicity and high reliability while ensuring sufficient maneuverability and cruise efficiency.

We sincerely thank you for your suggestion, which prompted us to articulate more clearly the design trade-offs and decision-making logic between "simplification" and "replication" in engineering biomimetics.

Reference:

[1]. Harvey, C. et al. A review of avian-inspired morphing for UAV flight control. Progress in Aerospace Sciences 132, 100825 (2022).

[2]. Murayama, Y., Nakata, T. & Liu, H. Aerodynamic performance of a bird-inspired morphing tail. JBSE 18, 22-00340-22–00340 (2023).

Overall I think this work is exploring a promising direction, but what's presented in this manuscript feels incomplete and lacks impact for this venue.

Minor points:

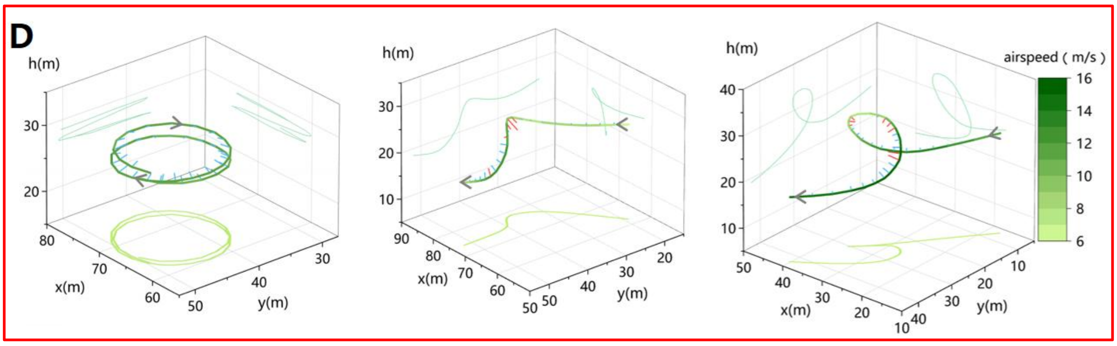
1. Consider citing this prior work on morphing tail:

@article{murayama2023aerodynamic, title = {Aerodynamic performance of a bird-inspired morphing tail}, author={Murayama, Yuta and Nakata, Toshiyuki and Liu, Hao}, journal={Journal of Biomechanical Science and Engineering}, volume={18}, number={1}, pages={22--00340}, year={2023}, publisher={The Japan Society of Mechanical Engineers}}

We appreciate the literature you provided, which has been cited in the Introduction. In this reference, the avian-inspired morphing tail model underwent systematic ground-based experimental validation. The results indicate that both tail morphing (extension/retraction) and global deflection can generate pitch control moments. Notably, the morphing control mode exhibits lower drag and energy consumption, rendering it a more efficient control mechanism. This provides robust support for our adoption of tail morphing to generate pitch control moments in this study.

2. Figure 6A will be easier to read if trajectories are projected on to all three planes

We thank you again for your suggestion. We have supplemented Fig. 6D (formerly Fig. 6A) with projections of the 3D trajectory onto the other two coordinate planes to enhance readability.



Response to Reviewer 2's comments:

This paper presents a bird-inspired flapping-wing robot (NPU-Sparrow) featuring a reconfigurable tail and coordinated wing angle-of-attack control. Through the combined control of tail span morphing and wing pitch modulation, the system achieves a balance between energy-efficient cruising and highly agile flight. The work demonstrates significant innovation in both mechanical design and control strategy, especially in the in-depth exploration of tail functionality. Overall, the study is innovative but needs additional comparisons and robust experimental validation.

We thank the reviewer for their highly professional and constructive comments.

1. Bird tails combine spreading and deflection mechanisms, while most fixed-wing aircraft use elevators for maneuverable flight. This article opts for a extending mechanism instead of a deflection mechanism. How can it be proven that the spreading mechanism offers a more significant advantage over the deflection mechanism?

We appreciate your insightful comments. The core objective of this study is to strike a

balance between retaining key biomimetic functions and ensuring engineering feasibility. As you correctly pointed out, avian pitch control is achieved through the coupling of various methods, such as wing sweeping, twisting, camber variation, tail pitching, and morphing[1,2]; this point has been re-emphasized in the Introduction of the revised manuscript.Attempting to fully replicate these mechanisms on a micro flapping-wing robot would lead to a drastic increase in structural weight, reduced reliability, and heightened control complexity. Therefore, adhering to the bio-inspired design philosophy of 'mechanism-based simplification,' we selected tail morphing as the primary pitch control mechanism. This mechanism utilizes a single actuation to simultaneously achieve pitch control and tail volume modulation, thereby balancing maneuverability with the capability to extend the flight envelope while avoiding the complexity associated with introducing morphing structures to the flapping wings.Combined with flapping wing incidence angle control, this forms the control configuration of 'dynamic tail area adjustment combined with flapping wing incidence angle control.' Wind tunnel and flight experiments indicate that this simplified strategy enables the robot to achieve a wide speed envelope and high maneuverability, verifying the effectiveness and practicality of this design at the studied scale. We believe that on future higher-performance platforms, introducing a controllable tail deflection degree of freedom could further enhance control bandwidth and redundancy; however, this does not diminish the novelty and utility of the current simplified scheme under the specific scale and objectives of this study. **Reference:** [1]. Harvey, C. et al. A review of avian-inspired morphing for UAV flight control. Progress in Aerospace Sciences 132, 100825 (2022). [2]. Murayama, Y., Nakata, T. & Liu, H. Aerodynamic performance of a bird-inspired morphing tail. JBSE 18, 22-00340-22–00340 (2023).
2. One of the core conclusions of this paper is that the negative-lift tail configuration constitutes a superior engineering solution because it provides static stability. However, the authors also acknowledge in the Discussion that bird tails typically generate positive lift during flight. This suggests that birds—as biological prototypes—commonly operate under statically unstable conditions. Could the authors further elaborate on this discrepancy? Why have birds evolved to adopt this more challenging (statically unstable) flight mode, whereas the NPU-Sparrow design favors a safer (statically stable) configuration? Does this imply that the proposed design represents a bio-inspired engineering optimization rather than a strict biomimetic replication? The trade-offs between biological fidelity and engineering practicality merit deeper discussion.

We thank you for raising this profound and critical question. Biological studies indicate that avian tails often generate positive lift, rendering birds statically unstable or neutrally stable. This phenomenon relies on their sophisticated neuromuscular systems, which enable real-time, multi-degree-of-freedom control to harness this instability for enhanced maneuverability. However, for micro flapping-wing robot platforms like NPU-Sparrow, which face constraints in sensing, computation, and actuation, directly replicating such a statically unstable configuration would significantly increase weight and control complexity, thereby reducing engineering feasibility.Therefore, the selection of the tail configuration in this study does not negate biological principles but rather represents an optimization aimed at engineering implementation. The adoption of a negative-lift tail is intended to ensure that the platform maintains longitudinal static stability and safety during cruise flight, akin to traditional fixed-wing aircraft. Meanwhile, we have not abandoned the pursuit of high maneuverability; the key innovation lies in leveraging the potential for the reversal of aerodynamic characteristics of this tail at high angles of attack. As illustrated in the wind tunnel data presented in Fig. 4D and the flight data shown in Figs. 6D and E of the revised manuscript, during low angle of attack cruise, the negative-lift tail maintains static stability. However, during high-AoA maneuvers that require significant overload (AoA > 13°), this same tail transforms into an auxiliary lifting surface that generates positive lift. The extension of the tail further amplifies this advantage, significantly enhancing the overall maximum lift coefficient and overload capacity. This endows the NPU-Sparrow with dual flight modes: it operates stably and reliably like a fixed-wing aircraft during cruise, while also possessing the capability to extend the tail to generate auxiliary lift for high agility—similar to birds—during maneuvers. This represents an engineering optimization strategy that is more effectively aligned with the practical constraints of robotic platforms.
3. The title and abstract emphasize "energy-efficient," but the main text lacks corresponding experimental validation and quantitative analysis. he key evidence supporting this claim mainly derives from Fig. 6E, which shows a theoretical available thrust curve extrapolated from wind-tunnel data, rather than direct measurements of in-flight power consumption. To strengthen the reliability of this conclusion, the authors are advised to include real-time power data from actual flight tests comparing the conventional fixed-tail configuration and the morphing-tail configuration, to empirically demonstrate that tail retraction indeed reduces energy consumption during high-speed cruise.
We appreciate your attention and valuable suggestions. In response to your recommendation, we designed and conducted additional outdoor flight experiments to

compare the flight speed envelope and power consumption between the morphing tail configuration and the baseline model, which features a fixed tail area.As illustrated in Fig. 6B of the revised manuscript, empirical data demonstrate that at flight speeds exceeding the design cruise speed of 7 m/s, the power consumption curve of the NPU-Sparrow, which possesses tail-tucking capabilities, is significantly lower than that of the baseline model. The core mechanism underlying this phenomenon is that as airspeed increases, the robot's trim angle of attack decreases; tucking the tail effectively reduces drag, thereby decreasing the power required to maintain level flight. Furthermore, the active tail morphing capability extends the level flight speed range by 22.5% (from 4.5 to 13.2 m/s).These direct empirical flight results quantitatively validate the dual advantages of the "dynamic tail area adjustment" strategy in enhancing cruise energy efficiency and expanding the flight envelope of flapping-wing robots, providing robust support for the core conclusion regarding energy efficiency presented in the manuscript.

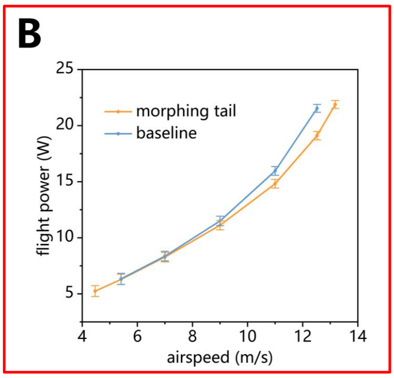


Fig.6B. Comparison of the flight speed envelope and power consumption between NPU-Sparrow with a morphing tail and the baseline model.

4. According to Fig. 5B, the positive-lift tail configuration is marked as “unstable” at both 0° and 20° angles of attack. Does this indicate that this configuration — even with the assistance of wing angle-of-attack control—cannot maintain stable flight throughout the entire flight envelope? This limitation appears critical and should be more explicitly stated and discussed in the manuscript, including whether it represents the primary reason why this configuration was ultimately discarded.

We appreciate the reviewer's insightful comments regarding this crucial issue. As illustrated in Fig. 5B of the main text, even when employing the positive-lift tail configuration with the control strategy of 'tail extension combined with decreased flapping wing incidence angle' — which theoretically provides the highest compensation capability — pitch controllability is only feasible within a limited range of angles of attack. The system's inherent pitch static instability makes it highly sensitive to external disturbances, such as the periodic aerodynamic pulsations generated by flapping. Consequently, even minor deviations can easily lead to attitude divergence.Moreover, this configuration presents an intrinsic functional contradiction: achieving the necessary pitch-up moment during high-angle-of-attack maneuvers necessitates a reduction in the tail planform area (i.e., tucking). However, this action inadvertently diminishes the essential lift contribution from the tail, which directly opposes the fundamental requirement for maneuverability: 'increasing the lifting surface area to enhance maximum overload capacity.' Therefore, we opted against the positive-lift tail configuration. This point has been explicitly stated and discussed in the revised manuscript：

> flight[3], enabling rapid changes in heading and reductions in airspeed. It is important to note that the positive-lift tail configuration exhibits longitudinal static instability. Even with a control strategy that combines tail extension and pronation, pitch control is theoretically viable only within a limited range of angles of attack. The pitch disturbances generated during flapping can easily disrupt this delicate equilibrium. Additionally, at high angles of attack, the positive-lift configuration necessitates tucking the tail (thereby reducing the area) to produce a pitch-up moment. However, this action inadvertently decreases the lifting surface area, which contradicts the requirement for enhanced high-load-factor capability in high angle-of-attack regimes. In contrast, the negative lift tail configuration provides

5. The paper notes that tail deployment leads to a significant rearward shift of the aerodynamic center, but it does not sufficiently explain how this change affects flight stability in practice, or how such movement is compensated during flight to maintain steady conditions. The authors should provide additional analysis or clarification on this point.

You have astutely identified a critical side effect that must be addressed when utilizing the tail morphing mechanism to extend the flight envelope: the significant shift of the aerodynamic center due to control actions, which consequently impacts the static stability and handling characteristics of the robot.As quantitatively illustrated by the wind tunnel data in Fig. 3D, under the control logic of "tail extension combined with an increased flapping wing incidence angle," when the tail is fully extended, the overall aerodynamic center of the NPU-Sparrow shifts aft by as much as 34.1% of the mean aerodynamic chord (MAC). This shift results in an increased static stability margin. In low-speed, high-angle-of-attack flight conditions, this inherent stability provides a fundamental safeguard for the safe execution of aggressive maneuvers such as loops.However, from a controllability standpoint, an excessive static stability margin can render the longitudinal control response "sluggish" or "heavy," thereby objectively constraining the full utilization of its agility potential. Consequently, we have included a supplementary analysis on this issue in Section 3 (Discussion section) of the revised manuscript：

However, it is important to note that the tail morphing motion induces a significant shift in the position of the aerodynamic center relative to the control input, which substantially affects the pitch stability of the robot. Wind tunnel data indicate that as the tail of NPU-Sparrow extends, the overall aerodynamic center shifts considerably aft, with a displacement reaching up to 34.1% of the mean aerodynamic chord (see Fig. 3D). This shift results in a marked increase in the static stability margin, causing the control response to become 'sluggish.' Although our control strategy employs a synergistic approach of 'tail extension combined with an increased flapping-wing incidence angle'—leveraging enhanced wing lift to partially offset the pitch-up moment requirement and improve overall high-load-factor capability—this remains a relatively inefficient compensation strategy. In contrast to birds, which can actively manage the aerodynamic center through multiple degrees of freedom, such as wing extension, sweeping, and tail depression, the NPU-Sparrow faces challenges in handling large excursions of the aerodynamic center under its current configuration. This limitation hinders the full utilization of its maneuverability and, as a result, restricts its ability to adjust its attitude under highly complex airflow conditions. We propose that the introduction of a back-and-forth wing sweeping degree of freedom, decoupled from flapping motion, could facilitate active control of the aerodynamic center without increasing the structural complexity of the wings. Concurrently, asymmetric wing sweeping actuation may offer potential for yaw control. Moreover, if the modulation of wing incidence angle and tail area variation can be decoupled, with the tail area dynamically adjusted according to flight speed, near-bird-level flight performance could be achieved at a modest engineering cost.

6. Conventional aircraft achieve smaller turning radii by increasing roll angles or elevator deflection angles. The article's claim of a "steady turning radius reduced by 18.5%" is based solely on theoretical calculations. It is recommended that the authors provide flight experiment data to enhance persuasiveness

We appreciate the reviewer's critical suggestion. In response, we have enhanced the revised manuscript by incorporating direct comparative experiments of steady turn flight between the NPU-Sparrow and the baseline model (with the tail area fixed at the median value), while also removing the theoretical prediction section.Empirical data (Fig. 6G) indicate that the steady turn radius of the NPU-Sparrow, equipped with a morphing tail, is reduced by 20.4% compared to the baseline model. This value deviates from the theoretical estimation presented in the main text, which relied on wind tunnel static lift coefficient data. We conducted a thorough analysis of the two primary reasons for this discrepancy:First, a fundamental difference exists between the theoretical model and real flight conditions. The theoretical calculation was based on static lift coefficients measured in the wind tunnel at a 15° angle of attack, without accounting for thrust trim. However, during actual steady turn flight, the lift and thrust produced by the flapping wings are highly coupled; the robot primarily generates the greater aerodynamic forces required for high overload by increasing flight speed rather than significantly increasing the angle of attack.

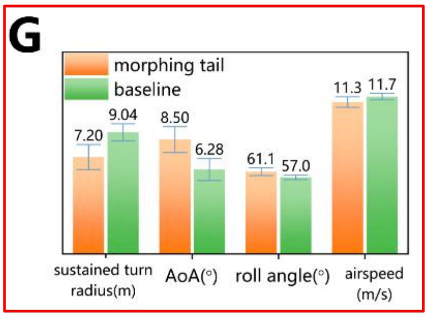


Fig.6G.Comparison of average turn radius, angle of attack, roll angle, and flight speed between NPU-Sparrow with a morphing tail and the baseline model during a complete steady turn. Error bands represent the standard deviation across data from one complete turn.

Second, and most critically, as illustrated in Fig. 6G, under similar turning speeds, the morphing tail configuration can achieve a higher trim angle of attack. This capability arises because the extended morphing tail generates a more powerful pitch-up control moment, thereby enabling the robot to attain a higher overload capacity. This point has been further elaborated upon in the discussion section of the revised manuscript：

> Compared to the baseline model, the steady turn radius of NPU-Sparrow with its morphing tail is reduced by 20.4%. Given that the turning speeds are nearly identical, this significant difference can be primarily attributed to the maneuvering AoA (Fig. 6G). At this specific AoA, the tail generates negative lift; however, the lift requirement for steady turning necessitates a pitch-up command. The extended tail provides a larger pitch-up moment than the baseline, enabling a higher load factor and consequently reducing the turn radius.

In summary, the supplemented flight experimental data strongly validate the effectiveness of the tail morphing mechanism in enhancing actual maneuvering performance. The discrepancy between theory and experiment precisely illustrates that in strongly nonlinear and coupled systems, such as flapping-wing robots, dynamic control capability is as crucial as steady-state lift characteristics. Our findings indicate that tail area variation, by simultaneously optimizing these two aspects, is key to reducing the actual turn radius and enhancing agility.

7. The paper mentions that flight control is implemented using a “simple PID algorithm.” However, the NPU-Sparrow is a highly coupled multi-input – multi-output (MIMO) system: tail area variation affects the overall aerodynamic center, while wing angle-of-attack control simultaneously influences pitch and roll. It is questionable whether a single “simple PID” controller can effectively stabilize such a complex dynamic system.

We thank the reviewer for raising this profound and critical concern. We have

undertaken several measures to ensure that a simple PID controller can effectively control the robot.First, at the control allocation level, we adopted a mixing logic similar to "elevons" in fixed-wing aircraft. The pitch and roll commands computed by the flight controller are mapped to a set of decoupled actuator commands: pitch commands simultaneously and equally drive the flapping wing incidence angles on both sides and control the tail spread angle; roll commands differentially drive the flapping wing incidence angles, thereby generating pure roll moments.Second, the negative-lift tail configuration of NPU-Sparrow provides the robot with inherent longitudinal static stability, significantly reducing the stringent requirements for control bandwidth and precision.Finally, employing a cascaded PID structure, the inner loop rapidly stabilizes angular rates while the outer loop controls attitude angles. This classical control approach has proven to be sufficient and robust within our flight envelope. The final flight experiments — including the stable execution of high-maneuverability actions—serve as direct proof of the controller's effectiveness.We fully agree that for more extreme maneuvers or complex missions, more advanced multivariable control methods may be required. However, this study validates that through meticulous aerodynamic configuration design (providing static stability) and rational control allocation (mixing logic), it is possible to reduce the complexity requirements for control algorithms, thereby achieving reliable and agile flight on micro bio-inspired platforms at a lower engineering cost. This, in itself, constitutes an important engineering insight.
Minor: 1. The arrangement and layout of subfigures in Fig. 1 could be further optimized to improve logical coherence. 2. The arrows in Fig. 3D do not clearly reflect the specific meanings of "supinating" and "pronating." Is there a clearer way to annotate them? 3. The color and shading of the curves in Fig. 4D are easily confused with those in Fig. 4A. It is suggested to improve their distinguishability.
We appreciate the reviewer's critical suggestion. Accordingly, we have rearranged the order of the panels in Fig. 1, optimized the arrow annotations in Fig. 3D and similar instances throughout the text, and adjusted the curve colors in Fig. 4D to enhance visual distinction.

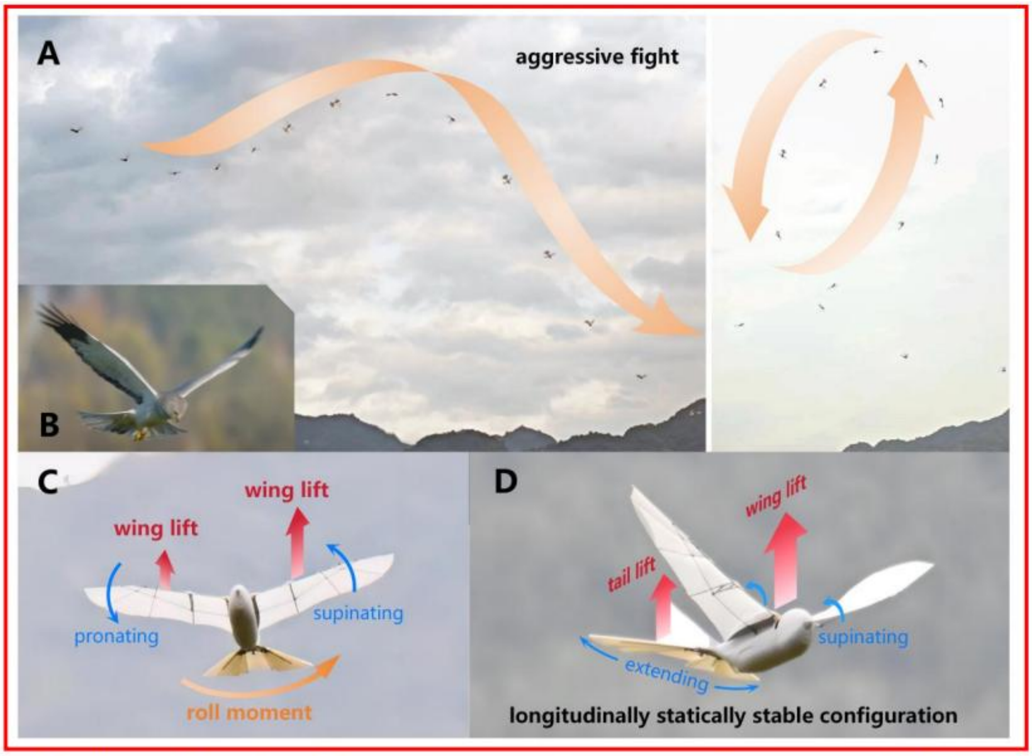


Fig. 1. Bird-inspired wing–tail morphing control strategy. A. The aggressive flight trajectories of NPU-Sparrow : the left panel illustrates a barrel roll maneuver(as shown in Supplementary Video 1), while the right panel depicts a loop maneuver(as shown in Supplementary Video 2). B. A Eurasian sparrowhawk spreads its tail during agile maneuvering. C. The NPU-Sparrow generates roll control moments through the differential control of flapping-wing incidence angles. D. The extended tail of the NPU-Sparrow produces positive lift during maneuvering flight.

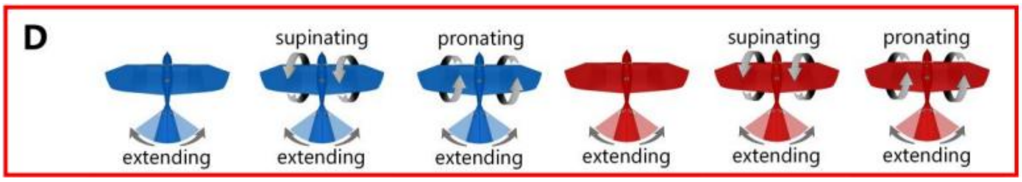


Fig. 3D

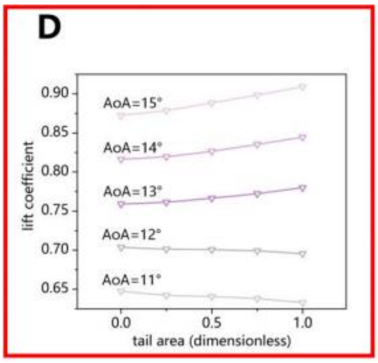


Fig. 4D

Response to Reviewer 3's comments:

-Summary：

This manuscript introduces NUS-Sparrow, a flapping-wing aerial robot featuring a morphable tail and controllable wing-pitching mechanism. The platform is claimed to decouple roll and pitch control and to allow a trade-off between agility (tail deployed) and reduced drag (tail compact). The paper provides experimental characterization (including wind-tunnel tests) and flight experiments After careful reading, I find the manuscript contains interesting engineering work and simple experimental validation, but — in its current form — it is not recommended for publication in Nature Communications. The major reasons are concerns about motivation, unquantified claims of improvement, unclear novelty relative to prior art, and issues with clarity, presentation, and missing technical details. Below I list major and minor issues for editors and authors reference.
We appreciate your meticulous review of the manuscript and the profound insights you provided. Your comments were highly constructive. In response to your core concerns, we have systematically rewritten, reorganized the structure, and enriched the content of the entire manuscript. Below is a point-by-point response to your main comments, indicating specific corresponding improvements in the revised manuscript (marked with red underlines).
-Major concerns: Motivation and Contribution: 1) The manuscript reads largely like an engineering demonstration rather than a clear conceptual advance in flapping-wing aerodynamics or control. 2) Key claimed benefits (improved agility vs. cruise efficiency trade-off) are qualitative. Important quantified comparisons (with baseline / ablated configurations and/or to representative prior works) are lack, such as A. Flight agility (measurable metrics such as maximum angular acceleration, turn rate, rise time to command, etc.). B. Cruising efficiency (flight power, power loading W/kg or g/W, and power consumption vs speed). C. Net system-level trade-offs.
We appreciate the reviewer's profound insights regarding the research motivation and contributions. We fully concur that exemplary research should transcend mere engineering implementation and must clearly articulate its core scientific questions and methodological contributions. In this revision, we have thoroughly rewritten and restructured the Introduction and Conclusion sections to distinctly highlight the core thrust of this study: instead of pursuing a

direct replication of the complex morphology and redundant control mechanisms of birds, we are committed to deeply investigating the physical principles underlying their flight and effectively reconstructing these principles through simplified methods that fulfill engineering practical requirements.Based on this philosophy, we explicitly propose the bio-inspired control configuration of "dynamic tail area adjustment combined with flapping wing incidence angle control" as the specific technical pathway. Its innovation and contribution lie in employing a low-degree-of-freedom, low-complexity engineering system (controlling only tail area and flapping wing incidence angle) to substitute for the high-degree-of-freedom wing-tail coupled morphing of birds. This achieves simultaneous pitch/roll control while dynamically modulating tail volume and wing loading. Consequently, NPU-Sparrow not only possesses a level flight speed range comparable to similarly sized passerine birds but also executes high-difficulty maneuvers such as barrel rolls and loops.

To quantitatively validate the advantages of this simplification strategy, we systematically conducted comparative experiments between NPU-Sparrow and the baseline model (with the tail area fixed at the median value), thereby transforming our conclusions from qualitative observations to data-driven assertions.

1) Regarding maneuverability: Through steady turn flight experiments, we confirmed that the morphing tail configuration of NPU-Sparrow achieves a 20.4% reduction in turn radius compared to the baseline (Fig. 6G),. This finding directly validates the effectiveness of the configuration in enhancing overload capacity and directional change capability.

2) Regarding speed envelope expansion and energy efficiency: By supplementing empirical flight speed range and power consumption curves (Fig. 6B), we provided robust evidence that, compared to the baseline, active tail morphing extends the level flight speed range by 22.5%. Simultaneously, during horizontal flight at speeds exceeding 7 m/s, NPU-Sparrow consistently exhibits lower power consumption than the baseline, benefiting from the drag reduction effect of tail tucking.

Therefore, the contribution of this study lies in proposing and demonstrating a functional bio-inspired engineering pathway grounded in a mechanistic understanding. We confirm that through the purposeful deconstruction and simplification of biological principles, it is feasible for micro flapping-wing robots to reproduce the core flight characteristics of avian broad adaptability and high maneuverability without significantly increasing system complexity. This offers a novel perspective for the future design of bio-inspired aerial robots.

Novelty and Relation to Prior Works:

Morphable tails / morphing control surfaces and their benefits have been explored in propeller-based MAVs and other small aircraft. The manuscript does not clearly explain what is genuinely new here: Is the novelty in the mechanism design, the way it is applied to a flapping-wing vehicle, a control strategy, or new aerodynamics measurements for flapping platforms?

A concise, pointed "novelty statement" in the Introduction that explicitly contrasts this work with the most relevant prior studies should be included.

Or detail the unique challenges of adapting morphable tails to flapping wings (e.g., unsteady aerodynamics, coupling with wing flapping, control latency due to low bandwidth) and show how the current design addresses them. The Introduction part should include more related reference for comparision and highlight the uniqueness and contribution of the proposed study.

We appreciate the reviewer's valuable comments regarding the novelty of our work and its relationship with prior research. In the Introduction of the revised manuscript, we have focused on enhancing this aspect to clearly articulate the novelty of our study.

Previous research utilizing fixed-wing platforms[1,2] has demonstrated that incorporating avian-inspired wing-tail morphing capabilities can effectively extend the flight envelope. However, these studies are based on platforms operating in steady airflow with separated thrust and drag, which fundamentally differs from the unsteady aerodynamics and passive flexible deformation characteristics of flapping-wing systems. Directly transplanting complex morphing mechanisms onto flapping wings would significantly compromise the aeroelastic response upon which they depend for generating lift and thrust, while also imposing unacceptable weight and inertial penalties. Meanwhile, biological observations indicate that both avian tail morphing (extension/retraction) and deflection serve critical functions in pitch control. This has been confirmed through wind tunnel experiments on bio-inspired tail models[3], which demonstrated that tail morphing is a highly efficient method for achieving pitch control.Consequently, we proposed and implemented a control configuration termed "dynamic tail area adjustment combined with flapping wing incidence angle control." The essence of this configuration is to utilize the single degree of freedom inherent in tail morphing as a substitute for the pitch control function of a traditional elevator. This approach simultaneously achieves aerodynamic effects akin to the avian dynamic modulation of tail volume and wing loading. When integrated with flapping wing incidence angle control, it effectively reconciles the conflicting performance demands of high maneuverability and high efficiency in flapping-wing robots.Through wind tunnel experiments and extensive outdoor flight tests on the NPU-Sparrow system, we have thoroughly validated the feasibility of this simplification strategy for real flapping-wing robots. This approach not only enhances cruise efficiency but also enables a flight speed range comparable to that of similarly sized birds, while retaining the capability to perform complex maneuvers such as loops and barrel rolls.The contribution of this study transcends mere imitation of biological morphology and offers a bio-inspired design paradigm of "functional reconstruction," grounded in a mechanistic understanding and aligned with engineering constraints.

Reference:

[1]. Ajanic, E., Feroskhan, M., Mintchev, S., Noca, F. & Floreano, D. Bioinspired wing and tail morphing extends drone flight capabilities. Sci. Robot. 5, eabc2897 (2020).

[2]. Ajanic, E., Feroskhan, M., Wüest, V. & Floreano, D. Sharp turning maneuvers with avian-inspired wing and tail morphing. Commun Eng 1, 34 (2022).

[3]. Murayama, Y., Nakata, T. & Liu, H. Aerodynamic performance of a bird-inspired morphing tail. JBSE 18, 22-00340-22–00340 (2023).

Readability and Quality:

The manuscript requires substantial improvement in organization and writing quality to ensure readability. Numerous issues related to language, clarity, and technical presentation make the paper difficult to follow (particularly in the Result sections). In particular, there are frequent instances of incorrect or imprecise vocabulary, inconsistent use of technical terminology, and missing definitions for important concepts and parameters. Many paragraphs lack logical flow, and the narrative often feels fragmented, making it challenging for readers to understand the authors' intended meaning. A thorough restructuring and careful rewriting are strongly recommended to meet the high standards of clarity and precision expected for Nature Communications. This includes improving logical transitions, standardizing terminology, and providing clear explanations for all key ideas, variables, and experimental procedures.

We appreciate the reviewer's meticulous comments regarding the readability and quality of the manuscript, which are crucial for enhancing the clarity and rigor of the presentation. We have conducted a systematic revision of the entire text based on your suggestions, specifically addressing the core issues you highlighted.

Structurally, we have reorganized and rewritten the Introduction and Discussion sections. We removed redundant narratives, strengthened the logical thread transitioning from biological mechanisms to engineering simplification, and deepened the discussion on research limitations and future directions, thereby improving the depth and coherence of the argumentation.

Regarding terminology and phrasing, we have implemented a comprehensive standardization. Throughout the text, we have strictly distinguished the previously misused "angle of attack" into two distinct terms: "flapping-wing/tail incidence angle" (referring to the geometric setting angle) and "robot angle of attack (AoA)" (referring to the angle between the freestream and the fuselage). All abbreviations appearing for the first time (e.g., MAC) have been explicitly defined. The "angle of attack" analyzed primarily in the text now explicitly refers to the angle of the entire robot relative to the freestream, as clearly illustrated in the revised Fig.3A.

In terms of experimental description, we have explicitly stated that the wind tunnel experiments were conducted at the design cruise speed (7 m/s). All aerodynamic data are presented as dimensionless coefficients to ensure universality and comparability of the results. Furthermore, we conducted a comprehensive check of the correspondence between figures and the main text, optimizing annotations to ensure consistency and clarity between visual representations and textual descriptions.

We believe that through these targeted revisions, the linguistic accuracy, logical flow, and academic standards of the manuscript have been significantly improved.

-Detailed Comments

1) Misuse of "angle of attack" throughout the manuscript. The authors repeatedly use "angle of attack" to describe the geometric posture or installation angle of the tail. However, angle of attack refers specifically to the angle between the incoming airflow and an airfoil, which is distinct from a body-frame installation angle. This terminology is misleading and technically incorrect.

Please replace these instances with more appropriate terms such as tail installation angle, tail pitch angle, or tail configuration angle.

For example, in Line 93, the so-called "wing angle-of-attack control mechanism" appears to adjust the wing's angle in the body frame, not its aerodynamic angle of attack (which is not measured).

Similarly, in Line 97, the meaning of "13°" is unclear—this seems to refer to the vehicle pitch angle rather than an angle of attack. Please clarify.

We appreciate the reviewer for highlighting the critical issue regarding the inaccurate use of terminology in the manuscript. In the revised manuscript, we have uniformly corrected the previously misused term "flapping wing angle of attack control" to "flapping wing incidence angle control" to accurately describe the geometric angular adjustment of the flapping wings relative to the fuselage reference. In addition to this correction, all other mentions of "angle of attack" in the text refer to the robot angle of attack (AoA)—defined as the angle between the entire robot and the freestream — as illustrated in Fig. 3A. For instance, in the statement "the tail generates positive lift when the angle of attack exceeds 13°," the "13°" refers to the robot's angle of attack relative to the freestream. We apologize for the previous lack of rigor in our expression and have standardized the terminology throughout the revised manuscript.

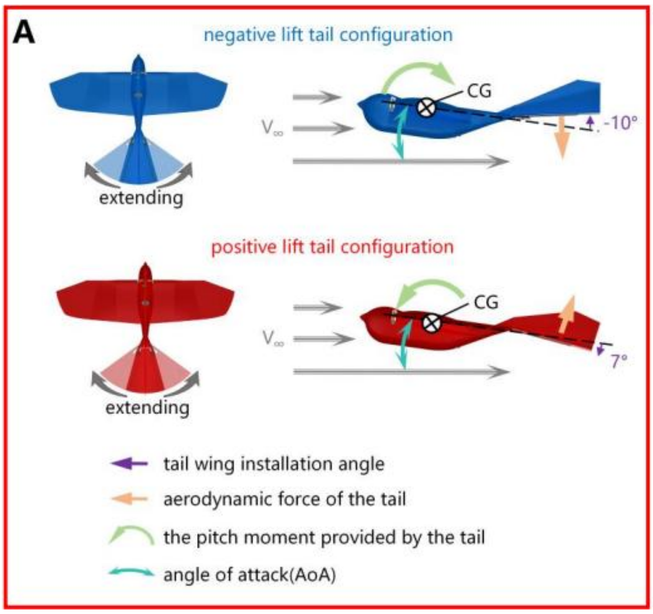


Fig. 3A. The installation angles of the tail for different configurations are as follows: -10° for the negative lift tail, which generates a nose-up moment as the tail extends, and +7° for the positive lift tail, which generates a nose-down moment upon extension.

2) It is not evident what information Figure 2C is intended to convey or how it contributes to the main text. A clearer explanation or justification for its inclusion is needed.

We appreciate the reviewer's meticulous attention to the details presented in the figures. Figure 2C aims to illustrate the specific bio-inspired tail feather structure employed by NPU-Sparrow, which is constructed by bonding a carbon fiber shaft to an expanded polyethylene foam sheet. This composite structure ensures the lightweight nature of the tail feathers.More importantly, the carbon fiber shaft serves as the kinematic linkage for the tail morphing actuation mechanism in this design, a point we have emphasized in the revised manuscript. It acts as the core mechanical component responsible for achieving precise and reliable morphing functions. Therefore, illustrating these structural details is crucial for a comprehensive understanding of the entire bio-inspired morphing tail design.

3) Line 121: unclear biological reference and naming rationale. The authors cite morphometric data of Oriolus oriolus to justify a wingspan of 0.45 m. The relevance of this species to the design is not explained. Furthermore, if the design is based on Oriolus, why is the robot named “NPU-Sparrow” instead of a name tied to Oriolus? This is confusing and should be clarified.

We thank the reviewer for the inquiry regarding the naming convention and the biological reference basis. In the revised manuscript, we have provided supplementary explanations. This study aims to develop a flapping-wing robot that combines agile flight capabilities with efficient cruising performance. Consequently, we selected passerine birds—known for their exceptional maneuverability and long-distance migratory abilities—as the reference model for bio-inspired performance. The nomenclature 'NPU-Sparrow' is derived from this category of biomimetic prototypes. The robot's key morphological parameters (weight: 90 g, wingspan: 0.45 m) and design cruise speed (7 m/s) were chosen based on the statistical range of morphological data from various medium-sized passerines (e.g., orioles, thrushes, and starlings) (please refer to the newly added Table 1). Experimental flight results indicate that, facilitated by active tail morphing, the level flight speed range of the NPU-Sparrow (4.5–13.2 m/s) is comparable to that of similarly sized passerines (e.g., the European Starling, which ranges from 6 to 14 m/s). This demonstrates that our design effectively approximates the biological prototype in terms of critical kinematic performance.

Table 1. Morphological and flight data of medium-sized passerine birds and NPU-Sparrow.[1–5]

	Oriolus chinensis	Turdus viscivorus	Sturnus vulgaris	NPU-Sparrow
weight (g)	46.2-104	83-140	75-100	90
Wingspan (m)	0.44-0.47	0.42-0.48	0.31-0.415	0.45
Theoretical minimum-power flight speed (m/s)	6.8	7.1	6.8	

Reference:

[1]. Farner, D. S. Dimensional Relationships for Flying Animals. *Auk* **78**, 653–654 (1961).

[2]. Dimaki, M., Alivizatos, H. & Kokkini, P. Ringing studies of the Golden Oriole Oriolus oriolus (Aves: Oriolidae) during passage through Antikythira Island, southwestern Greece. *Ringing & Migration* **34**, 113–119 (2019).

[3]. Jr, J. B. D. CRC Handbook of Avian Body Masses.

[4]. Blem, C. R. Geographic Variation in Mid-Winter Body Composition of Starlings. *The Condor* **83**, 370 (1981).

[5]. Bruderer, B. & Boldt, A. Flight characteristics of birds: *Ibis* **143**, 178–204 (2001).

4) Lines 139–140 lack clarity. The meaning of this sentence is difficult to follow. It should be rewritten for clarity and logical flow.

We appreciate the reviewer's suggestion. We have rewritten this sentence in the revised manuscript:

> derived from the design standards of conventional fixed-wing aircraft[18] (Fig. 2B,D). To ensure yaw stability, NPU-Sparrow utilizes a conventional vertical stabilizer. The area of this stabilizer was determined using the tail volume method, resulting in a coefficient of 0.15, which is consistent with the design standards of traditional fixed-wing aircraft.

5)Line 164, Eq. (1) appears unnecessary. Equation (1) does not seem to play a role in the subsequent analysis or discussion of flight stability. Unless it directly supports later derivations, it may be unnecessary.

We appreciate the reviewer's valuable suggestion. In accordance with your advice, we have removed Equation (1) and its associated redundant discussion from the revised manuscript. This modification enhances the overall presentation by making it more concise and focused, thereby eliminating potential distractions from non-essential content and strengthening the core argumentation.

6)Line 168: wind tunnel setup unclear and overly complex description. A figure illustrating the wind-tunnel experimental setup and vehicle mounting would greatly improve clarity. The text in Lines 168–171 is overly dense and difficult to follow. It is also unclear how the authors determined the two installation angles of 7° and −10°. Please explain the selection process and provide supporting data.

We appreciate the reviewer's critical suggestion. In Figure 3A of the revised manuscript, we have explicitly labeled the angle of attack (AoA) for both positive- and negative-lift tail configurations. All references to "angle of attack" in the text pertain to the robot AoA, which is defined as the angle between the robot's longitudinal axis and the freestream direction; this definition is consistently applied across both wind tunnel and flight experiments. Furthermore, we have provided a clearer explanation of the method used to determine the tail incidence angle:

> To facilitate subsequent comparative analyses, the tail incidence angles were determined based on wind tunnel results. The criterion was to achieve equivalent total lift for both configurations at a entire vehicle angle of attack (AoA) of 10°, with the tail positioned at its median planform area. At an AoA of 10°, the lift generated by the wing-body assembly is 93.8g (Fig. 3B), while the lift contributions from the tail in both configurations are nearly identical in magnitude. The distinction lies in their directionality: in the positive-lift configuration, the tail lift aligns with the flapping wing lift, whereas in the negative-lift configuration, it opposes the flapping wing lift. Consequently, the installation

7)Line 178: MAC undefined and paragraph structure problematic. The term “MAC” is introduced without definition (it should be explained at the first time it appears). The paragraph consists of only three long, complex sentences that are difficult to read. Breaking them into shorter, clearer statements is recommended.

We appreciate the reviewer's suggestion. We apologize for any confusion caused by the imprecise phrasing in the original manuscript and have corrected these expressions in the revised text:

> During the tail morphing process, the influence on the center of gravity (CG) of NPU-Sparrow is negligible. At the median tail planform area, the aerodynamic center locations for both tail configurations are identical. The primary distinction lies in the pitching moment generated at the aerodynamic center: the positive-lift configuration exhibits a negative moment (i.e., zero-lift moment < 0, see Fig. 3C), necessitating a trim CG position aft of the aerodynamic center. This results in a state of longitudinal static instability, with the trim CG calculated at 1.12 MAC (Mean Aerodynamic Chord) from the wing leading edge. Conversely, the negative-lift configuration exhibits a positive zero-lift moment, requiring the trim CG to be positioned forward of the aerodynamic center, thereby imparting longitudinal static stability; the corresponding trim CG is calculated at 0.21 MAC.

8)Line 199: unclear origin of numerical values. The values 17.3 and 17.5 are introduced without explanation. Are these measured values or results from calculation? Please specify the method and context.

We appreciate the reviewer's concerns regarding the values of the neutral point aft shift illustrated in Fig. 3D, which are 17.3% and 17.5% of the Mean Aerodynamic Chord (MAC) for positive- and negative-lift tail configurations, respectively, under pure tail extension control logic. These values are derived from the wind tunnel experimental results conducted on the robot. We determined the neutral point position by measuring the slope of the pitching moment coefficient relative to the lift coefficient ($\frac{dC_m}{dC_l}$) across different tail area states. This slope effectively represents the ratio of the distance between the neutral point and the reference point to the MAC. Consequently, the aft shift depicted in the figure is a result that is quantitatively derived from actual aerodynamic data, reflecting the influence of tail area variation on the overall aerodynamic center of the body.

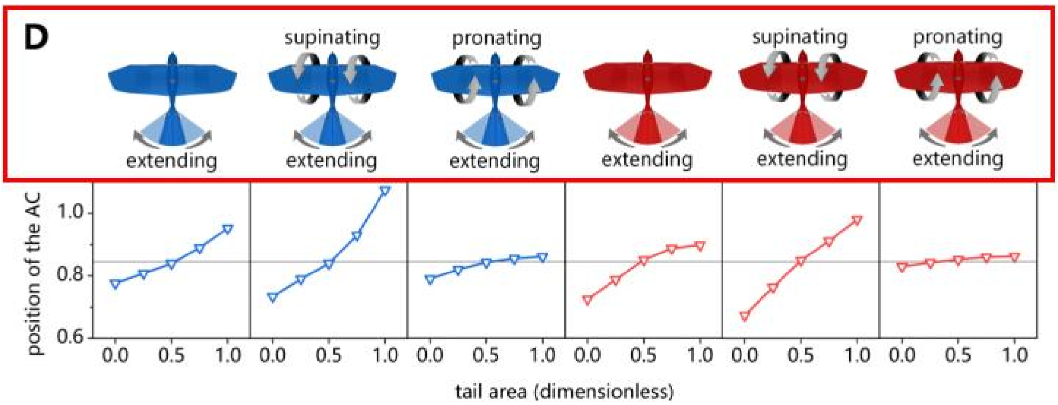


Fig. 3D. This section discusses the variation of the aerodynamic center (normalized focal position) with dimensionless tail area across six control strategies. The focal position is defined as the distance from the leading edge of the flapping wing to the aerodynamic center, normalized by the mean aerodynamic chord. A dimensionless tail area of 1 represents a fully extended tail, while a value of 0 indicates a fully retracted tail.

9) Line 301: negative-lift tail raises contradictions in cruise-power claims. The optimized configuration appears to require the tail to generate negative lift, which increases takeoff weight burden and reduces net aerodynamic lift. Under such conditions, it is unclear how tail morphing directly reduces cruise power consumption.

A more appropriate interpretation may be that morphing helps mitigate additional drag induced by the tail, rather than reducing the absolute cruise power requirement. The text should be revised accordingly.

We appreciate the reviewer for highlighting this critical issue. We fully understand your concern: the negative-lift tail configuration generates negative lift for the entire robot during the cruise state (robot AoA<13°). If the tail area were fixed, this adverse effect would become increasingly pronounced as flight speed increases and the trim AoA decreases.As you have insightfully noted, the core advantage of this design lies precisely in the variability of the tail area: as speed increases and trim AoA decreases, the NPU-Sparrow actively tucks the tail to reduce its planform area, thereby significantly mitigating the associated parasitic drag. This has been validated by the supplementary comparative flight power consumption experiments (Fig. 6B) in the revised manuscript, which demonstrate that at identical speeds, the power consumption of the morphing tail configuration is lower than that of the fixed-area baseline model.Therefore, we have incorporated your feedback and refined the relevant expressions in the revised manuscript: the core value of the tail morphing mechanism lies in optimizing drag characteristics through area modulation, thereby effectively extending the flight speed envelope. Specifically, in the revised manuscript, we have adjusted the phrasing from '**Tail morphing reduces cruise power consumption**' to '**Tail morphing reduces drag and extends flight speed envelope**.' We thank you for your rigorous and valuable comments, which have helped us articulate the aerodynamic benefits inherent in this design more precisely.

10) Section 2.5 lacks quantitative analysis of tail-induced power cost. The manuscript does not provide sufficient information on how the tail configuration (installation angle, area) affects total power consumption during cruise flight. A quantitative analysis of the tail's aerodynamic and energetic impact is recommended.

We thank the reviewer for their valuable comments. In response to the request for a quantitative analysis of the impact of tail morphing on flight power consumption, we have systematically supplemented the revised manuscript with empirical power consumption data for the NPU-Sparrow at various flight speeds.Given the inherent characteristics of flapping wings, where thrust and drag are difficult to decouple, wind tunnel experiments cannot quantitatively analyze the influence of tail morphing on flight power consumption. Therefore, this study employs empirical flight data from the NPU-Sparrow robot to demonstrate the advantages of the morphing tail.

We compared the power consumption performance of the NPU-Sparrow robot against a baseline model across different flight speeds. The baseline model maintained its tail area at a median fixed value and did not participate in pitch control, while all other parameter settings remained consistent. Automated flight tests were conducted via the flight controller to capture power consumption data under various conditions.The results indicate that the flight speed range of the morphing tail configuration is expanded by 22.5% compared to the baseline, reaching 4.5–13.2 m/s (Fig. 6B). In reference to European starlings of similar takeoff weight, which exhibit a level flight speed range of 6 – 14 m/s[1] and a takeoff speed of approximately 4.1–4.2 m/s[2], the NPU-Sparrow has effectively attained a level flight speed range comparable to similarly sized passerine birds.Furthermore, at flight speeds exceeding 7 m/s, the power consumption of the morphing tail configuration is significantly lower than that of the baseline (Fig. 6B). This reduction is attributed to the decrease in the required trim angle of attack (AoA) necessary for maintaining level flight at these speeds; compared to the baseline, the morphing tail can tuck to reduce its planform area (Fig. 6C), thereby achieving relatively lower flight drag.

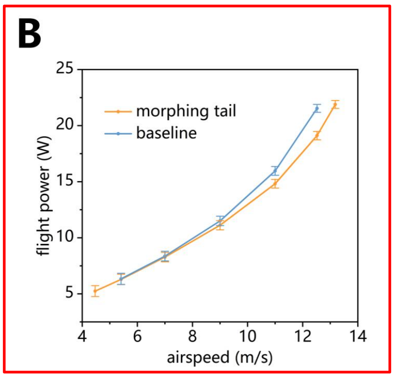


Fig.6B. Comparison of the flight speed envelope and power consumption between NPU-Sparrow with a morphing tail and the baseline model.

Reference:

[1]. Ward, S. *et al.* Metabolic power of European starlings *Sturnus vulgaris* during flight in a wind tunnel, estimated from heat transfer modelling, doubly labelled water and mask respirometry. *Journal of Experimental Biology* **207**, 4291–4298 (2004).

[2]. O'Hagan, D., Andrews, C. P., Bedford, T., Bateson, M. & Nettle, D. Early life disadvantage strengthens flight performance trade-offs in European starlings, Sturnus vulgaris. *Animal Behaviour* **102**, 141–148 (2015).

11) Line 315 and Section 2.6: missing experimental setup and unclear cross-referencing. Section 2.6 should clearly describe the experimental measurement setup — sensor types,

sampling rate, data processing, and how each plotted quantity was obtained. (Please also give direct reference if those information are provided in future sections) The analysis and conclusions should be directly tied to Figure 6 through explicit cross-references. For instance, Line 321 refers to "horizontal accelerations (Fig. 6A)," yet Figure 6A shows only trajectory and speed. Reviewers and readers expect clear, direct correspondence between text and figures.
We appreciate the valuable comments provided by the reviewers. In the revised manuscript, we have addressed the previously missing cross-references and have enhanced the details of the relevant figures for clarity and comprehensiveness.Specific details regarding the flight experiment setup, including sensor configuration and data acquisition, have been thoroughly described in Section 4.3 ('Flight Experiment Setup') of the main text. This ensures clarity and traceability of the cross-references.
12) Lines 350–360 appear misplaced. This paragraph reiterates the rationale for using a negative-lift tail, which has already been addressed earlier. It does not connect logically to the flight experiments and seems out of place in this section.
We appreciate the reviewer's suggestion. In the revised manuscript, we have removed the paragraphs you identified as lacking logical coherence with the surrounding text and containing redundant content. This modification renders the overall argumentation more focused and streamlined.
13) Flight experiments lack direct evidence supporting claimed trade-off. The Introduction claims a trade-off between agility and cruising power consumption, but the flight experiments do not provide direct quantitative evidence for this claim. Measuring total power consumption under different flight speeds and tail configurations should be straightforward and is essential to support the central contribution. The whole flight experiment section need insightful analysis and conclusion.
We appreciate the reviewer's important suggestion regarding the power consumption measurement section. As detailed in our response to Comment (10), we fully recognize the necessity of providing direct experimental evidence. In the revised manuscript, we have systematically supplemented critical empirical flight data and included a discussion concerning the experimental section as follows.

Outdoor flight experiments validate NPU-Sparrow's wide speed envelope and high maneuverability in real-world environments, providing robust evidence for the design philosophy of 'dynamic tail area adjustment combined with flapping wing incidence angle control.' The results indicate that the negative-lift tail configuration not only ensures cruise stability but also transitions into a positive lifting surface during high-load-factor maneuvers, effectively reducing wing loading and turn radius. This demonstrates that the trade-off between cruise and maneuvering flight can be effectively balanced through the synergy of tail area morphing and flapping wing incidence angle control, without the need for complex biological replication. The flight tests of NPU-Sparrow confirm that this engineering simplification strategy, grounded in aerodynamic mechanisms, represents an ideal pathway toward efficient bio-inspired flight.

14) Section 3 (Discussion) lacks depth and appropriate structure. The current Discussion reads largely as a short Conclusion rather than a true discussion. It should include more information like what is the unique advantage and limitation of the current design. How does this work inpire future directions.

We appreciate the reviewer's profound insights. In accordance with your suggestions, we have performed a thorough rewrite of the Discussion section. The revised section is now presented in Section 3 of the manuscript (marked with red underlines). It not only summarizes the core findings but also delves into the unique advantages and inherent limitations of this design paradigm, the engineering rationality behind the strategic deviations from biological prototypes, and clearly outlines future research directions, such as introducing active neutral point control. This revision has significantly enhanced the depth and structure of the discussion, ensuring it meets the analytical and forward-looking standards expected of a 'Discussion' section. The revised Discussion section is presented below:

3.DISCUSSION

Inspired by the avian ability to synergize tail and wing morphing for balancing efficient cruising with agile maneuvering, we developed the NPU-Sparrow micro flapping-wing robot. This project explores a bio-inspired design pathway that transitions from biological structural mimicry to engineering mechanism-based simplification. Departing from the redundant control inherent in the highly complex avian musculoskeletal system, this robot employs a novel control configuration. It utilizes a unique linkage mechanism to modulate the tail planform area for pitch control, combined with a flapping wing incidence angle control mechanism to achieve both pitch and roll authority. The negative-lift tail configuration ensures longitudinal static stability while providing effective pitch control moments and auxiliary lift. This underactuated design strategy does not compromise core performance;

experimental results demonstrate that the robot achieves a flight speed envelope comparable to similarly sized birds (4.5 to 13.2 m/s) and successfully executes demanding maneuvers such as loops and barrel rolls. This confirms that at the bird scale, 'mechanism-based simplification'—rather than 'morphology-based full replication'—can equally reproduce the superior flight envelope characteristics of birds.

Although biological observations indicate that avian tails often generate positive lift for weight support during cruising and high-load-factor conditions during maneuvering, directly mimicking this feature may subject the robot to significant longitudinal static instability. The negative-lift tail configuration adopted by NPU-Sparrow ingeniously resolves the conflict between stability and maneuverability. During low-angle-of-attack cruise, the negative-lift tail ensures longitudinal static stability and provides the necessary trim moment. Conversely, during high-angle-of-attack (>13°) maneuvering flight, as the tail extends, its aerodynamic role reverses, transitioning to generate positive lift aligned with the flapping wings. This mechanism ensures that during high-load-factor maneuvers, the extended tail is no longer a payload burden but transforms into a substantial auxiliary lifting surface, significantly reducing wing loading and the steady turn radius. While this design represents a morphological deviation from the conventional avian state, it constitutes a superior engineering solution that captures the evolutionary advantage of avian dynamic tail lift modulation in terms of functional logic.

However, it is important to note that the tail morphing motion induces a significant shift in the position of the aerodynamic center relative to the control input, which substantially affects the pitch stability of the robot. Wind tunnel data indicate that as the tail of NPU-Sparrow extends, the overall aerodynamic center shifts considerably aft, with a displacement reaching up to 34.1% of the mean aerodynamic chord (see Fig. 3D). This shift results in a marked increase in the static stability margin, causing the control response to become 'sluggish.' Although our control strategy employs a synergistic approach of 'tail extension combined with an increased flapping wing incidence angle'—leveraging enhanced wing lift to partially offset the pitch-up moment requirement and improve overall high-load-factor capability—this remains a relatively inefficient compensation strategy. In contrast to birds, which can actively manage the aerodynamic center through multiple degrees of freedom, such as wing extension, sweeping, and tail depression, the NPU-Sparrow faces challenges in handling large excursions of the aerodynamic center under its current configuration. This limitation hinders the full utilization of its maneuverability and, as a result, restricts its ability to adjust its attitude under highly complex airflow conditions. We propose that the introduction of a back-and-forth wing sweeping degree of freedom, decoupled from flapping motion, could facilitate active control of the aerodynamic center without increasing the structural complexity of the wings. Concurrently, asymmetric wing sweeping actuation may offer potential for yaw control. Moreover, if the modulation of wing incidence angle and tail area variation can be decoupled, with the tail area dynamically adjusted according to flight speed, near-bird-level flight performance could be achieved at a modest engineering cost.

Despite the existing performance gap between NPU-Sparrow and the passerine birds it emulates, this study confirms that a significant expansion of the flight envelope can be achieved solely through the manipulation of tail planform area and flapping wing incidence angle. This validates the considerable potential of the 'engineering simplification' strategy in bio-inspired design. This research not only provides a solution characterized by lower engineering costs and superior efficacy under current technological constraints but also establishes a physical model for elucidating the multiple aerodynamic functions of avian tails. It suggests that the design of bio-inspired aerial robots should extend beyond mere imitation of biological anatomical structures; rather, it should emphasize a thorough investigation of the physical principles underlying biological flight and the effective reconstruction of these principles through simplified methods that align with engineering practical requirements. In the current technological landscape, this simplification design paradigm, rooted in a mechanistic understanding, undoubtedly presents a more valuable engineering pathway for the future development of high-performance, cost-effective bio-inspired flapping-wing robots.

Comments on Figures

15)Figure 1:

Panels C and D do not appear to be referenced or discussed in the main text. If these subfigures are not essential to the scientific narrative, it is recommended to remove them to avoid unnecessary distraction.

We appreciate the reviewer's comment. In response to the suggestions from Reviewer 2, we have rearranged the order of the panels in Figure 1 in the revised manuscript. The original Figures 1C and 1D are now presented as Figures 1B and 1C, respectively.Specifically, Figure 1B illustrates the biological prototype, demonstrating how birds actively spread their wings and tails, coordinated with tail deflection, to modify aerodynamic moments during maneuvering flight, such as landing or low-speed flight. Figure 1C correspondingly elucidates how the NPU-Sparrow generates roll moments through differential flapping wing incidence angles. Both figures have been explicitly cited and elaborated upon in the main text of the revised manuscript.

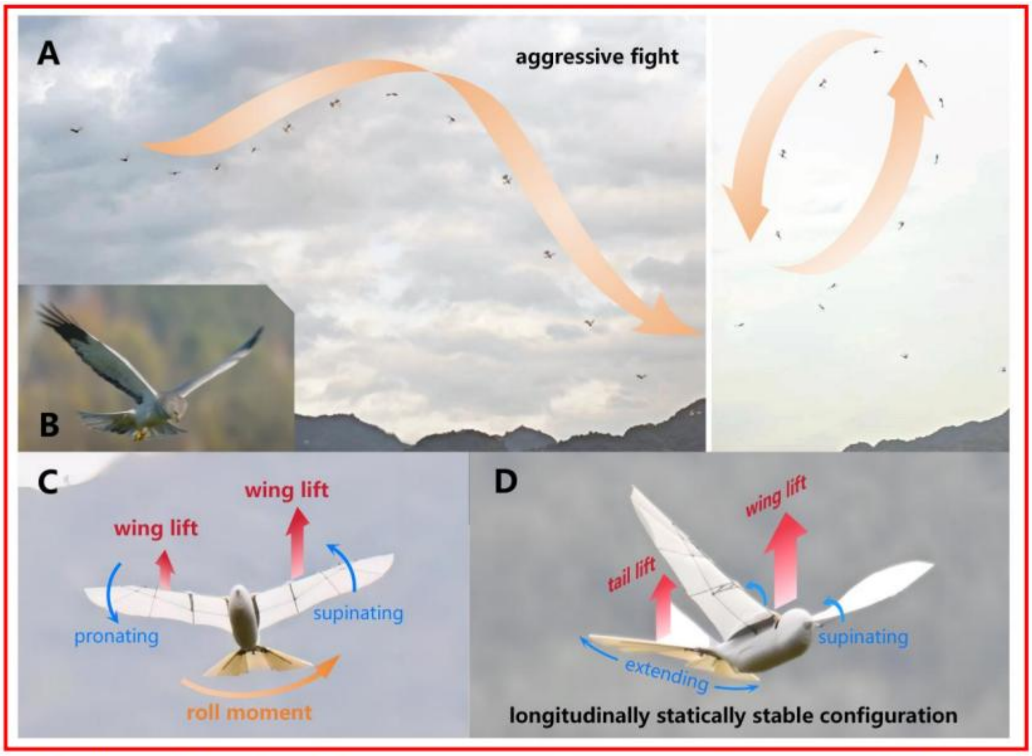


Fig. 1. Bird-inspired wing–tail morphing control strategy. A. The aggressive flight trajectories of NPU-Sparrow : the left panel illustrates a barrel roll maneuver(as shown in Supplementary Video 1), while the right panel depicts a loop maneuver(as shown in Supplementary Video 2). B. A Eurasian sparrowhawk spreads its tail during agile maneuvering. C. The NPU-Sparrow generates roll control moments through the differential control of flapping-wing incidence angles. D. The extended tail of the NPU-Sparrow produces positive lift during maneuvering flight.

16)Figure 3:

Additional clarification is required for Panel B and C. For example:

- What does the x-axis represent? Is it the “angle of attack” of the vehicle or of the tail?

- What does the y-axis represent? Is it the lift generated by the tail alone, or the total lift of the whole vehicle?

- What is the wind speed used in the test?

- Please clearly define the “lift coefficient.” Is it the conventional Cl defined same as in Blade element thoery?

- Does this Cl correspond to the tail or the entire vehicle?

- Why was 20° chosen as the maximum testing angle? Is this related to the expected stall angle of the tail? If so, this should be explained.

We appreciate the reviewer's inquiry and have provided supplementary explanations regarding this information in the revised manuscript.The horizontal axis of Fig. 3B represents the robot's angle of attack (AoA), as defined in Fig. 3A, while the vertical axis illustrates the lift measured during wind tunnel experiments. Specifically, the black curve depicts the lift of the wing-body combination, whereas the red and blue curves represent the total lift associated with the positive- and negative-lift tail configurations, respectively.The lift coefficients (C_l) and pitching moment (C_M) coefficients shown in Fig. 3C are dimensionless parameters for the entire robot, calculated using the following equations:

$$C_l = \frac{l}{qs} \quad , \quad C_M = \frac{M}{qsc}$$

Where l denotes the lift of the entire vehicle, M represents the pitching moment of the entire vehicle, q is the dynamic pressure, s is the flapping wing area, and c is the mean aerodynamic chord.

All wind tunnel experiments were conducted at a wind speed of 7 m/s, which aligns with the robot's designed cruise speed; this information has been specified in the Materials and Methods section (Section 4.2). As indicated in the revised manuscript, all references to "angle of attack" pertain to the whole vehicle AoA.

The maximum experimental AoA was set at 20°, as the range of 0° to 20° is sufficient to comprehensively elucidate the variation laws of static stability, control effectiveness, and lift characteristics concerning AoA, which are central to this study. Although the actual stall AoA of the flapping wings and the tail (located in the wake) may be higher, this range is adequate to support the core analysis and conclusions of this paper.

17)Figure 6:

Several issues require clarification and correction:

- The meaning of "overload" in Panel B is unclear. Is it equivalent to the load factor?

- Is the "angle of attack" in this figure identical to the measured pitch angle? Why is there a consistent error between the pitch command and the measured angle of attack?

- In Panel B, the second and third plots contain three legends but four curves, which must be corrected or better clarified.

- Panel C is never referenced in the manuscript. If it does not contribute to the analysis, consider removing it.

- Panel D contains a line that is not explained in the legend. This needs clarification.

- Panel D shows that when the tail becomes smaller, the airspeed increases while the angle of attack decreases. This raises several concerns: How does the altitude change during this period? A decreasing angle of attack should lead to reduced lift. Is additional wing pitching angle applied to compensate for lift loss? Does the total power consumption increase when the wing angle changes to maintain flight equilibrium?

None of these questions are addressed in the current manuscript and must be clarified. - Panel E lacks sufficient organization, description, and explanation. A detailed interpretation should accompany the figure, including how the plotted data were measured and how they support the claims in the text.
We appreciate the reviewer's meticulous queries. We have comprehensively revised and clarified the content related to Fig. 6 in the revised manuscript: Regarding Revised Fig. 6E (corresponding to original Fig. 6B): While the term "overload" is indeed physically equivalent to "load factor," we acknowledge that using "overload" to describe the ratio of lift to gravitational weight is non-standard. Therefore, we have unified the terminology to the professional term "load factor" throughout the manuscript. Distinction between "Angle of Attack" and "Pitch Command": In Revised Fig. 6E, "pitch cm" refers to the control command issued by the human pilot. During the steady turn maneuver, this command was maintained at maximum pitch-up (-1.0), while the actual angle of attack reflects the trim limit under this condition. The 13° Reference Line in Fig. 6E: The 13° AoA reference line (gray line) is utilized to visually indicate the boundary where the tail transitions between generating positive and negative lift. This annotation has been elucidated in the figure legend.The 13° Reference Line in Revised Fig. 6C (corresponding to original Fig. 6D): This line serves the same purpose. This figure illustrates the level flight acceleration process: as airspeed increases and dynamic pressure rises, the required trim AoA for the robot decreases. Consequently, the tail tucks synchronously, and the flapping wing incidence angle adjusts accordingly (see Fig. 6B). The power consumption required for this process increases with speed. Revised Fig. 6E (corresponding to original Fig. 6C): This panel displays the time history of roll control and has been referenced in the main text's analysis concerning roll agility. Revised Fig. 6A (corresponding to the original Fig. 6E) presents empirical data obtained from wind tunnel experiments conducted at a wind speed of 7 m/s and a flapping frequency of 8 Hz. This panel illustrates the curves of lift and thrust coefficients for the negative-lift tail configuration across various spread areas. Reference lines are included to indicate the lift necessary to counteract gravity and the zero-thrust point.

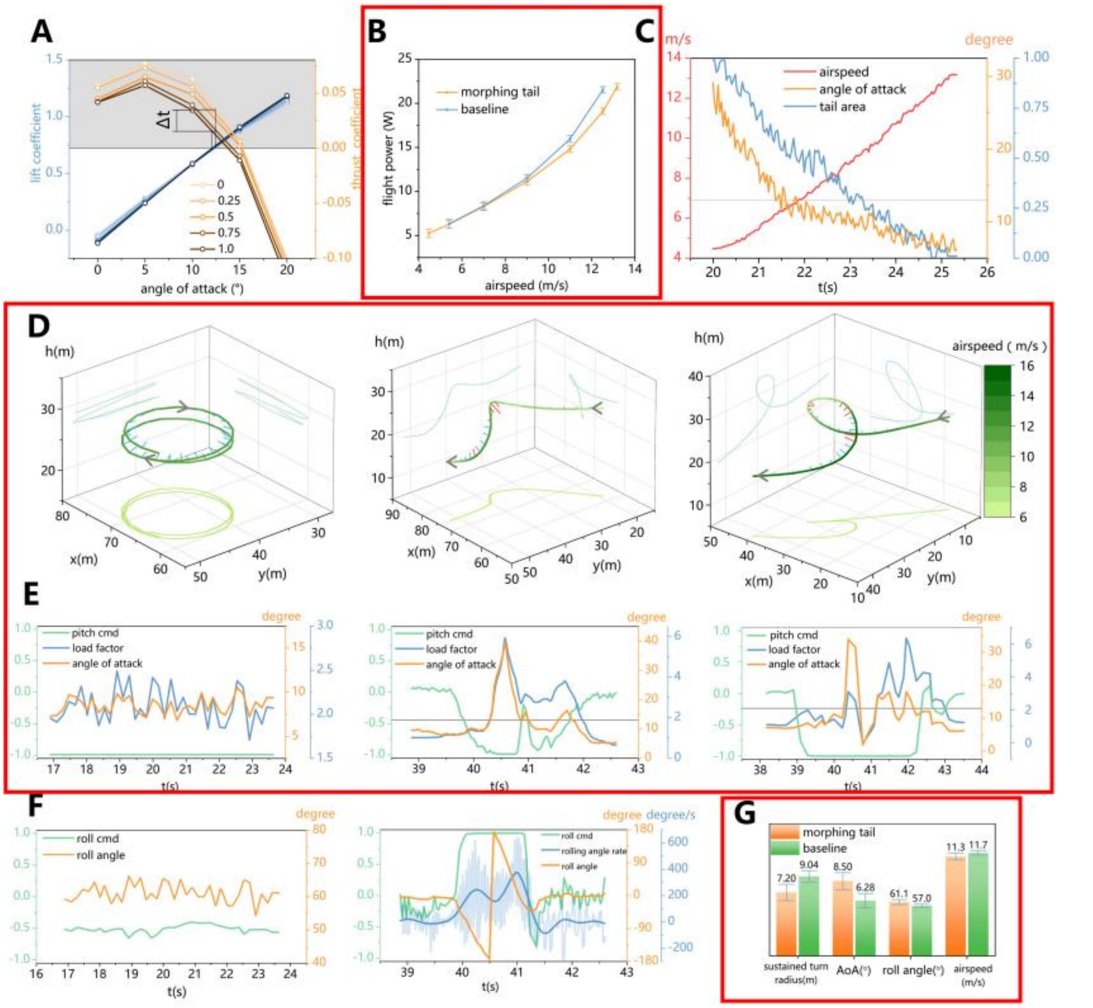


Figure 6 Outdoor flight experiment of NPU-Sparrow. A. The relationship between wind tunnel measured lift and thrust coefficients versus angle of attack under various tail areas at a fixed flapping frequency (8Hz) in the negative lift tail configuration is examined. Reference lines indicate the lift r equired for weight support and the thrust balance point (zero net force). Δt represents the thrust difference between maximum and minimum tail area configurations necessary for level flight. B. Comparison of the flight speed envelope and power consumption between NPU-Sparrow with a morphing tail and the baseline model. C. The time series of airspeed, angle of attack, and tail area during horizontal acceleration is illustrated. The horizontal reference line indicates an AoA of 13°, above which the tail generates positive lift. D. The spatial trajectories of steady turn, barrel roll, and loops maneuvers are depicted from left to right. The trajectory colors indicate airspeed, while the length of the perpendicular short bars signifies the instantaneous load factor. Red segments denote periods during which the tail generates positive lift. E. The time series of pitch command, load factor, and angle of attack during aggressive maneuvers are presented. The term "Pitch cmd" refers to the pilot input normalized to the maximum allowable command (positive values indicate nose-up, while negative values indicate nose-down). The horizontal reference line marks an AoA of 13°; values exceeding this threshold indicate that the tail generates positive lift. F. A time series of roll command, roll angle, and roll rate is shown. "Roll cmd" indicates the pilot input normalized to the maximum allowable command (positive values correspond to right roll, while negative values correspond to left roll). Both raw (light blue) and 1 Hz low-pass filtered roll rate signals (dark blue) are displayed for the barrel roll maneuver. G.Comparison of average turn radius, angle of attack, roll angle, and flight speed between NPU-Sparrow with a morphing tail and the baseline model during a complete steady turn. Error bars represent

the standard deviation across data from one complete turn.

Responses to the Reviewers' Comments on the Manuscript

ID NCOMMS-25-70548

Dear reviewers,

On behalf of my co-authors, we sincerely thank you for giving us the opportunity to revise our manuscript. We are very grateful to the editor and reviewers for their positive and constructive comments and suggestions on our manuscript entitled **"Avian-inspired tail morphing enables balanced energy-efficient and agile flight for a flapping robot" (ID NCOMMS-25-70548)**. We have carefully studied all the comments and recognize that, although the previous version had improved the structural implementation of the robot and the presentation of the flight experiments, further strengthening was still needed in terms of the theoretical framework, design principles, definition of novelty, figure organization and terminology accuracy. In response to these issues, we have mainly completed the following revisions in this round:

1. We clarified the central question and contribution of this work. We have further defined the focus of this study as how a micro flapping-wing robot can simultaneously balance cruise efficiency, longitudinal static stability and maneuvering capability under low structural complexity and limited actuation degrees of freedom. Accordingly, in the revised manuscript, cruise efficiency and maneuvering capability are reformulated as quantifiable design objectives. We also explicitly state that the central contribution of this work is not simply the implementation of a flapping-wing robot with a morphing tail, but the proposal and validation of a model-guided, low-degree-of-freedom wing–tail coordinated design framework.

2. We added and strengthened the predictive aerodynamic model and parametric design analysis. Based on this framework, the revised manuscript constructs a cruise–maneuver Pareto design map to explain the design rationale of the negative-installation-angle tail configuration and the wing–tail coordinated control logic.

3. We reorganized the experimental validation and highlighted the key aerodynamic mechanism. We have reorganized the wind tunnel and flight-test results so that they no longer serve only as performance demonstrations, but instead validate the model predictions. This revision further clarifies the aerodynamic role-transition mechanism of the negative-installation-angle tail across different flight states.

4. We added systematic performance comparisons. We compared the experimental results of NPU-Sparrow with the trends predicted by the model, and further compared its Cost of Transport, maximum load factor and flight speed envelope with those of similarly

sized birds, existing flapping-wing robots and avian-inspired morphing aerial robots. These comparisons provide a more comprehensive demonstration of the effectiveness and performance advantages of the proposed design framework.

5. We improved figure organization, figure quality and terminology. We added a new Fig. 3 to present the predictive model and Pareto design map, integrated the original experimental-result figures into the new Figs. 4 and 5, and added a new Fig. 7 to show the consistency between the model predictions and actual flight-test results, as well as the systematic performance comparison. Meanwhile, we improved the resolution and layout quality of the figures throughout the manuscript, revised the description of Fig. 1D, and standardized the use of terms such as "stability" to avoid conceptual confusion among longitudinal static stability, control authority and maneuvering capability.

All major revisions have been marked with blue underlined text in the revised manuscript. We believe that this revision more clearly demonstrates the central contribution of this work: the proposal and validation of a model-guided, low-degree-of-freedom wing–tail coordinated design framework, and the aerodynamic mechanism by which this framework balances cruise efficiency, longitudinal stability and maneuvering capability in a flapping-wing robot. Below, we provide point-by-point responses to the specific comments raised by the reviewers.

Sincerely,

The authors

Response to Reviewer 1's comments:

The authors have made substantial and commendable efforts in the rebuttal. The manuscript is significantly improved in terms of writing quality, and included biological connection (Table 1, flight envelope validation), improved experimental rigor (baseline comparisons, empirical power data). Again, I commend the authors on the detailed experimental results. However, my fundamental concerns remains as regards to theoretical contribution and generalizability of this work.
We sincerely thank you for your careful review of our manuscript and for your valuable suggestions. In response to your major concerns, we have added a predictive aerodynamic model and have substantially deepened, reorganized and systematically rewritten the manuscript. Below, we provide a point-by-point response to your main comments. The corresponding revisions have also been indicated in the revised manuscript with blue underlined text.
1. Lack of theoretical framework and modeling. This remains my primary concern. Despite improvements, the work is fundamentally an experimental engineering demonstration

without predictive aerodynamic models, design principles or optimization framework, oparametric studies, or theoretical analysis of stability margins and control coupling. The authors state design parameters are based on "passerine birds" and "fixed-wing aircraft standards," but do not show the design process of how these were actually chosen. As a design it's perfectly acceptable to pick certain parameters, but what is the guiding design principle/objective function? The auhtors calaims this work as "efficient avian-inspired control configuration". But was the design optimized for efficiency? The authors did not provide much analysis otherthan comparison to baseline, providing limited contribution. Even with simple modeling, the authors could have provided guiding design principles/insights. As you move the design along the pareto front, perhaps the morphological parameter trends, potential negative/positive lift shift could have been revealed. These are the key insights the author should provide.
We sincerely thank the reviewer for this important and constructive comment. We fully agree with your assessment. The previous version of the manuscript mainly focused on the structural implementation and flight experiments of NPU-Sparrow, but did not sufficiently elaborate on the theoretical framework, predictive model, and parameter-selection rationale that support the design. As a result, the manuscript did not fully reveal how the proposed design balances cruise efficiency and maneuvering capability on a flapping-wing platform.In particular, the original manuscript did not clearly explain how the tail installation angle, the range of tail area variation, and the coordination logic of flapping wing incidence angle control were determined. It also did not explicitly define the design objectives and evaluation metrics associated with “efficiency” and “maneuverability”. In fact, during the early design stage of NPU-Sparrow, we had conducted preliminary analyses and evaluations of these issues, but these considerations were not adequately presented in the original manuscript. We sincerely appreciate the reviewer for pointing out this central issue, and we have therefore made substantial revisions to the manuscript. In response to the reviewer’s concerns regarding the lack of a theoretical framework and modelling, as well as the absence of guiding design principles, we have constructed a complete design framework in the revised manuscript that proceeds from design principles to model prediction and experimental validation. The specific revisions are summarized as follows. First, the revised manuscript further clarifies the design trade-off between cruise efficiency and maneuvering capability and quantitatively defines the corresponding evaluation metrics. We agree that “efficiency” should not be treated merely as a qualitative

description. In the revised manuscript, the cruise requirement is quantified by the minimum flapping frequency required for steady level flight: a lower frequency indicates a smaller actuation input and lower power demand for maintaining level flight, and can therefore serve as an engineering metric of cruise efficiency. Maneuvering capability is evaluated using the available load factor under a prescribed maneuvering condition. Based on these definitions, the design problem is explicitly formulated as a trade-off between low-drag/low-frequency cruise and high-angle-of-attack, high-load-factor maneuvering. This cruise–maneuver trade-off, together with the rationale for selecting tail area, tail installation angle and flapping wing incidence angle as the key variables for achieving this balance, has been reformulated in Section 2.1 of the revised manuscript:

> **2.1 Cruise-maneuver trade-off**
>
> Maneuvering capability is defined as the ability of an aircraft to change its flight speed, altitude, and direction, and is closely related to the magnitude of the aerodynamic forces that the aircraft can generate. In contrast, cruise efficiency is primarily determined by the lift-to-drag ratio under cruising conditions. For an aircraft with a constant takeoff weight, maneuvering capability is mainly governed by the available lifting surface area, while cruise efficiency is dominated by aerodynamic drag during cruise. Therefore, achieving a balance between cruise efficiency and maneuverability requires minimizing cruise drag while maintaining sufficient lift availability.
>
> Inspired by the tail kinematic degrees of freedom observed in birds, the area variation of an avian-inspired morphing tail at different installation angles can simultaneously affect lift generation, pitching moment, and longitudinal static stability. In this study, we investigated the aerodynamic characteristics of a flapping-wing robot across various combinations of tail installation angles and tail areas. The objective was to identify feasible flight-capable design points that provide high available lift under maneuvering conditions and low cruise drag during level flight. By exploiting the underactuated characteristics of the novel control configuration of NPU-Sparrow, this parameter-space exploration enables the expansion of both maneuvering capability and cruise speed range.

Second, in this revision, we have newly established a predictive aerodynamic model and a parameter-analysis framework. The aerodynamic forces of the complete robot are decomposed into contributions from the wing–body assembly and the tail. The wing–body assembly model describes the cycle-averaged lift, thrust and pitching moment generated by the flapping wings and fuselage under different freestream velocities, angles of attack, flapping frequencies and flapping wing incidence angles. The tail model calculates the lift, drag and pitching moment of the tail according to tail area, local inflow velocity and effective angle of attack. To capture the influence of the wake induced by the flapping wings, we further introduce the induced downwash angle and the dynamic pressure ratio at the tail to correct the effective angle of attack and local flow velocity of the tail. With this formulation, the model can predict the effects of tail installation angle, tail area and flapping wing incidence angle on the lift, drag, pitching moment, aerodynamic-center position and longitudinal static stability of the complete robot. As a result, the study no longer relies solely on experimental observation, but establishes a closed-loop design framework of "model prediction–parameter selection–wind tunnel validation–flight validation".

Based on the predictive model, we performed a parametric analysis of tail installation angle and tail area, and constructed a cruise–maneuver Pareto design map (Fig. 3C). The model shows that a conventional fixed-tail configuration corresponds to only a single operating point in the design space, whereas introducing tail area modulation through a morphing tail allows the robot to move across a broader design region. Increasing tail area enhances pitch control authority and load-factor capability at high angles of attack, but also introduces additional cruise drag. Conversely, reducing tail area benefits high-speed, low-drag flight, but weakens maneuvering load capability. The flapping wing incidence angle is not simply an additional degree of freedom. Rather, it compensates for the lift and moment variations induced by tail extension and tucking. Coupling tail extension with an increase in flapping wing incidence angle expands the operating region that cannot be covered by tail extension and tucking alone, whereas coupling tail extension with a decrease in flapping wing incidence angle suppresses the rearward migration of the aerodynamic center. Based on the trade-off between stability and maneuverability, we selected the negative installation angle configuration of (-10°). During low-angle-of-attack cruise, the tail generates negative lift, providing a nose-up moment and a longitudinal static stability margin. During high-angle-of-attack maneuvering, the effective angle of attack of the tail increases, causing the lift direction to reverse. The tail then becomes an auxiliary positive lifting surface, and its extended area further increases the available load factor. This role-transition mechanism is highlighted as the core aerodynamic mechanism of the proposed design. These revisions have been presented in Sections 2.3 and 2.4 of the revised manuscript.

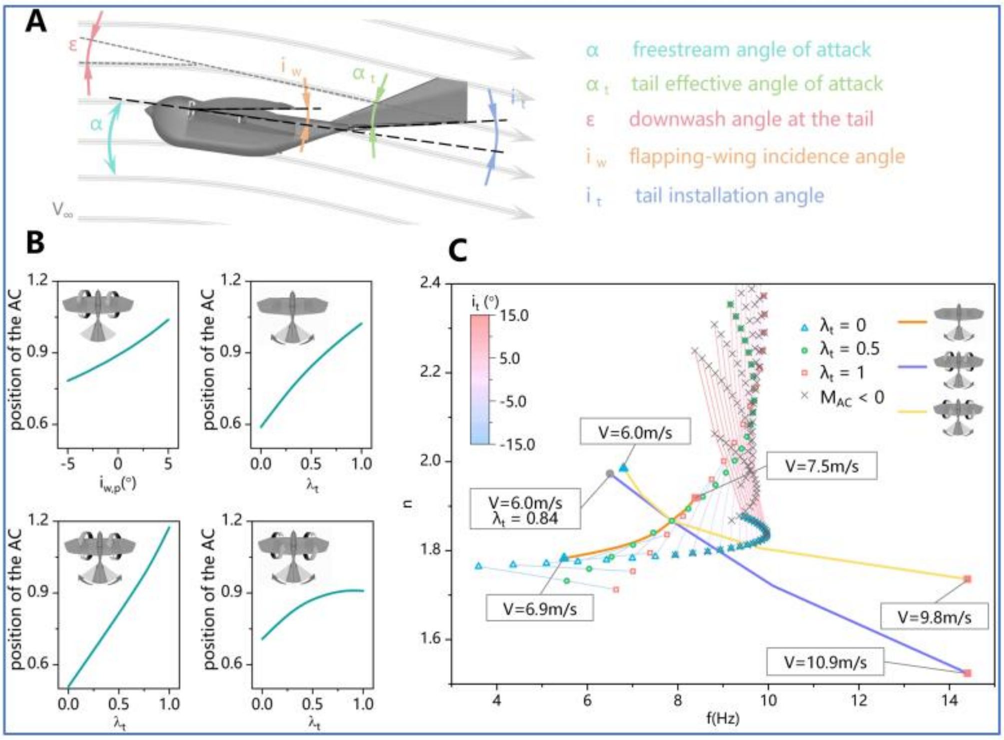


Fig. 3 Predictive aerodynamic model of NPU-Sparrow. A. Definitions of the flapping wing and tail installation angles, together with the associated aerodynamic angles. B. Model prediction of control-induced aerodynamic-center (normalized aerodynamic center) migration, The aerodynamic center is defined as the distance from the leading edge of the flapping wing to the aerodynamic center, normalized by the mean aerodynamic chord. C. Pareto map of the robot. The horizontal axis denotes the minimum flapping frequency required for level flight, representing cruise efficiency; the vertical axis denotes the maximum load factor under the prescribed maneuvering condition, representing maneuvering capability.

Third, the revised manuscript reorganizes the wind tunnel and flight-test results to provide a systematic validation of the model predictions and the resulting design principles. The wind tunnel experiments compare the positive- and negative-lift tail configurations and reveal their fundamental difference in zero-lift moment and longitudinal static stability. Although the positive-lift configuration can generate stronger pitch moments, its trimmed center of gravity is located aft of the aerodynamic center, leading to longitudinal static instability. In contrast, the negative-lift configuration maintains the trimmed center of gravity ahead of the aerodynamic center and therefore preserves longitudinal static stability. The experiments further confirm the aerodynamic-center migration predicted by the model, the control coupling between tail extension and tucking and flapping wing incidence angle, and the lift-direction reversal of the negative-lift tail when the angle of attack exceeds approximately (13°). These results demonstrate that this configuration can reconcile cruise static stability with high-angle-of-attack load capability. Outdoor flight tests further show that NPU-Sparrow reduces drag and power consumption for high-speed efficient cruise by tucking the tail, while increasing the effective lifting surface area and maneuvering load capability through tail extension. As a result, the flight speed envelope is substantially expanded. The variation of the flight states in the Pareto map is consistent with the model predictions, validating the design principle revealed in this study: tail area primarily regulates the aerodynamic configuration between low-drag cruise and high-load maneuvering, whereas flapping wing incidence angle compensates for the resulting lift and moment variations. Together, these two control variables expand the feasible operating range near the Pareto front.

Finally, the revised manuscript adds a comparison between the actual flight performance of NPU-Sparrow and that of similarly sized birds and other aerial robots. NPU-Sparrow exhibits a Cost of Transport (COT) and maximum load factor comparable to those of birds at a similar scale(Fig. 7B). Meanwhile, its flight performance demonstrates a clear advantage over existing flapping-wing aerial vehicles. In addition, the revised manuscript compares the experimental results of NPU-Sparrow with the predictions of the aerodynamic model in the Pareto map, and the two show consistent trends (Fig. 7A).

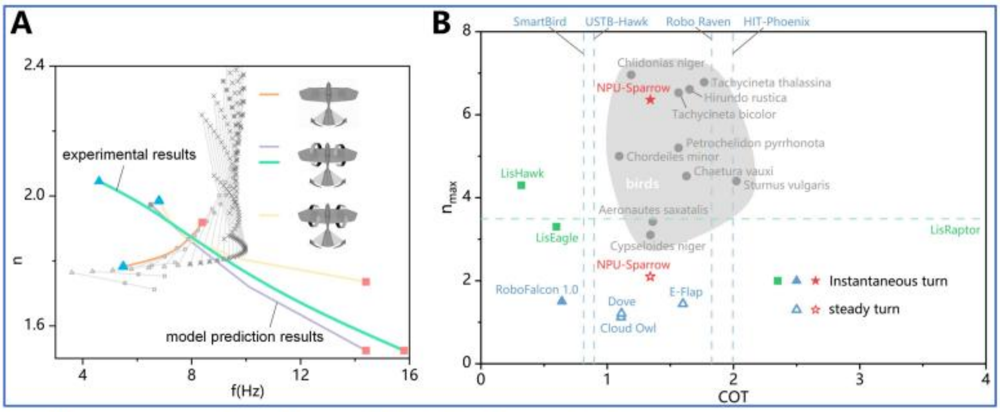


Fig. 7 illustrates the analysis of the experimental results for NPU-Sparrow. A. presents a comparison between the experimental results and the model predictions within the context of the Pareto map. B. contrasts the Cost of Transport (COT) and the maximum load factor among NPU-Sparrow, various bird species, and other aerial robots. The grey points illustrate the estimated maximum turning load factors of birds[33,34] at a flight speed of 10 m s^{-1}. The blue points represent data from flapping-wing robots[15,17,35–40], while the green points indicate morphing robot data derived from fixed-wing platforms[12,14,41]. Dashed markers denote aerial robots for which only one metric, either COT or maximum load factor, is available[36–39,41].

We believe that these additions, spanning quantitative metrics, predictive modelling, parametric analysis, experimental validation, and performance comparison with similarly sized birds and other aerial robots, systematically address the reviewer's concerns regarding the theoretical framework, design principles and key insights of the study. We sincerely thank the reviewer again for these valuable comments.

2. Limited novelty and scope. Prior work established morphing tails on fixed-wing MAVs (Ajanic 2020, 2022), wing morphing for roll (Di Luca 2017, Chang 2020), and tail morphing effectiveness (Murayama 2023). This validates tail morphing

works on flapping-wing platform with specific implementation. Question: Is cross-platform validation sufficient novelty without theoretical framework explaining why it transfers?

We sincerely thank the reviewer for raising this important and insightful question regarding the novelty and scope of our study. We fully agree with your assessment that morphing tails, morphing wings and avian-inspired tail aerodynamic effects are not entirely new concepts. Previous studies have already demonstrated the effectiveness of these technologies on fixed-wing micro aerial vehicles. Therefore, if the present work merely transferred the concept of a morphing tail from fixed-wing platforms to a flapping-wing platform and provided a cross-platform validation, it would indeed be insufficient to constitute the central scientific contribution of this study. Your comment prompted us to systematically reconsider the theoretical depth and positioning of the manuscript. Accordingly, we have substantially rewritten the Introduction and Discussion sections in the revised manuscript to more clearly define the theoretical contribution of this work. We now explain why the proposed design strategy is effective, as well as the theoretical framework underlying it, from the following three perspectives.

1. Unique aeroelastic constraints and control trade-offs of the flapping-wing platform. In the revised Introduction, we have clarified why morphing strategies developed for fixed-wing platforms cannot be directly applied to flapping-wing robots. In flapping-wing robots, the main wings are not passive load-bearing fixed lifting surfaces, but flexible unsteady aerodynamic systems that simultaneously generate lift and thrust. Their aerodynamic performance strongly depends on the coupling between flapping motion and passive aeroelastic deformation of the flexible wing surface. If morphing strategies developed for fixed-wing micro aerial vehicles, such as those reported by Ajanic et al. (2020, 2022), were directly transferred to the flapping wings by introducing complex active changes in area, camber or stiffness, they would not only substantially increase structural complexity and weight, but could also disrupt the inherent passive deformation mechanism, thereby markedly degrading aerodynamic efficiency and reliability. Therefore, identifying a new strategy that can expand the flight envelope without compromising the flexible characteristics of the flapping wings constitutes the fundamental motivation of this study. In the revised manuscript, we have more clearly stated that this work does not aim to fully replicate the multi-degree-of-freedom wing-tail morphing observed in birds. Instead, the primary morphological variable is deliberately limited to tail area, while control input on the wings is introduced only through global regulation of the flapping wing incidence angle. This strategy maximally preserves the intrinsic passive aeroelastic mechanism of the flapping

wings while still enabling wing-tail coordinated control.

2. Model-guided, low-degree-of-freedom wing–tail coordinated design framework. This study does not assume that morphing principles developed for fixed-wing platforms can be directly transferred to flapping-wing robots. Instead, we propose, for the first time for a flapping-wing robot, the control configuration of "dynamic tail area adjustment combined with flapping wing incidence angle control", and establish a design framework based on this configuration. Within this framework, variation in tail area extends beyond the conventional role of an elevator, which primarily provides pitching moments. It simultaneously modifies tail volume, longitudinal control effectiveness, effective lifting area and wing loading. The decoupled control of flapping wing incidence angle, inspired by the pitch–twist mechanism of avian wings, can independently generate roll moments and provide auxiliary pitch control, while avoiding the adverse aeroelastic interference that would arise from directly changing the area of the flapping wings. As a result, we achieve a balance among cruise efficiency, longitudinal stability, load-factor capability and maneuvering control with minimal control degrees of freedom, namely two wing-incidence servos and one tail-area servo. Therefore, the novelty of this work does not lie in a single tail morphing mechanism alone. Rather, it lies in unifying tail area modulation, negative-tail-installation-angle selection and flapping wing incidence angle control into a modelable, parametrically assessable and experimentally verifiable design framework for flapping-wing robots.

3. Aerodynamic role transition of the negative-lift tail configuration. Through model prediction and experimental validation, we reveal the physical mechanism by which the tail in the negative-lift tail configuration transitions from a negative-lift surface to a positive lifting surface at high angles of attack. Both the model and experiments show that, during low-angle-of-attack cruise, the tail with a negative installation angle generates negative lift, providing an appropriate nose-up moment and a longitudinal static stability margin for the robot. When the robot enters high-angle-of-attack maneuvering conditions exceeding 13°, the effective angle of attack of the tail increases as the tail extends, causing the lift direction to reverse. The tail then becomes an auxiliary positive lifting surface aligned with the flapping wings, thereby substantially increasing the available load factor. This aerodynamic role transition explains why we ultimately selected the negative-lift tail configuration, rather than simply adopting the positive-lift tail configuration with higher local lift. It is precisely this state-dependent functional transition of the tail that enables the aircraft to reconcile cruise static stability with high-angle-of-attack load capability.

To further support this framework, we have added systematic comparisons in the manuscript. First, we compare the positive- and negative-lift tail configurations in terms of longitudinal static stability, load-factor capability and drag penalty. These comparisons demonstrate that the negative-lift tail configuration can maintain static stability during cruise while achieving load capability close to that of the positive-lift tail configuration through role transition at high angles of attack (Fig. 5). Second, we compare different control logics, including tail extension and tucking alone and tail extension and tucking combined with flapping wing incidence angle modulation. These results show that flapping wing incidence angle is an important control input for compensating lift and moment variations and regulating aerodynamic-center migration (Fig. 4). Finally, we compare the flight performance of NPU-Sparrow with that of the baseline configuration with a fixed tail area. The results demonstrate an expanded speed range, by 22.5%, reduced power consumption during high-speed cruise, and a smaller sustained turning radius, reduced by 20.4% (Fig. 6). These comparisons further clarify that the contribution of this study is not a simple cross-platform validation of the effectiveness of a morphing tail. Rather, through modelling, wind tunnel measurements and flight experiments, this work systematically reveals the mechanisms by which wing–tail coordinated control operates on a flapping-wing platform.

In summary, in the revised manuscript, we have repositioned the central contribution of this work from “implementing a morphing tail on a flapping-wing robot” to proposing and validating a model-guided, low-degree-of-freedom wing–tail coordinated design framework for flapping-wing platforms. This framework explains why tail area modulation can be effective on a flapping-wing platform, reveals the aerodynamic role-transition mechanism of a negative-installation-angle tail between cruise and maneuvering flight, and systematically validates its effects on flight envelope, cruise efficiency, stability and maneuvering capability through experiments. We believe that these systematic additions, spanning theoretical modelling, physical mechanism elucidation and experimental validation, clearly address the reviewer’s concerns regarding novelty, research scope and the mechanism of cross-platform transfer. We sincerely thank the reviewer again for these valuable comments.

Response to Reviewer 2’s comments:

The revised version clarified the relationship between tail fin deployment and main wing angle of attack for pitch control. In fact, changes in the main wing angle of attack and tail fin deflection produce a similar effect, which does indeed help with pitch control.

A minor issue: in Figure 1D, the longitudinal static stability layout contradicts the tail fin lift direction, and the center of gravity position is not indicated. The center of gravity position is crucial for determining longitudinal stability.

We sincerely thank the reviewer for pointing out this important detail, and we fully agree with your comment that longitudinal static stability must be assessed based on the relative positions of the center of gravity and the aerodynamic center. The original intention of Fig. 1D was to illustrate that, under a longitudinally statically stable configuration, the tail extends and generates positive lift during high-angle-of-attack maneuvering. Therefore, the label "longitudinally statically stable configuration" was included in the figure. However, we agree that this could easily lead readers to misinterpret the figure as also being intended to explain longitudinal static stability itself. In the instantaneous maneuvering state where the tail generates positive lift, the absence of the center of gravity and aerodynamic center annotations indeed made this description insufficiently rigorous.

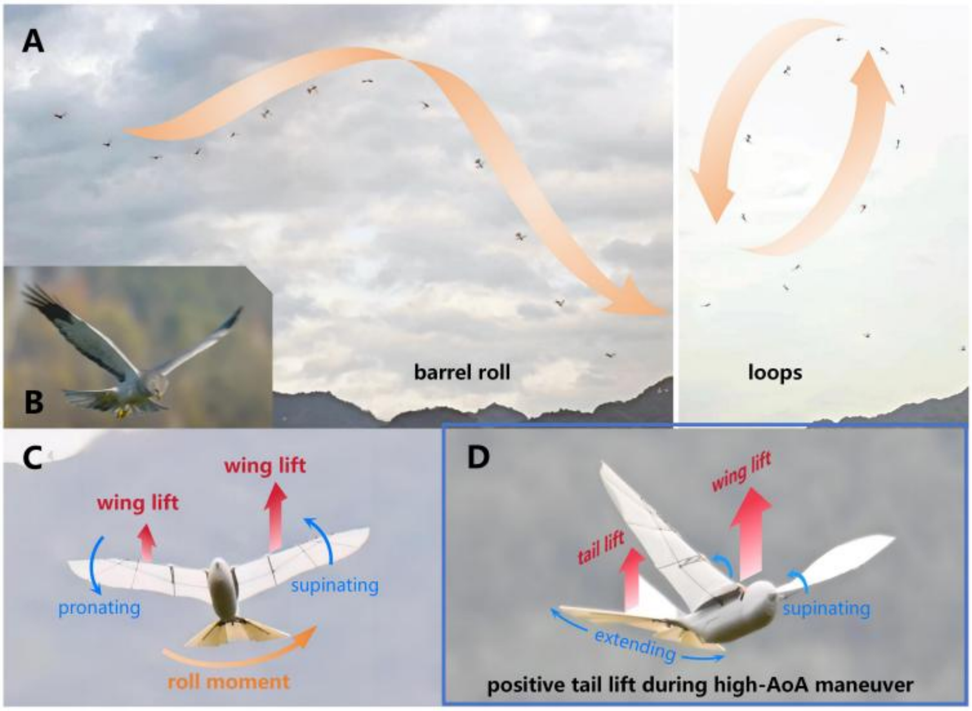


Fig. 1. avian-inspired wing-tail morphing control configuration. A. The aggressive flight trajectories of NPU-Sparrow : the left panel illustrates a barrel roll maneuver (as shown in Supplementary Video 1), while the right panel depicts a loop maneuver (as shown in Supplementary Video 2). B. A Eurasian sparrowhawk spreads its tail during agile maneuvering. C. The NPU-Sparrow generates roll control moments through the differential control of flapping wing incidence angles. D. The extended tail of the NPU-Sparrow produces positive lift during maneuvering flight.

Following the reviewer's suggestion, we have revised Fig. 1D. Specifically, we replaced the original label "longitudinally statically stable configuration" with "positive tail lift during high-AoA maneuver". The revised Fig. 1D is no longer used to illustrate longitudinal static stability, but only to show the phenomenon that the tail reverses its lift direction and generates positive lift during high-angle-of-attack maneuvering. Correspondingly, we have also revised the figure caption to clarify that Fig. 1D shows that "the extended tail of NPU-Sparrow produces positive lift during maneuvering flight", thereby avoiding any confusion between the high-angle-of-attack maneuvering state and the cruise static-stability configuration.

Meanwhile, we have clearly distinguished the roles of the tail under two different flight states in the main text. During low-angle-of-attack cruise, NPU-Sparrow adopts a tail with a negative installation angle that generates negative lift, thereby providing appropriate longitudinal trim and a static stability margin. In contrast, during high-angle-of-attack maneuvering conditions above 13°, the effective angle of attack of the tail increases, causing the lift direction to reverse. The tail then becomes a positive lifting surface aligned with the flapping wings, thus satisfying the high-load-factor requirement for maneuvering flight. Fig. 1D illustrates this latter high-angle-of-attack maneuvering state, rather than the longitudinal static stability under cruise conditions.

To explain longitudinal static stability more rigorously, we have added a detailed discussion in the new Section 2.4 of the revised manuscript, where the effects of tail area and tail installation angle on longitudinal static stability are analyzed using the predictive aerodynamic model (Fig. 3C). We further validate the relationship among the center of gravity, aerodynamic center and pitching moment through wind tunnel experiments. In particular, by comparing the positive- and negative-lift tail configurations, we explicitly show that the zero-lift moment of the positive-lift configuration requires the trimmed center of gravity to be located aft of the aerodynamic center, leading to longitudinal static instability. In contrast, the negative-lift configuration allows the trimmed center of gravity to remain ahead of the aerodynamic center, thereby maintaining longitudinal static stability.

We sincerely thank the reviewer again for this careful correction. This revision makes the physical meaning of Fig. 1D clearer and fundamentally avoids the possible misunderstanding caused by conflating the “cruise static-stability state” with the “high-angle-of-attack positive-lift maneuvering state”.

Response to Reviewer 3’s comments:

I appreciate the authors’ detailed responses and the revisions made based on my previous comments. The manuscript has improved in clarity and presentation.

Summary of the Work:

1, This study presents a bird-inspired flapping-wing drone (NPU-Sparrow) featuring independently variable wing pitching angles and a size-morphable tail to enhance flight authority.

2, The primary motivation is to achieve bird-like flight capabilities, including aggressive maneuvering and efficient cruising.

3, Specifically, the manuscript:

(A) introduces the overall design of NPU-Sparrow and claims to address maneuverability challenges in flapping-wing systems through a relatively simple and engineering-feasible platform;

(B) analyzes how the proposed wing configuration influences maneuverability;

(C) investigates how tail size affects power consumption;

(D) validates the design through outdoor flight experiments..

We sincerely thank the reviewer for the summary and positive assessment of our work. Your comments accurately summarize the main aspects of this study, including the overall design of the NPU-Sparrow robot, the wing-tail coordinated control configuration, the effects of tail extension and tucking on cruise and maneuvering performance, and the outdoor flight validation. Following your further suggestions, we have systematically revised and strengthened the manuscript in terms of novelty clarification, theoretical modelling, figure organization and the logic of experimental validation. Below, we provide a point-by-point response to your specific comments.

Comments and Suggestions:

1. Novelty. I personally concern the novelty of the proposed design, is it the first implementation of size-morphable on a flapping wing drone? if it is, please highlight. If not, maybe the proposed configuration (variable wing together with the morphable tail) is a new strategy (I guess so).

   In the response letter, the authors state:

   "Directly transplanting complex morphing mechanisms onto flapping wings would significantly compromise the aeroelastic response upon which they depend for generating lift and thrust, while also imposing unacceptable weight and inertial penalties."

   However, in the current design, the morphable structure appears to be applied only to the tail, not to the wings. Therefore, this argument does not seem fully aligned with the actual implementation. Furthermore, introducing additional actuators for independent variable wing pitching would also increase system weight and extra power consumption.

   The authors are encouraged to clarify this novelty-related statement more directly and consistently. Specifically, they should explain how their design avoids the stated drawbacks while still achieving meaningful functional improvement, and clearly define what constitutes the core innovation of the proposed platform.

We sincerely thank the reviewer for raising this important and specific comment. Your suggestion prompted us to reconsider and more clearly distill the core novelty of this study.

In the previous version of the manuscript and response, our description of the novelty was not sufficiently direct, and we did not adequately distinguish between the novelty of the control configuration and the central scientific contribution of this work. Meanwhile, our statement regarding "avoiding the direct transplantation of complex morphing mechanisms onto the flapping wings" was not precise enough, which could have led to the misunderstanding that complex active morphing structures were adopted on the flapping wings in this study. In addition, the engineering trade-offs associated with the added actuator weight, inertia and power consumption introduced by flapping wing incidence angle control also required further clarification. To address these issues, we have systematically revised the Introduction, Results and Discussion sections in this revision. We have added a new section entitled "Predictive aerodynamic model and Pareto design map", and have reorganized and rewritten the wind tunnel and flight experiment sections. These revisions further clarify the novelty of the proposed control configuration, the central contribution of this work, the model-guided design framework, and the physical mechanism of the negative-lift tail configuration. Below, we provide a more detailed response to the reviewer's concerns.

First, regarding the novelty of the control configuration, we have provided a more direct definition in this revision. To the best of our knowledge, this is the first study to combine a morphing tail with decoupled left–right flapping wing incidence angle control to form a low-degree-of-freedom wing–tail coordinated control configuration, namely "dynamic tail area adjustment combined with flapping wing incidence angle control", and to apply it to a micro flapping-wing robot for simultaneous pitch control, roll control, cruise-efficiency regulation and maneuvering-capability enhancement. Previous studies have demonstrated the effects of wing and tail morphing on flight-envelope expansion and maneuvering capability in small fixed-wing aerial vehicles or isolated tail models[1,2]. Other studies have also achieved roll control through changes in wing attitude or wing morphology[3-6]. Therefore, we do not regard the individual functions of "tail area can be varied" or "wing incidence angle can be changed" as the primary novelty of this work. Rather, the novelty first lies in their coordinated integration on a flapping-wing robot platform. In this configuration, tail area variation serves as the primary mechanism for regulating lifting surface area and pitching moment, whereas flapping wing incidence angle provides roll moment and assists in compensating for the lift and moment variations induced by tail extension and tucking. To avoid the misunderstanding that this work is merely the implementation of a single morphing tail mechanism, we have further emphasized in the revised manuscript the originality of this control configuration as a wing-tail coordinated strategy.

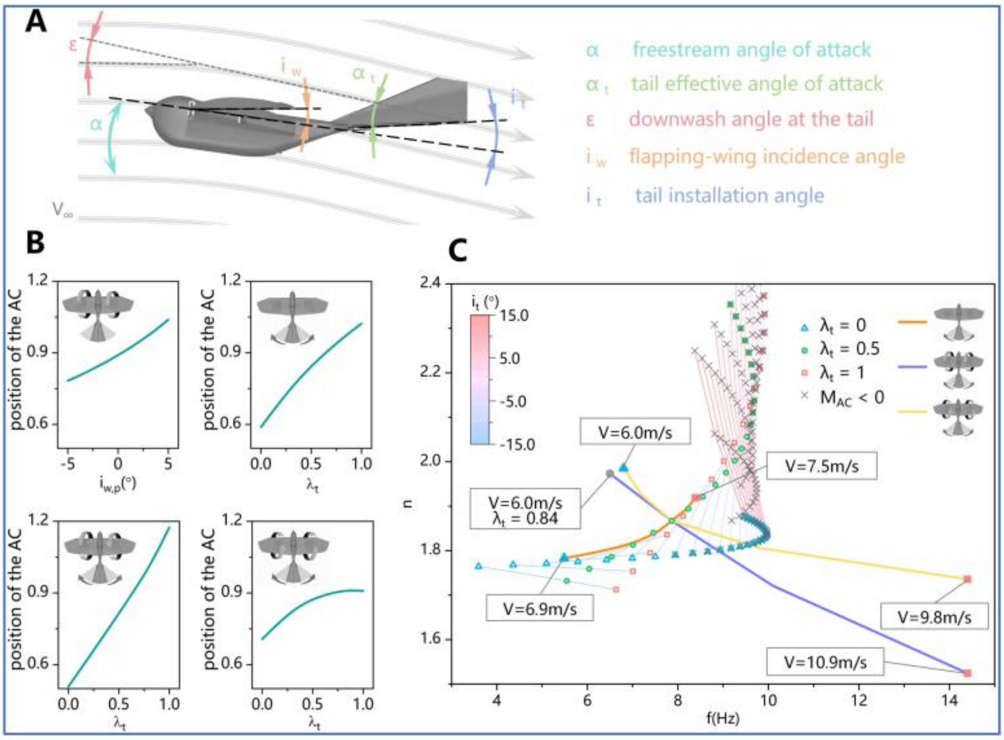
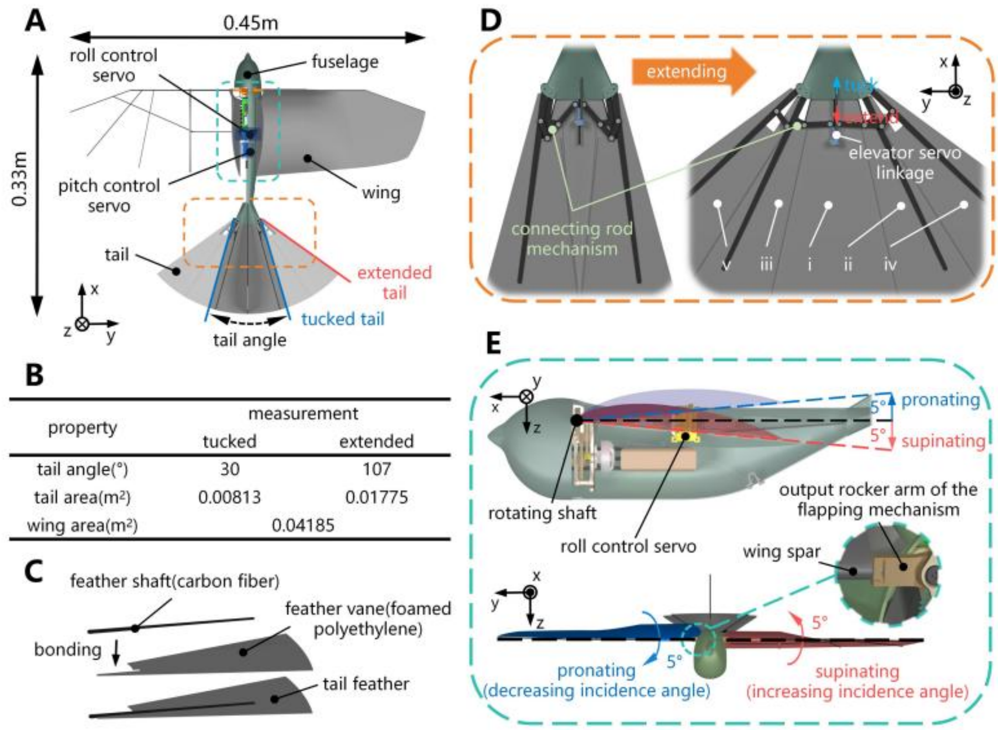


Fig. 3 Predictive aerodynamic model of NPU-Sparrow. A. Definitions of the flapping wing and tail installation angles, together with the associated aerodynamic angles. B. Model prediction of control-induced aerodynamic-center (normalized aerodynamic center) migration, The aerodynamic center is defined as the distance from the leading edge of the flapping wing to the aerodynamic center, normalized by the mean aerodynamic chord. C. Pareto map of the robot. The horizontal axis denotes the minimum flapping frequency required for level flight, representing cruise efficiency; the vertical axis denotes the maximum load factor under the prescribed maneuvering condition, representing maneuvering capability.

However, although this control configuration is novel, it is not the central scientific contribution of this work. The central contribution of this study lies in proposing and validating a model-guided, low-degree-of-freedom wing–tail coordinated design framework. Within this framework, tail area variation is no longer treated as a simple substitute for conventional elevator deflection. Instead, it is defined as a morphological parameter that simultaneously affects tail volume, pitching moment, aerodynamic-center position, effective lifting area and load-factor capability. Similarly, flapping wing incidence angle is not merely an additional control input, but a low-dimensional control variable used to regulate wing–tail aerodynamic coupling, compensate for the lift and moment variations induced by tail extension and tucking, and provide roll control together with auxiliary pitch control. In response to the reviewer's previous concerns regarding the theoretical framework and design rationale, we have newly added and strengthened the predictive aerodynamic model in this revision. In this model, the aerodynamic forces of the complete robot are decomposed into contributions from the wing–body assembly and the tail. The effects of flapping-wing-induced downwash, local dynamic pressure at the tail, effective tail angle of attack, tail area and flapping wing incidence angle are further incorporated. Based on this model, the cruise–maneuver Pareto design map (Fig. 3C) links tail area, tail installation angle and flapping wing incidence angle to cruise efficiency, longitudinal static stability, aerodynamic-center migration and maximum load-factor capability. This establishes a closed-loop design methodology of "model prediction–parameter selection–wind tunnel validation-flight validation".

More importantly, in this revision, we have further highlighted and systematically explained the aerodynamic role-transition mechanism of the negative-lift tail configuration across different flight states. Both the model predictions and wind tunnel experiments show that, during low-angle-of-attack cruise, the tail with a negative installation angle generates negative lift, providing a nose-up moment and a longitudinal static stability margin for the robot. When the robot enters high-angle-of-attack maneuvering conditions, however, the effective angle of attack of the tail increases, causing the lift direction of the tail to reverse. The tail then transitions from a negative-lift surface into an auxiliary positive lifting surface aligned with the flapping wings, thereby substantially increasing the available load-factor capability. This mechanism explains why we ultimately selected the negative-lift tail configuration, rather than simply adopting a tail configuration that more readily generates positive lift in the conventional sense. In other words, the negative-lift tail is not used only for stable trim; instead, it is actively transformed into a source of maneuvering load at high angles of attack, thereby establishing a new balance between cruise static stability and high-angle-of-attack maneuvering capability. To address the reviewer's question regarding the core innovation of this work, we have explicitly stated in the revised Discussion that revealing this mechanism and applying it to a real flapping-wing robot constitute one of the key contributions that distinguish this study from previous studies on morphing tails for fixed-wing platforms and from studies focused on the implementation of a single mechanism.

We have also clarified the inconsistency in wording pointed out by the reviewer in this revision. Our previous statement that we "avoid directly transplanting complex morphing mechanisms onto the flapping wings" did not mean that no control input is applied to the flapping wings. Rather, it means that this study avoids introducing complex active wing-surface morphing into the flexible flapping wings themselves, such as active changes in wing area, planform shape, camber or stiffness. For flapping-wing robots, the flapping wings simultaneously generate lift and thrust, and their aerodynamic performance strongly depends on the passive aeroelastic deformation of the flexible membrane wings during high-frequency flapping. Directly adding complex morphing structures to the flapping wings could alter the stiffness distribution, inertia distribution and passive deformation response of the wing surface, thereby disrupting the original lift- and thrust-generation mechanism. Therefore, in this revision, we have revised the relevant statement to clarify that what we avoid is complex active morphing of the flapping wing surface, rather than all control inputs related to the flapping wings. By contrast, the flapping wing incidence angle control adopted in this study rotates the entire flapping wing by a small angle around the fore spar (Fig. 2E). It does not change the planform shape, area, membrane structure or flexible deformation mechanism of the flapping wing. Therefore, it is fundamentally different from complex active wing-surface morphing and represents a control method that introduces relatively little interference with the passive aeroelastic response of the flapping wings.



Regarding the additional weight, inertia and power consumption introduced by the actuators, NPU-Sparrow indeed includes two flapping wing incidence-angle servos and one tail-area servo. However, the placement and function of these actuators are fundamentally different from those of complex flapping-wing morphing mechanisms. The flapping wing incidence-angle servos are mainly installed inside the fuselage (Fig. 2E) and adjust the global incidence angle of the flapping wings through a linkage/rotational-axis mechanism. The servos themselves do not undergo high-frequency reciprocating motion together with the flapping wings, and therefore do not substantially increase the moving inertia of the main flapping transmission. Moreover, flapping wing incidence angle control is a small-angle, low-frequency or quasi-static control input. It does not participate in the high-frequency actuation of the main flapping motion. Therefore, its power consumption mainly occurs during attitude adjustment and transitions between control states, rather than continuously contributing to the power required for flapping. Similarly, the tail extension and tucking mechanism adjusts tail area through a simple linkage mechanism, with the objective of achieving simultaneous changes in tail volume, effective lifting area and pitch control authority at relatively low structural complexity. In other words, we do not deny that the added actuators introduce certain penalties in weight and power consumption. Rather, by limiting the actuator number to the minimum necessary degrees of freedom and avoiding complex active morphing structures on the flapping wings themselves, the additional cost is kept lower than the functional benefits it provides. We have provided a more cautious and consistent explanation of this engineering trade-off in the revised manuscript.

In summary, following the reviewer's suggestion, we have revised the manuscript to more clearly articulate the novelty and central contribution of this work. In this revision, we have systematically addressed this issue through a rewritten Introduction, supplemented mechanism description, newly added predictive model, Pareto design-map analysis, integrated wind tunnel validation, and a deeper Discussion. The proposed control configuration of "dynamic tail area adjustment combined with flapping wing incidence angle control" is, to the best of our knowledge, the first implementation of such a unified wing–tail coordinated control strategy on a micro flapping-wing robot platform. However, the more central contribution of this work is the establishment and validation of a model-guided, low-degree-of-freedom wing – tail coordinated design framework, together with the revelation and utilization of the physical mechanism by which the negative-lift tail configuration transitions from a negative-lift surface to an auxiliary positive lifting surface at high angles of attack. By limiting the primary morphological variation to the tail and restricting flapping-wing control to small global changes in wing incidence angle, this study avoids the aeroelastic interference and high-inertia penalties associated with complex active morphing of the flapping wings themselves. At the same time, it achieves a balance among cruise efficiency, longitudinal stability, load-factor capability and maneuvering control performance. We believe that these revisions more clearly and consistently address the reviewer's concerns regarding novelty, core innovation and actuator-related costs.

Reference:

[1]. Ajanic, E., Feroskhan, M., Mintchev, S., Noca, F. & Floreano, D. Bioinspired wing and tail morphing extends drone flight capabilities. Sci. Robot. 5, eabc2897 (2020).

[2]. Ajanic, E., Feroskhan, M., Wüest, V. & Floreano, D. Sharp turning maneuvers with avian-inspired wing and tail morphing. Commun Eng 1, 34 (2022).

[3]. Chen, A., Song, B., Wang, Z., Xue, D. & Liu, K. A Novel Actuation Strategy for an

Agile Bioinspired FWAV Performing a Morphing-Coupled Wingbeat Pattern. IEEE TRANSACTIONS ON ROBOTICS 39, (2023).

[4]. Di Luca, M., Mintchev, S., Heitz, G., Noca, F. & Floreano, D. Bioinspired morphing wings for extended flight envelope and roll control of small drones. Interface Focus. 7, 20160092 (2017).

[5]. Meng, R., Song, B., Xuan, J., Yang, X. & Xue, D. Design and Experimental Verification of a Roll Control Strategy for Large Wingspan Flapping-Wing Aerial Vehicle. J Bionic Eng 21, 1644–1661 (2024).

[6]. Chang, E., Matloff, L. Y., Stowers, A. K. & Lentink, D. Soft biohybrid morphing wings with feathers underactuated by wrist and finger motion. Sci. Robot. 5, eaay1246 (2020).

2. Another concern relates to the level of scientific contribution. Incremental improvements in engineering feasibility alone may not be sufficient for publication in its current form. To strengthen the manuscript, the authors are encouraged to provide deeper scientific insights — such as more rigorous flight control development, quantitative performance evaluation, or systematic comparisons — that clearly demonstrate the advancement beyond an engineering prototype.

Although the authors have not fully addressed my concerns (still on novelty and scientific contribution), I do not believe it is necessary for me to recommend rejection of the revised manuscript, as the other reviewers and the editor have already requested major revisions on this issue (I will follow the majority view). In addition, the revised version has introduced new problems. I recommend that these issues must be properly addressed before the manuscript can be considered for publication.

We sincerely thank the reviewer for this important comment regarding the depth of the scientific contribution of this work. We fully understand and accept your concern: if this study only presented an engineering-feasible prototype of a flapping-wing robot, or merely demonstrated a certain performance improvement over a baseline configuration, such an incremental engineering improvement would indeed be insufficient to fully support the scientific contribution of the manuscript. The previous version of the manuscript placed greater emphasis on the structural implementation of NPU-Sparrow and its outdoor flight demonstrations, while insufficiently explaining the underlying design principles, predictive model, parameter-selection rationale, wing–tail coupling mechanisms and quantitative performance evaluation. This may have led readers to interpret the study primarily as a prototype validation focused on engineering implementation. Following the reviewer's suggestion, we have substantially restructured the manuscript in this revision. We have further clarified the central positioning of this work as the proposal and validation of a model-guided, low-degree-of-freedom wing–tail coordinated design framework, rather than simply the demonstration of a flapping-wing robot platform equipped with a morphing tail. Around this central contribution, we have strengthened the scientific contribution of the manuscript from the following aspects.

First, in this revision, we have clarified the scientific question and engineering design problem addressed in this study: how a flapping-wing robot can simultaneously balance cruise efficiency, longitudinal stability and maneuvering capability under limited structural complexity and limited actuation degrees of freedom. For micro flapping-wing robots, high maneuverability typically requires large available lift, strong pitch control authority and low wing loading, whereas high cruise efficiency requires minimizing cruise drag and actuation power. These requirements are inherently conflicting. Therefore, the revised manuscript no longer treats "efficiency" or "agility" only as qualitative descriptions. Instead, we reformulate this trade-off as a quantifiable design problem. The cruise requirement is characterized by the minimum flapping frequency required for steady level flight; a lower frequency indicates lower actuation input and lower power demand for maintaining level flight. Maneuvering capability is characterized by the available load factor under a prescribed maneuvering condition; a higher load factor indicates stronger load-carrying capability during high-angle-of-attack maneuvering. Based on these two metrics, Section 2.1 of the revised manuscript explicitly defines the design objective as seeking a reasonable trade-off between low-frequency/low-drag cruise and high-angle-of-attack, high-load-factor maneuvering. Through this revision, the focus of the manuscript has shifted towards explaining how cruise-maneuver performance balance can be achieved through an interpretable wing–tail coordinated mechanism.

2.1 Cruise-maneuver trade-off

Maneuvering capability is defined as the ability of an aircraft to change its flight speed, altitude, and direction, and is closely related to the magnitude of the aerodynamic forces that the aircraft can generate. In contrast, cruise efficiency is primarily determined by the lift-to-drag ratio under cruising conditions. For an aircraft with a constant takeoff weight, maneuvering capability is mainly governed by the available lifting surface area, while cruise efficiency is dominated by aerodynamic drag during cruise. Therefore, achieving a balance between cruise efficiency and maneuverability requires minimizing cruise drag while maintaining sufficient lift availability.

Inspired by the tail kinematic degrees of freedom observed in birds, the area variation of an avian-inspired morphing tail at different installation angles can simultaneously affect lift generation, pitching moment, and longitudinal static stability. In this study, we investigated the aerodynamic characteristics of a flapping-wing robot across various combinations of tail installation angles and tail areas. The objective was to identify feasible flight-capable design points that provide high available lift under maneuvering conditions and low cruise drag during level flight. By exploiting the underactuated characteristics of the novel control configuration of NPU-Sparrow, this parameter-space exploration enables the expansion of both maneuvering capability and cruise speed range.

Second, in this revision, we have newly added and strengthened the predictive aerodynamic model and parametric analysis framework, based on which we constructed the cruise – maneuver Pareto design map (Fig. 3C). For the low-degree-of-freedom wing – tail coordinated control configuration of NPU-Sparrow, we decompose the aerodynamic forces of the complete robot into contributions from the wing – body assembly and the tail. The wing – body assembly model describes the cycle-averaged lift, thrust and pitching moment generated by the flapping wings and fuselage under different freestream velocities, complete-robot angles of attack, flapping frequencies and flapping wing incidence angles. The tail model calculates the lift, drag and pitching moment of the tail according to tail area, local inflow velocity at the tail and effective tail angle of attack. To account for the aerodynamic coupling between the flapping wings and the tail, the model further introduces the flapping-wing-induced downwash and the dynamic pressure ratio at the tail, thereby correcting the effective angle of attack and local flow velocity of the tail. With this formulation, the model can predict the effects of tail installation angle, tail area and flapping wing incidence angle on the lift, drag, pitching moment, aerodynamic-center position and longitudinal static stability of the complete robot. As a result, this study no longer relies solely on experimental analysis, but establishes a closed-loop design methodology of “model prediction–parameter selection–wind tunnel validation-flight validation”.

The cruise – maneuver Pareto design-map analysis constructed from the predictive model shows that a conventional fixed-tail configuration corresponds to only one operating point in the design space (Fig. 3C). By introducing tail extension and tucking, the robot can regulate cruise efficiency and maneuvering capability over a broader operating region. Increasing tail area enhances pitch control authority and load-factor capability at high angles of attack, but also introduces additional cruise drag. Conversely, reducing tail area benefits high-speed, low-drag cruise, but weakens maneuvering load capability. Meanwhile, the flapping wing incidence angle is not an isolated additional control input. Rather, it is a key control variable used to compensate for the lift and moment variations induced by tail extension and tucking, and to regulate aerodynamic-center migration. Through the Pareto map, the revised manuscript explains why the negative-lift tail configuration should be selected, and why tail extension should be coordinated with an increase in flapping wing incidence angle. In other words, this study does not simply compare the performance of different configurations. Instead, the model reveals how tail area, tail installation angle and flapping wing incidence angle jointly determine cruise efficiency, longitudinal stability and maneuvering capability.

Third, through the predictive model and the reorganized experimental validation, we further clarify and strengthen the aerodynamic role-transition mechanism of the negative-lift tail configuration. The model predicts that, during low-angle-of-attack cruise, the tail with a negative installation angle generates negative lift, providing a nose-up moment and a longitudinal static stability margin for the robot. When the robot enters high-angle-of-attack maneuvering conditions, the effective angle of attack of the tail increases, causing the lift direction of the tail to reverse. The tail then transitions from a negative-lift surface into an auxiliary positive lifting surface aligned with the flapping wings, thereby substantially increasing the available load-factor capability. This model prediction has been further validated and clarified through the reorganized wind tunnel analysis in the revised manuscript. Therefore, the negative-installation-angle tail in this study is not merely a statically stabilizing component used for trim. Instead, it is an aerodynamic component with state-dependent functional transition: during cruise, it acts as a negative-lift tail that helps the robot maintain longitudinal static stability; during high-angle-of-attack maneuvering, it transforms into an auxiliary positive lifting surface and becomes a source of maneuvering load. We believe that this aerodynamic role transition of the negative-lift tail from a "stable-trim component" to a "maneuvering-load component" represents one of the important scientific findings that distinguishes this work from a simple engineering prototype demonstration. It also further shows that the proposed low-degree-of-freedom wing-tail coordination strategy is not a direct imitation of complex avian wing-tail motions, but rather a reconstruction of the key aerodynamic functions underlying avian win-tail coordination through model-based analysis.

Finally, in response to the reviewer ' s suggestion that quantitative performance evaluation and systematic comparison are needed, we have added and strengthened multi-level performance comparisons in the revised manuscript to demonstrate that the contribution of this work extends beyond engineering feasibility. In addition to comparing NPU-Sparrow with the baseline configuration with a fixed tail area, we compare the experimentally obtained performance changes with the Pareto trends predicted by the model (Fig. 7A). The results show consistent trends, indicating that the improvement in flight performance is not an incidental engineering outcome, but arises from the wing - tail coordination mechanism revealed by the model. Furthermore, we have added a systematic comparison of the Cost of Transport, maximum load factor and flight speed envelope of NPU-Sparrow with those of similarly sized birds, existing flapping-wing robots and avian-inspired morphing aerial robots (Fig. 7B). These comparisons further show that the performance improvement of NPU-Sparrow is not only reflected in its improvement over its own baseline configuration, but also in its comparability with existing aerial robots and similarly sized birds.

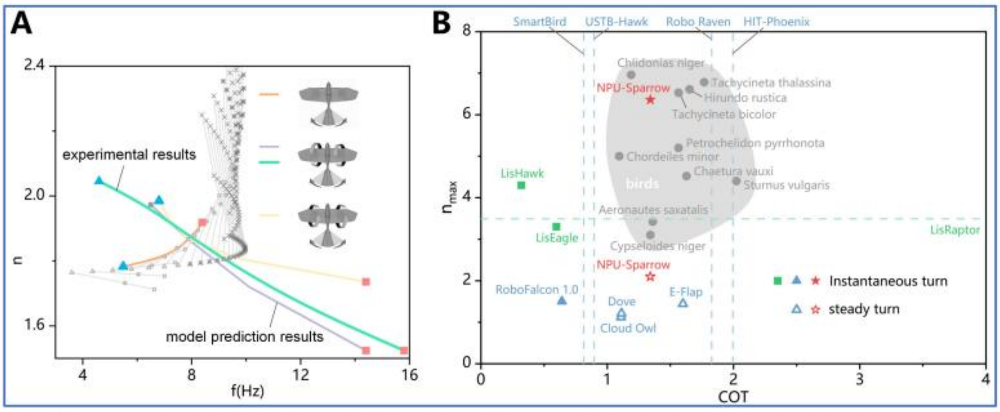


Fig. 7 illustrates the analysis of the experimental results for NPU-Sparrow. A. presents a comparison between the experimental results and the model predictions within the context of the Pareto map. B. contrasts the Cost of Transport (COT) and the maximum load factor among NPU-Sparrow, various bird species, and other aerial robots. The grey points illustrate the estimated maximum turning load factors of birds[33, 34] at a flight speed of 10 m s^{-1}. The blue points represent data from flapping-wing robots[15,17,35–40], while the green points indicate morphing robot data derived from fixed-wing platforms[12, 14, 41]. Dashed markers denote aerial robots for which only one metric, either COT or maximum load factor, is available[36–39,41].

In summary, following the reviewer's comments, we have systematically revised the manuscript. The revised manuscript first clarifies the scientific and engineering design problem addressed in this study, namely the trade-off between cruise efficiency and maneuvering capability. It then adds and strengthens the predictive aerodynamic model and parametric analysis framework, based on which the cruise–maneuver Pareto design map is constructed. Furthermore, through model prediction and reorganized wind tunnel and flight experiments, the revised manuscript reveals and validates the aerodynamic role-transition mechanism of the negative-installation-angle tail across different flight states. Finally, through systematic comparisons with the baseline configuration, existing aerial robots and similarly sized birds, we demonstrate the effectiveness of the proposed design framework. We believe that these revisions show that the central contribution of this work is not an incremental engineering prototype, but a model-guided, low-degree-of-freedom wing–tail coordinated design framework, together with the wing–tail coupling aerodynamic mechanism revealed and validated by this framework.

3. While the overall paper quality has improved, several figures still suffer from low resolution and suboptimal organization (e.g., Figure 6). The figures should be revised to meet publication standards.

We sincerely thank the reviewer for the valuable suggestion regarding the quality and organization of the figures. Following your suggestion, we have reorganized and improved the figures throughout the manuscript so that they better support the central contribution of this work: a model-guided, low-degree-of-freedom wing–tail coordinated design framework.

First, we have added a new Fig. 3 to present the newly developed predictive aerodynamic model and the cruise–maneuver Pareto design map. Second, in accordance with the rewritten experimental validation section, we have integrated and reorganized the relatively scattered Figs. 3, 4 and 5 in the original manuscript into the revised Figs. 4 and 5. In addition, we have added a new Fig. 7 to show the consistency between the actual flight-test results and the model-predicted trends. Finally, we have improved the overall quality of all figures in the manuscript.

4. Sections 2.3 ("Influence on Flight Stability") and 2.4 ("Influence on Maneuverability") would benefit from clearer organization and greater concision. There appears to be some overlap between these sections. In addition, I suggest reconsidering the use of the term "stability" in Section 2.3. In control and dynamical systems, "stability" typically refers to the input–output or equilibrium behavior of a system, whereas the discussion in this section seems to address a different concept (sounds like torque generation capability or control authority, etc). A more precise term would improve clarity.

We sincerely thank the reviewer for this accurate and highly constructive comment. After carefully re-examining the original manuscript, we fully agree with your assessment that Sections 2.3 and 2.4 indeed overlapped in content, and that the use of the term "stability" was not sufficiently rigorous in the context of control and flight dynamics. In response to the two issues raised by the reviewer, namely manuscript structure and terminology, we have thoroughly reorganized the relevant sections and systematically standardized the terminology throughout the revised manuscript.

1. Reorganizing the section logic to eliminate content overlap. In the revised manuscript, we have thoroughly reorganized the original Sections 2.3 and 2.4, so that the Results section now follows a progressive logic of "problem definition (Section 2.1)–design (Sections 2.2 and 2.3)–model (Section 2.4)–validation (Section 2.5)–flight performance (Section 2.6)". Specifically, we have added a new section entitled "2.4 Predictive aerodynamic model and Pareto design map". Starting from a unified theoretical model, this section integrates the variations in lift, drag, pitching moment and aerodynamic-center position into a single predictive framework, thereby clarifying the intrinsic relationships among these aerodynamic characteristics from the outset. Subsequently, the wind tunnel analyses that were previously distributed between the "stability" and "maneuverability" sections have been consolidated and refined into a new section, "2.5 Aerodynamic validation of model predictions". Following a unified logical thread, this section uses wind tunnel data to systematically validate the comprehensive effects of the control logic on aerodynamic-center position, which forms the basis of longitudinal static stability, pitching moment coefficient, which represents control authority, and lift coefficient and maximum load factor, which characterize maneuvering capability. This structure, in which the predictive model is first established and then comprehensively validated through experiments, eliminates the content overlap between the original two sections and makes the overall presentation more concise, compact and logically convincing.

2. Standardizing the terminology related to flight dynamics and control. We fully accept the reviewer's correction and have carefully reviewed and revised the terminology throughout the manuscript. In the revised manuscript, the term "stability" is strictly limited to the description of longitudinal static stability, and is used only when discussing the relative positions of the aerodynamic center and the trimmed center of gravity. For example, we explicitly state that, in the negative-lift tail configuration, the trimmed center of gravity is located ahead of the aerodynamic center, and therefore the robot exhibits longitudinal static stability. For content in the original manuscript that actually described moment-generation capability or control authority, we have replaced the wording with more precise technical terms, such as "pitch control authority", "pitch control effectiveness", "pitching moment coefficient" and "pitch control capability". For example, when describing the effects of different control logics, we now state that the positive-lift tail configuration "achieves the largest pitching moment coefficient", and that tail extension can "enhance pitch control

capability". In addition, we have revised several expressions that could have led to misunderstanding in terms of dynamic stability. For example, cases in which certain configurations fail to provide sufficient nose-up moment have been rephrased as "corresponding to unfavorable pitch-trim characteristics", rather than being ambiguously described as "unstable". This revision more accurately reflects the scope of conclusions supported by the experimental data.

We sincerely thank the reviewer again for these careful suggestions regarding the structure of the manuscript and the accuracy of the terminology. These revisions have substantially improved the logical clarity and academic rigor of the manuscript, and we hope that the revised structure and wording adequately address the reviewer's concerns.

Responses to the Reviewer's Comments on the Manuscript

ID NCOMMS-25-70548

Dear reviewer,

On behalf of all co-authors, we sincerely thank you for your contribution to improving the quality of our manuscript. We are grateful to the editor and reviewers for the constructive comments and suggestions on our manuscript entitled "Wing-tail coordination balances efficient cruising and maneuvering flight in an avian-inspired flapping robot" (ID NCOMMS-25-70548).

In this revision, we further clarified the empirical response-surface nature and domain of applicability of the predictive aerodynamic model, and added a sensitivity analysis of the quantitative discrepancy in aerodynamic-center migration and its effect on the Pareto-design conclusions. We also expanded the explanation of Fig. 3C and revised the Pareto-axis convention, reconciled the description of the flight-speed envelope, and distinguished performance data with different sources and load-factor definitions in Fig. 7B while softening the cross-platform comparison. The model parameters and sensitivity analysis are additionally provided in the Supplementary Notes to improve the transparency of the methods and results. Our point-by-point responses are provided below.

Sincerely,

The authors

Response to Reviewer 1's comments:

I thank the authors for a substantial and thoughtful revision. They have restructured the paper and repositioned the central claim from "a morphing tail on a flapping robot" to a model-guided wing-tail coordination design framework, revising the title accordingly. This directly targets my primary concern from the previous rounds. Great to see the new predictive model and the Pareto front (Fig. 3C), which formalize the cruise-efficiency / maneuverability trade-off and are used to motivate the design choices, materially strengthens the contribution.
We sincerely thank the reviewer for the careful evaluation and constructive comments. Across the successive rounds of review, your comments have helped us sharpen the manuscript logic, strengthen the scientific rigor, and clarify the central contribution. We greatly appreciate this guidance.
Major concerns: 1.On whether the "predictive model" is genuinely predictive. I appreciate the effort the authors put into building the model and the Pareto map -- this is a real improvement and

largely addresses my earlier request for design principles. I would, however, still like to see this qualified honestly in the text. As implemented, the model is an empirical response-surface fit to this specific robot's own wind-tunnel data; it interpolates within the tested envelope (and the authors note it breaks down beyond ~25 degrees AoA) rather than providing a scale-transferable framework a reader could use to design a different robot. So explicitly calling out this caveat is important.

Related to this, the model appears to overestimate the magnitude of aerodynamic-center migration relative to the wind-tunnel measurements. Comparing the source data for Fig. 3B and Fig. 4D, the predicted AC shift exceeds the measured shift by roughly a factor of 2-3 across all three control strategies (e.g., tail-morphing-only: 43% predicted vs. 17.5% measured). Since the stability boundary (M_AC < 0), the selected tail angle, and the breadth of the exploitable Pareto region all depend on AC position, I would ask the authors simply to (a) state explicitly that the model is a robot-specific empirical fit valid within the tested range, and (b) briefly comment on how sensitive the Pareto front and the -10 degree design point are to this quantitative discrepancy. Please explicitly discuss this in the manuscript.

Response: Thank you for raising this important point. We agree that the nature and scope of the predictive aerodynamic model should be stated more precisely. In the revised manuscript, we retain the term "predictive aerodynamic model" to describe its function in predicting the aerodynamic performance of NPU-Sparrow within the sampled design space, while explicitly defining it as a robot-specific empirical response-surface representation. It should not be interpreted as a general model that can be directly transferred across scales or to different flapping-wing robot configurations.

The model is constructed from wind-tunnel measurements of the NPU-Sparrow wing-body assembly and tail. Its primary role is to provide aerodynamic-response interpolation, design-space screening, and relative comparison among different wing-tail coordination strategies within the experimentally sampled parameter domain, and thereby to construct the Pareto design map between cruise efficiency and maneuvering capability. The original manuscript did not sufficiently emphasize this limitation. We have now explicitly added this qualification in the model description and discussion, and have revised wording that could otherwise imply cross-configuration predictive capability. The relevant changes are shown below:

engineering variables. A robot-specific predictive aerodynamic model, constructed from empirical response surfaces fitted to separate wing-body and tail wind-tunnel measurements, is used to guide the selection of the tail installation angle and wing-tail coordination strategy by mapping the trade-off between cruise efficiency and maneuvering capability. The

The model is a robot-specific empirical response-surface representation constructed from wind-tunnel measurements of NPU-Sparrow. It is intended for trend analysis and design-space screening within the experimentally sampled parameter domain, rather than for direct extrapolation or quantitative aerodynamic prediction across flapping-wing robots of different scales or configurations. In addition, because the reduced-order representation of the combined wing-tail aerodynamics does not fully resolve the nonlinear wing-tail interactions that become increasingly pronounced at high angles of attack, the quantitative accuracy of the model decreases in this regime.

We further examined the source of the quantitative discrepancy in aerodynamic-center migration between the model predictions and the full-vehicle wind-tunnel measurements. The aerodynamic-center position is not independently fitted; rather, it is calculated from the angle-of-attack derivatives of the complete-robot lift and pitching moment:

$$x_{AC} = -\frac{\partial M/\partial\alpha}{\partial L/\partial\alpha} = -\frac{M_\alpha}{L_\alpha}$$

Accordingly, the quantitative discrepancy in aerodynamic-center migration can be affected by prediction errors in both the lift slope and the pitching-moment slope.

Using the full-vehicle wind-tunnel data underlying Fig. 4D, we further decomposed and compared L_α and M_α from the experiments and the model. The results show that the model correctly captures the direction and relative ordering of aerodynamic-center migration among the three wing-tail control strategies. In other words, the enhancement or suppression of aerodynamic-center migration produced by tail morphing and by coordinating tail morphing with different flapping-wing incidence angles is consistent with the experiments. However, the model overpredicts the magnitude of the control-induced changes in the aerodynamic slopes. The overprediction is more pronounced for the variation in M_α, while the variation in L_α also contributes to the final aerodynamic-center position.

Our analysis indicates that this discrepancy mainly arises because the current reduced-order model overpredicts the incremental aerodynamic sensitivity induced by tail morphing. In the model, the complete-robot lift and pitching moment are obtained by combining the wing-body and tail response surfaces, while the influence of the flapping-wing wake on the tail is approximated through simplified relations for the effective tail inflow and downwash. This treatment captures the principal aerodynamic trends, but does not explicitly resolve the nonuniform and unsteady wing-tail interactions that vary with tail area and flapping-wing incidence angle, such as changes in the local downwash distribution, effective dynamic pressure, and the effective interaction region of the tail within the flapping wake. Therefore, the model captures the relative effects of the different control strategies, but retains a quantitative discrepancy in the magnitude of aerodynamic-center migration.

Sensitivity analysis

To address the reviewer's further question of whether this quantitative AC discrepancy changes the Pareto front or the -10° design point, we performed the following sensitivity analysis.

In the current quadratic tail response surface, the $S_t\alpha_t$ cross term directly governs how changes in tail area affect the lift and pitching-moment slopes. Because this cross term appears in both the tail-lift and tail pitching-moment response surfaces, we introduced a dimensionless sensitivity scaling factor k_t only to reduce the incremental aerodynamic sensitivity generated by deviations in tail area from a reference configuration.

Using the median tail area S_{ref} as the reference state, the original $C_{S\alpha}S_t\alpha_t$ term was represented in the sensitivity analysis as $C_{S\alpha}[S_{ref}\alpha_t + k_t(S_t - S_{ref})\alpha_t]$, which is equivalently written as:

$$Q_t^{sens} = Q_t^{nominal} + (k_t - 1)C_{S\alpha}(S_t - S_{ref})\alpha_t$$

where Q_t denotes either tail lift or tail pitching moment. When $k_t = 1$, the nominal empirical response-surface model used in the main text is recovered exactly. When $S_t = S_{ref}$, the aerodynamic forces, moments, and trim state of the reference configuration remain unchanged regardless of k_t . The perturbation therefore acts only on the incremental aerodynamic response associated with tail morphing and does not alter the baseline design state.

We compared three representative perturbations, $k_t = 1,\ 0.75, 0.5$. Here, $k_t = 1$ is the nominal model used in the main text, $k_t = 0.75$ represents a moderate perturbation, and $k_t = 0.5$ is used as a conservative lower-bound perturbation. As shown in Fig. 1, at $k_t = 0.5$ the predicted control-induced aerodynamic-center migration for the tail-morphing-only strategy is close to the experimental measurement. This case is used only as a bounded robustness perturbation rather than as a recalibration of the aerodynamic model.

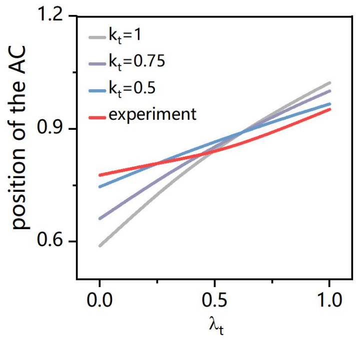


Fig. 1. Measured aerodynamic-center migration and predictions obtained with different values of the dimensionless sensitivity factor k_t for the tail-morphing-only strategy.

The Pareto maps under the three perturbation levels (Fig. 2) show that reducing the incremental aerodynamic sensitivity induced by tail morphing has only a limited effect on the overall Pareto design space. First, the absolute positions of the Pareto trajectories shift to a limited extent as k_t changes, while the overall trade-off between cruise efficiency and maneuvering capability remains essentially unchanged. Thus, the overprediction of AC-migration magnitude in the nominal model does not alter the fundamental cruise-maneuver trade-off identified in this study. Second, the relative relationship between the performance trajectory generated by tail morphing alone and the Pareto front is preserved. In other words, the design mechanism by which tail morphing moves the operating state between cruise-efficient and maneuverability-favored regions is not sensitive to the exact magnitude of AC migration. Likewise, the trajectory generated by coordinating tail extension with flapping-wing supination remains in essentially the same high-performance region under the different perturbation levels, and its performance-space extension relative to tail morphing alone is preserved. The sensitivity analysis therefore does not change the basis for selecting the wing-tail coordination logic.

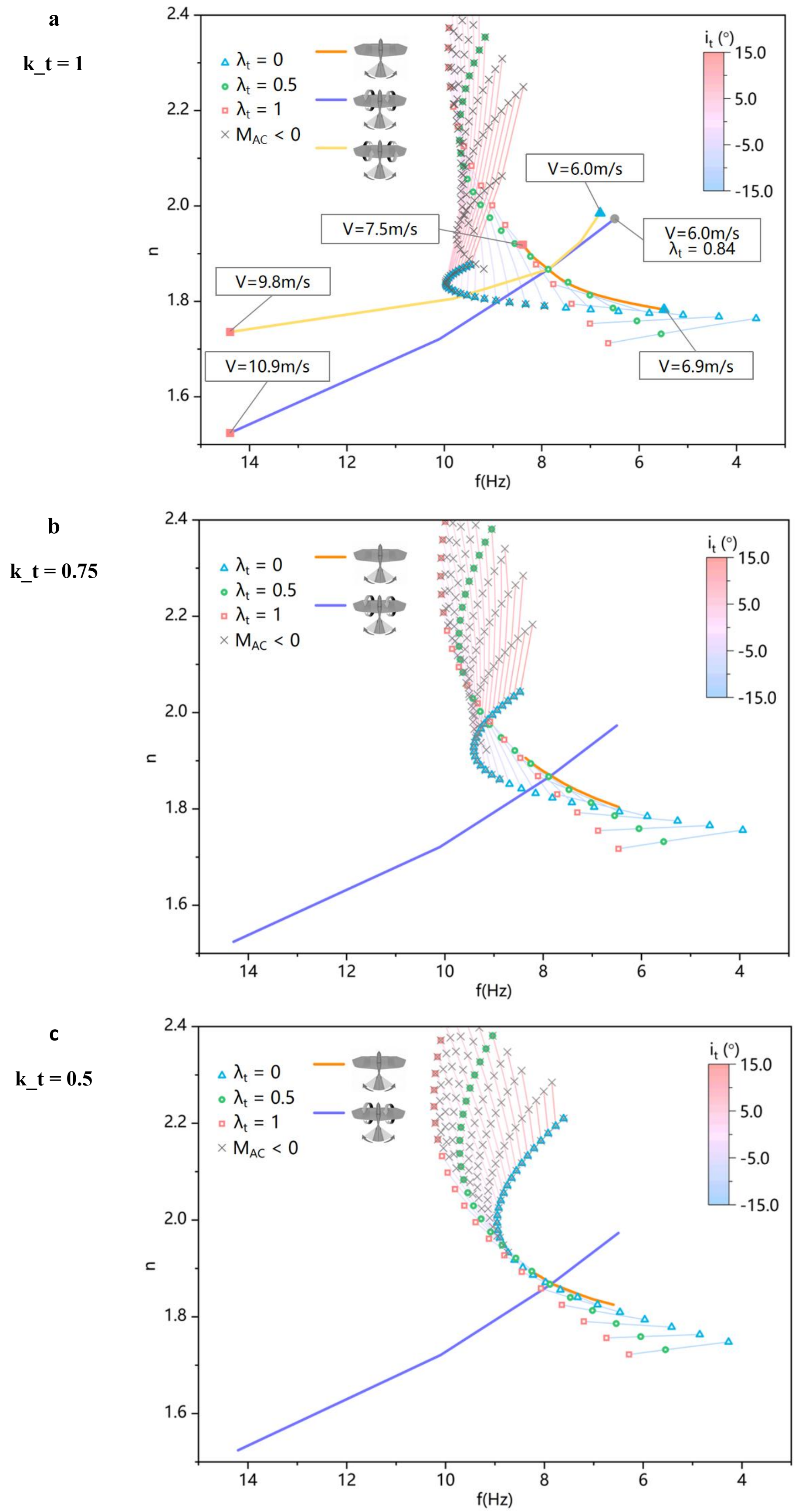


Fig. 2. Pareto design maps under the three representative sensitivity perturbations, k_t = 1, 0.75, and 0.5.

By contrast, the most sensitive quantity is the zero-lift pitching moment and the corresponding longitudinal static-stability boundary. As k_t changes, the stability boundary shifts to some extent. This indicates that the exact optimum tail installation angle predicted by the nominal empirical model is sensitive to the quantitative discrepancy in AC migration, and therefore -10° should not be interpreted as a unique mathematical optimum that remains invariant under all model perturbations. Nevertheless, throughout the perturbation range considered here, the -10° tail installation angle remains within the longitudinally statically stable region and provides increased static-stability margin as k_t is reduced. At the same time, the corresponding design remains in a region of high maneuvering capability and does not move into an unfavorable Pareto region as the AC-migration magnitude is reduced.

The sensitivity analysis therefore indicates that -10° is not necessarily the unique mathematical optimum, but rather a practical design point that is robust to the quantitative uncertainty of the aerodynamic model, provides sufficient longitudinal static-stability margin, and retains high maneuvering capability. Importantly, this stability conclusion does not rely solely on the empirical response-surface model: the full-vehicle wind-tunnel experiments directly show that the negative-lift tail configuration remains longitudinally statically stable throughout the tail-morphing range with an appropriate stability margin.

In summary, the revised manuscript now briefly discusses how the model discrepancy affects the Pareto front and the selection of the -10° design point. The corresponding revision is shown below:

Compared with the experimental results, the predictive aerodynamic quantitatively overpredicts the magnitude of aerodynamic-center migration, while correctly capturing its qualitative trend. This discrepancy reflects the limitations of the reduced-order aerodynamic representation of the wing-tail system, particularly its inability to explicitly resolve complex nonlinear wing-tail interactions, including variations in the local downwash gradient and effective dynamic pressure at the tail. Sensitivity analysis indicates that this quantitative overprediction produces only limited shifts in the Pareto trajectories and does not alter the overall cruise-maneuver trade-off, the selected wing-tail coordination strategy, or the relative performance ranking among different configurations (Supplementary Note). The corresponding aerodynamic trends and relative differences among the configurations are further supported by the full-vehicle wind-tunnel experiments.

2. Figure 3 is hard to interpret. The caption defines the axes of panel C but never identifies the three colored curves, the marker shapes (lambda_t = 0 / 0.5 / 1), the color scale (i_t), or the "x" symbol; the reader must reconstruct the legend from three separate paragraphs of body text or legends from later figures (pronation vs supination). Please consider adding some text to guide the reader on how to read and interpret the figure

(where the final design sits, and how the lines move as the morphological parameters change, etc.).
Response: Thank you for this suggestion. We agree that the original manuscript did not provide sufficient guidance on how to read Fig. 3C or interpret its physical meaning. We have therefore expanded both the figure caption and the corresponding explanation in the main text. First, the revised Fig. 3C caption now states that the horizontal axis is the minimum flapping frequency required for cruise flight, while the vertical axis is the attainable load factor under the prescribed maneuvering condition. For each fixed tail installation angle i_t, the connected design points represent the cruise-maneuver performance trajectory generated by varying tail area. Triangles, circles, and squares denote the fully tucked, median-area, and fully extended tail states, respectively; the color scale denotes i_t; and gray crosses denote longitudinally statically unstable configurations. Second, the main text now explains how these trajectories move as the morphological parameters vary. By changing tail area, the robot redistributes performance between operating states favoring cruise efficiency and those favoring maneuvering capability. Considering both longitudinal static-stability margin and maneuvering capability, we selected i_t = -10° as the practical design configuration. Its reference cruise state lies near the middle of the corresponding trajectory, and subsequent tail extension or tucking allows the robot to move along this trajectory between different operating states. In addition, the three wing-tail coordination strategies are now explicitly highlighted. The results show that, once flapping-wing incidence-angle coordination is introduced together with tail extension, the accessible performance region extends beyond the Pareto envelope obtained using tail morphing alone, with tail extension coordinated with flapping-wing supination providing the broader operating range. For the selected negative-incidence tail, the aerodynamic role of the tail also changes with flight state: it provides trim and longitudinal static stability during cruise, but becomes an auxiliary lifting surface during high-angle-of-attack maneuvering flight. With these revisions, Fig. 3C now more clearly identifies the selected design configuration, the performance migration induced by tail morphing, and the extension of the Pareto performance space produced by wing-tail coordination. The corresponding revision is shown below:

mean aerodynamic chord. c Cruise-efficiency-maneuverability Pareto design map of NPU-Sparrow. The horizontal axis denotes the minimum flapping frequency required for cruise flight, whereas the vertical axis denotes the attainable load factor under the prescribed maneuvering condition. Each thin line connects design points corresponding to different tail morphing states at a fixed tail installation angle it. Triangles, circles, and squares denote the fully tucked (λt=0), median-area (λt=0.5), and fully extended (λt=1) tail states, respectively. Gray crosses denote longitudinally statically unstable configurations. For the selected it=−10°configuration, the thick orange, blue, and yellow trajectories represent tail morphing alone, tail extension coordinated with flapping-wing supination, and tail extension coordinated with flapping-wing pronation, respectively. The labeled values of V indicate the corresponding level-flight speeds.
Minor points: 1. Pareto-front axis convention. By convention a Pareto front is plotted so that both competing objectives improve along their axes, placing the jointly-optimal (hard-to-reach) region in the top-right corner. Here the vertical axis (load factor) increases upward, but the horizontal axis is minimum flapping frequency, where lower is better. I suggest reversing the frequency axis (or plotting an efficiency proxy that increases rightward) and stating explicitly that lower flapping frequency corresponds to higher cruise efficiency, so the desirable region sits in the top-right as readers expect.
Response: Thank you for this suggestion. We agree that using the conventional Pareto-map orientation, in which both competing objectives improve in a consistent direction along their axes, substantially improves the readability of Fig. 3C. Accordingly, we reversed the horizontal axis of minimum flapping frequency in the revised Fig. 3C, such that the minimum flapping frequency decreases from left to right while load factor continues to increase upward. Cruise efficiency and maneuvering capability therefore both improve toward the upper-right region of the Pareto map, consistent with the conventional presentation of a Pareto front. We also clarified the physical meaning of the horizontal axis in both the main text and the figure caption: for NPU-Sparrow, the minimum flapping frequency required to sustain level flight represents the cruise propulsive requirement; a lower minimum flapping frequency therefore corresponds to a lower propulsive requirement and higher cruise efficiency.
2.Inconsistent flight-envelope numbers. The Introduction states a "193% expansion of the flight speed envelope," whereas the Results report the envelope is "extended by 22.5% compared to the baseline." These describe the same quantity two different ways -- the 193% appears to be the speed range relative to its own minimum (e.g., (13.2-4.5)/4.5), not an expansion versus the baseline. Please reconcile these and use a single consistent framing; as written, the 193% in the Introduction reads as inflated.
Response: Thank you for identifying this inconsistency. In the revised manuscript, we

removed the "193% expansion" statement and now use a single definition throughout: the expansion of the level-flight speed envelope relative to the fixed median-tail baseline configuration. The revised manuscript therefore consistently states that active tail morphing expands the level-flight speed envelope of NPU-Sparrow by 22.5% relative to the baseline configuration, with an experimentally measured level-flight speed range of 4.5-13.2 m s^{-1}.

3. Fig. 7B comparison. The comparison against birds and other robots mixes points reported on a single metric with different definitions of load factor (instantaneous vs. steady-state). This makes the "clear advantage over existing flapping-wing vehicles" claim somewhat apples-to-oranges. I am not asking for additional experiments-please either annotate these differences in the figure/caption or soften the claim accordingly.

Response: Thank you for this suggestion. We agree that the performance data in Fig. 7B are not fully homogeneous in either source or measurement definition. In particular, some platforms report only one of the two metrics, COT or maximum load factor, while the available load-factor data include both instantaneous-turn and steady-turn definitions. We therefore agree that the original statement of a "clear advantage" could lead to an overly strong interpretation.

In the revised Fig. 7B and its caption, we explicitly distinguish these data types: filled markers denote instantaneous turning load factors, open markers denote steady-turn load factors, and dashed markers indicate platforms for which only one metric, either COT or maximum load factor, is available. The load-factor value reported for LisRaptor is additionally identified as an instantaneous turning load factor.

We also softened the cross-platform comparison in the main text, replacing "demonstrates a clear advantage over existing flapping-wing aerial vehicles" with the more cautious statement "demonstrates competitive flight performance relative to existing flapping-wing aerial vehicles." The revised wording is intended to indicate that NPU-Sparrow exhibits competitive overall performance within the range of currently available published data, without claiming an absolute advantage across different testing conditions or metric definitions.