nature portfolio

Peer Review File

Fast ground-to-air transition with avian-inspired multifunctional legs

Corresponding Author: Mr Won Dong Shin

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

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)
The manuscript entitled “Fast ground-to-air transition enabled by avian-inspired multifunctional legs” introduce a new type of bird-inspired multifunctional leg and demonstrated multimodality on the ground and for jumping take-off from the ground to the air.

The major contributions of this research are 1) the simplification and reduction in weight while implementing the various functions of the bird's legs such as walking, hopping, height jump and jumping take-off, 2) extending the application scope by adapting this novel leg to aerial robots, and 3) providing insights through experimental results and analyses regarding the energy efficiency of multi-modal robots and leg muscle mass corresponding to locomotor ecologies.
Overall, the manuscript has originality and gives us very good insights to understand nature. The development of a bird-inspired leg that can perform a variety of locomotion is interesting and worthy of further exploration. The analysis is also meticulously carried out and is persuasive and inspiring to other researchers.

I believe this work is suitable for publication in Nature, after minor revision. More detailed comments are as follows.

1. If possible, it would be better for readability to show each movement in a continuous sequence. Presenting the mission scenario shown in Figure 1c as a video would be more effective. Lines 124-126: “The jumping legs enabled ~” a video would also be necessary.
2. How does RAVEN compare to other multi-modal robots in terms of energy efficiency and generation speed when performing jumping take-off?
3. I understand the analysis of the impact of various take-off strategies on RAVEN's flight acceleration using the jumping legs. However, since Raven has fixed wings and uses propellers for propulsion, comparing it with take-off strategies that are not suitable for flying robots (such as vertical standing) seems to overstate the analysis. It would be nice to show the usefulness of jumping legs in a fairer situation.
4. Lines 19-21: “We show ~” could be misleading. The term " solely propeller-based take-off" is confusing and unclear, as it conjures up images of a typical takeoff of a fixed-wing aircraft.
5. It appears that the height jump is not included in the Froude number and Cost of Transport (CoT) analysis in Figures 3g and 3h. Is there a reason for its omission? It would be

Referee #2

(Remarks to the Author)
The article presents a novel multi-modal bird-inspired robot capable of transitioning from terrestrial to aerial locomotion. The authors present a detailed design, simulation, and evaluation of bird-inspired legs that enable such transition as well as hopping, walking, and jumping on the ground. The article is well-written, and the analysis is presented well. I have a few minor suggestions for the authors.

1) For the robot's performance, distances and velocities are sometimes presented as just absolute values or as absolute values and percentages of the leg length. I recommend presenting things more consistently. Also, consider presenting takeoff velocity and height (and other relevant metrics) as body properties rather than just leg properties. For example, in line

174, the authors write, "The experiments showed that the drone could walk at a forward speed of 0.23 ms−1". In my opinion, this should be reported in terms of body length per second rather than leg length per second.

2) Figure 3g would benefit from adding bird data for comparison, similar to what the authors did for 3h.

3) Finally, I really appreciate the authors' efforts in comparing the energetics of the different and relating that to birds' takeoff strategies, as I think this is a very valuable use of physical models to test biological hypotheses. However, for mechanical systems, I suggest that the authors clarify or discuss how these efficiency numbers would shift for different takeoff strategies if the legs were designed for that strategy. For example, for the falling takeoff strategy, the legs could simply be wheels or simple landing gear, and the robot weight would be significantly less, and the power consumption would be significantly less for the lighter robot.

Overall, I commend the authors on a strong publication.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)
I appreciate the author's efforts in responding to the review comments. Through their responses, I have come to understand the reasons behind the absence of continuous scenarios and comparisons with other studies. I'm satisfied with the revisions and happy to recommend acceptance.

Referee #2

(Remarks to the Author)
The authors addressed all my concerns. Thank you for your thorough response.

Authors' Response to the Comments from Reviewers

Journal: Nature

Manuscript ID: 2024-04-06661

Title: Fast ground-to-air transition enabled by avian-inspired multifunctional legs

Authors: Won Dong Shin, Hoang-Vu Phan, Monica A. Daley, Auke J. Ijspeert, Dario Floreano

We greatly appreciate the time and effort of referees and editor in reviewing our manuscript and the overall positive appreciation of the results. We believe that the recommendations of the reviewers helped us improve the quality of the article. Please find our response to each comment below. To make it easier to locate the modified parts of the manuscript, we have attached screenshots of the revised manuscript and marked the edited sentences in red. We hope that our responses adequately address the reviewers' comments.

Referee #1 (Remarks to the Author):

The manuscript entitled "Fast ground-to-air transition enabled by avian-inspired multifunctional legs" introduce a new type of bird-inspired multifunctional leg and demonstrated multimodality on the ground and for jumping take-off from the ground to the air.

The major contributions of this research are 1) the simplification and reduction in weight while implementing the various functions of the bird's legs such as walking, hopping, height jump and jumping take-off, 2) extending the application scope by adapting this novel leg to aerial robots, and 3) providing insights through experimental results and analyses regarding the energy efficiency of multi-modal robots and leg muscle mass corresponding to locomotor ecologies.

Overall, the manuscript has originality and gives us very good insights to understand nature. The development of a bird-inspired leg that can perform a variety of locomotion is interesting and worthy of further exploration. The analysis is also meticulously carried out and is persuasive and inspiring to other researchers.

I believe this work is suitable for publication in Nature, after minor revision. More detailed comments are as follows.

- We thank the reviewer for the positive comments.

1. If possible, it would be better for readability to show each movement in a continuous sequence. Presenting the mission scenario shown in Figure 1c as a video would be more effective. Lines 124-126: "The jumping legs enabled ~" a video would also be necessary.

- We thank the reviewer for the suggestion and agree that showing each movement in a continuous sequence would improve the readability. However, due to the limited control input to the main microcontroller, we are unable to command the robot to do different locomotion modes without reprogramming for each locomotion mode. It is difficult to replace this microcontroller because this microcontroller is essential for synchronous

movements of the leg motors.

- To address this recommendation, we added supplementary video 1 to the revised manuscript where we concatenate all locomotion modes in a single video.
- For lines 124-126, we have referred to the jumping take-off video and figure 2a in the revised manuscript, as shown below.

the required take-off speed (Fig. 2c; at t = 0.17 s), similar to birds[9]. The jumping legs enabled the robot to start flight at a height of 0.4 m (0.8 BL), helping it clear potential ground obstacles (Fig. 2a and Supplementary Video 3).

2. How does RAVEN compare to other multi-modal robots in terms of energy efficiency and generation speed when performing jumping take-off?

- We appreciate the reviewer for the thoughtful comment. To the best of our knowledge, RAVEN is the first fixed-wing drone that can perform jumping take-off for powered flight, walk, hop, and jump over obstacle. Therefore, we are unable to compare energy efficiency and generation speed for jumping take-off with other winged multi-modal robots. There exist smaller-scale winged robots that can jump and glide or flap. Unfortunately, the articles describing these robots do not provide sufficient information to assess energy efficiency and generation speed, and compare them with RAVEN's. For jumping speed, those robots mostly use winches and a releasing latch to load and store energy: although this strategy can generate high jumping speed, it cannot be used to support multiple gait patterns as RAVEN does.

3. I understand the analysis of the impact of various take-off strategies on RAVEN's flight acceleration using the jumping legs. However, since Raven has fixed wings and uses propellers for propulsion, comparing it with take-off strategies that are not suitable for flying robots (such as vertical standing) seems to overstate the analysis. It would be nice to show the usefulness of jumping legs in a fairer situation.

- We appreciate the reviewer's advice and agree that the vertical standing take-off is not an ideal strategy for fixed-wing drones. Indeed, runway or launcher-assisted take-off is more appropriate for these types of drones. However, our objective was to test take-off in scenarios where a runway or launcher is not available. Therefore, we narrowed down the take-off strategies to jumping, falling, and vertical take-offs, which are possible options for birds, to study advantages of jumping take-off and better understand why this strategy is preferred by birds. To avoid overstating the analysis, we added the following text to the revised manuscript.

Page 5:

To examine the advantage of using jumping legs rather than using only the propeller for take-off in scenarios where a runway or launcher is not available, we conducted experiments on falling take-off and standing take-off where flight initiation relied solely on the propeller. We then compared these

4. Lines 19-21: “We show ~” could be misleading. The term " solely propeller-based take-off" is confusing and unclear, as it conjures up images of a typical takeoff of a fixed-wing aircraft.

- We agree that this statement could confuse readers and modified the sentence in the revised manuscript as follows:

Page 1:

obstacles and gaps similar to the multi-modal locomotion of birds. We show that jumping for take-off contributes substantially to initial flight take-off speed[6–9] and, remarkably, that it is more energy-efficient than taking off without the jump. Our analysis suggests an important tradeoff in mass

5. It appears that the height jump is not included in the Froude number and Cost of Transport (CoT) analysis in Figures 3g and 3h. Is there a reason for its omission? It would be [Hopefully, there were no other major comments omitted when the editor compiled the reviews!]

- We did not include height jump in the Froude number and Cost of Transport (CoT) analysis because these two metrics are mostly used for horizontal locomotion. In addition, robot and animal data shown in Figures 3g and 3h refer only to horizontal ground travel. We therefore think that it is comparatively appropriate to use only horizontal locomotion (walking and forward hopping) of our robot for the data shown in Figures 3g and 3h.

Referee #2 (Remarks to the Author):

The article presents a novel multi-modal bird-inspired robot capable of transitioning from terrestrial to aerial locomotion. The authors present a detailed design, simulation, and evaluation of bird-inspired legs that enable such transition as well as hopping, walking, and jumping on the ground. The article is well-written, and the analysis is presented well. I have a few minor suggestions for the authors.

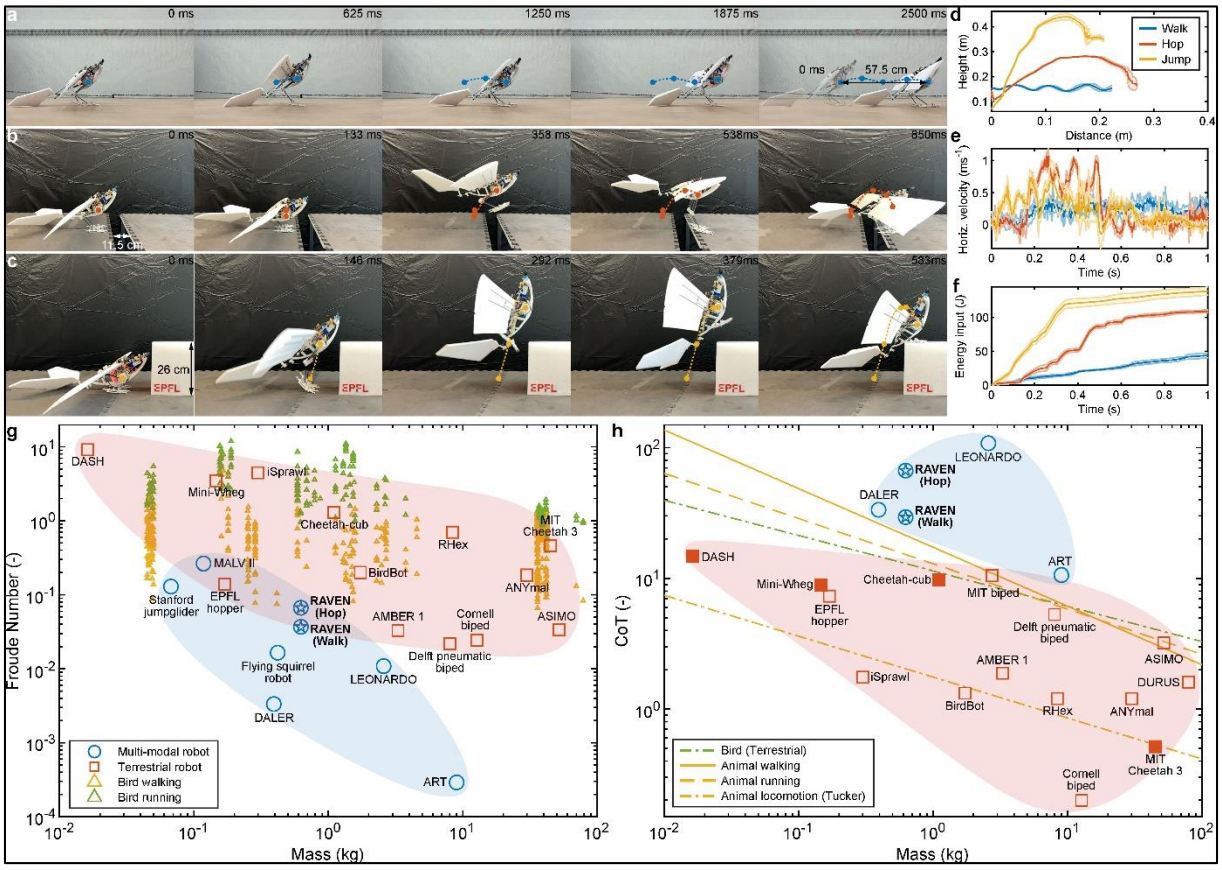
- We thank the reviewer for the positive comments.

1) For the robot's performance, distances and velocities are sometimes presented as just absolute values or as absolute values and percentages of the leg length. I recommend presenting things more consistently. Also, consider presenting takeoff velocity and height (and other relevant metrics) as body properties rather than just leg properties. For example, in line 174, the authors write, "The experiments showed that the drone could walk at a forward speed of 0.23 ms−1". In my opinion, this should be reported in terms of body length per second rather than leg length per second.

- We thank the reviewer for the comment. In the revised manuscript, we have stated both absolute values and body lengths.

2) Figure 3g would benefit from adding bird data for comparison, similar to what the authors did for 3h.

- We thank the reviewer for the suggestion and added bird Froude numbers to Figure 3g of the revised manuscript and a small discussion on the bird Froude numbers:



performance. The Froude numbers tend to decrease with weight for both robots and birds, but the decreasing rate of robots was steeper. When comparing birds and robots of similar weights, birds achieve higher Froude numbers than multimodal robots. Most multi-modal drones exhibited a higher

3) Finally, I really appreciate the authors' efforts in comparing the energetics of the different and relating that to birds' takeoff strategies, as I think this is a very valuable use of physical models to test biological hypotheses. However, for mechanical systems, I suggest that the authors clarify or discuss how these efficiency numbers would shift for different takeoff strategies if the legs were designed for that strategy. For example, for the falling takeoff strategy, the legs could simply be wheels or simple landing gear, and the robot weight would be significantly less, and the power consumption would be significantly less for the lighter robot.

- We agree with the reviewer that efficiency would shift for different take-off strategies without legs. Replacing the complicated legs with simple wheels for running take-off or landing gear for vertical take-off would reduce total body mass, and thus increase take-off efficiency. Legs represent an extra payload in flight even for birds. However, although legs reduce flight efficiency, they let the drone increase ground mobility and do not require a runway or launcher. We have added more discussion in the revised manuscript as follows:

Page 6:

method to convert actuation energy to kinetic and potential energies for flight. For falling and standing take-off, legs could be replaced by simpler mechanisms, such as wheels, to reduce total body mass and thus increase take-off efficiency. However, bird-inspired legs, such as those described here, offset their added mass in drones and birds by increasing ground mobility and avoiding need for a runway or launcher.

Overall, I commend the authors on a strong publication.

- We would like to thank the reviewer again for the positive feedback and appreciation of the manuscript.