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

Peer Review File

ATMO: An Aerially Transforming Morphobot for Dynamic Ground-Aerial Transition

Corresponding Author: Professor Morteza Gharib

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
To make the paper fit into the scope of the journal the authors need to be clearer about a few things:
a. What is different between this design and the work in [16] (Specially in terms of design)?
b. Look at morpho-transition dynamics papers in the past, and be more careful about statements that specify that morphological adaptation has not been utilized for multi-modal behavior before. Because it absolutely has, evidently in a lot of work in aerial-aquatic transitions for example (flying-swimming, flying-sailing, etc.).
i. Zufferey, R., Ancel, A.O., Raposo, C., Armanini, S.F., Farinha, A., Siddall, R., Berasaluce, I., Zhu, H. and Kovac, M., 2019. Sailmav: Design and implementation of a novel multi-modal flying sailing robot. IEEE Robotics and Automation Letters, 4(3), pp.2894-2901.
c. Define clearly in the introduction and abstract why this particular transition is absolutely necessary, especially for these use cases: including last mile delivery, space exploration, large scale fire-fighting, and industrial maintenance and inspection. (Just naming possible use cases that are significantly different from each other with different functional requirements doesn't help).
d. Comment on the lateral drifting of the ATMO during mid-air transitions
e. Demonstrating outdoor flight transitions is crucial

Reviewer #2

(Remarks to the Author)
This paper describes a ground-aerial vehicle that can tilt its rotors in mid-air to perform seamless ground-aerial transition. The authors also showed that ground effect contributes to increase the rotor tilting angle of the vehicle during the transition. Overall, the paper is well-structured, and thorough in design, characterization and practical demonstration. These points make the paper worth publishing in Communications Engineering. I have several points that I hope the authors can address before further consideration.

1. The reviewer enjoyed reading the paper but the writing is somewhat unclear and can be shorten. I recommend the authors to polish the paper to make it more concise.
2. What are the drawbacks of the mid-air transformation? For example, how is the energy cost of this method compared to that of on-ground transformation? The authors should discuss this in the paper.
3. Lines 21-22, page 3: “Surprisingly, we find that the robot is able to land in body configurations more extreme than those expected when ignoring aerodynamic effects” This sentence is a bit unclear. The review find difficult to understand its meaning without reading the whole paper. The authors should state explicitly what aerodynamic effects are (ground effect?). Anyway, ground effect always presents during landing and takeoff, and so, it is not so surprised. In addition, no comparison was done between the two cases with and without aerodynamic effects. How the authors come to this conclusion if the vehicle transforms and descends in both cases?
4. Do landing angle, body angle, and tilt angle all refer to the wheel tilt angle? If so, please make it consistent.
5. The authors characterized and tested for tilt angles of higher than 40 degrees. What if the tilt angle is just 30 degrees or lower, where is sufficient to land the wheels, instead of the belly, on the ground, and continue the transformation while running? Energy cost should be also less in this case.
6. The reason for the mid-air transformation is for the scenario that the vehicle cannot do it on the ground. However, all demonstrations took place on a flat surface. It is therefore better if the vehicle can demonstrate some use cases on inclined or rough surfaces.
7. The authors should explain in the paper how the safety cable works and its effects on the transition.
8. Page 5, line 17: What is the nominal thrust?

9. Page 5, lines 26-27: Please state clearly what the aerodynamic effects are.
10. Page 5, lines 29-32: The authors should elaborate more why cascaded PID cannot handle this task. In the supplementary videos, the transition was also manually controlled without position control (?) and the vehicle was not very stable. Then, with only attitude control, can cascaded PID do that?
11. Page 7, lines 7-11 should be moved to Fig. 5 caption.
12. Fig. 3, please define the normalized thrust? For consistent and clarity, it is also better to normalize all the thrust values to that from the zero tilt angle without the ground effect to see how thrust changes with the tilt angle.

Reviewer #3

(Remarks to the Author)
The authors have presented a bi-modal morphing drone capable of transitioning continuously between ground and aerial operations. There are three contributions, but the novelty is mild:

1) Design of the morphing drone, which is similar to Morphobot[1].
2) Continuous transition achieved using MPC with an adaptive objective function, but the effect is unclear without a comparison to a simpler control solution. Judging from video 2, the operation is not smooth, as the drone falls rapidly when reaching proximity of ground. It could be argued that a conventional controller might provide similar performance.
3) Revealed the propeller's ground effect in the presence of rotor tilting, providing useful insights for the application of closely positioned tilting rotors, but this finding is unlikely to provide new understandings with crucial influence in the field.

The preparation of the manuscript also needs improvement. It lacks important information, and the text is generally not easy to follow. Figures should be also be improved for clarification. The study has the potential for a good conference paper, but the novelty along with the manuscript quality do not meet the standards for publication in Communications Engineering.
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[1] Sihite, Eric, et al. "Multi-Modal Mobility Morphobot (M4) with appendage repurposing for locomotion plasticity enhancement." Nature communications 14.1 (2023): 3323.

Below are some specific comments that could be helpful for improving the manuscript:

1. Page 4 row 5, the sentence "ATMO achieves flying and driving using the same dual-purpose actuators" is misleading, because each "dual-purpose actuator" has two motors dedicated to flying and driving respectively.

2. The terminology for the "dual-purpose actuator" varies in the text ("wheel-thrust actuators" on p3r4, "wheel thruster combination" on p7r7, "wheel-thruster combination" on p7r15). A consistent term should be used.

3. On p4r24, if \phi=60 provides critical thrust, then \phi=50 provides 35% thrust margin doesn't seem correct, but the Methods section is not providing more information on this.

4. The symbol v is used as both tilt angle velocity and ground velocity.

5. A clear illustration of the morphing mechanism should be provided in Fig. 2B, where the joints, slider and constraints should be clearly visible. Currently, it is not possible to tell how tilting is achieved. The rotors could also be included in the drawing to help understanding.

6. P7r17, according to the authors, the \Delta\phi=15 is an important indicator of controller performance, but it is unclear to me why a large \Delta\phi is beneficial to the operation. A smoother landing could be achievable with a smaller \Delta\phi.

7. Fig.3 reported normalised thrust. How is this normalisation done?

8. Video 3 is not cited in the text.

9. I find the manuscript difficult to follow. For instance, the abstract can be expanded for clarity. E.g., the author-defined terms including "dynamic wheel landing manoeuvres", "flights-initiating driving takeoffs" are not readily understandable.

10. The introduction should be improved to provide a clearer message. The results are mixed into the introduction without explanation, e.g., on page3, row10-14, "a critical body shape where the available thrust in the vertical direction is not enough to counteract the force of gravity" is not understandable without reading the result section. On p2r25, the authors mentioned the morphing can "minimise landing impact", but it is unclear to me why this is the case.

11. Also in introduction, p3r21,"Surprisingly, we find that the robot is able to land in body configurations more extreme than those expected when ignoring aerodynamic effects. This is achieved by exploiting a ground-effect body posture relationship that was uncovered experimentally…" Is the exploited effect the increase of thrust owning to ground effect? Should be more specific.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The authors have reflected all my previous comments and I think the paper is now acceptable in CE.

Reviewer #3

(Remarks to the Author)
The authors have addressed my previous comments to a satisfactory extent, and the paper, including writing, figures and videos are much improved. The contribution of the paper has been validated by the added result of comparison with PID controller, as well as the additional videos of operation without safety cable. The video of landing on slope also verifies the robustness of the method.

The result of the paper is now worth publishing. However, the paper still needs a more straightforward storyline. Currently, the motivation of the study is still not clear to readers, and the design decisions made by the authors still appear confusing. The authors should modify the abstract and introduction to address a few more considerations especially regarding the clarity of the story.

1. To my understanding, the objective of the research is to land the vehicle in a folded state to avoid the terrain-vehicle interaction during morphing. However, instead of using the method proposed by the authors, this can be done by transforming mid-air while hovering, then descend and land, but according to the authors this is not achievable without leveraging the ground effect. If my understanding is correct, the authors may consider improving the story, e.g., by explaining it like: Considering the weight-sensitive nature of aerial vehicles, robots like ATMO re-use the rotor structure for ground operation, at a cost of reduced actuator redundancy. As a result, morphing is needed to transition between aerial and ground locomotion modes. It is beneficial to conduct morphing mid-air rather than on the ground to avoid the complexity of dealing with ground-vehicle interactions during morphing, but this requires the robot to operate beyond actuator capability. The paper address this problem in an innovative way that morphing is conducted near ground to leverage a ground effect, which achieves a smooth and complete transition, the method is also potentially useful for other ground-aerial vehicles with tilting rotors. I suggest the authors to consider implementing a more straightforward storyline in the abstract and introduction. Currently, the motivation is still not clear to the readers.

2. Connected to the previous point, in the 5th paragraph of introduction, the authors mentioned adverse aerodynamic effects such as the "fountain effect". However, to my understanding, the study is leveraging favourable aerodynamic effect instead of dealing with adverse effects, and the "fountain effect" is only mentioned in the introduction. This paragraph is therefore confusing the reader.

3. In the 4th paragraph of Introduction, the authors motivates the design decision to transform mid-air by stating "to minimise landing impact of an actuator fails, avoid obstacles, and improve fault tolerance". To me, the motivation can be simply understood as "to avoid ground-vehicle interaction during morphing". I don't understand why mid-air transition can help with actuator failure and improve fault tolerance. Of course "minimise landing impact of an actuator fails" is true if transition happens near ground (although most readers probably won't get this point), but this is not an advantage of mid-air transition as mentioned here.

4. Also in paragraph 4, the author mentioned "debris or otherwise rough terrain". I find this confusing, because "debris" reminds me of objects that moves under propeller wake. To the concern of the paper, debris should already be included in the term rough terrain.

5. The phrase "unified structural and actuation system" in the abstract and elsewhere is not a standard term. The authors should elaborate or simplify.

6. The revised Fig.2B is much better, but could still benefit from minor modifications: Lines should be added between the two boxes on the left to show the relation between the two. To meet the standard for publication, the sketch on the right should adhere to the convention of kinematic diagrams, e.g., it is currently unclear whether the link CDE is a unified link pivoted on D, rather than two separates links CD and DE, and it is unclear that A is a slider.

We would like to thank the Reviewers for their helpful comments and critiques. We have addressed all their comments, each of which improved and clarified the manuscript. Major changes include:

- We have added an overview video that summarizes the work (Video 1). This video better motivates our work and explains the key concepts and results in an easily accessible format.

- We performed a comparison of our controller to a standard PID controller via numerical experiments that highlight the advantage of our approach. The results have been added as Supplementary Note 1: Comparison to Cascaded PID controller, as well as a video showing the controller comparison in action (Video 10).

- We improved the controller tuning and replaced the results on Figure 6(A) and (B) with a new driving, flying, landing experiment that is much smoother than before, and that does not use the safety tether. The new experiment can be seen in Video 3.

- We performed four new experiments showing improved controller performance:
  - Driving takeoff and landing with forward velocity *without a tether* (Video 3)
  - Autonomous landing and takeoff *without a tether* (Video 4).
  - Landing on a slope (Video 5).
  - Landing with forward velocity (Video 6).

- We added more detail regarding the aerodynamic testing as Supplementary Note 2: Aerodynamics.

- We simplified the Introduction and Abstract to make the message clearer and expanded the Discussion section to better contextualize the work within the literature.

- We changed the paper title from "Mid-Air Robotic Transformation for Dynamic Ground-Aerial Transition" to "ATMO: An Aerially Transforming Morphobot for Dynamic Ground-Aerial Transition" in an effort to make the paper message clearer.

All changes are detailed in point-by-point responses below. All responses and changes to the manuscript are colored in blue.

Reviewer #1

1. This work and their previous work on morphobots in Sihite et. al [16] highlight an interesting approach to aerial-terrestrial translations, utilizing the wheels as thrusters.

   a. The add-on in this work is the dynamic model of the flight dynamics during quasi-static morphing

2. The authors state the enabling of rapid transitions:

   a. Dynamic wheel landing maneuvers
   b. Driving-to-flying and flying-to-driving transitions

3. Exploring the near-ground aerodynamics at different landing angles is definitely an interesting scientific problem.

4. Figures are well organized and developed.

Video Submission Notes: Videos highlight the system's mid-air transformation well. In one of the videos, a phone on the side drops as the morphobot lands, maybe the team can just crop this so the focus in solely on the robot itself.

Response: We thank the Reviewer for their positive summary of our work. We have cropped the mentioned video to remove the phone which had dropped during the experiment, improving the video quality. We agree with all the concerns of the Reviewer expressed in the following section, and we have addressed each comment below.

Comments to Authors:

1. The fundamental question regarding this work is:

   a. Whether it is necessary to even perform mid-air transitions for the tasks the authors have mentioned

   b. Why not just land and then transition or transition before flight?

      Response: We agree with the reviewer's points (a) and (b) that we have not sufficiently highlighted the potential use cases of the proposed mid-air transition maneuver. We have made significant efforts to amend this – see our responses to point 1(c) and 7(c) for further explanations.

   c. Why does the transition have to be gradual and not in a more rapid manner?

      i. Authors have stated that morphobots need this ability to minimize landing impact, avoid obstacles, and improve fault tolerances.

ii. The reason authors have stated this need is because of debris and rough terrain that hinders the ground motion of the robot appendages. But morphobot's transformational workspace does not take a lot of space, so I'm not sure if this is the strongest reason why.

Response: Regarding points (i) and (ii), we agree with the Reviewer that there are other reasons why mid-air transition can be preferable to ground transformation. However, we still contend that debris and rough terrain can hinder the motion of ground appendages.

To make this point clearer, we have included an example where the robot gets stuck when transforming on rough terrain in summary Video 1. Here, in the last scene we show that when ATMO transforms on the ground it cannot tilt its wheels all the way, due to the ground terrain hindering the appendage motion. This then does not allow it to effectively drive away from the rough ground. However, when the robot has a higher tilt angle it can drive out from the rough terrain with ease.

Regarding the Reviewer's question of why the transition should be gradual and not in a more rapid manner: this is an excellent point. Indeed, transitioning in a rapid manner may provide different benefits that we have not explored in this paper. However, this is difficult to achieve with the actuators that we have found on the market when considering space and weight restrictions. Furthermore, we believe that gradual transformation can help achieve smoother landings, especially in the case of larger/heavier robots where controlling the impact velocity is essential. By gradually transforming rather than a rapid transformation we are also able to leverage the ground effect to smooth the impact. Please also see our response to point 1(d) below.

We hope that these points help to clarify the role of mid-air transformation for our use case.

iii. The second reason regarding autonomous landings due to the aerodynamic fountain-effect is a relatively fixed problem in quadrotors, so the morphobot can just land and transition too.

Response: Indeed, the robot could just land and transform like a regular quadrotor, but this might not be possible on inclined landing terrain or rough terrain. We have added a comment that addresses this concern in the Discussion section of the paper. We write:

> "[…] landing with lower, or no, tilt angle may be acceptable when the landing site is flat."

d. Personally, I think the main reason for mid-air transitions is to control the impact velocity (as the authors have mentioned) and then transition quickly into terrain travel. For flight it seems better to transform first or rapidly transform instead of a gradual one.

Response: We agree with the reviewer on the point that mid-air transitions can be used to control impact velocity and transition quickly into terrain travel. We have further highlighted this in the manuscript by explicitly stating in the abstract that:

> "[…] the ability to change shape mid-air while landing can offer a distinct advantage, enabling landing on rough terrain where ground transformation may not be possible, landing on slopes, as well as improving transition speed and protecting actuators"

Thus, we highlight one of the main points for which mid-air transformation can be beneficial. Regarding the question of whether it is better to transform first or rapidly transform we have partly addressed this in response to Reviewer's point 1(c). As mentioned previously, gradually transforming may be beneficial for smoother landings by using the ground effect. Furthermore, rapid transformation may require heavier or more complex actuators. To clarify the reason why gradual transformation is used we have included the following sentence in the Results section when describing the Ground-Aerial Morpho-Transition Controller:

> "The use of ground effect during the landing is a key reason for which gradual transformation may be advantageous compared to rapid transformation in morpho-transition landings."

2. For example Page 2, line 11

   a. For aerial-terrestrial you could cite (seems like a better match then [8]).

      i. Ramirez, J.P. and Hamaza, S., 2023. Multimodal locomotion: next generation aerial– terrestrial mobile robotics. Advanced Intelligent Systems, p.2300327.

   Response: We thank the reviewer for bringing this reference to our attention. We agree that this is a good match to support our claims and have referenced it in the main text.

3. For line 19-12 in Page 2 (Introduction), authors have cited a lot of work on terrestrial-aquatic transitions which don't necessarily support this work that looks at flight transitions [17-20]. Instead, I would look at work that transitions between air-water & air-ground for these citations. Even air-to-perching too. Authors honestly are missing a lot of citations from morphing-arm based aerial robots that tackle the same problem when

morphing their arms, here are some examples (note that a lot of work is currently being done for morphing flight and morpho-transition dynamics in terms of dynamics and controls too, unlike what the authors claim):

a. Ruiz, F., Arrue, B.C. and Ollero, A., 2022. Aeroelastics-aware compensation system for soft aerial vehicle stabilization. *Frontiers in Robotics and AI*, *9*, p.1005620.
b. Ruiz, F., Arrue, B. and Ollero, A., 2023. A novel concept for Titan robotic exploration based on soft morphing aerial robots. arXiv preprint arXiv:2311.08952.
c. Jinjie Li, Junichiro Sugihara, Moju Zhao. Servo Integrated Nonlinear Model Predictive Control for Overactuated Tiltable-Quadrotors. IEEE Robotics and Automation Letters, 2024.
d. Moju Zhao, Tomoki Anzai, Takuzumi Nishio. Design, Modeling, and Control of a Quadruped Robot SPIDAR: Spherically Vectorable and Distributed Rotors Assisted Air-Ground Quadruped Robot. IEEE Robotics and Automation Letters, 2023.
e. Zheng, P., Xiao, F., Nguyen, P.H., Farinha, A. and Kovac, M., 2023. Metamorphic aerial robot capable of mid-air shape morphing for rapid perching. Scientific Reports, 13(1), p.1297.
f. Ryll, M. and Katzschmann, R.K., 2022, May. SMORS: A soft multirotor UAV for multimodal locomotion and robust interaction. In 2022 International Conference on Robotics and Automation (ICRA) (pp. 2010-2016). IEEE.
g. Falanga, D., Kleber, K., Mintchev, S., Floreano, D. and Scaramuzza, D., 2018. The foldable drone: A morphing quadrotor that can squeeze and fly. IEEE Robotics and Automation Letters, 4(2), pp.209-216.

Response: Complied. We agree with the Reviewer that we should tailor some of our references to more specifically target work that looks at flight transitions. Our claim that Morphobot designs are “thought to enhance the efficiency of mobile autonomous robots faced with changing unstructured environments” is well supported by references [17,18,20] on the original manuscript. However, we agree with the Reviewer that reference [19] less adequately demonstrates the claim. We removed reference [19] and added two of the suggested references (a) and (e) that better demonstrate how shape change, particularly for flight transitions, can enhance robot efficiency in unstructured environments.

Regarding the Reviewer’s claim that we are missing some references from the morphing-arm literature, we would like to mention that reference (g) stated by the Reviewer to be missing was already included in the initial manuscript as reference [38].

Regarding references (c), (d), and (f) above. We agree with the Reviewer’s assessment that these are highly relevant to our discussion concerning other state-of-the-art morphing quadrotor designs. We have added them to support the Discussion section. We also use reference (d) to make our claims about morphological adaptation being used for multi-modal behavior before more precise (point 7b of the Reviewer's initial comments).

4. Are the transitions more energy efficient than just transitioning before flying or terrain travelling?

   Response: We cannot claim that mid-air transition is more energetically efficient than landing and then transitioning, because of the additional thrust required to fly with tilted thrusters. Of course, depending on the landing terrain, it might be necessary to land with large tilt angles. Nevertheless, we have added a brief section about the energetic efficiency in the Discussion section of the text:

   > "[…] Other than high tilt angles at landing being an important metric for controller performance, landing with larger tilt angles can also enable ATMO to clear debris that may be present at the landing site. On the other hand, since flying with a larger tilt angle also demands a higher thrust, it is less energetically beneficial. Indeed, landing with lower, or no, tilt angle may be acceptable when the landing site is flat while also consuming less power."

5. There seems to be a lot of vibration during ground-to-air transitions in the videos, as well as drifting side-to-side during air-to-ground transitions. I would assume this wouldn't be safe for critical landing scenarios; how do the authors plan to fix this?

   Response: We have added a comment regarding this issue in the results section and performed a second experiment to show that our controller can perform better. The results are shown in Video 4 – there is much less lateral drifting now. We believe that the lateral drifting was due to wind disturbances present in the flight arena or controller cost function parameters. We have written the following to bring this to the Reader's attention:

   > "Note that, the robot shows a noticeable lateral drift during the maneuver (Video 2). This might have been due to wind disturbances present in the CAST flight arena or controller tuning. We repeated the experiment with better tuned cost function parameters (see Methods section) and report noticeably less lateral drifting, as can be seen in Video 4 of the supplementary materials. The safety tether was also removed showing that additional forces were not applied to the robot during the maneuver."

   Please also see our response to Reviewer's comment 7(d).

6. In the last paragraph of the introduction one of the contributions of this work is the design of the ATMO, how is this design significantly different than the authors' previous work in [16]?

Response: We agree with the Reviewer that we have not sufficiently emphasized the novelty of ATMO's design in the manuscript, which can lead to confusion. ATMO differs from M4 in 4 major ways:

a. The actuators used on the M4 robot only allowed for ground transformation since sustaining the torque requirements of continuous mid-air transformation would have required much heavier and more expensive actuators. ATMO was designed specifically for mid-air transformation through a novel tilt actuator design (depicted in Figure 2) that is self-locking by virtue of the screw mechanism used. This allows ATMO to transform during flight without actuator damage.
b. The M4 robot has more actuators for body posture manipulation that allows it to perform different locomotion gaits but also complexifies the design. ATMO simplifies the design paradigm down to the essentials of ground-aerial locomotion – the ability to drive and fly. We achieve this using a single actuation mechanism that changes the shape of all four wheel-thruster appendages simultaneously as opposed to the 12 actuators that were used for body posture manipulation in the M4 robot. This mechanism greatly simplifies design, reduces cost, and results in symmetric shape change by virtue of the mechanics without the need of a software implementation to synchronize many servo motors.
c. We use a differential drive system with belts that synchronize the left and right wheel pairs respectively, as opposed to the 4 separate motors that are used for each wheel on the M4 robot.
d. The electronics architecture is much simpler since no external micro-controller is used and the software is built on one central onboard computer that interfaces with a flight controller. We have developed a general-purpose code for ground aerial locomotion vehicles with mid-air transformation capabilities that works on ROS2 which we believe can greatly accelerate development of versatile ground-aerial vehicles in the robotics community. We are prepared to make our code public if our manuscript is accepted for publication.

Please see our response to point 7(a) for a summary of the changes made to clarify these points.

7. To make the paper fit into the scope of the journal the authors need to be clearer about a few things:

    a. What is different between this design and the work in [16] (Specially in terms of design)?

       Response: We have incorporated the differences between ATMO and M4 (see our response to point #6 above) in various places in the manuscript.

In the Introduction, when ATMO was introduced as a contribution, we emphasized the novelty in the design by adding that ATMO distinguishes itself from other state of the art flying-driving robots like the M4,

> "[…] through a unified structural and actuation system that enables body shape change mid-flight with minimal actuation requirements"

To make this point clearer to the reader we have added in the Results section the sentence:

> "To achieve [the problem of mid-air transformation], we re-used some design principles from the M4 robot with the key difference that all posture manipulation actuators were removed and replaced by a single morphing mechanism. The morphing mechanism, depicted in Figure 2(B) dynamically controls the tilt angle, \varphi, of four wheel-thruster pairs using a single brushed DC motor."

We also made the contribution in terms of the tilt actuator design clearer through the following text which explains how the mechanism works:

> "[The morphing mechanism] works using a closed-loop kinematic linkage that is actuated by a DC motor that rotates a central worm gear. This rotation results in linear motion of joint A which is then converted to rotational motion of joints B, C, and D - tilting the wheel-thruster appendages symmetrically"

To make this even clearer, we have amended Figure 2(B) to make the tilt actuator mechanism clearer. We have added more detail in terms of the joints and links, and we have also added a video (Video 9) which shows how the mechanism works. Hopefully, this clarifies the novelty in terms of the design. To further emphasize this, we have added the following sentence in the Results section:

> "Compared to the M4 robot [14], the number of actuators controlling the body posture is reduced from 12 to 1 resulting in an overall simpler system with fewer failure points."

Finally, in the Discussion section we have added that,

> "ATMO distinguishes itself from other flying-driving robots by virtue of a self-locking tilt actuator mechanism that enables mid-air transformation with minimal actuation requirements, lower cost, and simpler overall design."

b. Look at morpho-transition dynamics papers in the past and be more careful about statements that specify that morphological adaptation has not been utilized for multi-modal behavior before. Because it absolutely has, evidently in a lot of work in aerial-aquatic transitions for example (flying-swimming, flying-sailing, etc.).

1. Zufferey, R., Ancel, A.O., Raposo, C., Armanini, S.F., Farinha, A., Siddall, R., Berasaluce, I., Zhu, H. and Kovac, M., 2019. Sailmav: Design and implementation of a novel multi-modal flying sailing robot. IEEE Robotics and Automation Letters, 4(3), pp.2894-2901.

Response: We agree with the Reviewer's assessment that morphological adaptation has indeed been used for multi-modal behavior before. We did not intend to claim that we were the first work to study/show this but instead we wanted to highlight how mid-air transformation can enhance ground-aerial behavior. We have softened some of our claims to address this:

a. In the Introduction, instead of claiming that "a current gap in the capabilities of Morphobots is the ability to transform mid-air", we instead write:

   > "A lesser explored capability of Morphobots is the ability to use shape change to transform mid-air as a means to enhance ground-aerial locomotion."

b. We have changed the claim in the Discussion, page 8 lines 7-9:
   "Although other folding quadrotor designs have been employed for fitting through narrow gaps [38, 39, 40, 41, 42], or for achieving full actuation [43], their morphologies do not extend to applications which require multi-modal behaviour" to instead read:

   > "Although other morphing quadrotor designs have been employed for fitting through narrow gaps [33, 34, 35, 36, 37], or for achieving full actuation or manipulation capabilities [18,38,39], fewer works have used mid-air transformation to enhance ground-aerial locomotion performance [40]."

   Note that we have also expanded the references we cite following some of the Reviewer's suggestions (point #7b) as well as from other sources. In particular, we have emphasized the example of SPIDAR, suggested by the Reviewer, that we cite as reference [40] (reference (d) from point #7b) as an example of another robotic systems that use mid-air transformation to enhance ground aerial locomotion.

c. Define clearly in the introduction and abstract why this particular transition is absolutely necessary, especially for these use cases: including last mile delivery, space exploration, large scale fire-fighting, and industrial maintenance and inspection. (Just naming possible use cases that are significantly different from each other with different functional requirements doesn't help).

Response: We agree with the Reviewer that we had not made the proposed use cases of the mid-air transition maneuvers clear enough. As mentioned previously we have added a video that showcasing landing on an inclined slope. We have also demonstrated the scenario where ATMO can get stuck on rough terrain if it does not have a sufficiently high tilt angle in summary Video 1. We have emphasized the potential use cases in many places within the text, particularly the abstract and introduction. In the abstract we state:

> "Robotic explorers that navigate their terrains by combining ground and aerial locomotion often encounter complex, unstructured environments, including rough landing or takeoff sites. In such scenarios, the ability to change shape mid-air while landing can offer a distinct advantage, enabling landing on rough terrain where ground transformation may not be possible, landing on slopes, as well as improving transition speed and protecting actuators."

In the introduction we have also added that another potential use case for mid-air transformation is:

> "A lesser explored capability of Morphobots is the ability to use shape change to transform mid-air as a means to enhance ground-aerial locomotion. This could provide them with the crucial ability to reconfigure optimally to minimize landing impact if an actuator fails, avoid obstacles, and improve fault tolerance."

Regarding the use cases mentioned (last mile delivery, space exploration, large scale fire-fighting, and industrial maintenance and inspection) we agree with the Reviewer that the use cases are significantly different from each other. We have removed fire-fighting and industrial maintenance as examples and have retained only last mile delivery and space exploration which share similar characteristics like the nature of landing terrains that such robots may have to contend with.

d. Comment on the lateral drifting of the ATMO during mid-air transitions

Response: We have added a comment on lateral drifting in the text:

> "Note that, the robot shows a noticeable lateral drift during the maneuver (Video 2). This might have been due to wind disturbances present in the CAST flight arena or controller tuning. We repeated the experiment with better tuned cost function parameters (see Methods section) and report noticeably less lateral drifting, as can be seen in Video 4 of the supplementary materials. The safety tether was also removed showing that additional forces were not applied to the robot during the maneuver."

As mentioned previously, we have also performed a second experiment to show that our controller can perform better. The results are shown in Video 4 – with significantly less lateral drifting now.

e. Demonstrating outdoor flight transitions is crucial

Response: We agree with the Reviewer that it would have been more appealing to demonstrate outdoor flight transitions. However, the sensing required to achieve this exceeds our current capabilities. Instead, we have added untethered experiments indoors, as well as a landing on a slope to demonstrate the robustness of our approach. We would also like to note that the CAST flight arena is indeed outdoors and wind disturbances are quite common in the arena. This makes us confident that these flight transitions would indeed work in an outdoor environment.

Although we are unable to perform outdoor flight transitions at this time, this is a top priority for us as soon as we can extend the sensor suite of the robot. We have included a comment in the Discussion section to state this intention:

> "Immediate next steps involve […] extending ATMO's sensor suite to enable flight transitions in outdoor environments".

With these revisions, we hope the Referee finds the manuscript suitable for publication.

Reviewer #2

Reviewer: This paper describes a ground-aerial vehicle that can tilt its rotors in mid-air to perform seamless ground-aerial transition. The authors also showed that ground effect contributes to increase the rotor tilting angle of the vehicle during the transition. Overall, the paper is well-structured, and thorough in design, characterization and practical demonstration. These points make the paper worth publishing in Communications Engineering. I have several points that I hope the authors can address before further consideration.

Response: We thank the Reviewer for their positive summary of our work. We agree with all major concerns of the Reviewer, and we have addressed each comment below.

> 1. The reviewer enjoyed reading the paper, but the writing is somewhat unclear and can be shorten. I recommend the authors to polish the paper to make it more concise.
>
> **Response:** We appreciate the Reviewer's positive comment regarding reading our paper. As suggested by the Reviewer, we have made significant efforts to make the writing clearer. Major changes include modifying the abstract and shortening the introduction. Some of these changes are detailed below.
>
> We have removed lines 12-14 from the original manuscript:
>
>> **"**Indeed, as the robot morphs mid-flight, vertical thrust is lost, resulting in the existence of a critical body shape where the available thrust in the vertical direction is not enough to counteract the force of gravity.**"**
>
> This part is unnecessary since it mixes results into the introduction, obfuscating the message we want to convey. We have also removed lines 21-24 since they were difficult to understand without reading the results section:
>
>> "Surprisingly, we find that the robot is able to land in body configurations more extreme than those expected when ignoring aerodynamic effects. This is achieved by exploiting a ground-effect body posture relationship that was uncovered experimentally through aerodynamic testing and flow field visualization."
>
> These considerations are now reserved for the Results and Discussion sections.
>
> We also removed pg. 5 lines 24-26 from the section *Ground-Aerial Morpho-Transition Control* to improve readability:
>
>> "These three phases are characterized by distinct dynamic equations of motion. Although quadrotor flight dynamics and control have been well studied, both morphing flight and morpho-transition dynamics are unexplored by the aerial robotics community."

Overall, we have polished the paper throughout, and we hope that the writing is now more concise and easier to read.

2. What are the drawbacks of the mid-air transformation? For example, how is the energy cost of this method compared to that of on-ground transformation? The authors should discuss this in the paper.

Response: As the Reviewer has pointed out, energetic efficiency is indeed a drawback of mid-air transformation. Because of the additional thrust required when flying in a tilted configuration, the power consumed is greater when landing with larger tilt angles. Of course, depending on the landing terrain, it might be necessary to land with large tilt angles. We have added these considerations about the energetic efficiency in the Discussion section of the text:

> "High tilt angles at landing are an important metric for controller performance, since they are challenging to achieve with standard control methods that do not account for actuator constraints. Landing with larger tilt angles also enables ATMO to clear debris that may be present at the landing site. Of course, since flying with a larger tilt angle also demands a higher level of thrust, it is less energetically beneficial. As a result, landing with lower, or no, tilt angle may be acceptable and consume less power in some cases - for example when the landing site is flat and ground transformation is possible."

3. Lines 21-22, page 3: "Surprisingly, we find that the robot is able to land in body configurations more extreme than those expected when ignoring aerodynamic effects" This sentence is a bit unclear. The review find difficult to understand its meaning without reading the whole paper. The authors should state explicitly what aerodynamic effects are (ground effect?). Anyway, ground effect always presents during landing and takeoff, and so, it is not so surprised. In addition, no comparison was done between the two cases with and without aerodynamic effects. How the authors come to this conclusion if the vehicle transforms and descends in both cases?

Response: We have decided to remove this part from the Introduction, as stated in response #1 above, since it contained results that were difficult to understand without reading the entire paper, as the Reviewer has stated. However, since we also made a similar claim in the Abstract, we have decided to rephrase the Abstract to clear confusion.

Firstly, we agree with the Reviewer that we should be clearer when referring to aerodynamic effects. We have amended the abstract to clearly mention "ground-effect in the presence of rotor tilting."

Furthermore, we agree that it is not possible to compare cases with and without aerodynamic effects, since we cannot remove the influence of aerodynamics in our experiment. To reduce the confusion, we have removed the claim (page 1 line 9 - page 2 line 2) in our Abstract,

> "Surprisingly, we show that it is possible to land and takeoff from body configurations that would have been impossible when ignoring aerodynamic effects, by utilizing an experimentally uncovered relationship between ground-proximity and body posture,"

And we have replaced it with:

> "We study how aerial transformation influences the near-ground aerodynamics and find that ground-effect under propeller tilting is present but only persists up to a certain tilt angle. By leveraging these aerodynamics as well as a dynamic model of morphing flight dynamics, we develop a model-predictive controller that adapts to ground proximity and body shape. The control method is validated by demonstrating smooth transitions from air to ground, and vice-versa. Notably, we find that ATMO can land at body postures past its actuator saturation limits by virtue of the uncovered ground-effect."

Overall, we have made explicit that the aerodynamic effect we are referring to is the ground effect, we have removed the use of the word "surprisingly". We also removed the implicit comparison of the cases with and without aerodynamic effects and we instead make the softer claim that ground effect contributes positively to the landing maneuver.

4. Do landing angle, body angle, and tilt angle all refer to the wheel tilt angle? If so, please make it consistent.

Response: Complied. Body angle and tilt angle indeed both refer to the wheel tilt angle. We have removed references to the body angle and replaced them by tilt angle. Landing angle refers to the tilt angle at landing i.e. the tilt angle when the robot touches the ground. To clarify this point we have replaced all instances of landing angle by "tilt angle at landing".

5. The authors characterized and tested for tilt angles of higher than 40 degrees. What if the tilt angle is just 30 degrees or lower, where is sufficient to land the wheels, instead of the belly, on the ground, and continue the transformation while running? Energy cost should be also less in this case.

Response: This is an excellent point. The current implementation of ATMO can indeed land at 30 degrees or lower and this might be sufficient for some applications. However, the focus of this manuscript is to show how far we can push the mid-air transformation while still landing with a desired impact velocity. We have amended the text to highlight in the discussion why it is important to maximize the tilt angle at landing. We added the following comment:

> "High tilt angles at landing are an important metric for controller performance, since they are challenging to achieve with standard control methods that do not account for actuator constraints. Landing with larger tilt angles also enables ATMO to clear debris that may be present at the landing site. Of course, since flying with a larger tilt angle also demands a higher level of thrust, it is less energetically beneficial. As a result, landing with lower, or no, tilt angle may be acceptable and consume less power in some cases - for example when the landing site is flat and ground transformation is possible."

6. The reason for the mid-air transformation is for the scenario that the vehicle cannot do it on the ground. However, all demonstrations took place on a flat surface. It is therefore better if the vehicle can demonstrate some use cases on inclined or rough surfaces.

Response: We thank the Reviewer for bringing this to our attention. We have added two more demonstrations to address this comment.

First, in summary Video 1 (last scene) we have added an example showing that when ATMO transforms on the ground it cannot tilt its wheels all the way, due to the ground terrain hindering the appendage motion. This in turn does not allow it to drive out of the rough area. When the robot has a higher tilt angle, and the chassis is elevated off the ground it is able drive away from the rough terrain with ease. Thus, we have showed an example of why mid-air transformation may be useful for landing on rough terrain.

Second, we have taken the Reviewer's advice and added a demonstration of landing on an inclined surface. We performed an experiment of landing on a slope of known height and position. The results have been included in the Experimental validation section. Figure 6 has been amended to include these new results, and we have added a new video (Video 5) to showcase the capability.

We hope that these two examples make clearer the utility of our method, specifically regarding landing on rough or inclined surfaces.

7. The authors should explain in the paper how the safety cable works and its effects on the transition.

Response: We thank the Reviewer for bringing this omission to our attention. We have repeated some of the experiments without the safety tether to show that it was not influencing our results.

We repeated the experiment in Figure 6(A) (previously Video 1) without the safety tether and show the results in Video 2. Our results show that we are able to perform the flight transitions without the safety tether in place.

We also repeated the experiment shown in Figure 5 to show that it can be done without the safety tether as well. We have included a comment to bring this to the reader's attention in the Experimental Validation section:

> "The safety tether was also removed showing that additional forces were not applied to the robot during the maneuver."

8. Page 5, line 17: What is the nominal thrust?

Response: We thank the reviewer for bringing this to our attention. We have indeed not defined the nominal thrust. What we are referring to is the thrust away from the ground at the same tilt angle. We have removed mention to the nominal thrust and have replaced it with "thrust away from the ground" to remove any confusion. The text now reads:

> "Taking into account the standard deviation, we observe that the thrust force can fall to as low as 85% of the thrust away from the ground as the robot approaches the ground for \varphi=70 degrees."

For completeness we have also added the unnormalized thrust values in Supplementary Note 2. We have notified the reader of this addition in the Aerodynamic Testing section of the methods:

> "For the unnormalized thrust values obtained in this experiment, the reader is referred to Supplementary Note 2."

9. Page 5, lines 26-27: Please state clearly what the aerodynamic effects are.

Response: We thank the reviewer for bringing this omission to our attention. We were referring to rotor-rotor downwash interactions but since we have stated this point multiple times we decided to remove these lines to make the message of the text clearer and more concise, as suggested in Point #1.

10. Page 5, lines 29-32: The authors should elaborate more why cascaded PID cannot handle this task. In the supplementary videos, the transition was also manually controlled without position control (?) and the vehicle was not very stable. Then, with only attitude control, can cascaded PID do that?

Response: Clarification. The transitions were all done in position control. For the results in Figure 5 no manual input is given and the robot tracks a predefined spatial trajectory.

For the results of Figure 6 the user is giving position commands. However, this was done simply for convenience and can also be done without any human input.

We agree with the Reviewer that we should elaborate more on why cascaded PID cannot handle this task. We have added a comparison of our controller to the cascaded PID controller from the PX4 autopilot software, a framework widely adopted by the quadrotor community, via numerical experiments in the Gazebo Simulation framework.

Our results are documented in: "Supplementary Note 1: Comparison to Cascaded PID controller." Here, we show that the cascaded PID controller is unable to stabilize ATMO when morphing while flying. We also provide an explanation for this by examining the dynamic couplings which emerge as ATMO morphs while flying. Thus, we have shown that a standard cascaded flight controller cannot stabilize ATMO in morphing flight. We have added a comment in the main manuscript to alert the reader of this supplemental result:

> "[…] off-the-shelf conventional flight control architectures which rely on cascaded PID loops that decouple attitude and position control do not directly apply for the stabilization of mid-flight morphing robots of this type, as shown via numerical experiments in Supplementary Note 1 and Video 10."

Of course, if only attitude control is needed then it would be possible to modify the standard cascaded PID for quadrotors to achieve this. One way to achieve it would be through gain-scheduling on the tilt angle at the lowest body rate level and replacing the SE3 attitude controller with another gain-scheduled PID controller or LQR controller. However, this requires significant engineering effort and does not generalize to the control of other morphing aerial robots as the body rate level has to be tuned independently for each robot.

The advantages of our approach are that:

1. Our MPC controller takes into account actuator constraints without further engineering effort. The nature of the problem we are trying to solve is one where actuator constraints play a major role since approaching or surpassing the critical angle requires careful consideration of the thrust limits of the robot.
2. Our MPC controller can adapt to ground proximity via a high-level adaptive objective function. This approach can also be applied to other robotic systems with different ground effect characteristics with minimal controller re-design. The alternative would again be to adapt to ground proximity via gain scheduling on the height variable. However, this may be very difficult to achieve due to the large amount of experimentation needed to accomplish. Furthermore, this approach does not offer the same flexibility or interpretability.
3. Our approach is simpler to set up and can be applied to other aerial robots. With the code developed, the dynamics model is the only major change that must be

made when transferring this method to a robot with different dynamics in ground-aerial transition.

We have included these considerations in the Discussion section of the manuscript to make clearer the advantage of our approach. We state:

> "Since the nature of the morpho-transition problem for ATMO is one where actuator constraints play a major role, using a model predictive controller allows us to seamlessly incorporate constraints such as the thrust limits into the controller. While it is in theory possible to use different control methods such as gain scheduling combined with linear quadratic control, these methods require significant engineering effort and offer less interpretability."

11. Page 7, lines 7-11 should be moved to Fig. 5 caption.

Response: Complied. We have moved the lines indicated to the Figure 5 caption. We agree that this information is more suitable within the figure caption rather than in the main text of the paper.

12. Fig. 3, please define the normalized thrust? For consistent and clarity, it is also better to normalize all the thrust values to that from the zero-tilt angle without the ground effect to see how thrust changes with the tilt angle.

Response: The current reported values on Figure 3 are thrust values measured at the load cell that are normalized by the thrust far away from the ground. This choice of normalization gives a measure of the amount of ground effect, which is useful when looking at this specific morpho-transition maneuver. We agree with the Reviewer that this should be explained within the text of the paper. To this end, we have added a comment on how the normalization is done within the caption of Figure 3, and we have also added more details on the normalization within the Aerodynamic Testing section of the methods.

Regarding the Reviewer's request to normalize thrust values from the zero-tilt angle without the ground effect to show how thrust changes with tilt angle, we have performed these measurements using our aerodynamic test rig and have provided plots with this information in the Supplementary Note 2 and Figure S.3. This shows the approximate cosine decay that is expected when normalizing with respect to the zero-tilt angle without ground effect. We think this is an interesting addition and thank the Reviewer for the insightful comment.

With these revisions, we hope the Referee finds the manuscript suitable for publication.

Reviewer #3

Reviewer: The authors have presented a bi-modal morphing drone capable of transitioning continuously between ground and aerial operations. There are three contributions, but the novelty is mild:

Response: We thank the Reviewer for the succinct summary of our paper contributions. We address each of the comments below in response:

1. Design of the morphing drone, which is similar to Morphobot [1].

   Response: The Aerially Transforming Morphobot (ATMO) differs from the design of M4 (referenced by the Reviewer as [1]) in 4 main ways.

   a. The M4 robot was only capable of transforming on the ground since the actuators employed were unable to sustain the torque requirements of continuous mid-air transformation. On the other hand, ATMO was designed and built specifically for mid-air transformation through a novel tilt actuator design (depicted in Figure 2) that is self-locking by virtue of the screw mechanism used. This allows ATMO to transform during flight without actuator damage.
   b. The M4 robot has more actuators for body posture manipulation that allows it to perform different locomotion gaits but also complexifies the design. ATMO simplifies the design paradigm down to the essentials of ground-aerial locomotion – the ability to drive and fly. We achieve this using a single actuation mechanism that changes the shape of all four wheel-thruster appendages simultaneously as opposed to the 12 actuators that were used for body posture manipulation in the M4 robot. This mechanism greatly simplifies design, reduces cost, and results in symmetric shape change by virtue of the mechanics without the need of a software implementation to synchronize many servo motors.
   c. We use a differential drive system with belts that synchronize the left and right wheel pairs respectively, as opposed to the 4 separate motors that are used for each wheel on the M4 robot.
   d. The electronics architecture is much simpler since no external micro-controller is used and the software is built on one central onboard computer that interfaces with a flight controller. We have developed a general-purpose code for ground aerial locomotion vehicles with mid-air transformation capabilities that works on ROS2 which we believe can greatly accelerate development of versatile ground-aerial vehicles in the robotics community. We are prepared to make our code public if our manuscript is accepted for publication.

We agree with the Reviewer that the manuscript did not clearly expose these points. To amend this we have incorporated the differences between ATMO and M4 in various places in the manuscript.

In the Introduction, when ATMO was introduced as a contribution, we emphasized the novelty in the design by adding that ATMO distinguishes itself from other state of the art flying-driving robots like the M4,

> "[…] through a unified structural and actuation system that enables body shape change mid-flight with minimal actuation requirements"

To make this point clearer to the reader we have added in the Results section the sentence:

> "To achieve [the problem of mid-air transformation], we re-used some design principles from the M4 robot \cite{Sihite2023} with the key difference that all posture manipulation actuators were removed and replaced by a single morphing mechanism. The morphing mechanism, depicted in Figure 2(B) dynamically controls the tilt angle, \varphi, of four wheel-thruster pairs using a single brushed DC motor."

We also made the contribution in terms of the tilt actuator design clearer through the following text which explains how the mechanism works:

> "[The morphing mechanism] works using a closed-loop kinematic linkage that is actuated by a DC motor that rotates a central central worm gear. This rotation results in linear motion of joint A which is then converted to rotational motion of joints B, C, and D - tilting the wheel-thruster appendages symmetrically"

To make this even clearer, we have amended Figure 2(B) to make the tilt actuator mechanism clearer. We have added more detail in terms of the joints and links, and we have also added a video (Video 9) which shows how the mechanism works. Hopefully, this clarifies the novelty in terms of the design. To further emphasize this, we have added the following sentence in the Results section:

> "Compared to the M4 robot [14], the number of actuators controlling the body posture is reduced from 12 to 1 resulting in an overall simpler system with fewer failure points."

Finally, in the Discussion section we have added that,

> "ATMO distinguishes itself from other flying-driving robots by virtue of a self-locking tilt actuator mechanism that enables mid-air transformation with minimal actuation requirements, lower cost, and simpler overall design."

2. Continuous transition achieved using MPC with an adaptive objective function, but the effect is unclear without a comparison to a simpler control solution. Judging from video 2, the operation is not smooth, as the drone falls rapidly when reaching proximity of ground. It could be argued that a conventional controller might provide similar performance.

   Response: We agree with the Reviewer's comment that comparing our MPC controller to a simpler control solution would better demonstrate the advantages of the proposed controller. We compare our controller to the cascaded PID controller from the PX4 autopilot software, a framework widely adopted by the quadrotor community, via numerical experiments in the Gazebo Simulation framework.

   Our results are documented in: "Supplementary Note 1: Comparison to Cascaded PID controller." Here, we show that the cascaded PID controller is unable to stabilize ATMO when morphing while flying. We also provide an explanation for this by examining the dynamic couplings which emerge as ATMO morphs while flying. Thus, we have shown that a standard cascaded flight controller cannot stabilize ATMO in morphing flight. We have added a comment in the main manuscript to alert the reader of this supplemental result:

   > "[…] off-the-shelf conventional flight control architectures which rely on cascaded PID loops that decouple attitude and position control do not directly apply for the stabilization of mid-flight morphing robots of this type, as shown via numerical experiments that in Supplementary Note 1 and Video 10."

   Of course, one might still question why using MPC is necessary to stabilize ATMO during morphing flight and ground-aerial transitions. While it might indeed be possible to modify the standard cascaded PID algorithm by gain-scheduling on the tilt angle at the lowest body rate level and replacing the SE3 attitude controller with another gain-scheduled PID controller or LQR controller, this requires significant engineering effort. Furthermore, this process does not generalize to the control of other morphing aerial robots as the body rate level has to be tuned independently for each robot.

   The advantages of our approach are that:

   1. Our MPC controller takes into account actuator constraints without further engineering effort. The nature of the problem we are trying to solve is one where actuator constraints play a major role since approaching or surpassing the critical angle requires careful consideration of the thrust limits of the robot.
   2. Our MPC controller can adapt to ground proximity via a high-level adaptive objective function. This approach can also be applied to other robotic systems with different ground effect characteristics with minimal controller re-design.

The alternative would again be to adapt to ground proximity via gain scheduling on the height variable. However, this may be very difficult to achieve due to the large amount of experimentation needed to accomplish. Furthermore, this approach does not offer the same flexiblity or interpretability.

3. Our approach is overall simpler to set up and can be applied to other aerial robots. With the code developed, the dynamics model is the only major change that must be made when transferring this method to a robot with different dynamics in ground-aerial transition.

We have included these considerations in the Discussion section of the manuscript to make clearer the advantage of our approach. We state:

> "Since the nature of the morpho-transition problem for ATMO is one where actuator constraints play a major role, using a model predictive controller allows us to seamlessly incorporate constraints such as the thrust limits into the controller. While it is in theory possible to use different control methods such as gain scheduling combined with linear quadratic control, these methods require significant engineering effort and offer less interpretability."

3. Revealed the propeller's ground effect in the presence of rotor tilting, providing useful insights for the application of closely positioned tilting rotors, but this finding is unlikely to provide new understandings with crucial influence in the field.

Response: We would like to emphasize that mid-air transition is generally of interest to the fields of aerial robotics as well as aviation. With the advent of novel ground aerial vehicles with non-trivial morphologies we believe that a thorough characterization of propeller interactions with boundaries and other rotor flows is essential for safe operation and new capabilities.

Tilted rotor flows are already present in various aerial vehicles like the tilted propeller quadrotors. Systems like this, among others, are likely to benefit from a more thorough characterization of the aerodynamic flow fields, particularly in the presence of boundaries, to ensure safe and efficient operation. To emphasize the importance of the propeller ground effect in the presence of rotor tilting and rotor interactions we have done some literature search to find potential applications. We have included in the Discussion the following references:

1. Yiliang Liu, Zi Kan, Huadong Li, Yuzhe Gao, Daochun Li, Shiwei Zhao, Analysis and modeling of the aerodynamic ceiling effect on small-scale propellers with tilted angles, Aerospace Science and Technology, 2024.
2. Ambar Garofano-Soldado, Pedro J. Sanchez-Cuevas, Guillermo Heredia, Anibal Ollero, Numerical-experimental evaluation and modelling of

aerodynamic ground effect for small-scale tilted propellers at low Reynolds numbers, Aerospace Science and Technology, 2022.
3. Garofano-Soldado, Ambar and Gonzalez-Morgado, Antonio and Heredia, Guillermo and Ollero, Anibal, Assessment and Modeling of the Aerodynamic Ground Effect of a Fully-Actuated Hexarotor With Tilted Propellers, IEEE Robotics and Automation Letters, 2024.
4. Hsiao, Yi Hsuan and Chirarattananon, Pakpong, Ceiling Effects for Surface Locomotion of Small Rotorcraft, International Conference on Intelligent Robots and Systems (IROS), 2018.
5. Hsiao, Yi-Hsuan and Bai, Songnan and Zhou, Yongsen and Jia, Huaiyuan and Ding, Runze and Chen, Yufeng and Wang, Zuankai and Chirarattananon, Pakpong, Energy efficient perching and takeoff of a miniature rotorcraft, Communications Engineering, 2023.
6. Ding, Runze and Hsiao, Yi-Hsuan and Jia, Huaiyuan and Bai, Songnan and Chirarattananon, Pakpong, Passive Wall Tracking for a Rotorcraft With Tilted and Ducted Propellers Using Proximity Effects, IEEE Robotics and Automation Letters, 2022.
7. Ding, Runze and Bai, Songnan and Dong, Kaixu and Chirarattananon, Pakpong, Aerodynamic effect for collision-free reactive navigation of a small quadcopter, npj Robotics, 2023.

We also included in the Discussion how we see our findings extending to other areas of robotics based on the literature search conducted:

> "Aerodynamic models for robotic systems with tilted thrusters approaching the ground are still in their infancy [44,45], even more so when rotor-rotor interactions are included in the analysis. Our findings may be applied for emerging scenarios such as passive wall tracking using tilted propellers [46], collision-free reactive navigation [47], or energetically efficient perching maneuvers that exploit proximity effects like the ceiling effect [48,49] but have not yet considered the potential benefits of using tilted rotors [50]."

The preparation of the manuscript also needs improvement. It lacks important information, and the text is generally not easy to follow. Figures should also be improved for clarification.

Response: We agree with the Reviewer, that the text readability and Figures should be improved to ameliorate the manuscript. As suggested by the Reviewer, we have made significant efforts to make the writing clearer. Major changes include modifying the abstract and shortening the introduction. Some of these changes are detailed below.

We have removed lines 12-14 from the original manuscript:

> “Indeed, as the robot morphs mid-flight, vertical thrust is lost, resulting in the existence of a critical body shape where the available thrust in the vertical direction is not enough to counteract the force of gravity.”

This part is unnecessary since it mixes results into the introduction, obfuscating the message we want to convey. We have also removed lines 21-24 since they were difficult to understand without reading the results section:

> “Surprisingly, we find that the robot is able to land in body configurations more extreme than those expected when ignoring aerodynamic effects. This is achieved by exploiting a ground-effect body posture relationship that was uncovered experimentally through aerodynamic testing and flow field visualization.”

These considerations are now reserved for the Results and Discussion sections.

We also removed pg. 5 lines 24-26 from the section *Ground-Aerial Morpho-Transition Control* to improve readability:

> “These three phases are characterized by distinct dynamic equations of motion. Although quadrotor flight dynamics and control have been well studied, both morphing flight and morpho-transition dynamics are unexplored by the aerial robotics community.”

In terms of changes to Figures, we have improved Figure 2 by specifically improving the depiction of the tilting mechanism. We also added more detail to the captions of Figures 2, 3, 5 and 6.

Overall, we have polished the paper and Figures throughout, and we hope that the writing is now more concise and easier to read and the content is more complete.

The study has the potential for a good conference paper, but the novelty along with the manuscript quality do not meet the standards for publication in Communications Engineering.

Response: We hope that our responses to points 1, 2, and 3 above can allow the Reviewer to reconsider. We have also added new content and improved overall paper quality. We refer the Reviewer to the major changes reported at the top of the document as well as our response to the subsequent comments for further information.

Below are some specific comments that could be helpful for improving the manuscript:

Response: We thank the Reviewer for the detailed comments. We agree with all of them and have addressed them below.

1. Page 4 row 5, the sentence "ATMO achieves flying and driving using the same dual-purpose actuators" is misleading, because each "dual-purpose actuator" has two motors dedicated to flying and driving respectively.

Response: We agree with the reviewer's assessment. Indeed, there are separate driving and flying actuators (4 thruster motors and 2 driving actuators). What we mean to highlight is that the same *appendages* are being used for driving and flying. To this end we have amended the text to read "ATMO achieves flying and driving using its dual-purpose appendages through shape change" - replacing the word "actuators" with "appendages".

2. The terminology for the "dual-purpose actuator" varies in the text ("wheel-thrust actuators" on p3r4, "wheel thruster combination" on p7r7, "wheel-thruster combination" on p7r15). A consistent term should be used.

Response: We agree with the reviewer that using different terms to refer to the same component is confusing. We have amended the text to include only references to *"wheel-thruster appendages"* instead of "wheel thruster combination", "wheel-thruster combination", or "wheel-thruster actuators". In some cases, we have retained the use of the adjective "dual-purpose" to emphasize that multiple functions are being fulfilled by the same appendages.

3. On p4r24, if \phi=60 provides critical thrust, then \phi=50 provides 35% thrust margin doesn't seem correct, but the Methods section is not providing more information on this.

Response: We thank the Reviewer for bringing this omission to our attention. We have added the calculation which shows that there is 35% thrust margin at 50 degrees maximum tilt angle in the critical angle subsection of the Methods section.

4. The symbol v is used as both tilt angle velocity and ground velocity.

Response: We have changed the symbol for ground velocity from lowercase v to uppercase V to reduce confusion.

5. A clear illustration of the morphing mechanism should be provided in Fig. 2B, where the joints, slider and constraints should be clearly visible. Currently, it is not possible to tell how tilting is achieved. The rotors could also be included in the drawing to help understanding.

Response: We agree with the Reviewer that it would be better to provide more detail on the morphing mechanism. We have updated Figure 2B to better illustrate the tilt mechanism. We have included three objects.

1. We have a full schematic of ATMO shown in a morphed configuration in flight. This gives the reader context as to where the tilt actuator is placed within the robot and what each component represents. It also shows where the rotors are relative to the tilt actuator mechanism as suggested by the Reviewer.
2. We included a diagram that shows how the tilt actuator is actuated by the two co-rotating bevel gears with all the joints clearly labeled.

3. We expanded the mechanism diagram on the right all the way up to the propeller and have clearly labeled all the joints and the degrees of freedom.

Finally, we have added a new video, Video 10, that shows an animation of the tilt mechanism in action. We also added an explanation of the mechanism in the new summary video (Video 1). We believe this clears up any confusion regarding how the tilting is achieved, and also makes clearer the contributions and novelty in terms of design.

6. P7r17, according to the authors, the \Delta\phi=15 is an important indicator of controller performance, but it is unclear to me why a large \Delta\phi is beneficial to the operation. A smoother landing could be achievable with a smaller \Delta\phi.

Response: We argue in this paper that landing with a large tilt angle is beneficial for aerial-ground transition for two major reasons 1) it allows for rapid dynamic transition i.e. the robot is already in driving mode at touch down, and 2) landing at larger tilt angles can be beneficial to clear debris present on rough landing terrains. We have added the following in the Discussion section to clarify why \Delta\phi = 15 is an important indicator of controller performance

> "High tilt angles at landing are an important metric for controller performance, since they are challenging to achieve with standard control methods that do not account for actuator constraints. Landing with larger tilt angles also enables ATMO to clear debris that may be present at the landing site."

We also discuss the drawbacks which include a higher energetic cost and state clearly that if mid-air transformation is not necessary landing and then transforming can conserve energy:

> "Of course, since flying with a larger tilt angle also demands a higher level of thrust, it is less energetically beneficial. As a result, landing with lower, or no, tilt angle may be acceptable and consume less power in some cases - for example when the landing site is flat and ground transformation is possible."

7. Fig.3 reported normalized thrust. How is this normalization done?

Response: The normalization is done by taking the thrust measured at the load cell and normalizing it by the thrust far away from the ground. As such, the normalized thrust value gives a measure of the amount of ground effect. To clarify this point we have added a comment on how the normalization is done within the caption of Figure 3, and we have expounded on the normalization in the Aerodynamic Testing section of the Methods.

8. Video 3 is not cited in the text.

Response: We thank the Reviewer for bringing this to our attention. Indeed, in the original manuscript, Video 3 was simply showing that the maneuver can be replicated. We have removed Video 3 since it did not add anything new to the manuscript. Instead, we have added new videos showcasing different capabilities - see the major changes section at the top of this document. We have also taken special care to cite all the included videos within the text.

9. I find the manuscript difficult to follow. For instance, the abstract can be expanded for clarity. E.g., the author-defined terms including "dynamic wheel landing manoeuvres", "flights-initiating driving takeoffs" are not readily understandable.

Response: We have expanded and clarified the abstract to remove undefined jargon like “dynamic wheel landing maneuvers” or “flight-initiating driving takeoffs” that are not readily understandable. Instead, we introduce the robot and its capabilities using the simpler phrasing shown below:

> “Here, we introduce the Aerially Transforming Morphobot (ATMO), a robot specialized for aerial transformation by virtue of a unified structural and actuation system that enables mid-flight shape change with minimal actuation requirements.”

We have also attempted to clarify the logic of the abstract to better reflect the content of the manuscript. We removed the confusing phrasing at the end of the abstract mentioned in point 11 below and we replaced it with the simpler

> “By leveraging these aerodynamics as well as a dynamic model of morphing flight dynamics, we develop a model-predictive controller that adapts to ground proximity and body shape. The control method is validated by demonstrating smooth transitions from air to ground, and vice-versa. Notably, we find that ATMO can land at body postures past its actuator saturation limits by virtue of the uncovered ground-effect.”

We hope that the many simplifications and improvements to the text (discussed previously), combined with removing unnecessary jargon and keeping the paper timeline clearer, we hope that the manuscript is now much easier to follow

10. The introduction should be improved to provide a clearer message. The results are mixed into the introduction without explanation, e.g., on page3, row10-14, "a critical body shape where the available thrust in the vertical direction is not enough to counteract the force of gravity" is not understandable without reading the result section. On p2r25, the authors mentioned the morphing can "minimise landing impact", but it is unclear to me why this is the case.

Response: We agree with the Reviewer that it would be much better to not include results in the introduction section without explanation. We have removed two such instances. As the reviewer mentions the phrase,

> “Indeed, as the robot morphs mid-flight, vertical thrust is lost, resulting in the existence of a critical body shape where the available thrust in the vertical direction is not enough to counteract the force of gravity,”

cannot be readily understood without reading the results section. We also believe that the following sentences,

> “Surprisingly, we find that the robot is able to land in body configurations more extreme than those expected when ignoring aerodynamic effects owing to increased thrust in proximity to the ground. This is achieved by exploiting a ground-effect body posture relationship that was uncovered experimentally through aerodynamic testing and flow field visualization. We utilize this finding to demonstrate the dynamic wheel landing maneuver, as well as a flight-initiating driving takeoff maneuver that consists of driving and rapidly taking off from ground configuration,”

also belong in the results section. As such we have removed two instances of results being mentioned in the introduction. We believe that the message of the introduction has become much clearer thanks to the Reviewer’s suggestions.

Regarding the comment on p2r25. We have amended this to state:

> “This could provide them with the crucial ability to reconfigure optimally to minimize landing impact if an actuator fails, avoid obstacles, and improve fault tolerance.”

What we mean is that mid-air transformation capabilities can enable fault tolerance. For example, reconfiguring the thrusters mid-flight might allow robots to compensate for one of the thrusters failing and regain some degree of control. We hope that the addition to the text makes this point clearer.

11. Also in introduction, p3r21,"Surprisingly, we find that the robot is able to land in body configurations more extreme than those expected when ignoring aerodynamic effects. This is achieved by exploiting a ground-effect body posture relationship that was uncovered experimentally…" Is the exploited effect the increase of thrust owning to ground effect? Should be more specific.

Response: As per the Reviewer’s suggestion in point #10, we have removed some of the results from the introduction section. However, we did make this point clearer whenever it was mentioned in the text. For example, in the abstract we write:

> “The control method is validated by demonstrating smooth transitions from air to ground, and vice-versa. Notably, we find that ATMO can land at body postures past its actuator saturation limits by virtue of the uncovered ground-effect.”

Thus, we explicitly state that the exploited effect is the increase of thrust owing to ground effect.

With these revisions, we hope the Reviewer finds the manuscript suitable for publication.

We would like to thank the Reviewers for their helpful comments and critiques. We have addressed all their comments, each of which improved and clarified the manuscript. All changes are detailed in point-by-point responses below. All responses and are colored in blue in the attached manuscript PDF file.

Reviewer #2

Reviewer: The authors have reflected all my previous comments and I think the paper is now acceptable in CE.

Response: We sincerely thank the reviewer for their valuable feedback and constructive suggestions, which have significantly improved the quality of our manuscript. We appreciate the time and effort dedicated to reviewing our work.

Reviewer #3

Reviewer: The authors have addressed my previous comments to a satisfactory extent, and the paper, including writing, figures and videos are much improved. The contribution of the paper has been validated by the added result of comparison with PID controller, as well as the additional videos of operation without safety cable. The video of landing on slope also verifies the robustness of the method.

Response: We thank the reviewer for their valuable and insightful feedback which greatly improved the quality of our manuscript, as well as the positive comments regarding the contribution of the paper. The time and effort dedicated to reviewing our work is evident in the thorough feedback that has been provided.

We agree with all the Reviewer's comments and have addressed them point by point below.

Reviewer: The result of the paper is now worth publishing. However, the paper still needs a more straightforward storyline. Currently, the motivation of the study is still not clear to readers, and the design decisions made by the authors still appear confusing. The authors should modify the abstract and introduction to address a few more considerations especially regarding the clarity of the story.

Response: We thank the Reviewer for their positive comment on our research results. We believe that, thanks to the suggestions given below, the Abstract and the Introduction have been greatly improved, and a simpler storyline has been implemented. We invite the Reviewer to see our detailed responses below.

1. **Reviewer:** To my understanding, the objective of the research is to land the vehicle in a folded state to avoid the terrain-vehicle interaction during morphing. However, instead of using the method proposed by the authors, this can be done by transforming mid-air while hovering, then descend and land, but according to the authors this is not achievable without leveraging the ground effect. If my understanding is correct, the authors may consider improving the story, e.g., by explaining it like: Considering the weight-sensitive nature of aerial vehicles, robots like ATMO re-use the rotor structure for ground operation, at a cost of reduced actuator redundancy. As a result, morphing is needed to transition between aerial and ground locomotion modes. It is beneficial to conduct morphing mid-air rather than on the ground to avoid the complexity of dealing with ground-vehicle interactions during morphing, but this requires the robot to operate beyond actuator capability. The paper addresses this problem in an innovative way that morphing is conducted near ground to leverage a ground effect, which achieves a smooth and complete transition, the method is also potentially useful for other ground-aerial vehicles with tilting rotors. I suggest the authors to consider implementing a more straightforward storyline in the abstract and introduction. Currently, the motivation is still not clear to the readers.

   Response: We thank the Reviewer for their detailed proposal on how we could refine and simplify the manuscript's story. We find the approach proposed by the Reviewer much clearer, drawing focus to the main messages we would like to convey. We have revised the abstract to follow this storyline. It now reads:

   > "Designing ground-aerial robots is challenging due to the increased actuation requirements which can lead to added weight and reduced locomotion efficiency. Morphobots mitigate this by combining actuators into multi-functional groups and leveraging ground transformation to achieve different locomotion modes. However, transforming on the ground requires dealing with the complexity of ground-vehicle interactions during morphing, limiting applicability on rough terrain. Mid-air transformation offers a solution to this issue but demands operating near or beyond actuator limits while managing complex aerodynamic forces. In this paper, we address this problem by introducing the Aerially Transforming Morphobot (ATMO), a robot which transforms near the ground achieving smooth transition between aerial and ground modes. To achieve this, we leverage the near ground aerodynamics, uncovered by experimental load cell testing, and stabilize the system using a model-predictive controller that adapts to ground proximity and body shape. The system is validated through numerous experimental demonstrations showing that ATMO can land at body postures past its actuator saturation limits by virtue of the uncovered ground-effect."

Furthermore, to ensure the Introduction is well aligned with the Abstract we have removed the 5th paragraph, which was confusing to the reader as suggested in point 2 below. Instead, we briefly mention the challenge of autonomous near ground operation for quadrotors in the second to last paragraph of the Introduction in the context of the challenge of mid-air transformation and near ground morphing. The added sentence reads:

> "[…] autonomous near ground aerial operation is a known challenging problem due to ground effect aerodynamics [21,22,23,24]."

We believe that the Abstract and Introduction are now much clearer. We have implemented a simpler storyline that highlights the main findings of our research work which we believe greatly improves the manuscript quality.

2. **Reviewer:** Connected to the previous point, in the 5th paragraph of introduction, the authors mentioned adverse aerodynamic effects such as the "fountain effect". However, to my understanding, the study is leveraging favourable aerodynamic effect instead of dealing with adverse effects, and the "fountain effect" is only mentioned in the introduction. This paragraph is therefore confusing the reader.

   Response: We agree with the Reviewer that mentioning the fountain effect can be confusing and does not add much to the story line. For this reason, we have removed this paragraph and added the essential part of it to the second to last paragraph of the Introduction, as stated in point 1 above. By doing so, we clarify the fact that the ground effect can be a difficult phenomenon to deal with for simpler aerial robots like quadrotors, let alone for the robots with more complex morphologies like ATMO, without confusing the reader with mentions to the fountain effect.

3. **Reviewer:** In the 4th paragraph of Introduction, the authors motivates the design decision to transform mid-air by stating "to minimise landing impact of an actuator fails, avoid obstacles, and improve fault tolerance". To me, the motivation can be simply understood as "to avoid ground-vehicle interaction during morphing". I don't understand why mid-air transition can help with actuator failure and improve fault tolerance. Of course "minimise landing impact of an actuator fails" is true if transition happens near ground (although most readers probably won't get this point), but this is not an advantage of mid-air transition as mentioned here.

   Response: We thank the Reviewer for their insightful way of framing the benefits of our work. We agree with the Reviewer that the essential benefit is "to avoid ground-vehicle interaction during morphing". We have implemented this phraseology in various parts of the introduction and abstract.

Furthermore, we have removed the confusing mentions to “minimizing landing impact if an actuator fails, avoid obstacles and improve fault tolerance”. We have instead replaced it with the Reviewer’s suggestion, leading to clearer and more succinct language. The sentence which was previously causing confusion now reads:

> “This could provide them with the crucial ability to avoid ground-vehicle interaction during morphing.”

4. **Reviewer:** Also in paragraph 4, the author mentioned "debris or otherwise rough terrain". I find this confusing, because "debris" reminds me of objects that moves under propeller wake. To the concern of the paper, debris should already be included in the term rough terrain.

   Response: We agree with the reviewer that the mention of debris can be unclear. We have removed it from paragraph 4 of the introduction and only refer to the rough terrain:

   > “[…] ground transformation may be impossible due to rough terrain that hinders the ground motion of the robot appendages.”

   We also removed mention of debris from the 4th paragraph of the Discussion section and replaced it with “uneven terrain”.

   We believe this simplification makes the motivation clearer.

5. **Reviewer:** The phrase "unified structural and actuation system" in the abstract and elsewhere is not a standard term. The authors should elaborate or simplify.

   Response: We agree with the reviewer that “unified structural and actuation system” is a non-standard term that may distract the reader from the main message of the text. We have replaced all mentions of it with the simpler “morphing mechanism”.

   When introducing morphobots (paragraph 4 of the introduction) instead of saying that they “reuse appendages through unified structural and actuation systems” we rephrased this as follows:

   > “Morphobots, or robots that reuse the same appendages for different tasks through shape change, are able to generate different locomotion modes while reducing system weight and complexity.”

   We believe these modifications express an equivalent message in clearer terms.

6. **Reviewer:** The revised Fig.2B is much better, but could still benefit from minor modifications: Lines should be added between the two boxes on the left to show the relation between the two. To meet the standard for publication, the sketch on the right should adhere to the convention of kinematic diagrams, e.g., it is currently unclear

whether the link CDE is a unified link pivoted on D, rather than two separates links CD and DE, and it is unclear that A is a slider.

Response: We agree with the Reviewer that Fig. 2B can be improved further. We have added dotted lines between the two boxes on the left to show the two extreme joints as well as the center line. This now allows the reader to relate the depiction of the mechanism with the depiction of the robot, improving readability.

We thank the reviewer for bringing to our attention some omissions from the kinematic diagram. We have modified it to adhere to the convention of kinematic diagrams. To do so, we changed the shape of link A to be a long rectangular shape depicted between two parallel grounded walls. This indicates that this joint can slide, as found in the literature of kinematic diagrams. We have also added the word "slider" to ensure a reader less familiar with the notation can understand the diagram.

Furthermore, we modified our depiction of joint D, which is indeed a fixed pivot point, as the reviewer has pointed out. We added the fixed pivot symbol from the literature as well as the phrase "fixed pivot".

As the reviewer points out, CDE is indeed a unified link pivoted on D and we hope that this is now clear directly from the figure. However, to ensure that this can be understood we have modified the Figure 2B caption to state this clearly:

> "CDE is a unified link pivoted on D."

Finally, we changed the color of all rotating or sliding joints to be "open" i.e. without color fill. We have added the following phrase in the Figure caption to make this clear to the reader:

> "Open colored joints represent rotating joints or sliders.

With these revisions, we hope the Referee finds the manuscript suitable for publication.