

A multi-modal hovering and terrestrial robot with adaptive morphology

S. Mintchev and D. Floreano

Abstract— Most current drones are designed with a static morphology aimed at exploiting a single locomotion mode. This results in limited versatility and adaptability to multi-domain environments, such as those encountered in rescue missions, agriculture and inspection, where multiple locomotion capabilities could be more effective. For example, hovering and terrestrial locomotion are complementary and can increase versatility by allowing the robot achieve speed and ease of obstacle negotiation during flight, or low power consumption and reduced noise signature while moving on the ground. With this aim, the paper presents the design and characterization of a multi-modal quadcopter with adaptive morphology by means of foldable arms. After landing, the quadcopter folds the frontal arms and uses wheels and tracks to move on the ground. The foldable arms allow to decrease the size of the robot in order to achieve more mobility in confined ground environments; to perform a self-righting maneuver if the drone falls upside down; and to negotiate large gaps by strategically unfolding them during terrestrial locomotion.

I. INTRODUCTION

The recent years have witnessed the rapid development of robots with hybrid or multi-modal locomotion in air, water and on ground [1][2]. The growing interest is associated to the quest for more versatile and adaptable robots in the fields of search and rescue, exploration and environmental monitoring, where multi-domain missions are a common place. Robots with a single mode of locomotion lack of versatility, which translates in a limited mobility and impossibility to perform a transition between different environments. Multi-modal robots overcome this problem by recruiting different modes of locomotion, each one of them suited for a specific environment.

Among the different types of locomotion modes, hovering flight and ground locomotion are complementary and their combination offers unique opportunities to largely extend the versatility and mobility of robots [3][4]. Hovering allows to rapidly overcome obstacles or to traverse uneven terrains, and to precisely fly to inaccessible locations, but it is energetically demanding. Terrestrial locomotion, compared to hovering, is more efficient, has a reduced noise signature and allows moving in confined space where flight is not possible or unsafe. The option of both modes of locomotion allows the robot to optimize over either speed and ease of obstacle negotiation or low power consumption and reduced noise signature. Furthermore, multi-modal aerial and ground locomotion also enables hybrid control strategies where, during terrestrial locomotion, steering [4] or adhesion [5] can be achieved or facilitated by aerodynamic forces. A promising application for multi-modal hovering and

terrestrial robots is search and rescue. For example, aerial locomotion can be used to rapidly fly above debris to reach a location of interest. Terrestrial locomotion can subsequently be used to thoroughly and efficiently explore the environment or to collect samples on the ground.

Although multi-modal locomotion is a viable solution to extend versatility and functionality of robots, it is still at an early stage of research and several challenges are limiting the effective development and deployment of multi-modal robots [1][2]. Often, multi-modal locomotion gives rise to unwanted trade-offs such as losses of maneuverability, speed and energetic efficiency [6][7]. Indeed, as animals, multi-modal robots are subject to conflicting requirements. These are imposed by the different physical properties of each environment that often require locomotion appendages with highly specialized morphologies and gaits. Therefore, an open research question is to identify design strategies that allow to seamlessly blend multiple modes of locomotion while maximizing performances over a broad range of environments. We showed that Adaptive Morphology is a viable design strategy to tackle this challenge [7]. Many flying animals such as birds, bats and insects change their morphology to transition from air to ground. Indeed, morphology plays an important role in behavioural and locomotion strategies of living systems, and there is biological evidence that adaptive morphological changes can extend dynamic performances by reducing trade-offs during multi-modal locomotion [7].

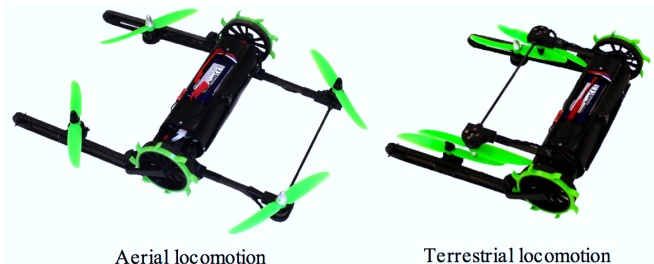


Figure 1. Multi-modal hovering and terrestrial robot. The drone is equipped with wheels and tracks for terrestrial locomotion. It can fold its frontal arms when transitioning to terrestrial locomotion

While state-of the art multi-modal hovering drones have fixed bodies (see section II), we leverage adaptive morphology to increase the versatility of the prototype by adding new functions and by increasing its mobility on the ground. The proposed design, depicted in Fig. 1, is a quadcopter in H configuration equipped with wheels for terrestrial locomotion. The morphology of the drone can be adapted by means of an actuator that folds the two frontal arms above the rear ones. In

the paper, we show that this morphing frame allows: (i) to transition from a shape suited for flight, to one tuned for terrestrial locomotion, (ii) to decrease the size for ease of transportation and of locomotion in confined ground environments, (iii) to perform a self-righting maneuver if the robot falls upside down, and (iv) to facilitate gap negotiation during terrestrial locomotion.

This paper aims at describing the design and the characterization of the hovering and terrestrial robot with foldable arms. First, an overview of previous works in the field of multi-modal hovering and terrestrial robots is presented. Then, the strategies adopted for the design of the robot are described. A first prototype of a morphing quadrotor is built and locomotion capabilities are tested. A discussion of the results concludes this paper.

II. PREVIOUS WORK

Multi-modal hovering and terrestrial robots are receiving a growing interest from researchers. Firstly, the trade-off between mobility and energetic consumption, can be overcome by combining flight with ground locomotion. Secondly, compared to multi-modal robots capable of forward flight, multi-modal hovering platforms can transition from ground to air without the need of additional take-off mechanisms [8], with the advantage of a simplified mechanical design and more robust operation.

Fig. 2 summarizes some state-of-the-art examples of multi-modal hovering and terrestrial drones. Overall, researchers focused on adding terrestrial capabilities on hovering platforms through wheels, legs or lightweight cages that can be exploited for rolling on the ground. For each prototype, the main challenge is to keep the platform as lightweight and simple as possible to avoid compromising the time of flight and maneuverability during hovering.

A first approach involves cages that can freely rotate around the hovering platform. Examples are HyTAQ [9] (Fig. 2A) and Gimbal [3] (Fig. 2B). The cage allows the drones to efficiently roll on the ground by using the thrust

generated by the propellers. Although this solution is elegant and mechanically simple, it has several drawbacks. Firstly, rolling cages produce additional drag, therefore increasing the sensitivity to wind during flight. Secondly, the cage increases the overall size of the robot, thus hindering the access to narrow gaps and exploration of cluttered environments. Thirdly, terrestrial locomotion is less efficient when performed by means of propellers rather than with wheels or legs [5]. Finally, propellers actuated near the ground generate dust that can reduce visibility, which is a critical requirement for inspection and reconnaissance.

In a second approach, passive wheels or legs are added to multicopters. For example, the Quadroller [10] is equipped with passive low friction wheels to travel on smooth surfaces (Fig. 2C). Like the previous prototypes, the thrust generated by the propellers allows the drone to move forward and to steer. DUCK is a quadcopter that exploits passive legs to walk [11] (Fig. 2D). The thrust from quadcopter's propellers enables the robot to take steps and walk on flat and inclined surface. Although these types of hovering drones are not equipped with cumbersome cages, they are still larger than terrestrial vehicles with similar weight. This is due to the non-negligible size of the aerodynamic surfaces required to sustain the weight during flight. Not surprisingly, many flying animals fold their aerodynamic surfaces, for instance wings, to do not hinder terrestrial locomotion in cluttered environments [12]. Moreover, the last two limitations described above for the first approach, apply to the second one as well.

To date, the most effective multi-modal drones employ additional active terrestrial locomotion systems, usually actuated wheels, tracks or legs. PicoBug is a miniature quadcopter with a single degree of freedom walking mechanism [4] (Fig. 2E). The origami legged mechanism is used to move the robot forward, and the torque generated by the propellers allows for steering. This integrated design approach where the same set of actuators is recruited for multiple modes of locomotion is exploited for weight and complexity reduction. A second example is B-Unstoppable [13], a quadcopter with caterpillar tracks for terrestrial



Figure 2. Examples of multi-modal hovering and terrestrial robots classified according to three different design strategies. I) Drones equipped with passively rolling cages, (A) HyTAQ and (B) Gimbal. II) Drones equipped with passive legs or wheels, (C) Quadroller and (D) DUCK. III) Drones equipped with actuated wheels or legs, (E) PicoBug, (F) B-Unstoppable and (G) prototype of multi-modal quadcopter with foldable arms for self-righting.

locomotion (Fig. 2F). Like the previous robots, also the ones belonging to this last category are oversized compared to terrestrial robots with a similar payload. In addition, these robots are not equipped with self-righting mechanisms, making impossible the take-off in case they fall upside down. An exception is the ground-air hybrid robot presented in [14] which is equipped with foldable arms used for self-righting (Fig. 2G). However, the proposed mechanical design is ineffective in uneven terrains where the arms fail to vertically stabilize the drone for takeoff. Furthermore, the energetic benefits of the hybrid locomotion are not analyzed.

III. PLATFORM DESIGN

The proposed multi-modal drone has been conceived implementing two design strategies: (i) an integrated design approach to minimize the weight, and (ii) the use of adaptive morphology to maximize versatility and to add functionalities. The goal of the integrated design is to minimize the overall weight of the platform by sharing components between the two modes of locomotion. Weight minimization is a critical objective, especially in flying robots where a heavy design can compromise the energetic and maneuverability of the flight. Therefore, in the proposed prototype, special attention has been devoted to maximizing the number of structural components shared between the aerial and the terrestrial locomotion. In addition, both modes of locomotion rely on the same control electronics and energy source. The quantification of the level of integration and its effect on energetics are discussed in Section III. The adaptive morphology of the robot is given by the folding capability of the frontal arms. The first benefit given by foldable arms is to increase the transportability and the maneuverability of the drone during terrestrial locomotion. In addition, a strategic deployment of the arms allows to overcome large gaps that would not be negotiable by the whegs only. In addition, these foldable appendages allow to functionalize the robot with self-righting capability as detailed in the next section.

The design of the robot is illustrated in Fig. 3. The robot is a quadcopter with arms in H configuration. It is equipped with additional mechanisms for terrestrial locomotion and for folding the frontal arms. The electronics and batteries are hosted inside the central core of the drone (Fig. 3B). The frontal arms can be folded around the axis of rotation shown in Fig. 3C. The folding motion is driven by a DC motor connected to the two frontal arms through a worm drive. The worm drive is non-back-drivable to hold the arms in the deployed configuration during flight without the need to provide energy to the DC motor. The transition to the terrestrial morphology is obtained by folding the frontal arms on top of the rear ones. The terrestrial locomotion is driven by two whegs connected to the central core of the frame. The whegs facilitate the locomotion in uneven terrains by gripping on obstacles. The whegs are also driving two timing belts located along the rear arms of the drone (see Fig. 3D). The timing belts acts as track to help the terrestrial locomotion by reducing the risk that the slender arms get stuck on rough terrains. Whegs and tracks are actuated by means of two independent DC motors located below each wheg (see Fig. 3D).

IV. IMPLEMENTATION AND RESULTS

A Sparky 2.0 autopilot (© Tau Labs) equips the robot for stabilization and control during hovering. The autopilot runs an additional PicoC code to control the actuators for terrestrial locomotion and morphing. The autopilot sends commands through UART to two motor drivers Qik 2s9v1 (Pololu, USA) that control the two motors of the whegs and the motor of the foldable arms. Hovering is performed using four propulsion units composed of DYS 3016 brushless motors (Dong Yang Model Technology co., Hong Kong) and Gemfan 5030 propellers. Terrestrial locomotion is driven by two independent driving systems, each of them powered by a DC motor (250:1 Micro Metal Gearmotor HP 6V, Pololu, USA). The morphing is driven by a single DC motor with a high reduction gearing (298:1 Micro Metal Gearmotor HP 6V, Pololu, USA). The robot is also equipped with a receiver for

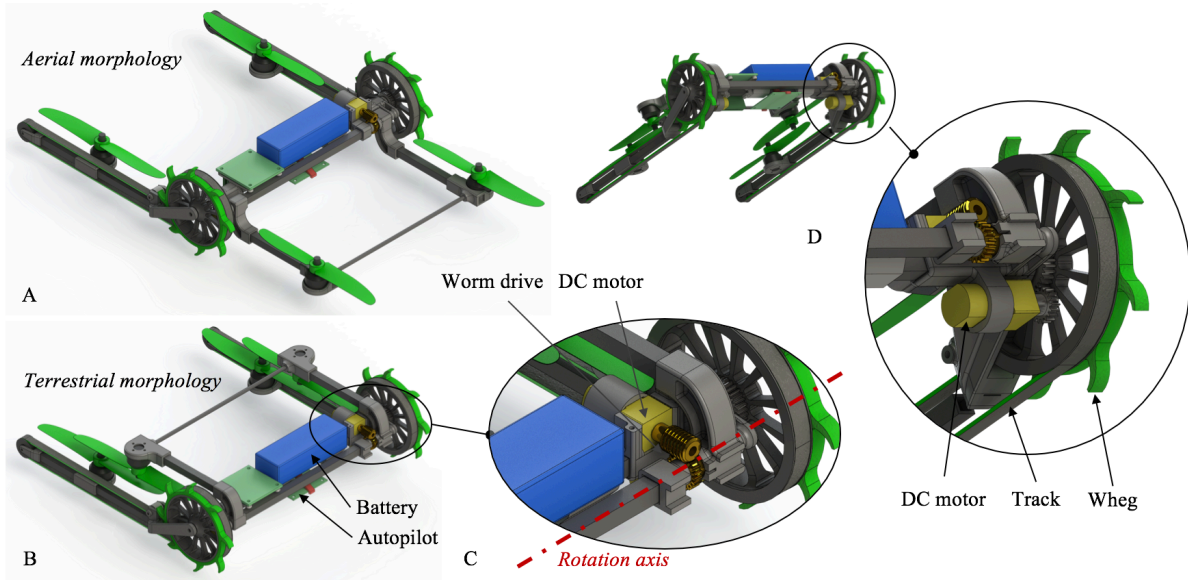


Figure 3. 3D model of the multi-modal quadcopter. For sake of clarity, the cover protecting the components is not shown. (A) Drone with deployed arms for aerial locomotion. (B) Drone with folded arms for terrestrial locomotion. (C) Detailed view of the folding mechanism of the arms. (D) Detailed view of the mechanism for terrestrial locomotion.

teleoperation using a standard remote controller. A frontal camera streams low latency video feedback to the user, and can be used for inspection beyond line of sight.

The main characteristics of the multi-modal drone are summarized in Table 1.

Table 1. Summary of the main characteristic of the multi-modal drone.

Characteristic	Value
Size of aerial morph.	370 x 300 x 80 mm
Size of terrestrial morph.	230 x 215 x 80 mm
Total weight (m_{TOT})	340 g
Weight of shared components (m_s)	124 g
Weight of terrestrial components (m_t)	89 g
Weight of aerial components (m_a)	127 g
Max payload	110 g
Autonomy of hovering loc.	15.6 min
Autonomy of terr. loc.	6.8 hour
Range of hovering loc.	7.1 km
Range of terr. loc.	12.4 km

A. Mass integration metric

In hovering robots, the mass is often a critical parameter due to its impact on the energetics of flight. Quadrotors have been found to consume about 200 W kg^{-1} [15]. The total mass of multi-modal robots is often minimized by using an integrated design strategy of their structure, where multiple components are shared between different modes of locomotion [6]. The mass integration metric, proposed in [16], quantifies the integration of components in multi-modal robots. The mass integration value for the proposed robot is:

$$I_{\text{mass}} = \frac{(m_t + m_s) + (m_h + m_s)}{m_{TOT}} = 1.36 \quad (1)$$

This value means that 36% of the mass is shared between the two modes of locomotion. Section III C discusses the effect on the range and time of flight of the mass added by the mechanisms required for terrestrial locomotion.

B. Adaptive Morphology

The adaptive morphology of the robot is obtained by folding the two frontal arms above the rear ones. The morphing appendages host three important functions: size reduction, self-righting and improvement of obstacle negotiation during terrestrial locomotion.

By folding the frontal arms, the quadcopter undergoes a significant size reduction that is instrumental for ease of transportation and mobility. The length of the drone is reduced by 37% when folding, thus facilitating the steering in cluttered environments. Furthermore, in the fully folded configuration, the drone can be stored in a 55% smaller volume for ease of transportation and deployment on the field.

The unfolding process of the fontal arms can be exploited as an active self-righting maneuver to recover the platform if it falls upside down during terrestrial locomotion or a harsh landing, similarly to what described in [17]. This function is instrumental not only to restore the terrestrial mode of

locomotion, but also to ensure that the propellers are always pointing upward to takeoff. An example of self-righting is depicted in Fig. 4A. When the robot's orientation is reversed, the arms unfolds causing a rotation of drone's main body. When the angle between the foldable and the fixed arms of the drone exceeds 90° , the drone passively rotates around the wheels and recovers the upright orientation. The same strategy can be also used on an inclined surface. On this substrate, a larger rotation of the frontal arms is required to compensate for the inclination of the surface. However, this can be easily achieved considering that the arms have a rotation range of 200° . Due to limited torque of the folding actuator, the mechanism is currently unable to recover the machine when is upside-down while the front arms are deployed, for example after a crash while flying.

The rotation of the frontal arms can be exploited to facilitate the negotiation of gaps without resorting to aerial locomotion. This locomotion strategy may be preferred to flight if a low noise signature is desired, or to avoid that propellers rise dust, hence reducing visibility. For example, as shown in Fig. 4B, when the arms are deployed across the gap, they can be used as support points and facilitate the crossing of large gaps without falling. With this locomotion strategy, the robot can negotiate 77% larger gaps with 100% success rate.

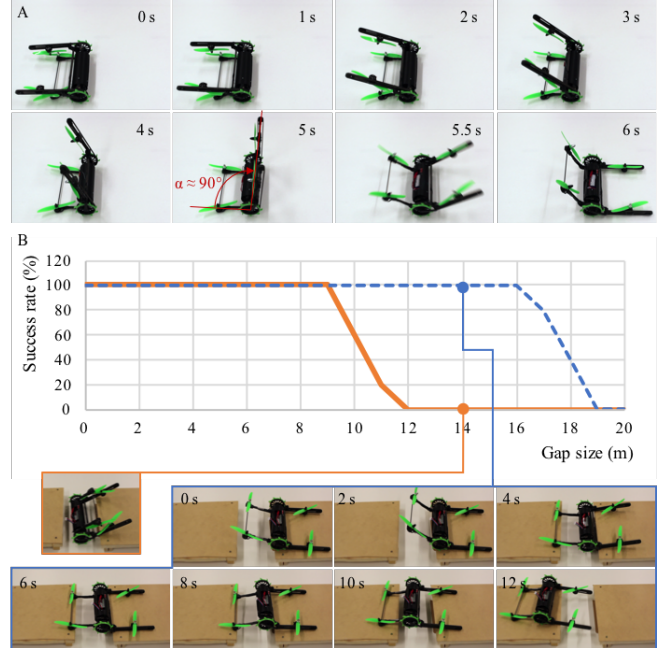


Figure 4. (A) Series of snapshots of a typical self-righting maneuver executed on a flat surface. (B) Success rate for gap negotiation of different sizes with or without adaptive morphology.

C. Energetics

The combination of hovering and terrestrial locomotion is useful to address the trade-off between mobility and energetic cost. Indeed, hovering locomotion allows to travel fast and easily negotiate obstacles, but requires high power. On the other hand, terrestrial locomotion allows to travel efficiently with a reduced acoustic signature, but it is ineffective in unstructured terrains. However, adding terrestrial capabilities on a flying platform is also causing drawbacks. Notably, the additional actuators and mechanisms required for terrestrial

locomotion increase the overall weight of the robot, therefore decreasing the time of flight and range during hovering. In this section, the trade-offs associated to multi-modal locomotion are quantitatively investigated by analyzing the energetics of aerial and terrestrial locomotion.

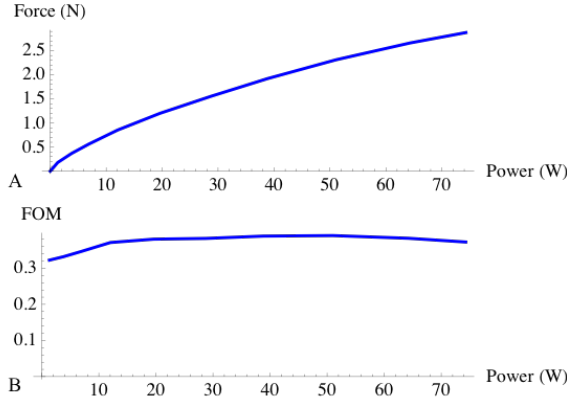


Figure 5. (A) Force generated by the propeller Gemfan 5030 for different values of electric power of the motor DYS 3016. (B) Figure of merit of the propeller.

At first, the propulsion units were characterized in order to evaluate the energetic cost of the flight. The power consumption as function of the static thrust was measured using a Series 1580 dynamometer (Tyto Robotics Inc., Canada). The experimental data are summarized in Fig. 5A and are used to compute the figure of merit (FOM) of the propeller (Fig. 5B), which has an average value of 35%.

The forces acting on the quadcopter during flight are summarized in Fig. 6A. The drag force is estimated as:

$$D = 0.5 c_d \rho r l v_f^2 \quad (2)$$

by assuming that the main body of the robot is a cylinder with a radius $r = 25$ mm and a length $l = 200$ mm. $c_d = 1$ is the drag coefficient of a cylinder, ρ is the air density and v_f is the forward flight velocity of the robot. Considering m as the mass of the robot, its weight is computed as:

$$W = mg \quad (3)$$

The total force generated by the four propellers needs to balance the drag and weight of the robot during flight according to the equation

$$F_{\text{tot}} = 4 F_{\text{prop}} = \sqrt{W^2 + D^2} \quad (4)$$

The pitch angle assumed by the drone during flight is

$$\theta = \tan^{-1} \left(\frac{W}{D} \right), \quad (5)$$

The velocity induced on the airflow by the propeller can be calculated by solving the quadratic equation:

$$v_{\text{ind}} = \frac{v_h^2}{\sqrt{(v_f \cos \theta)^2 + (v_{\text{ind}} + v_f \sin \theta)^2}} \quad (6)$$

In the previous equation, v_h is the induced velocity at hovering:

$$v_h = \sqrt{\frac{W/4}{2\rho\pi r_p^2}} \quad (7)$$

where $r_p = 64$ mm is the radius of the propellers.

The total power required by the propellers for flight is:

$$P_f = 4 \frac{F_{\text{prop}} (v_{\text{ind}} + v_f \sin \theta)}{\text{FOM}} \quad (8)$$

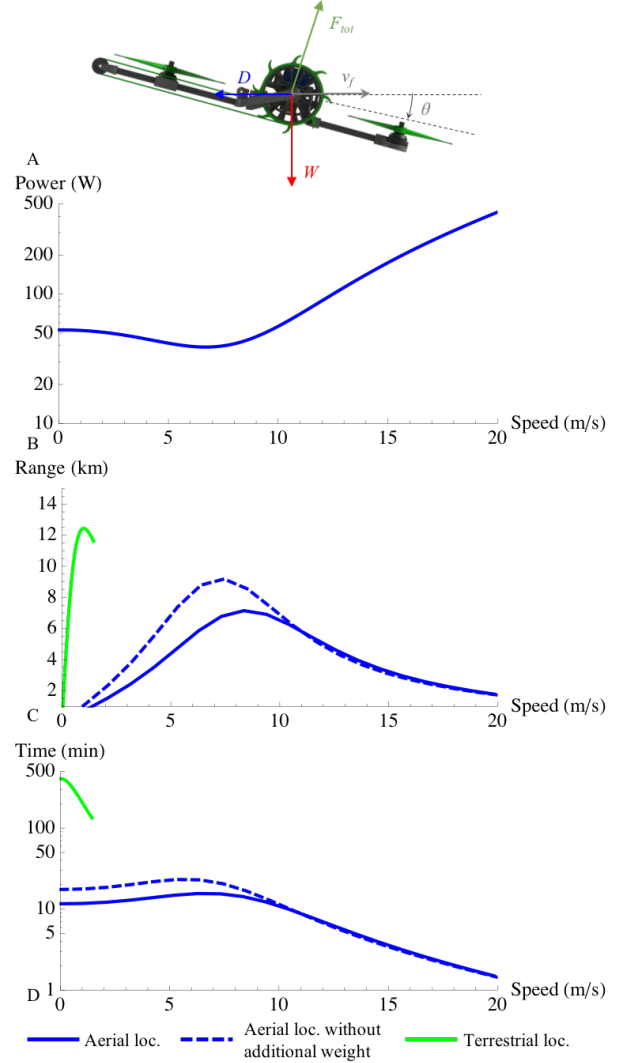


Figure 6. Results of the energetic analysis. (A) Mechanical power consumption in forward flight as function of speed. (B) Range as function of forward velocity for aerial and terrestrial locomotion. (C) Lifespan as function of forward velocity for aerial and terrestrial locomotion.

By combining the previous equations, it is possible to compute the power of flight in function of the forward velocity of the drone. The result is plotted in Fig. 6B. In agreement with the results reported in [15], the power consumption decreases for velocities up to 7 m/s, and then starts to increase. This reduction in power consumption is associated with translational lift; more air flows through the rotors in forward flight, thus improving rotor efficiency [15]. By knowing P_f , the range and time of flight given the energy available in the battery (E_b) is:

$$t_f = \frac{E_b}{P_f + P_i} \quad (9)$$

$$d_f = v_f t_f \quad (10)$$

where $P_i = 1.6$ W is the power consumption of the robot when idle. This power consumption accounts for the rate of energy

consumed by the autopilot and communication electronics. The range and time of flight as function of the forward velocity are shown by the blue line in Fig. 6C and D. The maximum flight speed achievable by the robot is approximately 21 m/s, and it is limited by the maximum thrust provided by the propulsion unit before overheating, which is approximately 2.25 N.

For the terrestrial locomotion, the power consumption as function of the forward velocity has been experimentally measured. The mean power has been logged for a straight-line motion on flat concrete. The maximum distance and time of operation were subsequently calculated similarly to equations (9) and (10). The results are plotted in green in Fig. 6C and D.

The results of the energetic analysis are summarized in Fig. 6C and D, that show the range and time of operation of the robot as function of the forward speed. The results highlight the trade-off between speed and energy consumption that can be addressed by multi-modal hovering and terrestrial locomotion. In hovering, range and time of flight are 7.1 km and 15.6 minutes respectively. On the other hand, a slower but more efficient terrestrial locomotion allows to cover longer distances and to increase the time of operation, respectively up to 12.4 km and 6.8 hours.

The blue dashed lines in Fig. 6C and D show the range and time of flight of a quadcopter without the additional weight due to the mechanisms required for terrestrial locomotion and morphing. Both the range and time of flight increase to 9.1 km and 23 minutes respectively. As expected, the additional terrestrial mode of locomotion has a negative impact on the aerial performance of the multi-modal robot. However, the loss in aerial performance is largely compensated by the extended range and lifespan obtained on the ground during multi-modal missions.

V. DISCUSSION

Adaptive morphology, in the form of foldable arms, allowed to develop a new multi-modal robot which can fly, hover and crawl on the ground. The versatility offered by the combination of these modes of locomotion is valuable for multi-domain tasks, such as search and rescue, environmental monitoring and agriculture. As shown in the video support material (<https://youtu.be/kmePwv5bTcA>), the robot can be used to inspect a partially collapsed building. The robot can fly to reach an elevated edge of the building and subsequently sneak inside to efficiently pursue the exploration using the terrestrial locomotion. A camera on the drone allows to stream a live video feedback to the user.

The experimental results confirmed that adaptive morphology enhances indeed the versatility of the machine enabling a physical transformation that improves mobility on the ground by reducing the size, by facilitating the negotiation of large gaps and by allowing to self-right if the robot falls upside down.

Although the current design proved to be a valuable proof of concept, the implementation based on multi-joint mechanisms makes the prototype intrinsically fragile. A solution to this problem is to adopt variable stiffness materials to develop morphing frames that can change their shape when in the soft state, but also stiffen to bear forces during

locomotion [18]. Finally, the terrestrial locomotion mode can be improved by using hybrid control strategies where, steering [4] or adhesion for driving on steep slopes [5] can be achieved or improved through the aerodynamic forces generated by the propellers.

ACKNOWLEDGMENT

This work was supported by the Swiss National Science Foundation through the National Centre of Competence in Research Robotics (NCCR Robotics).

REFERENCES

- [1] R. J. Lock, S. C. Burgess, and R. Vaidyanathan, "Multi-modal locomotion: from animal to application," *Bioinspir. Biomim.*, vol. 9, no. 1, p. 11001, 2014.
- [2] K. H. Low, T. Hu, S. Mohammed, J. Tangorra, and M. Kovac, "Perspectives on biologically inspired hybrid and multi-modal locomotion," in *Bioinspiration & Biomimetics*, 2015, vol. 10, no. 2, p. 20301.
- [3] A. Briod, P. Kornatowski, J.-C. Zufferey, and D. Floreano, "A Collision-resilient Flying Robot," *J. F. Robot.*, vol. 31, no. 4, pp. 496–509, Jul. 2014.
- [4] Y. Mulgaonkar, B. Araki, J. S. Koh, L. Guerrero-Bonilla, D. M. Aukes, A. Mäkinen, M. T. Tolley, D. Rus, R. J. Wood, and V. Kumar, "The flying monkey: A mesoscale robot that can run, fly, and grasp," in *Proceedings - IEEE International Conference on Robotics and Automation*, 2016, vol. 2016–June, pp. 4672–4679.
- [5] M. T. Pope, C. W. Kimes, H. Jiang, E. W. Hawkes, M. A. Estrada, C. F. Kerst, W. R. T. Roderick, A. K. Han, D. L. Christensen, and M. R. Cutkosky, "A Multimodal Robot for Perching and Climbing on Vertical Outdoor Surfaces," *IEEE Transactions on Robotics*, vol. 33, no. 1, pp. 38–48, 2017.
- [6] L. Daler, S. Mintchev, C. Stefanini, and D. Floreano, "A bioinspired multi-modal flying and walking robot," *Bioinspir. Biomim.*, vol. 10, no. 1, p. 16005, 2015.
- [7] S. Mintchev and D. Floreano, "Adaptive Morphology: A Design Principle for Multimodal and Multifunctional Robots," *IEEE Robot. Autom. Mag.*, vol. 23, no. 3, pp. 42–54, 2016.
- [8] R. Siddall and M. Kovac, "Fast Aquatic Escape With a Jet Thruster," *IEEE/ASME Transactions on Mechatronics*, vol. 22, no. 1, pp. 217–226, 2017.
- [9] A. Kalantari and M. Spenko, "Modeling and performance assessment of the HyTAQ, a hybrid terrestrial/aerial quadrotor," *IEEE Trans. Robot.*, vol. 30, no. 5, pp. 1278–1285, 2014.
- [10] J. R. Page and P. E. I. Pounds, "The Quadroller: Modeling of a UAV/UGV hybrid quadrotor," in *IEEE International Conference on Intelligent Robots and Systems*, 2014, pp. 4834–4841.
- [11] C. J. Pratt and K. K. Leang, "Dynamic underactuated flying-walking (DUCK) robot," 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 3267–3274, 2016.
- [12] L. Dufour, K. Owen, S. Mintchev, and D. Floreano, "A drone with insect-inspired folding wings," in 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016, pp. 1576–1581.
- [13] <https://www.kickstarter.com/projects/2017062404/b-unstoppable/comments>
- [14] S. Morton and N. Papanikolopoulos, "A small hybrid ground-air vehicle concept," in *IEEE International Conference on Intelligent Robots and Systems*, 2017, vol. 2017–September, pp. 5149–5154.
- [15] K. Karydis and V. Kumar, "Energetics in robotic flight at small scales," *Interface Focus*, vol. 7, no. 1, Dec. 2016.
- [16] M. A. Woodward and M. Sitti, "MultiMo-Bat: A biologically inspired integrated jumping–gliding robot," *Int. J. Robot. Res.*, vol. 33, no. 12, pp. 1511–1529, Sep. 2014.
- [17] A. Klaptocz, L. Daler, A. Briod, J. C. Zufferey, and D. Floreano, "An Active Uprighting Mechanism for Flying Robots," *IEEE Trans. Robot.*, vol. 28, no. 5, pp. 1152–1157, 2012.
- [18] A. Tonazzini, S. Mintchev, B. Schubert, B. Mazzolai, J. Shintake, and D. Floreano, "Variable Stiffness Fiber with Self-Healing Capability," *Adv. Mater.*, vol. 28, no. 46, pp. 10142–10148, 2016.