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A Comprehensive Review on Reconfigurable Drones: Classification, Characteristics, Design and Control Technologies

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Recently, reconfigurable drones have gained particular attention in the field of automation and flying robots. Unlike the conventional drones, they are characterized by a variable mechanical structure in flight, geometric adaptability, aerial reconfiguration, high number of actuators and control inputs, and variable mathematical model. In addition, they are exploited to flight in more cluttered environments, avoid collisions with obstacles, transport and grab objects, cross narrow and small spaces, decrease different aerial damages, optimize the consumed energy, and improve agility and maneuverability in flight. Moreover, these new drones are considered as a viable solution to provide them with specific and additional functionalities. They are a promising solution in the near future, since they allow increasing considerably the capabilities and performance of classical drones in terms of multi-functionalities, geometric adaptation, design characteristics, consumed energy, control, maneuverability, agility, efficiency, obstacles avoidance, and fault tolerant control. This paper explores very interesting and recent research works, which include the classification, the main characteristics, the various applications, and the existing designs of this particular class of drones. Besides, an in-depth review of the applied control strategies will be presented. The links of the videos displaying the results of these researches will be also shown. A comparative study between the different types of flying vehicles will be established. Finally, several new challenges and future directions for reconfigurable drones will be discussed.

Keywords: UAVs; Reconfigurable drones; bio-inspired drones; transformable quadrotors; variable geometry; adaptive morphology; adaptive mechanical structure.

1. Introduction

Drones have known exponential growth over the last 20 years because they have become very important platforms for the laboratories, thanks to their low cost, their efficiency, their accuracy, and their ease of use. They are used in several domains such as photography, air transport, search operations, and aerial surveillance [1, 2]. However, many challenges must be well verified before implicating UAVs in these missions, in particular, that of navigating in unknown spaces especially during rescue missions, cross narrow spaces, transport and seizing objects, while guaranteeing good flight autonomy by optimizing the consumed energy [3]. For example, conventional drones have some limitations on their mechanical structure, which makes it extremely difficult to cross a space smaller than the size of their body with their fixed shape. Moreover, they do not have the ability to adapt to different flight conditions, which is generally observed in birds [4].

Another important point concerns the transport of objects, where conventional drones need to be equipped with one or more manipulator arms. This classic design increases considerably the structure complexity of the UAV, makes it limited in the case of several objects, reduces the payload, consumes important energy and degrades the flight stability by complicating the control strategy [5–8].

These challenges have led us to focus on the study of the huge potential of reconfigurable drones.

Aerial reconfiguration is any change in the mechanical structure, in the flight mode or in the propulsion mode of the drone, in order to accomplish specific missions by

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adapting its configuration or to minimize the consumed energy by seeking the adequate configuration or mode. This operation can be done in the hover phase or in the full flight phase using slow or fast mechanisms, where it is assured by the reconfigurable drones. These new drones include: Unconventional Quadrotors [9, 10], Transformable Multirotors [11–15], Foldable Drones [16–20], Bio-inspired UAVs [21–27], Drones with Extendable Arms [28–33], Morphing Geometry Quadcopters [28, 32, 34–37], Tilt-Arm Quadrotors [15, 18, 19, 35, 37–47], Quadcopters with A Tilting Frame [48–51], Deformable Drones [22, 23, 41, 52, 53], Agile Quadrotors [54, 55], Multilink Aerial Robots [12–14, 56–62], Drones with Adaptive Morphology [4, 35, 38, 63, 64], Drones with Changeable Geometry [29, 35, 64], Tiltable-Rotor Aerial Vehicles [55, 65–80], Convertible Drones [81–83], Hybrid UAVs [10, 84–105], and Modular Drones [106–119]. In recent years, and with the rapid development of UAVs, reconfigurable drones have given another vision for researchers towards flying robots and their usage. They have become one of the most important research axes in the robotics community.

This particular category of drones allows to perform special and various missions, such as flying and navigating in environments more dangerous and difficult, to access by adapting their structures, cross narrow openings by reducing the arm lengths, inspection and discovery of abandoned areas as well as the security of sensitive points using their high agilities and their maneuverability. They can also be exploited to transport multiple objects and with different sizes without additional mechanical mechanism, contrary to the conventional ones [3–5, 36, 120]. In addition, changing the configuration allows to introduce different movements (roll, pitch, yaw, translation), without affecting the rotational speeds of the motors in the case of the drone with rotating and extendable arms [9, 11, 20]. Furthermore, when the reconfigurable drone has a failed motor in flight, it can easily change its morphology using only three motors, in order to accomplish its mission without performance degradation.

Many structures of reconfigurable UAVs have been proposed in the recent literature by introducing adaptive mechanisms to the classic ones. These mechanisms can act on the orientation of the propellers or rotors, the length or number of arms, the orientation of arms, the external structure, etc. All of these will be detailed in the following section.

The rest of the paper is organized as follows. Section 2 presents the classification, characteristics, applications, and design technologies of reconfigurable drones. In Sec. 3, we will detail the different control strategies as well as a comparative study between the different research works. Conclusions and future challenges are given in Sec. 4.

2. Classification, Characteristics and Design Technologies

The development of reconfigurable drones has experienced strong expansion in recent times, which means that the classification and the use of this new class of UAVs are variable over time [121]. Moreover, different designs have been proposed, some have already been realized and tested in the field, others are just designed and are not yet realized. Classification, characteristics, applications, and design technologies of the different possible structures, are established in this section.

Based on the existing and very recent literature, we were able to classify reconfigurable drones into eight main subcategories, as illustrated in Fig. 1.

2.1. *Air-surface hybrid drones*

This sub-category of drones includes all types of UAVs, which have the characteristics of transformation from a flying robot configuration to a mobile robot or to an aquatic robot and vice versa.

2.1.1. *Air-ground hybrid drones*

These hybrid vehicles are known by three main names such as air-ground hybrid drone, UAV-Unmanned Ground Vehicle (UGV) and terrestrial-aerial drone [84–96]. They are exploited to navigate in congested environments and to avoid obstacles by employing mobile robot mode after transformation. They combine the capabilities and advantages of aerial vehicles and ground vehicles.

Note that this type of drones is usually slow to perform tasks, especially during the rolling phase such as obstacle avoidance. In addition, due to their mechanical structures, maneuverability decreases in tight spaces when using flight and ground modes.

An air-ground hybrid flying robot, which combines the capabilities of aerial mode with ground mode, has been proposed by Kossett *et al.* [84, 86] (see Fig. 2). However, due to some flaws in the mechanical structure such as the lack of some electronic components, this prototype needs to be improved and refined before its employment.

In order to improve the designs and robustness of [84, 86], an improved miniature ground-air robot has been proposed in [87] (see the prototype in Fig. 3).

The same idea is adopted by Morton *et al.* [93], where a reconfigurable hybrid prototype that can switch between ground and air configurations has been realized. This quadrotor can fly as a conventional quadrotor, and when it crosses a narrow place, it folds up and takes the configuration of a mobile unicycle robot (see Fig. 4). While this

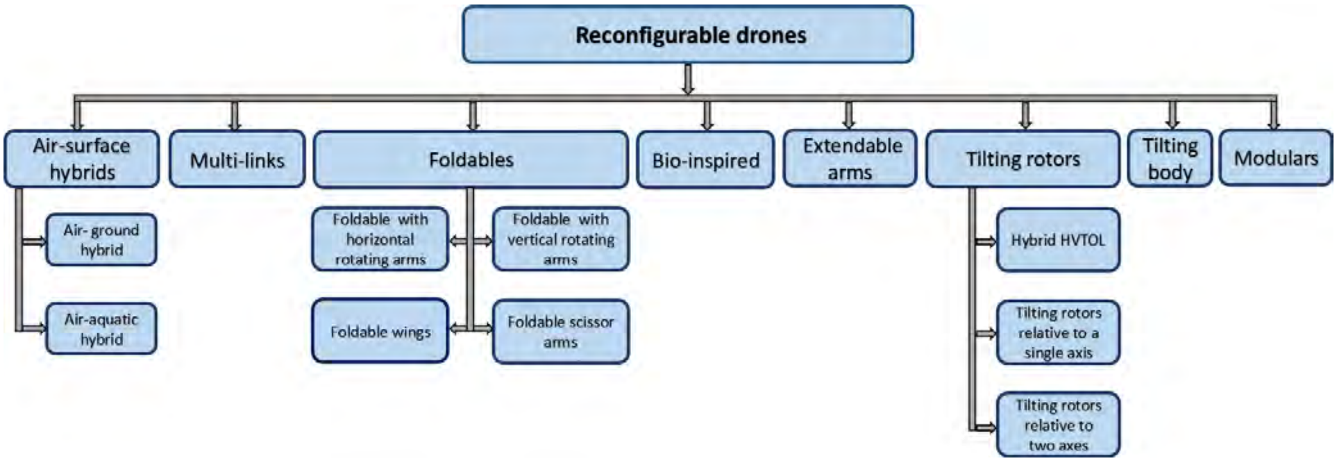

Fig. 1. Reconfigurable drones classification.

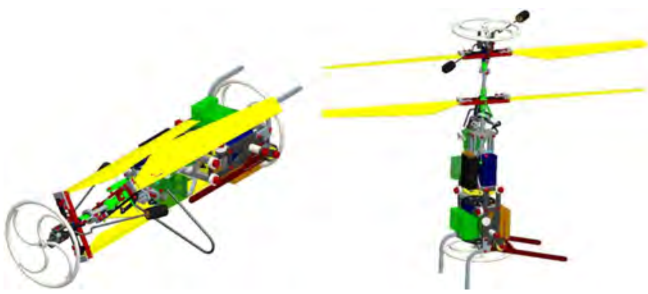

Fig. 2. Terrestrial mode on the left, aerial mode on the right [84].

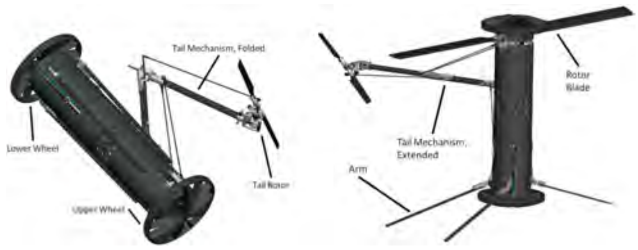

Fig. 3. Miniature ground-air robot [87].

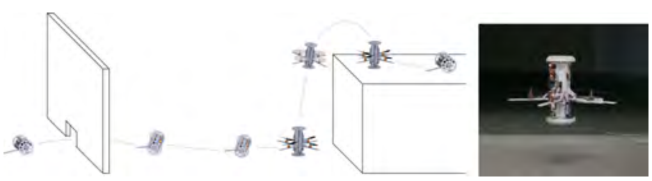

Fig. 4. Reconfigurable prototype. To the left; a demonstration of the capabilities of the hybrid ground-air robot, it is able to traverse through gaps and changes its aerial mode. To the right; realized prototype [93].

proposed structure cannot pass through a narrow place only when the robot is located on the ground.

Another hybrid flying robot was treated recently in [94] (see Fig. 5). In addition, a nonlinear model that represents the transformation operation (ground-air) of the robot is developed in this work. The authors have considered the model to be symmetrical to simplify its control strategy.

A terrestrial-aerial drone has been designed and modeled in [88]. The rolling robot mode is achieved by a cage located outside the structure (see Fig. 6). Thus, the experimental study has shown that when the robot is in rolling mode it consumes less energy compared to its flying mode.

The same principal has been adopted by Dudley *et al.* [92], where they have presented the modeling, design and fabrication of a micro air-ground robot (see Fig. 7). This flying robot can be used for multiple tasks such as surveillance, search and rescue. The structure is validated by some tests in land and air modes.

A quadrotor equipped with six wheels, which makes it possible to cover long distances, was realized by Page *et al.*

Fig. 5. Air-Ground vehicle prototype [94].

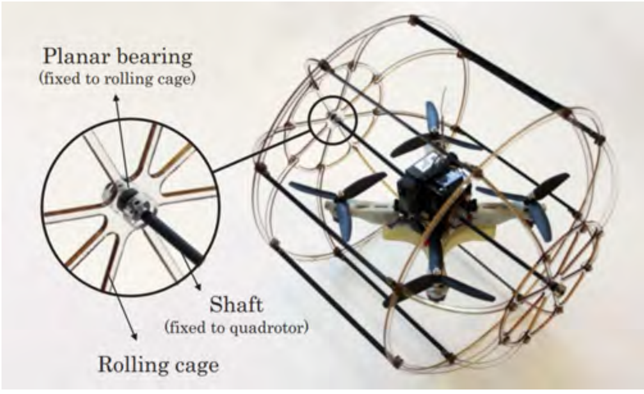

Fig. 6. Hybrid terrestrial-aerial drone [88].

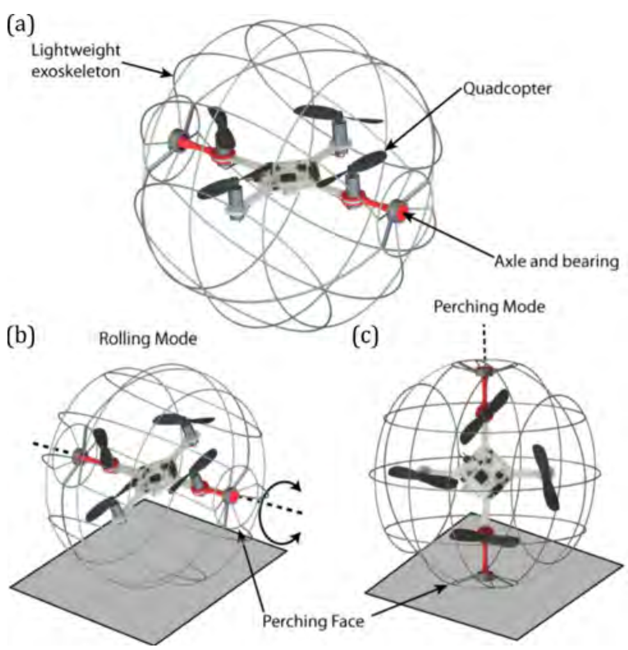

Fig. 7. Ground-air drone [92].

[89] (see Fig. 8). The authors in this work proved that the rolling mode gives more range compared to the flight mode.

The same principal is adopted by Kalantari *et al.* [96], where the new prototype is based on an aerial vehicle with four wheels that are operated independently. It is used to cross crowded places and to be robust against obstacles.

Daler *et al.* [91] developed a multi-modal folding wing drone, which can switch to a terrestrial morphology by folding its wings under different flight conditions. This structure offers an adaptive shape to pass to terrestrial locomotion (see Fig. 9). It is noted in this work that the folded wings of the drone improve the robot efficiency on the ground, while its extended wings maximize the lift during flight.

Fig. 8. Hybrid UAV prototype [89].

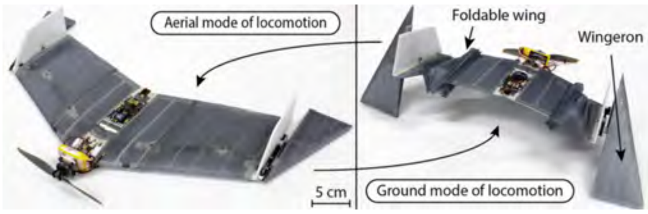

Fig. 9. Novel multi-modal folding wing drone [91].

2.1.2. *Air-aquatic hybrid drones*

Hybrid Unmanned Aerial Aquatic Vehicles (HUAAV) [10, 97–105] are part of air-surface hybrid drones. They are characterized by their adaptive platforms to switch between air mode and aquatic mode or vice versa. Furthermore, their structures allow them to be used in various domains such as navigating in two different environments (air-water), conducting underwater operations, taking underwater photography and making search and rescue operations.

Alzu *et al.* [10] proposed an unconventional HUAAV, which can conduct underwater and aerial operations (see Fig. 10). In order to control the depth, buoyancy and the transformation process of the hybrid robot, a ballast mechanism was used. The performances of the designed platform, such as agility, flight controllability, underwater maneuvers, have been validated by some experiments. However, the proposed structure needs to be improved to decrease the overall weight and drag force. In addition, the underwater communication poses a big problem for this type of drones.

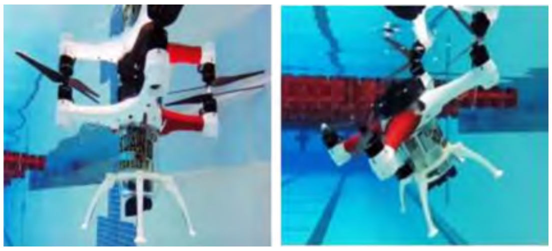

Fig. 10. Unconventional HUAAV platform [10].

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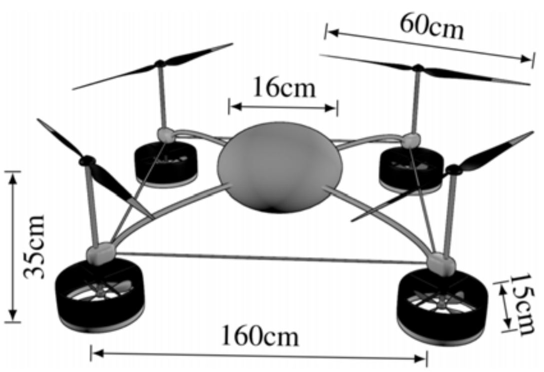

Fig. 11. Hybride UAV design [97].

Ranganathan *et al.* [100] analyzed a design of a hybrid air-aquatic robot. The hydrodynamic challenges were taken into account in this research. The real platform is not yet realized.

Drews *et al.* [97] presented a design that associates the capabilities of a drone with those of an underwater robot (see Fig. 11). This design is based on a special mechanical structure, which allows it to navigate in two environments. The dynamic and kinematic models are developed in this work. However, the transition between the two configurations must be validated experimentally to ensure the stability in this sensitive phase.

A hybrid air-underwater robot with seamless switching between the two modes was presented by Maia *et al.* [101]. The presented vehicle is used to improve reliability, stability, maneuverability as well as in air-water search and rescue missions. The experimental tests have shown satisfactory results, especially in the transition phase (see Fig. 12).

Mercado *et al.* [104] focused their study on the modeling of an aerial-aquatic drone with a single thrust force (see Fig. 13). The performance of the system was proven by some experiments.

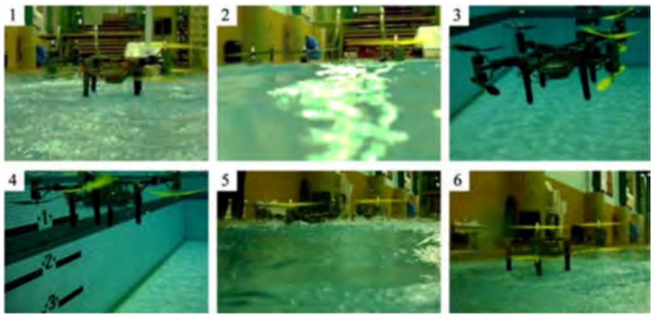

Fig. 12. Hybrid air-underwater robot. (1–3) the transition from the air to water configuration. (4–6) the transition from the water to air configuration [101].

Fig. 13. Air-aquatic vehicle in different configurations under water [104].

Neto *et al.* [105] presented a dynamic model that represents a Hybrid air-underwater UAV, where the aerodynamic effects and the transition operation have been considered.

2.2. *Multi-link drones*

The Multi-link multirotors [12–14, 56–62, 122] are another type of reconfigurable drones. They are equipped with several servomotors and rotors, which make the aerial robot capable to switch in flight in order to accomplish the desired tasks. They have a special feature: each rotor is linked to the adjacent rotor using a pivoting link actuated by a servomotor. This structure can be used to design a multirotor that works like a clamp without additional gripping mechanism or to cross small holes.

We find in the literature that Professor Zhao's research team from the Department of Mechano-Infomatics, the University of Tokyo, is the most dominant in this filed with several research works [12–14, 56–62].

A reconfigurable multirotor UAV composed of multiple two-dimensional links has been developed by Zhao *et al.* [12, 13]. In flight, it can fold up and takes many forms, from a wavy line to a square. This robot is designed to manipulate objects to grab them, pick them up, transport them and drop them in different places, thanks to three servomotors located between each two rotors (see Fig. 14). The limitation of this structure is that it cannot transform during the flight, it must be maintained at a fixed altitude for it to fold up.

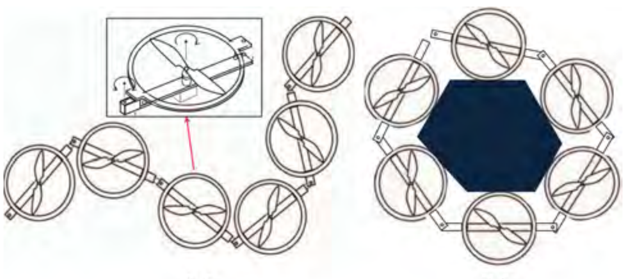

Fig. 14. (a) Proposed structure and link module. At the end of the module, there are joint modules with servomotors. (b) Whole-body grasping using two-dimensional multi-links [13].

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Fig. 15. Multi-link multirotor in different configurations [58].

Zhao *et al.* in [58] proposed another multi-link multirotor similar to [13] (see Fig. 15), where the joints are actuated slowly. This structure is inspired by the ability of a snake to cross through a small hole by changing its shape. However, the large number of rotors and servomotors makes the folding process so difficult and more complex.

A new deformable multi-link UAV that combines between two main characteristics the handling of objects and maneuverability has been designed in [62] (see Fig. 16). This work adopts the same principal with [12, 13, 58], where the structure is designed to improve the controllability as well as the estimation of autonomous flight states. Besides, the dynamic model and control strategy are also developed to ensure the stability of the transformation process and hovering. While the transition from one morphology to another can be done by keeping a fixed altitude and then continuing the desired task. Experiment videos are available at: https://youtu.be/LkDGP82sg1I.

The proposed design in [122] concerns a reconfigurable multi-link micro aerial vehicle, capable of transporting objects and crossing narrow places (see Fig. 17). The main objective of this work is to fully exploit its variable geometry to find the best trajectory and avoid collision with obstacles.

A video of the conducted simulations is available at: https://youtu.be/wP8Mg9_YEh8.

The main advantages and disadvantages of the prototypes proposed in this subcategory are presented in Table 1.

2.3. *Foldable drones*

This type of unconventional drones [9, 15–20, 34, 35, 37–47, 52, 54, 63, 123–126] has many advantages, which are the reduction of the dimensions for navigation in narrow and dangerous places, high agility and precision and high endurance. In addition, some configurations make them possible to optimize energy and increase autonomy in the various flight scenarios.

Adding actuators to theses designs, such as servomotors increases the number of the control inputs and makes the system over-actuated.

The transition from one configuration to another can be done either by keeping a fixed altitude, transforming and then continuing the mission, or during the execution of the mission.

We can classify them according to their structures as follows:

2.3.1. *Foldable drones with horizontal rotating arms*

This type of drones has horizontal rotating arms (at 2D horizontal level), where the angle between these arms varies in different ways: either each arm pivots independently thanks to servomotors or arms rotate simultaneously with a single servo motor or the arms are connected two by two by a servomotor and crank system.

The advantages of these aerial configurations are summarized as follows: cross narrow places by changing the morphology, conservation and transport of the payload by reducing the size and correct the under-actuation problem by adding other inputs for roll and pitch control. However, some configurations cause a loss of controllability in roll or pitch, which requires the use of such configurations in particular cases.

A quadrotor with foldable arms has been studied by Mintchev *et al.* [16], where the fabrication of this robot is

Fig. 16. (a) Main UAV prototype, (b) the upper connection part, (c) the joint part and its servo motor, (d) the tilt rotors and (e) the lower connection part [62].

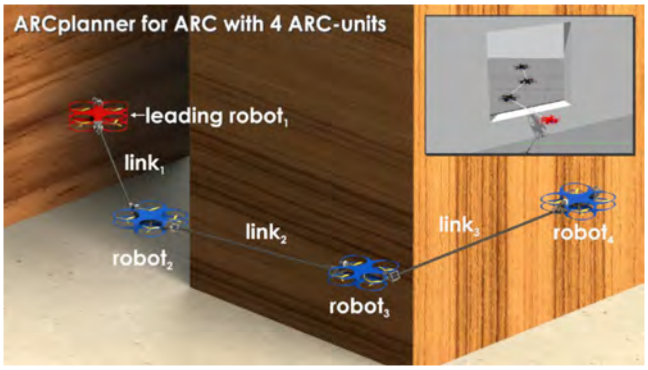

Fig. 17. Reconfigurable multi-linked micro aerial vehicles with 4 Aerial Robotic Chain (ARC)-units [122].

based on origami technique using multi-layer material (see Fig. 18).

In [54], Riviere *et al.* proposed a quadrotor that can fold its structure through a vertical or tilted window. However, a loss of roll control is observed due to the alignment of the four rotors when the robot is in its folded state (see Fig. 19).

In the work presented in [17], a self-folding quadrotor has been presented where the rotation of the four arms is done horizontally at the same time, using a single servomotor (see Fig. 20). This simple mechanism allows the drone to optimize the dimensions of its shape, which allows it to navigate easily in narrow places and carry out tasks with great autonomy.

In terms of energy consumption, and since the autonomy of the current batteries is not significant enough, Xiong *et al.* [40] treated the problem of optimizing the energy of a quadrotor with rotating arms (see Fig. 21).

The same principle is adopted by [18, 35] to minimize the energy according to the followed missions (see Fig. 22).

All the videos of the experiments are displayed in these links: https://www.youtube.com/watch?v=jmKXCdEbF_E, https://youtu.be/Na0yrkCsC-M.

Remaining in the same context, Derrouaoui *et al.* [9, 20] proposed a new design of a quadrotor with horizontally rotating arms (see Fig. 23). This prototype is proposed to improve the previous works [18, 40], in terms of mechanical structure and control strategy.

Table 1. Advantages and disadvantages of the multi-link drones.

Authors/References	Year	Advantages	Disadvantages
Bhat *et al.* [122]	2006	Transport of objects Cross narrow places Avoidance of the collisions with obstacles	Complex design
Zhao *et al.* [12]	2016	Manipulation of objects Transport and seizure of objects	Complex structure Can transform only in hovering flight
Zhao *et al.* [13]	2017	Manipulation of objects Transport and seizure of objects	More complex structure Can transform only in hovering flight
Anzai *et al.* [56]	2017	Transport of several objects Improvement of the transport efficiency Flight stability	More complex structure Slow aerial transformation
Zhao *et al.* [58]	2018	Cross through a small hole by changing its shape	Joints are actuated slowly Folding operation is difficult and more complex
Anzai *et al.* [57]	2018	Seizure of objects Avoidance of the collisions with obstacles	Slow and unstable aerial transformation
Anzai *et al.* [59]	2019	High autonomy of the prototype Control of the orientations and positions independently Elimination of the singularity problem High stability	Slow aerial reconfiguration
Shi *et al.* [61]	2019	Optimization of the thrust force and trajectory Fast aerial folding	Complex structure
Shi *et al.* [60]	2019	Agile and rapid transformation	Large number of joints
Zhao *et al.* [62]	2020	Transport and Seizure of objects Maneuverability Improvement of the controllability Estimation of autonomous flight state	Large number of joints Can transform only in hovering flight

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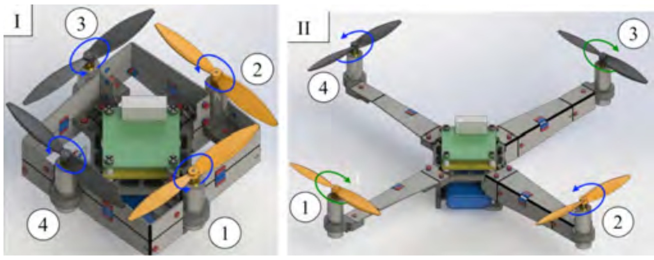

Fig. 18. (I) Folded state. (II) Unfolded state [16].

Fig. 19. Morphing drone [54].

Another design of reconfigurable drones was considered in [38, 125] (see Figs. 24 and 25), which can change the angle between their arms while flying. The flight robot in [125] is composed of two arms: the upper one is supposed to be mobile and the lower arm is supposed to be fixed, which are connected by a single servomotor. It is observed in these works that the proposed structures are light, which means that the payload is not large enough as well as the

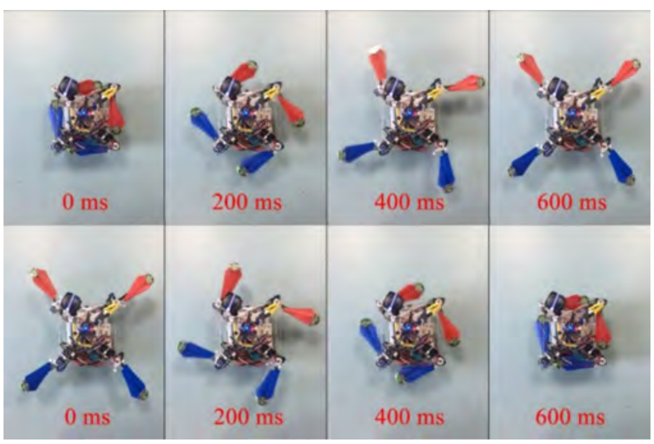

Fig. 20. Folly quadrotor changes its configuration from the folded to deployed state (or vice versa) in 600 ms [17].

Fig. 21. Quadrotor with rotating arms: (a) optimal configuration; (b) conventional configuration [40].

Fig. 22. Different configurations of foldable drone [18].

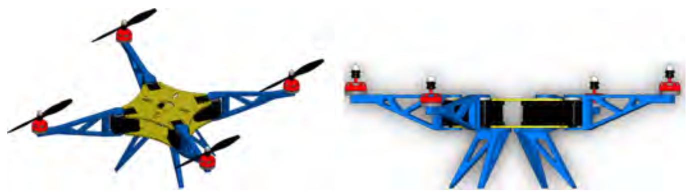

Fig. 23. Quadrotor with horizontally rotating arms [9, 20].

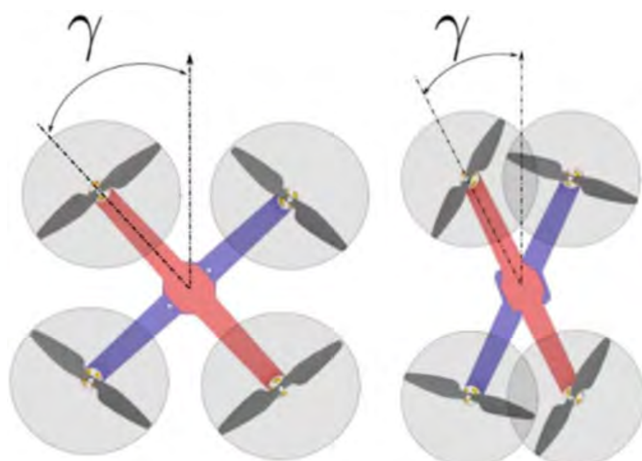

Fig. 24. Foldable drone with rotating arms [125].

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Fig. 25. Illustration of a flight scenario through a narrow place by changing the morphology of the quadrotor [38].

rotations of the four arms are not independent compared to [9, 18, 20, 35, 40].

2.3.2. *Foldable drones with vertical rotating arms*

Unlike the drones with horizontal rotating arms, the arms rotate relative to a horizontal axis. Folding process is done either by servomotors mounted on the beginning of the arms, or by a spring mechanism, which allows the arms to tilt while decreasing the trust force. This mechanism requires a great precision and consumes more energy.

The idea proposed by Bucki *et al.* [39] concerns the design of a new foldable quadrotor without additional actuators, where the arms lean down in case of weak thrusts produced by the four propellers (see Fig. 26). This quadcopter is designed to execute certain critical missions that a conventional quadcopter cannot do. An animation of the mechanism is viewed here: https://youtu.be/MSvoQT_c9U.

In [19], a foldable multirotor with vertical ballistic takeoff from an unstable platform has been studied (see Fig. 27). This launching mechanism allows to avoid collisions with the outside environment and increases considerably the UAV range of missions. In addition, the system transition operation from a ballistic launch morphology to a fully controllable flight morphology has been validated experimentally. The video which presents the experiments is available at: https://youtu.be/sQuKJfllyRM.

Fig. 26. Foldable quadrotor without additional actuators [39].

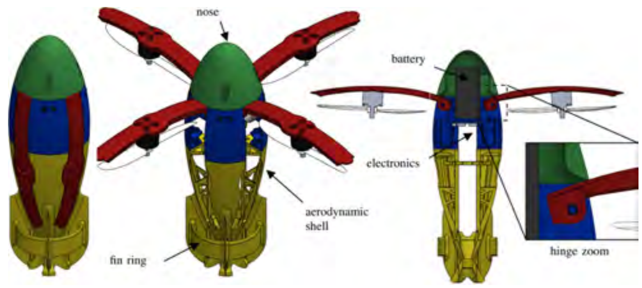

Fig. 27. Designed model. From left to right: ballistic morphology, UAV morphology view and section view with a hinge closer look [19].

Fig. 28. Foldable quadrotor for collision resilience [41].

A new design of a miniature quadrotor manufactured using foldable robotics methods for collision resilience (see Fig. 28), has been proposed more recently by Dilaverouglu *et al.* [41]. Low-speed flight tests have proven that the quadrotor can continue its task when colliding with obstacles.

2.3.3. *Foldable wing drones*

Contrary to fixed wing drones, folding-wing ones have the particularity of tilting the wings as found in birds, which allows them to reduce their size [34, 37, 46, 63]. Therefore, this tilting process generates less friction drag, which increases the speed of the drone and maintains a constant ground speed in relatively stronger headwinds [43]. Some works have improved the mechanisms of aerial robots to make their morphing wings robust and resistant to turbulence in very difficult flight situations [44, 45] (see Fig. 29). However, generally, this type of UAVs presents a difficulty of

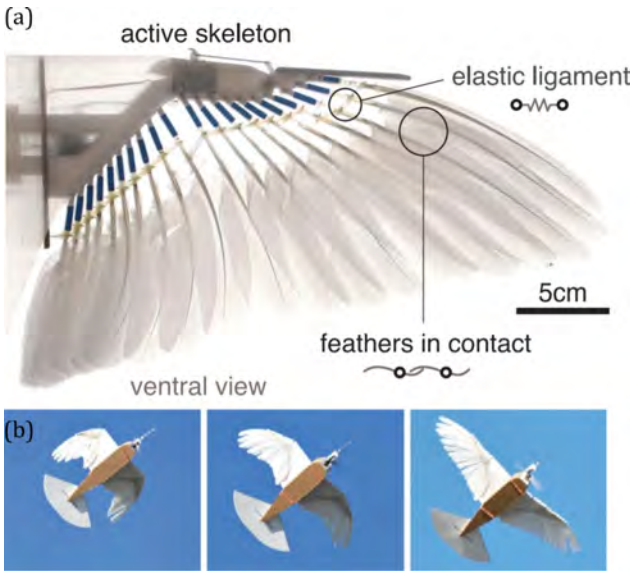

Fig. 29. Under-actuated bio-hybrid aerial robot [44].

control in particular during the presence of the wind as well as the structural complexity due to the additional actuators.

The Transformable Solar UAV-Quad (SUAV-Q) [15, 47, 123, 126] has been realized to improve the performance of the solar powered fixed-wing drone as well as flight transformation operation [127–129] (see Figs. 30–32). It uses a structure with 4 foldable wing sections to allow the drone to carry out the aerial transformation.

2.3.4. *Foldable scissor arm drones*

These aerial vehicles [42, 52, 124] are developed for "+" shaped quadrotors. They are designed on the basis of the inclined element to form a variable curvature. If we increase the number of angulated elements, the rate of deformation increases and we will have a precision on the deformation.

Fig. 30. Classic solar powered drone [127].

Fig. 31. Transformable solar powered quadrotor [126].

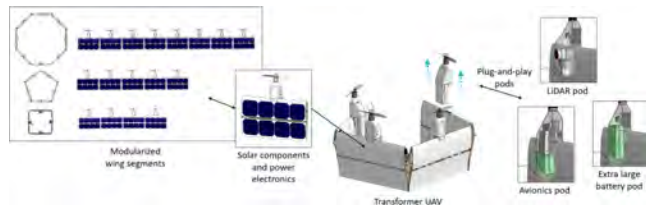

Fig. 32. Design of a solar UAV-Quad [15].

However, the high number of these angulated elements increases the complexity and the cost of the system.

In [52, 124], Zhao *et al.* developed a quadrotor based on foldable scissor-shaped structures. The designed structure is based on the angulated element to form a variable curvature. In this mechanism, the number of angulated elements is 16 to form a complete circle, three circles are intersected perpendicularly to form the deformation quadrotor. This foldable structure allows easily to adjust the volume of the drone to adapt it to different obstacles (see Fig. 33).

2.4. *Bio-inspired drones*

Bio-inspired reconfigurable drones have become one of the most used systems in recent aeronautical technologies, because they have overcome several problems and limits encountered previously in UAVs, namely geometric adaptation [130]. In addition, due to these aerial morphology limits, some researchers in [21–27, 53, 131–143] have thought of being inspired by the capacities found in birds, in insects and in organic molecules, in order to be able to navigate in congested and narrow places and fold or deform in the event of a collision with different obstacles to avoid damages (see Fig. 34).

For example, nature swifts [133] and pigeons [131] adapt their wings by folding them tightly and near to their body in order negotiate different openings, especially small vertical spaces (see Fig. 35).

Budgerigars fly in cluttered places, they raise their wings or fold them over their body (see Fig. 36), in order to avoid contact with the side panels [136].

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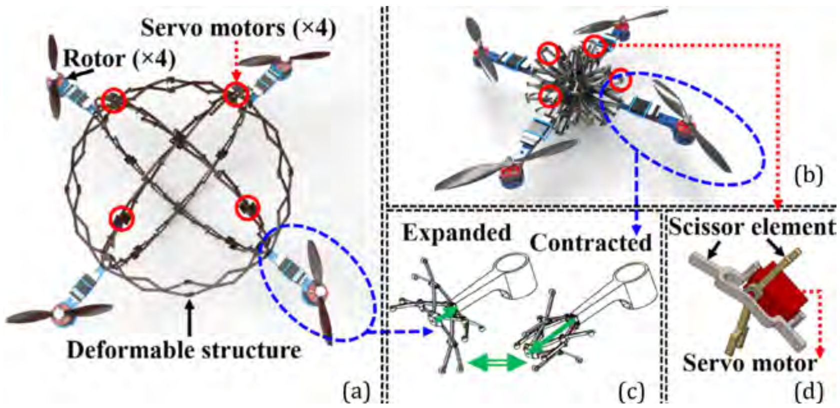


Fig. 33. Deformable UAV: (a) initial state, (b) contraction state, (c) rotor-scissor assembly, (d) servomotor-scissor assembly [52].

Fig. 34. Four-Winged insect flying micro-robot [143].

By inspiring the abilities of birds and insects, several prototypes of drones with folding wings have been developed in [21, 26]. In [21], a folding wing drone inspired by insects has been realized (see Fig. 37). The wing is remote controlled by the user to perform the assigned task with reduced time. In the folded structure, the span is 43% and the surface is 26% of the dimensions of the overall deployed structure. The realized prototype is tested experimentally.

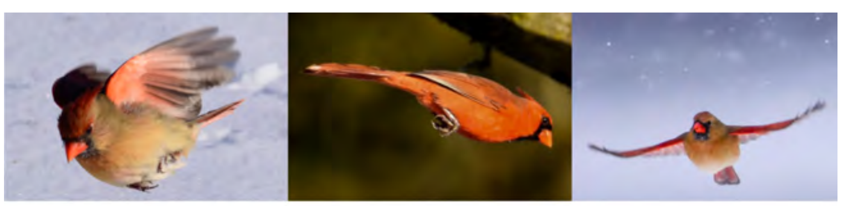
On the other hand, a new bio-inspired design has been proposed by the authors of [22, 23, 53]. The proposed quadrotor can fold and deform in the event of a collision with different obstacles to avoid damages using specific materials (see Fig. 38).

Researchers in [138] have studied a new bio-inspired design of the quadrotor. The proposed framework allows the quadrotor to fly and navigate through unknown gaps, using only a monocular camera and on-board sensing without exploiting the explicit 3D reconstruction technique of the scene.

Due to the limitations of the standard aerial configurations, a bio-inspired drone, called BioTetra, was presented in [24]. Its configuration was inspired by the the organic molecules CH_4 (see Fig. 39). In addition, it is able to flight in different directions, thanks to its adaptive mechanical design.

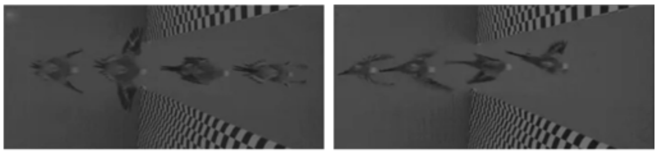
The missions of UAVs in rugged locations require an adaptive flight geometries to overcome the various aerodynamic limitations of fast cruise flight. In nature, some birds have these characteristics such as the northern goshawk, which presents high maneuverability and agility. In paper [26], flight performance such as agility, stability and energy efficiency of a winged drone have been studied experimentally using a new morphing aerial vehicle (see Fig. 40). Design and flight test videos are available at: https://zenodo.org/record/3648670.

A simple mechanism of an insect-inspired aerial robot has been designed in paper [27] to improve flight endurance using minimum power energy (see Fig. 41).



(a) (b) (c)

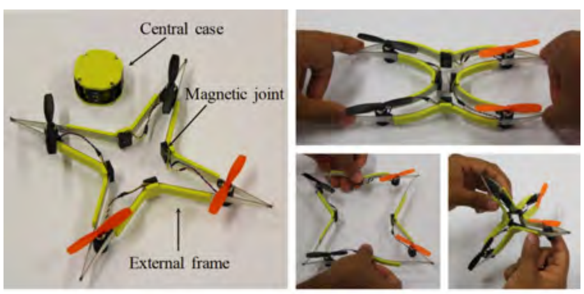
Fig. 35. (a), (b) Bird folds its wings vertically, (c) Bird folds its wings horizontally [133].



(a) (b)

Fig. 36. (a) A bird with its wings almost completely tucked back. (b) A budgerigar with its wings held above its body for a prolonged time [136].

Fig. 37. Bio-inspired drone in the folded and unfolded configurations [21].



(a) (b)

Fig. 38. Insect-inspired quadrotor. (a) The quadrotor is composed of the external frame and the central case, connected by magnetic joints. (b) Intrinsic flexibility of the external frame made with thin fiberglass arms [22].

Fig. 39. Biplane quadcopter [24].

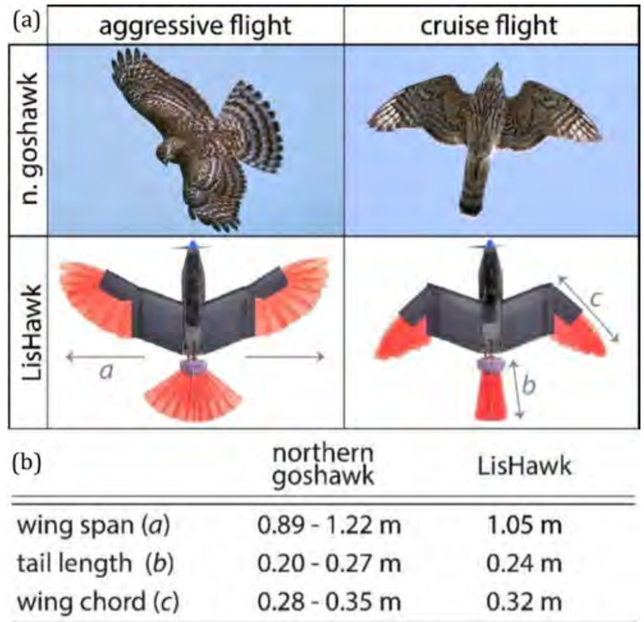


Fig. 40. Bio-inspired morphing drone [26].

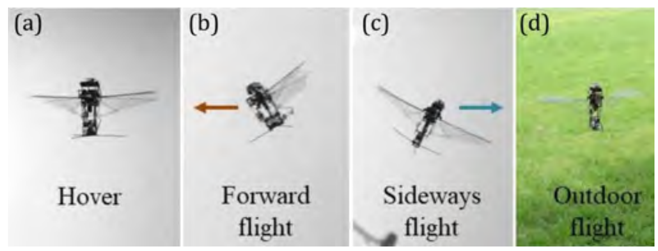


Fig. 41. Flight phases of a bio-inspired flying robot [27].

Experimental tests have been done to prove the optimization of consumed energy in flight. In addition, the flight results showed that the robot selects the wing, which can hover for 8.8 min.

Table 2 shows the main differences between the various works of bio-inspired drones.

2.5. *Extendable arm drones*

Drones with extendable arms offer the possibility of reducing multirotor dimensions, unlike the conventional ones. The reduction of arm length is usually done using servomotors and a gear system. Thanks to the extension of the arms, the drones can have pitching and rolling movements without modifying the speeds of the rotors, by varying only the length of the arms (front or rear) and (left or right), respectively, for a large configuration "X". To have a yaw movement they only vary the lengths of two arms of the same axis [144, 145] (see Fig. 42). Usually, these drones

Table 2. Comparative table of the bio-inspired drones.

Authors/References	Year	Modeling	Control	Experimental tests	Main objective	Inspiration
Perez *et al.* [135]	2011	Yes	No	Yes	Flight in cluttered environments	By insects
Klaptocz *et al.* [53]	2013	No	No	Yes	Flight in cluttered environments and collisions resistance	By insects
Perez *et al.* [137]	2015	Yes	Yes	Yes	Avoidance of the flight obstacles	By insects
Dufour *et al.* [21]	2016	No	No	Yes	Achievement complex and dangerous tasks	By insects
Mintchev *et al.* [22]	2017	No	No	Yes	Avoidance of the collisions	By insects
Mintchev *et al.* [23]	2018	No	No	Yes	Avoidance of the collisions and damages	By insects
Chukewad *et al.* [140]	2018	No	No	Yes	Navigation under obstacles	By insects
James *et al.* [141]	2018	No	No	No	Laser applications	By insects
Fuller *et al.* [142]	2019	Yes	Yes	Yes	Increasing the flight autonomy	By insects
Yang *et al.* [143]	2019	Yes	Yes	Yes	Improvement the flight performance	By insects
Li *et al.* [24]	2019	Yes	Yes	Yes	Improvement the flight efficiency	By organic molecules
Ajanic *et al.* [26]	2020	No	No	Yes	Improvement the agility, maneuverability and flight stability	By birds
Phan *et al.* [27]	2020	Yes	Yes	Yes	Improvement the flight endurance	By insects

present the same advantages and disadvantages as foldable drones.

Transformable quadrotors, which can extend and rotate theirs arms, are proposed by Wallace *et al.* [28]. The introduced mechanism makes the UAVs over-actuated systems. Therefore, the designed structures are assumed symmetrical to facilitate their study (see Fig. 43).

In paper [29], a morphing quadrotor was designed to perform special tasks with a variable configuration during the flight. It can hover and reach several specific places due to its abilities.

Another reconfigurable quadrotor was considered by Kamil *et al.* in work [30]. This design is mainly based on the variation of the length of the four arms to have a yaw movement, without modifying the speeds of the rotors, contrary to the standard quadrotor.

A new design of a morphing drone was presented in paper [146], where the authors have considered the extension and rotation of the quadrotor arms, which hold in the event of a rotor failure to ensure stable flight with three rotors. Only the design and modeling are treated in this work (see Fig. 44).

The same principal is detailed in [31], where the proposed morphing shape can be changed while flying to obtain position and attitude control (see Fig. 45). The authors have considered the variation of the center of gravity and inertia in the dynamics of the drone. This variation plays a very important role in the system control strategy.

Due to the unshielded propellers of delivery drones, a novel UAV that can extend and retract its four arms has been fabricated in [32]. The authors have developed a high density cage to protect and improve the efficiency of the drone during the flight. This drone can retract its arms in its cage when it flies near humans, which reduces its geometric dimensions (see Fig. 46).

In order to improve the mechanical design of the conventional quadrotors, Rizon *et al.* [33] proposed a new mechanism with variable arm lengths (see Fig. 47). The

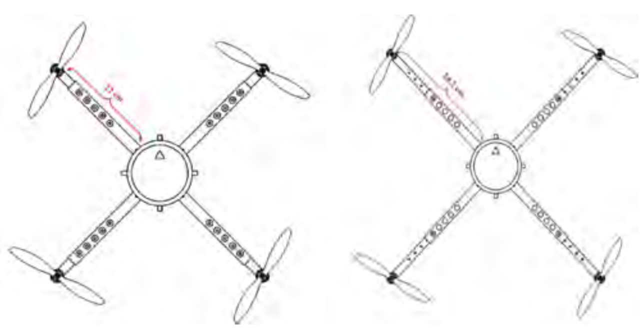


Fig. 42. Transformable quadrotor with and without extension of the arms [144].

Fig. 43. Transformable quadrotors: on the left with rotating arms; on the right with extended arms [28].

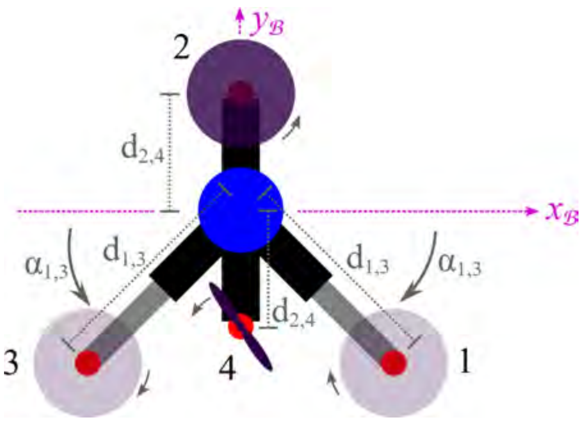


Fig. 44. Aerial vehicle configuration in the event of rotor failure. Rotors are numbered respectively 1, 2, 3 and 4. $d_{1,3}$, $d_{2,4}$ are the variation of the arm lengths and $\alpha_{1,3}$ is the variation of the arm angles [146].

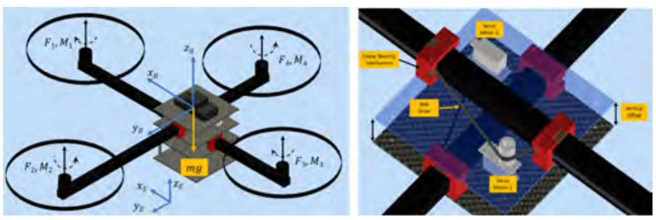


Fig. 45. Extendable arm mechanisms [31].

latter is based on the stepper motors to vary the arm lengths and therefore the drone orientation. In addition, the dynamic model relating the moments with the variation of the arm lengths has been analyzed in this work. However,

Fig. 46. (a) Drone with retracted arms. (b) Drone with extended arms [32].

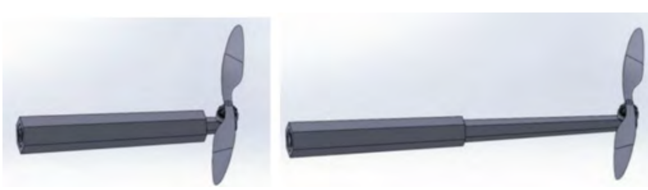


Fig. 47. Designed arm [33].

Fig. 48. Quadcopter with rotating and extendable arms [11].

the developed mathematical model does not take into account the variation of the center of gravity when the configuration changes.

More recently, the authors in [11] proposed another design of an unconventional drone based on simple servomotors (see Fig. 48). This drone can extend and rotate its arms at the same time. Moreover, the detailed mathematical model that takes into account the variation of the dynamics and configuration in flight has been presented. The designed system can be used for special tasks by choosing the right morphology for each one.

2.6. *Tilting rotor drones*

This type of UAVs concerns the drones that we have found in the literature under different names as: tilting propeller drones, tilt wing drones, tail-sitter drones and convertible drones [147]. They can be divided according to their mechanical structures and missions into three categories: hybrid Horizontal-Vertical Take-Off and Landing (HVTOL) drones, tilting rotor drones relative to a single axis and tilting rotor drones relative to two axes. The rotation of the rotors is done by servomotors mounted in different ways according to the desired orientation (vertical or horizontal orientation). Tilt rotor drones combine the advantages of fixed-wing and multirotor platforms such as increasing agility and precision, high endurance and maneuverability, adjustment of the thrust force by compensation in the event of a breakdown, horizontal and vertical displacement, elimination of the over-actuation problem, good flight autonomy and speed increase. However, the main disadvantage of tilting rotors is the poor hover performance caused by small rotor diameters and a large rotor mast. In addition, hovering may be not stable at a large inclination of the rotors because the lift forces are affected by this inclination. Using the rotation of the rotors, a drone with VTOL can transform to a drone with HTOL [81–83, 148–164], to fly with the same way as a fixed-wing aircraft. Due to the complex aerodynamic forces and torques acting on the aerial vehicles, deriving a dynamic model for a tilting rotor drone is a challenging task [165].

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2.6.1. *Hybride HVTOL drones*

The work presented in [81] concerns the design, modeling, control and flight tests of a tilt-rotors drone (see Fig. 49). This aerial vehicle can switch between two flying modes: VTOL to HTOL and vice versa, optimizing the mechanical design. In addition, the mathematical model which represents the variable dynamic of the drone was developed in this research.

In the same context, an over-actuated Vertical Take-Off and Landing (VTOL) tilting drone has been treated in [82]. In addition, the dynamic modeling that takes into account the different aerodynamic effects was developed. The authors have also demonstrated the maneuverability of this UAV in the different flight phases (cruise, transition, hovering) (see Fig. 50).

Cronin [83] studied the aerodynamic specifications of a Hybrid HVTOL UAV (see Fig. 51). A CFD simulation has been developed to characterize the relationship between the real position of the rotor and wing and lift force reduction of the aerial robot. In addition, the obtained results of the transitional flight have been validated.

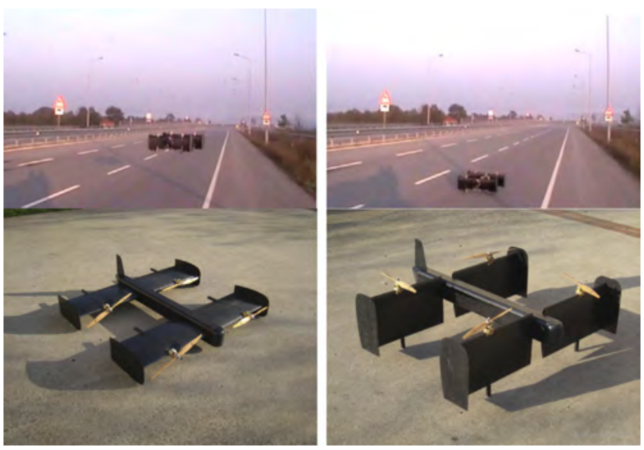

Fig. 49. UAV in horizontal and vertical flight configurations [81].

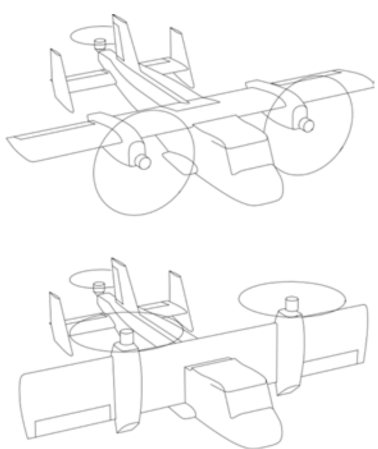

Fig. 50. Proposed drone in different configurations HTOL and VTOL [82].

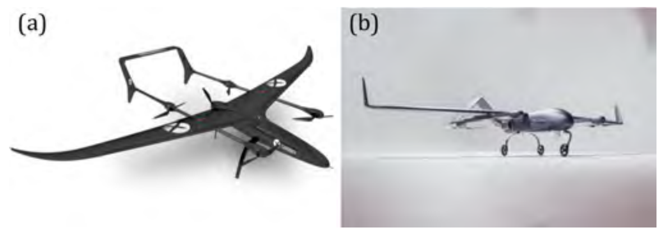

Fig. 51. An HVTOL drone considered in [83].

Authors in [150, 151, 161] have studied the modeling, design and control of Biplane quadrotors. These drones can switch between two flight modes: hover mode and cruise mode, by exploiting the rotation of the motors (see Fig. 52). A video showing the experiment of work [161] is available at: http://y2u.be/MjGfSMEPUGE.

Researchers in [152–154, 160, 166] proposed tailsitter drones based on a simple mechanism, which decreases the mechanical complexity of the structure (see Fig. 53).

In [160], a tail-sitter drone was designed, modeled and controlled to stabilize it in flight transformation phase (see Fig. 54). The simulation results are satisfactory especially in the transformation phases (cruise to hover and hover to cruise).

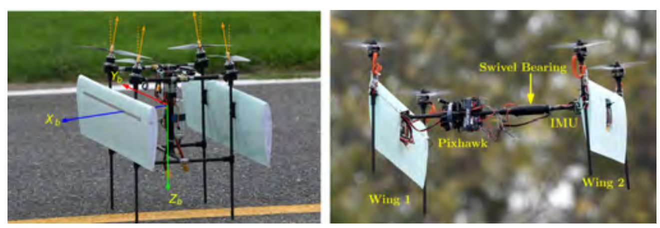

Fig. 52. Biplane quadcopter [161].

Fig. 53. Convertible tailsitter drone [152].

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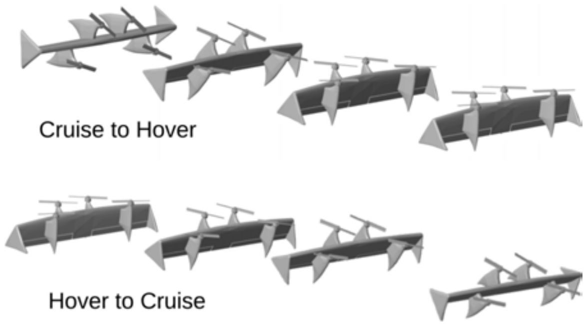

Fig. 54. Tailsitter drone in transition phase [160].

An animation video of work [160] is available at: https://youtu.be/frN5Bcow9xw.

2.6.2. *Tilting rotor drones relative to a single axis*

In a series of research works [55, 65–80, 167], authors have proposed different designs of quadrotor with tilting rotors in relative to a single axis (see Fig. 55). These quadrotors are characterized by four (4) additional control inputs, which ensure the control of the position and orientation of the drone. They can also generate the control of moments and forces independently in specific directions to overcome the gravity effect. However, due to the constraints of the actuators, some of them cannot fly in arbitrary directions.

A drone of type hexarotor had been studied by Kaufman *et al.* [70]. This UAV uses six variables rotors to control the orientation and position (see Fig. 56). Moreover, the large thrust allows the UAV to hover in any desired orientation.

An omnidirectional multirotor allowing the to exploit the dynamics of translation and rotation separately was presented in [73, 74]. It is based on reversible actuators, which have proven the feasibility of the design approach and the ability of the vehicle to generate thrust and torque independently and in different directions (see Fig. 57).

Fig. 55. Quadcopter prototypes [67, 77].

Fig. 56. Hexarotor UAV prototype [70].

Fig. 57. Omnidirectional multirotor [74].

A Voliro hexacopter with tilting rotors has been presented in [55]. The proposed UAV has six rotors uniformly arranged (see Fig. 58). The carbon-fiber tubes were used to build the six arms. Through this platform, the authors will be able to separate the orientation control to the position control.

Keeping the same idea, the researchers in [167] have presented another hexacopter drone, which allows to pass from an under-actuated to a fully-actuated structure using a single additional input and lightweight platform. It adapts its morphology by tilting all the propellers (see Fig. 59). In addition, the proposed design was validated experimentally.

2.6.3. *Tilting rotor drones relative to two axes*

In another part, some researchers have proposed quadrotor designs with two axis tilting rotors [168–171]. The mechanism used in this design is illustrated in Fig. 60, where a servomotor was exploited for the rotation of the rotors

Fig. 58. Voliro UAV [55].

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Fig. 59. Hexcopter prototype [167].

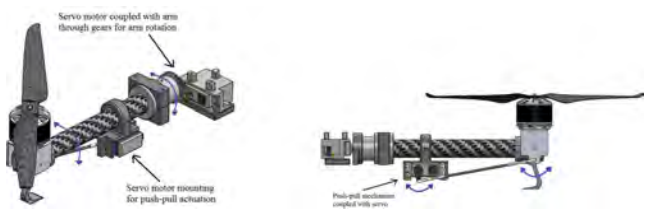

Fig. 60. Two-axes tilting rotor mechanism [169].

around the axis fixed to the main body and the other servomotor was used for rotation around the axis perpendicular to the latter. The proposed designs offer more precision and controllability of translation and orientation by comparing them to those with a single axis. In addition, they are characterized by their high agility, especially in narrow places.

The same subject is treated in [172, 173]. They have concentrated their studies on reconfigurable aerial vehicles to improve the control and stability while flying (see Fig. 61).

2.7. *Tilting body drones*

Drones with tilting body are almost similar to those with tilting rotors [48–51]. Indeed, they are found in the literature under the name "tilting body drones" and sometimes "tilting rotor drones" because the rotation of the body is done either by a servomotor mounted on the central body or by the rotation of the rotors, which rotate the central body. However, they have the disadvantage of high energy consumption for maintain balance in hover and transition.

In [49], a morphing multicopter has been designed so that only the central body spins (see Fig. 62). This platform can fly in vertical configuration unlike standard aerial vehicles. The study presented in this research takes into consideration the case of rotor failure whose vehicle can fly with only 2 or 4 rotors.

Fig. 61. Two-axes tilting quadrotor [173].

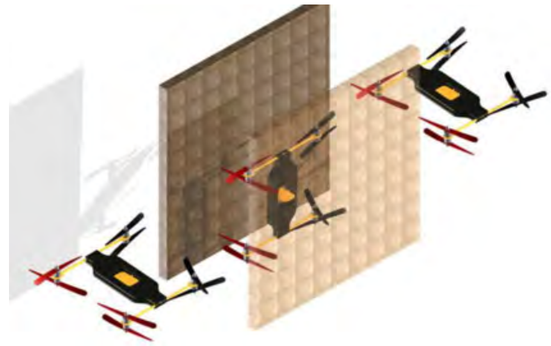

Fig. 62. Titling body UAV [49].

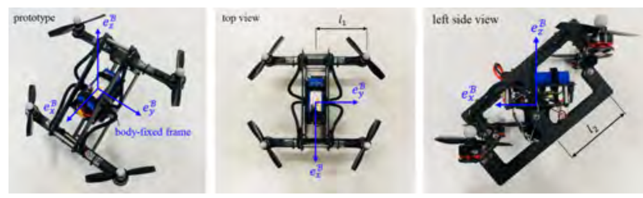

Fig. 63. Quadcopter prototype with different views, isometric, top view and left side view, respectively, [50].

Another multirotor prototype with tilting body has been developed by Sakaguchi *et al.* [50]. The new design consists of the tilting central body through the use of a parallel linkage mechanism (see Fig. 63). This chassis can tilt in the direction of pitching using a single servomotor, respecting the user-specified. However, this structure has some physical limitations to make other movements with a single servomotor.

2.8. *Modular drones*

Modular UAVs, such as those presented in [106–119, 174], are new reconfigurable aerial robots, which are composed of different modules interconnected with each other. Consequently, the modularity allows UAVs to become more flexible encouraging their use in the areas of transport, delivery, parachuting and search and rescue. They are characterized by their versatility in the execution of missions. However, most of the time, the modules used in these drones are complex than the actuators. In addition, the proposed prototypes in the literature have not proven their robustness. Note that these prototypes are also characterized by their high cost [116].

The design, modeling and control of a flight modular robot have been described by Oung *et al.* [109] (see Fig. 64). This structure was exploited as test bench in order to evaluate the implemented algorithms of control.

Fig. 64. Prototype of a flight modular robot [109].

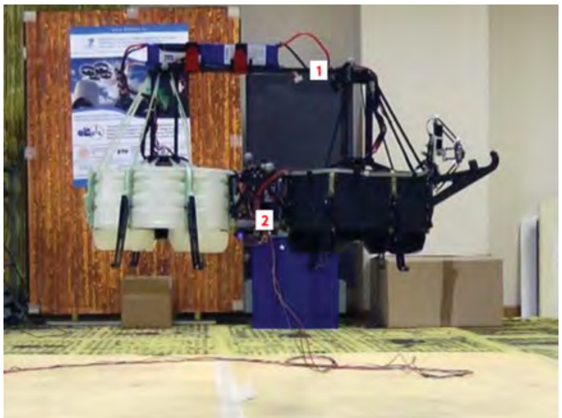

Fig. 65. Realized prototype with two-modules [110].

In [107, 110], the structure design, mathematical modeling, and control strategy of a modular drone are presented. The realized prototype is based on two ducted-fan vehicles in order to prove the efficiency of this structure (see Fig. 65).

Lee *et al.* [111] studied the possibility of introducing a new modular design to an UAV delivery system. In addition, the optimization of the management of several modular delivery UAVs was also investigated in this work. The obtained results have shown that the studied UAV can reduce the consumed energy and the delivery time unlike to the conventional one.

Saldana *et al.* [112] investigated a new design of modular UAV, which can self-assemble in flight (see Fig. 66). In addition, the large number of module allows to it to navigate in different directions.

To improve the performance of the hovering flight, Gabrich *et al.* [114] proposed a transformable modular drone (see Fig. 67). This drone can transport and grab objects, while the large number of modules makes the prototype so complex.

Authors in [117] focused their study on a modular aerial robotic platform to transform a rigid body into a special

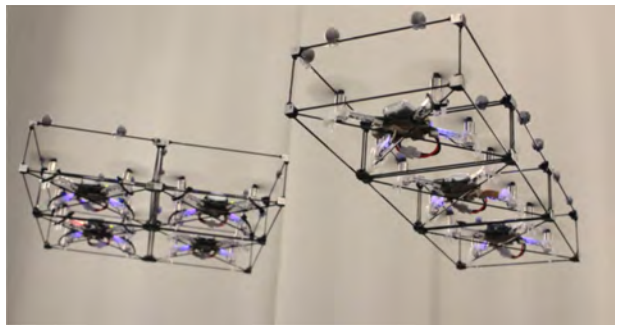

Fig. 66. Modular UAV in flight [112].

Fig. 67. Transformable modular drone in closed configurations to transport objects [114].

multirotor UAV (see Fig. 68). This platform design is characterized by an aerial reconfiguration, by adding or removing modules, changing payloads or adjusting modules. However, adding additional modules makes it more complex and influences the robot's flight performance.

Gabrich *et al.* [119] proposed a novel design of a modular aerial robot composed of six modules (see Fig. 69). In addition, these modules have been tested and validated experimentally.

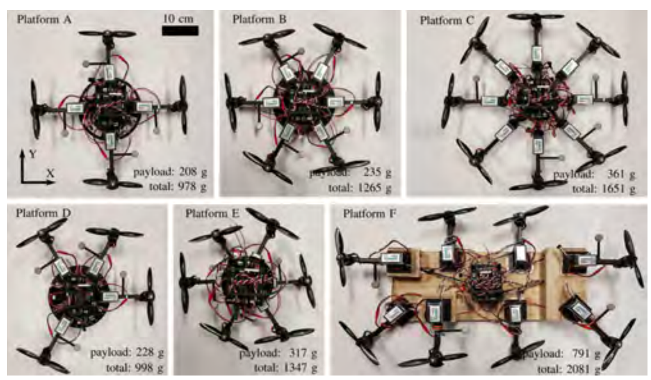

Fig. 68. Prototypes of the proposed multirotor UAV. The platforms shown in Figures A, B and C are symmetrically. Platform modules D, E and F are placed in nonsymmetrical configurations [117].

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Fig. 69. Modular drone prototype [119].

2.9. *Design technologies synthesis*

By synthesizing the different proposed structure technologies, we can conclude that most of the prototypes have a great number of motors and control inputs, which make them complex, highly non-linear and over-actuated systems that have agile and deformable geometries, slow transformation mechanisms, adaptive bodies and variable models contrary to the classical ones. Moreover, they are used to grab and transport objects, navigate in more dangerous places, optimize the consumed energy while flying, improve stability and controllability, eliminate fault tolerant control problem, inspect surfaces, cross small and narrow spaces, avoid the different collisions with obstacles, and increase efficiency and maneuverability.

3. Control Strategies Review

The above characteristics make the flight control strategies of this novel class of drones, a very challenging task. In this section, we seek to present the various strategies developed, basing on more recent scientific works.

3.1. *PID controller*

Dudley *et al.* [92] used a cascaded discrete PID controller to stabilize a hybrid air-ground robot in attitude according to the three angles of Euler (φ, θ, ψ). Zhao *et al.* [12, 13] controlled the position in the horizontal plane of a transformable UAV by a conventional PID. In addition, the developed controller is based on a simplified model and assumes that the CoG is always close to the geometric center. A classical control strategy based on PID regulator is exploited in [15, 42] to control the position and attitude of the transformable drones. Riviere *et al.* [54] used an adaptive PID controller to control a foldable Quad-Morphing, where they took into account the variation of the inertia matrix. Considering the rotation of the multirotor arms, Xiong *et al.* [40] were interested in optimizing energy consumption during the flight, where the attitude and the trajectory of the prototype have been controlled using two PID controllers. Desbiez *et al.* [125] designed an *X*-Morf quadrotor, with two rotating independent arms, where a Model Reference Adaptive Control (MRAC) is implemented to deal with the changes of the CoG and inertia and to control the angular velocities. In addition, a conventional PID controller combined with a dynamic reversal process have been used for the attitude control. Another drone with exendable arms was controlled in position and attitude using a PID regulator [30, 31]. In addition, the variation of the CoG and the inertia were taken into account in the dynamics of the robot [31]. A classical PID controller has been adopted by Oosedo *et al.* [71], to control the attitude transition for pitch angles of a tilt rotor drone. The proposed approach has been validated with some flight tests. De *et al.* [168] were able to control a tilt quadrotor with 12 control inputs unlike to standard ones. The obtained results have demonstrated the good following of the desired trajectory using a simple PID. The same controller has been exploited in [69, 76] to stabilize tilt rotor drones. Hintz *et al.* [49] stabilized a tilting body quadrotor, while the horizontal flight, using a PID controller. In addition, the simulations have shown satisfactory results of the applied control strategy. In order to properly control the tilting body drone around a tilt angle of 90°, Akinori *et al.* [50] proposed a conventional PID to control the attitude, the altitude and the tilt angle of this aerial robot. Ranganathan *et al.* [100] applied a standard PID in order to control the attitude of a hybrid air-aquatic robot. The obtained results have shown good tracking of the desired trajectory using the applied controller. Remaining in the same controller, Mercado *et al.* [104] controlled the 3D trajectory of an aerial-underwater vehicle. To deal with the variation in the robot configuration, a gain scheduling was used.

3.2. *LQR and LQI controllers*

Barbaraci *et al.* [64] discussed the use of the Linear Quadratic Regulation (LQR) on a quadrotor with variable geometry arms, whose angles between the arms change but the structure always remains symmetrical. An adaptive LQR controller was exploited by Falanga *et al.* [18] to control a quadrotor with rotating arms in the goal to guarantee stable flight. Bucki *et al.* [39] presented an LQR attitude controller of an aerial morphing robot, which can fold and unfold its arms. An LQR controller is adopted by [28, 146] to stabilize in flight a morphing quadrotor with extendable arms. Zhao *et al.* [12, 13] developed a controller for a transformable multi-link drone based on the Linear Quadratic Integral (LQI) for attitude and altitude control.

Table 3. Different research works comparison.

Categories	Design complexity	Cost	Agility and maneuverability	Control strategies
Air-surface hybrid drones [84–96] [10, 97–105]	Complex	High	Less agility and maneuverability	PID, Adaptive PID
Multi-link drones [12–14, 56–62, 122]	More complex	High	Agility and maneuverability	LQI, PID
Foldable drones [9, 15–20, 34, 35, 37–47] [52, 54, 63] [123–126]	Less complex	Low	More agility and maneuverability	Adaptive LQR, PID, MRAC Adaptive PID, LQR, Backstepping
Bio-inspired drones [21–27, 53, 131–143]	Less complex	Low	More agility	PID
Extendable arm drones [11, 28–33, 144–146]	Complex	Low	Agility	LQR, PID
Tilting rotor drones [55, 65–83, 148–173]	Complex	Low	More agility and maneuverability	DFL, PID
Tilting body drones [48–51]	Complex	Low	More agility	PID
Modular drones [106–119, 174]	Complex	High	Agility	SM, FCA

3.3. *Feedback linearization controller*

More recently, Raj *et al.* [161] used a strategy based on the Dynamic Feedback Linearization (DFL) to control the attitude of a reconfigurable UAV. In the same context, Flores *et al.* [160] controlled a transformable tail-sitter drone using a Feedback Linearization in order to stabilize it in flight. The propose controller has proven its efficiency especially in the transformation phase. Naldi *et al.* [110] stabilized a modular aerial robot using a combination of Feedback Control Algorithms (FCA) and control allocation.

3.4. *Robust and nonlinear controllers*

Derrouaoui *et al.* [20] applied a new control strategy based on the backstepping controller to stabilize a foldable UAV. From the simulation results, it can be concluded that the applied strategy has proven its effectiveness with respect to the variation of the arms angle and consequently the drone structure. To control the position of a modular multirotor, Mu *et al.* [117] exploited a Sliding Mode (SM) controller to achieve this purpose. In addition, an Inertial Measurement Unit (IMU) was used to recalculate the configuration change.

3.5. *Control strategies analysis and discussion*

The analysis of the works carried above showed that the most researchers have used PID, LQR, LQI, Feedback Linearization or their adaptive version. In addition, very little research works have been invested in the robust and nonlinear control strategies. Due to the complexity of the control strategy, the mechanical structure and the mathematical model of these drones, the researchers did not take into account all variable dynamic such as the variation in CoG, inertia and allocation matrix at the same time. Further, the aerodynamic phenomena created by this class of drones are neglected in order to simplify the modeling and consequently the application of the control strategies.

To summarize, analyze, and compare the different works of this paper, we elaborated Table 3 that contains a comparative study between the various types of these particular UAVs in terms of design, cost, agility, maneuverability and control strategies.

4. Conclusions and Future Challenges

In this paper, we focused on very recent advanced researches and studies, which concern a new type of flying robots, called reconfigurable drones.

A new classification of these particular UAVs was first given: Air-surface hybrids, Multi-links, Foldables, Bio-inspired, Extendable arms, Tilting rotors, Tilting body and modulars.

Due to their adaptive and variable structures, they can be exploited for transporting and grabbing objects, navigating in more crowded and dangerous places, ensuring good autonomy by optimizing the consumed energy, improving controllability and stability, eliminating of fault tolerant control problem, inspecting different surfaces, crossing narrow and small spaces, avoiding collision with obstacles, and increasing maneuverability, agility and efficiency.

The detailed synthesis of the different proposed designs technologies by researchers allowed us to conclude that most of these prototypes are over-actuated systems due the high number of the control inputs, complex because of the large number of motors and servomotors, highly non-linear systems, have slow aerial switching and transformation mechanisms, have variable mathematical models and have adaptive flight morphologies contrary to the conventional drones.

The analysis of the applied control strategies of the various research works shows that the vast majority of them have used classical approaches such as PID, LQR, LQI, Feedback Linearization as well as their adaptive form. The robust and nonlinear controllers were invested in few studies because of the novelty and variable parameters of the mathematical model. Furthermore, due the control complexity, the authors did not consider all the variable dynamics such as CoG, inertia and control matrix at the same time. Moreover, the aerodynamic phenomena generated by this class of drones were not taken into account in order to simplify the modeling and therefore the control loop.

Finally, a comparative study including the characteristics of the designs and control strategies was established.

Future challenges:

Reconfigurable drones are a promising solution in the near future, since they allow increasing considerably the capabilities and performance of the conventional drones. Moreover, the huge potential of their adaptive and variable structures needs to be invested and explored by researchers to exploit them in special missions and in severe flight conditions.

The continuity of the stability by changing the drone configuration during flight is a major constraint for the control of reconfigurable drones. Usually, it happens when switching between configurations is done quickly, which causes sudden changes in the dynamics of the drone and consequently the loss of its stability. This constraint is a challenging task that must be resolved by researchers.

Due to the small number of research works in the field of reconfigurable drone control, and since most of them have exploited classic control strategies such as PID, LQR, LQI, Feedback Linearization as well as their adaptive form, it is very encouraging to invest in the robust, adaptive, and nonlinear controllers.

Another important point concerns the problem of fault tolerant control in the event of failure of one of the rotors, where the drones with variable arms can accomplish their mission by changing easily and rapidly their aerial configuration differently to the conventional ones. These drones will be a very interesting research axe in this area to overcome this problem.

The morphological changes generate significant variations in the dynamic model, especially for drones with foldable and extendable arms. These variations remain a serious problem in the modeling of this generation of drones. In addition, their model needs to be improved, and the authors must take into account all the variable and important parameters such as, CoG, inertia and control matrix at the same time.

In terms of design complexity, the modularity encourages reconfigurable drones to use them in various domains and with high efficiency. Generally, the modularity is formed by: control modules, propelling modules, and payload. The number of these latter is variable according to desired flight configuration, which make most of the time the structure of these drones more complex and expensive. This is another constraint that must be explored in order to minimize the cost and the complexity of modular drones.

Optimization of the consumed energy is a great problem for UAVs while flying. For the reconfigurable drones, the problem has become more important because of the integration of additional actuators especially those used in the multilink, modular and tilting rotor drones, which increase considerably their complexity and consequently their weight. However, the aerial reconfiguration allows to minimize the consumed energy by seeking the optimal morphology for each flight phase using their adaptive and variable shape. This important point should be explored further.

In terms of multi-functionalities, multi-link drones are equipped with several servomotors and rotors, which make the aerial robot capable to switch in flight in order to accomplish the desired tasks. Unlike the classical drone, this mechanical design allows them to work like a clamp without additional gripping mechanisms to transport, seize, drop and manipulate objects by changing their form, from wavy line to square or circular. They can also be exploited to cross small holes and avoid collision with obstacles. All of these tasks can be performed by the same drone, in other words, all in one. These characteristics provide an excellent opportunity for researchers to exploit these capabilities.

Bio-inspired drones have overcome several problems and limitations encountered previously in conventional UAVs, namely geometric adaptation. The researchers have thought of being inspired by the capacities found in birds (swifts, pigeons, and Budgerigars), in insects and in organic molecules (CH_4) that allow to the drones to navigate in congested and narrow places, to fold or deform in the event of a collision with different obstacles to avoid damages, and to improve the consumption of energy. The design of this new class of drones is based on advanced technology, which is the origami manufacturing. The latter is a trend in bio-inspired designs because it offers high resilience, high load bearing, and dual stiffness at the same time.

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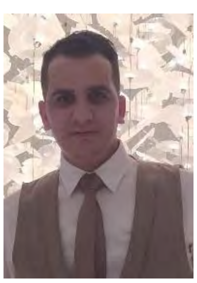

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