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Configurations, flight mechanisms, and applications of unmanned aerial systems: A review

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ABSTRACT

Unmanned Aerial Systems (UASs) have a variety of applications in our daily life that have attracted the attention of many researchers around the world. There are a variety of innovations in the flight mechanisms that UASs are applying for flight. There is also a significant interest in the development of new types of drones that can fly autonomously in different locations, such as cities, marine, and space environments and perform various missions. This paper reviews the different configurations, flight mechanisms, and applications of UASs. First of all, UASs are divided into four main categories, including Horizontal Takeoff and Landing (HTOL), Vertical Takeoff and Landing (VTOL), Hybrid, and Bio-Based drones. Then each category is divided into some sub-categories in order to have a coherent review. The characteristics, advantages and drawbacks of each category are discussed elaborately. Moreover, a comprehensive study is carried out on the applications of UASs and their specifications.

1. Introduction

In 1860, balloons were used to take photos for remote sensing [1]. In 1903, Julius Neubranner [2] designed and implemented a breast-mounted aerial camera to be carried by pigeons for photography. Even though this method was faster than balloons, they were not always reliable in following their flight paths [3]. Later by progress in aviation industries, these methods were replaced by aircraft for aerial photography. After launching the first satellites into orbit for military applications around 1960 and the development of more sensitive sensors and high-resolution cameras, the demand for using satellites for aerial surveillance increased [4]. Unmanned Aerial Systems (UASs) or drones that have many applications in both military and civilian sectors are attracting much attention. To this end, new unmanned vehicle concepts for different environments are being developed [5–9]. Each of these UASs exhibits certain advantages and disadvantages for deployment in particular missions and applications.

UASs can be equipped with various sensors and cameras that enable them to conduct both outdoor and indoor missions in very challenging environments [10–14]. The applications of these autonomous systems can be categorized based on the type of missions (military/civilian), flight zones (outdoor/indoor), and environments (underwater/on the water/ground/air/space) [5]. Drones have been used for search and rescue missions, mailing and delivery, environmental protection, as well as in missions undersea and planetary explorations [15–17].

Classifications of UASs are often carried out based on their weight and dimensions. Holland [18], Arjomandi et al. [19], Weibel and Hansman [20], and Hassanalian and Abdelkefi [5] have categorized the drones based on their weight and size. Table 1 depicts different classes of drones according to the methodology defined by Hassanalian and Abdelkefi [5]. This classification covers a wide range of UASs from Unmanned Aerial Vehicles (UAVs) to Smart Dust (SD). It should be noted that on most of those classifications, no consideration has been given to the configuration and scheme of unmanned aerial systems.

In 2018, Saeed et al. also proposed a method for classifying hybrid UAVs [21]. The classification proposed by Saeed et al. is based on the flight mechanism and scheme - considering only the hybrid-systems, such as tilt-rotors, tilt-wing, and tail sitter concepts.

This paper illustrates a comprehensive view and development of different types of UASs in recent years, focusing on the flight mechanism. Moreover, flight dynamics, control, aerodynamics, structure, and other UASs' specifications are considered. At the end of each section, we discuss each category's advantages and disadvantages and their design challenges. In the second part of the paper, the various drones'

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Table 1
Drones classification proposed by Hassanalian and Abdelkefi based on their weight and size [5].

Class	Weight Range	Wing Span Range
UAV	5–1500 kg	2–61 m
UAVμ	2–5 kg	1–2 m
MAV	50–2000 g	15–100 cm
NAV	3–50 g	2.5–15 cm
PAV	0.5–3 g	0.25–2.5 cm
SD	0.005–0.5 g	1–2 mm

applications are studied with a focus on flight mechanisms. We also review the requirements of different applications and flight mechanisms (categories) that are currently being used for those missions. In the end, we have tried to summarize the previous sections by suggesting a suitable configuration for each application. This review expects readers to get a good view of different flight mechanisms of UASs and their advantages and disadvantages, and the latest progress. We also hope it would help the designers make a good decision to choose or develop an appropriate configuration for their desired application.

In this paper, a general categorization of UASs based on their configurations is presented and critically reviewed. To this end, drones have been divided into four main categories, including Horizontal Takeoff and Landing (HTOL), Vertical Takeoff and Landing (VTOL), Hybrid, and Bio-based drones. Each of these categories is divided into a number of sub-categories in a coherent manner. Fig. 1 shows the organization of the proposed classification.

HTOL UASs are divided into four sub-categories, that is fixed-wings, morphing wings, Magnus effect UASs, and unmanned paragliders.

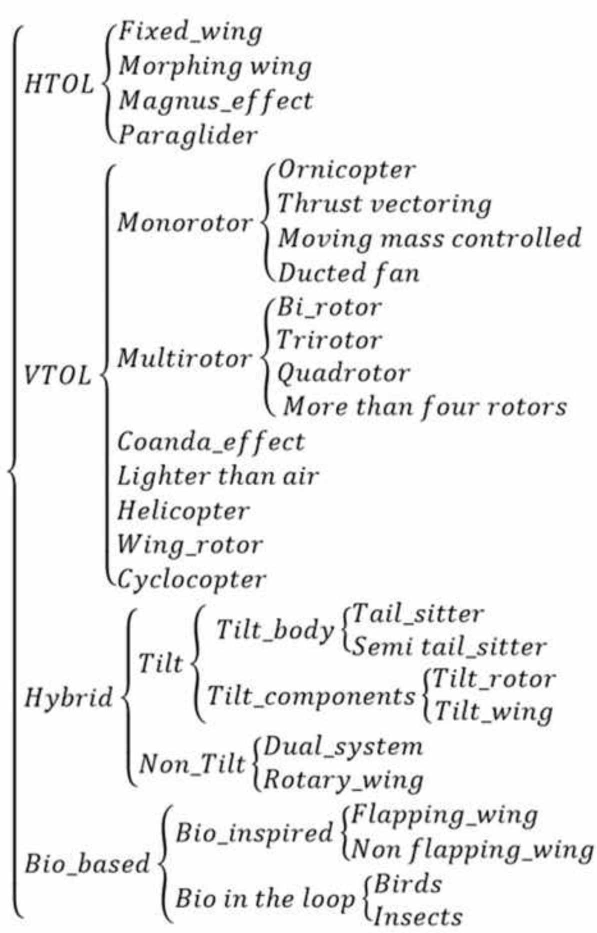

Fig. 1. Classification of UASs.

Similarly, VTOL aerial vehicles are classified into seven sub-categories; mono-rotors, multirotors, Coanda-effect, Lighter Than Air (LTA), unmanned helicopters, wing rotors, and cyclocopters. Mono-rotors can be divided into five groups: ornicopters, Thrust Vectoring mono-rotors (TV), Moving Mass Controlled (MMC), and ducted-fan mono-rotors. Multirotors are the most popular drones that have different configurations, including bi-rotors, tri-rotors, quadrotors, pentarotors, hexacopters, etc. Among multirotors, quadcopters can have different forms that include fixed-rotors, tilt-rotors, moving mass controlled, and Dyson fan configurations.

The third category is the hybrid aerial vehicles, which are the combination of VTOL and HTOL UASs. These types of drones takeoff and land vertically like VTOLs and have a horizontal cruise flight like HTOLs. Hybrid UASs are divided into two major sub-categories, such as tilt and non-tilt configurations. Generally, tilt UASs use a tilt mechanism to transfer from VTOL to HTOL mode, and there are two main groups in this sub-category, i.e., tilt-body and tilt-components. Tilt-body UASs can be found in two types: tail-sitter and semi-tail sitter. Tilt-components also have two major types: tilt-rotor and tilt-wing. Non-Tilt UASs are classified into two groups: dual systems and rotary-wings. All of these categories will be reviewed in detail in the next sections.

The bio-based category consists of two sub-categories, bio-inspired and bio in the loop drones. The bio-inspired drones which mimic living creatures like birds, insects, or aquatic animals can be classified into flapping-wings and non-flapping-wings. In the bio in the loop concept, live insects and birds are controlled and used as drones, and bio-materials are integrated into the drones' structure. It should be noted that there are some UASs that can belong to two or more categories; for example, flapping-wing drones sometimes can be VTOL, but the classification which is introduced in this paper focuses on their main idea of flight.

This overall classification scheme of UASs provides an insight into the selection of an appropriate configuration for different types of missions and applications. The remainder of this review article has been organized into the following sections: Horizontal Takeoff and Landing UASs are presented in Section 2. In section 3, different types of Vertical Takeoff and Landing UASs are shown. Hybrid and bio-based drones are examined in sections 4 and 5, respectively. Applications and capabilities of different UAS configurations are discussed in section 6. Finally, conclusions are given in Section 7.

2. Horizontal takeoff and landing UASs

Generally, the HTOL unmanned aerial systems need a runway to take off or require to travel a horizontal route to reach the necessary minimum takeoff speed [5]. This requirement can be satisfied by utilizing engines and rotors or by employing an initial external thrust, such as catapult-launched UASs. Moreover, the landing maneuver for these UASs is often done horizontally. Different types of HTOL UASs are discussed below.

2.1. Fixed-wing UASs

Fixed-wing classification is applied to classical UASs that use their wings to generate lift. Fixed-wing drones can have different wing designs and even more than one pair of wings depending on the mission [22–24]. Moreover, fixed-wing drones can have different configurations for the tail, in terms of count, placement, and shape, but the flight mechanism is based on the production of the lift using lifting surfaces. These differences in the configurations of the fixed-wing drones are generally aimed at increasing their performance, maneuverability, and payload capacity [5]. Fig. 2 depicts different configurations of the wings used for fixed-wing UASs. Similarly, tails of fixed-wing drones have varying structures for a multitude of applications, as shown in Fig. 3.

A fixed-wing UAS is typically composed of a wing, horizontal tail, vertical tail, fuselage, and a motor to produce the required lift [5].

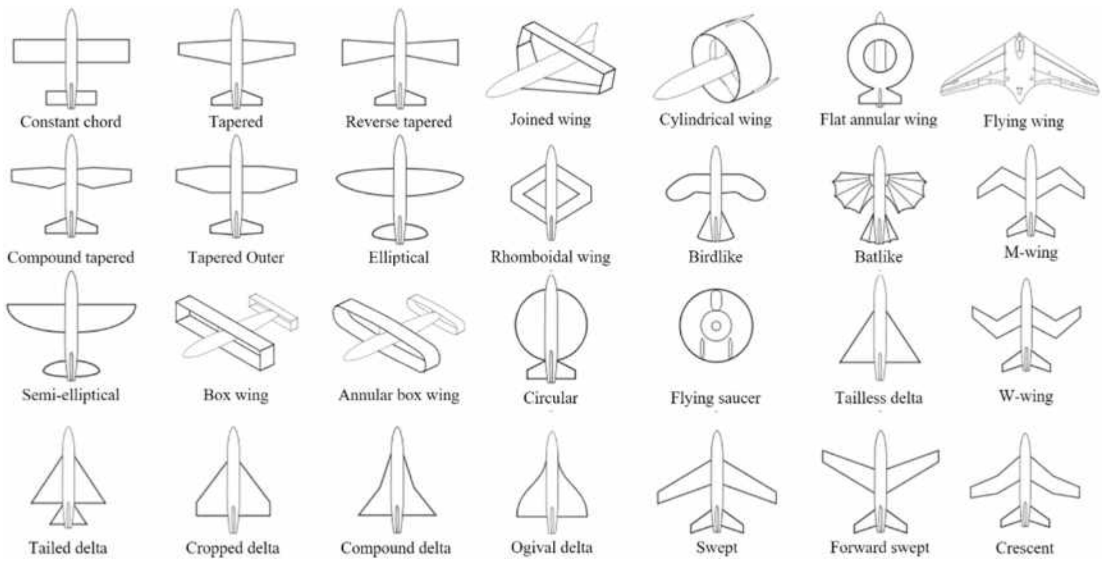

Fig. 2. Fixed-wing UASs with different wing configurations [25,26].

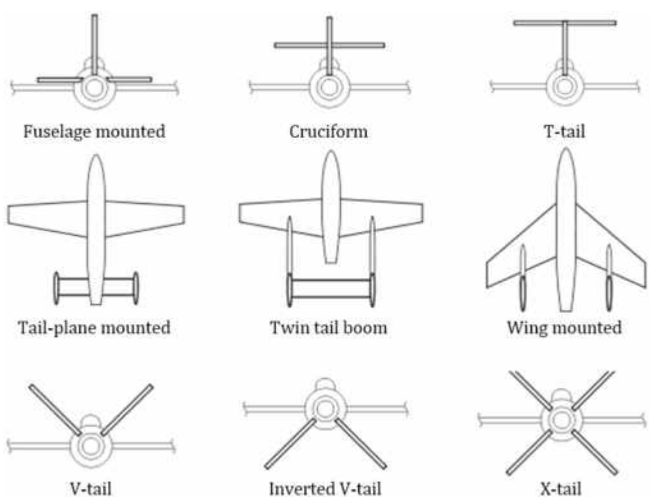

Fig. 3. Fixed-wing UASs with different tail designs [27].

Generally, on the wing and tail of fixed-wing aerial vehicles, the flight control surfaces are attached, which control the airflow and consequently lifting force. Applying three control surfaces on the wings, horizontal tail, and vertical tail, it becomes possible to control the UASs rotation along the roll, pitch, and yaw axes. In Fig. 4, types of control surfaces employed on fixed-wing drones are shown [28].

Fixed Wing UASs are very simple structurally and able to use different propulsion systems, such as fuel engines, solar and battery-powered electric motors [29,30]. These types of aerial vehicles can be designed in different sizes and classes, like Unmanned Air Vehicle (UAV), Micro Air Vehicle (MAV), and Nano Air Vehicle (NAV) [5]. Fixed-wing UASs can fly over a wide range of altitudes and distances. Despite all these benefits, they need a runway for taking off and landing, and unlike VTOLs, they usually cannot perform a hovering flight because of their low thrust to weight ratio. Moreover, the way of hovering flight in fixed-wing UASs may not be so applicable due to the high pitch angle. Even with these shortcomings, fixed-wing UASs are the most widely used drones, and several thousand of them have been built and flown around the world. For example, in China alone, around 1650, different models of fixed-wing UASs have been developed [31]. Fig. 5 depicts several examples of fixed-wing drones having different configurations.

2.1.1. *Challenges and benefits*

Among different types of drones, fixed-wings are the most developed and easiest ones to design and fabricate. They are ideal solutions for a wide range of operations, e.g., firefighting, search and rescue, coastline, reconnaissance, delivery missions and monitoring, as well as security surveillance and defense-related missions. Therefore, a wide variety of fixed-wing drones have been developed by different organizations and researchers across the world. The fixed-wing UASs have several advantages, such as the low operating cost, the ability to operate under adverse or hazardous conditions, and the increased flight endurance, which is one of the most important characteristics for the missions above [5,35]. Generally, fixed-wing UASs have longer endurance, which is only limited by the available fuel on-board. The flight endurance of fixed-wings is essentially up to the efficiency of the configuration. By enhancing the performance specifications (maximum speed, stall speed, rate of climb, turning radius, etc.), fixed-wing UAVs' versatility and potential can be further expanded [35].

While large fixed-wing UASs may have good performance in high altitudes and speeds, the smaller classes of fixed-wing drones like MAVs may face many challenges because of their lower speed and flight altitudes. These challenges are due to their dynamic flight environment and operational constraints, including flight at low Reynolds number, typically on the order of 10^4, which is lower than the majority of manned aircraft. Lower Reynolds number flow exhibits increased viscous effects, which result in higher drag penalties and reduced lift-to-drag ratio. Another constraint is that MAVs flights frequently occur in relatively

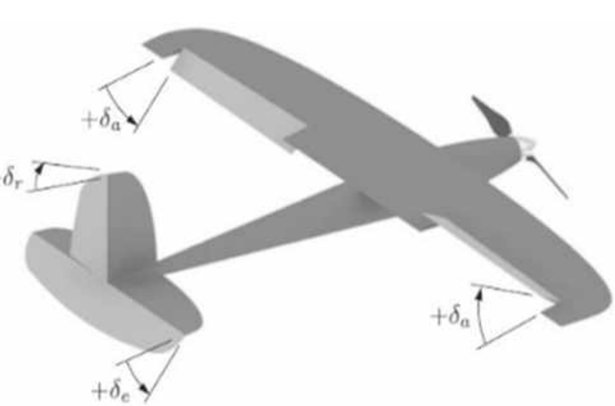

Fig. 4. Control surfaces of a typical fixed-wing UAS [28].

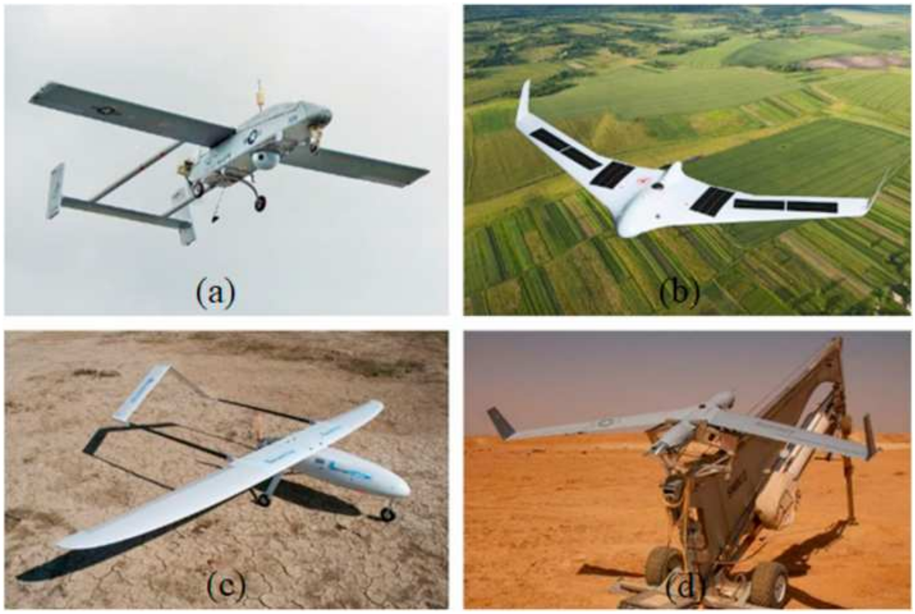

Fig. 5. Some different types of fixed-wing UASs [31–34].

unsteady flow conditions, where the flow fields are rapidly changing in time and space, which induces rapid changes in the forces and moments generated by the lifting surfaces [36].

Typically fixed-wing MAVs operate in low altitudes, where there are high levels of turbulence. These turbulent disturbances produce random roll and pitch inputs, severely disrupting MAVs' flight and making their control more challenging than manned fixed-wing aircraft or HALE UASs [36]. Fig. 6 illustrates a typical MAV mission and the environmental disturbances that affect the drone's flight.

The fixed-wing MAVs are also so sensitive to the wind direction and speed. Some studies show that they may fail to track the desired waypoint in the presence of a steady wind with a low critical speed (as low as 6 m/s) [37]. These drones have different flight speed, altitude, and endurance, depending on their defined mission. But compared with other types, such as multirotors or flapping-wings, they require relatively higher speeds for flight (for MAVs, it may vary from 6 to 20 m/s). Fixed-wing MAVs cannot fly slowly, and they do not hover due to a low thrust to weight ratio, which makes them unable to perform indoor missions. But for outdoor missions and where there is a need for high speeds, they are one of the best choices. Fixed-wing drones usually require a thrust loading of less than one and need less power to fly than a helicopter or multirotor with the same weight in hovering mode. Since the wing provides the required lift force that is highly dependent on the airflow speed, the thrust should be great enough to reach the required speed, but in multirotors or helicopters, the whole required lift should be produced by the rotor(s) [5].

2.1.2. *Joined-wing UASs*

Joined-wings have shown their superior performance in terms of aerodynamic efficiency and emissions reductions. Because of these advantages, joint wings have been utilized in UASs; for example, at Boeing, researchers have developed a joined-wing UAV and tested it in a wind tunnel (see Fig. 7(a)) [38]. There are also various versions of UAVs that are using box-wings or joined-wings combined with tilt-rotors, tilt-wing,

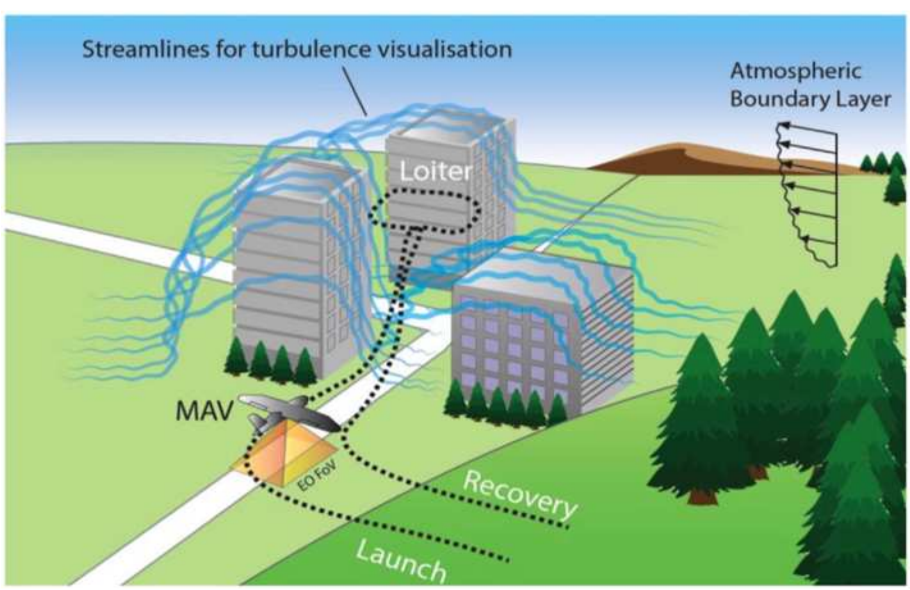

Fig. 6. View of a typical MAV mission [36].

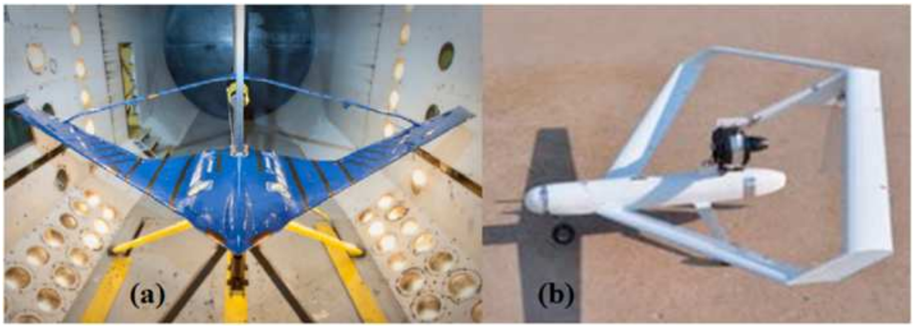

Fig. 7. (a) Wind tunnel model of Boing's joined-wing UAV [38] and (b) joined-wing UAV designed by Zafirov and Panayotov [43].

and ducted fans (see Fig. 7(b)) [39–44]. In the 2016 seminal review of the joined-wings UAVs by Cavallaro and Demasi, a particular focus was placed on the activities conducted in the United States on the joined-wing SensorCraft, PrandtlPlane, Strut- and Truss- Braced Wings, and Box Wings [45].

2.1.2.1. Challenges and benefits. Joined wings, based on their shape and design, may have better performance than traditional fixed-wings. For example, some researchers have shown that box wings produce less drag while having more complex structures than a conventional wing [45]. The general concept behind joined wings is to add an interconnected wing to form a complex over-constrained system, with a substantial increase of the design space and allowing more options in terms of aerodynamics, flight mechanics, engine integration, aeroelasticity, etc. It is not easy to consider a general advantage or disadvantage for all joined-wing UASs as their characteristics are highly dependent on their geometry. Besides their benefits, they may have challenges in terms of aerodynamic and structural nonlinearities. Emphasizing the importance of taking into account shocks and flow separations into aeroelastic analyses, and the significance of material and control surfaces' freeplay nonlinearities remained to be concerned [45].

2.2. Morphing-wing UASs

The Morphing-wing UASs use a similar flight mechanism to the fixed-wings, except that depending on the flying regime or other conditions, their wings can change to a different form [46,47]. This change can occur in the wings' specifications, such as the sweep-back or sweep-forward angle or in a more general way, like changing the airfoil shape or increase and decrease in the chord and wingspan. Fig. 8 depicts an example of a wing with a variable-sweep angle [48].

Understanding the aerodynamics and flight dynamics of the wing-deformation of UASs is challenging. Fig. 9, a view of a morphing-wing UAS with folding wings, is shown [49].

A different version of the morphing wing was developed by Ifju et al., in 2002, which uses a fixed, flexible wing concept (see Fig. 10) [50]. Li et al., in 2018, reviewed the literature related to modeling and analysis of the morphing wings [51]. They discussed the most notable examples of morphing wing concepts with their corresponding applications to two and three-dimensional wing models. This study also reviewed the commonly used methods and tools for the design and analysis of the morphing-wing UAVs, including structural and aerodynamic analyses and aspects related to control and optimization [51].

Fig. 8. Fixed-wing with a variable-sweep angle [48].

2.2.1. Challenges and benefits

Generally, fixed-wing UASs can fly at different flight conditions with corresponding requirements. They have different flight phases, such as take-off, landing, loiter or cruise flight [51]. The main idea of having a morphing structure for a fixed-wing UAS is to change the shape during the flight to obtain better performances in drag reduction, fuel consumption, endurance and flight range. Even though morphing UASs can decrease the cost and complexity of maintenance for different mission objectives and flight conditions, they have complexities in their morphing mechanisms, aerodynamic analysis and control. Despite these challenges, the above-mentioned benefits of morphing wings make them one of the best solutions for developing general-purpose UASs [51].

2.3. Magnus-effect UASs

Magnus-effect UASs employ an aerodynamic phenomenon called the Mangus-effect. The effect of Magnus leads to production of lift force by a rotating cylinder or the sphere that lies on the flow of air or is moving in a fluid. The German physicist, Heinrich Gustav Magnus was the first person that studied this effect and employed it as a control mechanism in the ships [52]. It should be noted that most of the existing Magnus UASs have a fuselage and tails like conventional fixed-wing drones, and they have a propeller in front. The only difference is in the shape and structure of their wing. The Magnus force's magnitude is much greater than the lifting force of the wing with the same projected area and dynamic air pressure. However, the Magnus effect as a flight mechanism has some challenges, which will be reviewed later in this paper. Fig. 11 shows a view of a fixed-wing UAV with a Mangus-effect design.

In general, Magnus wings are made of a simple cylinder or a cylinder covered with blades. Aerodynamic calculations of Magnus wing imply that a cylinder having a rough surface is more efficient than one having a smooth -surface [52]. Typically, the Magnus force consists of a lift force perpendicular to the airflow and drag, which is parallel to the direction of airflow. In this configuration, friction between the rotational surface and the surrounding airflow causes a moment, which must be neutralized by a mechanical system. On the other hand, the rotation of the cylinder causes the gyroscopic forces that should be considered in the context of flight control and stability [52]. The lift produced by Magnus wings or Magnus rotors depends on the wing's spinning rate, airflow speed, and body geometry. Unlike fixed-wing UASs, in Magnus effect drones, the aerodynamic forces are independent of the angle of attack, but they are highly dependent on the wings' rotational speed. The ratio between the rotor's circumferential speed and the free stream velocity has the main influence on a Magnus rotor's aerodynamic efficiency.

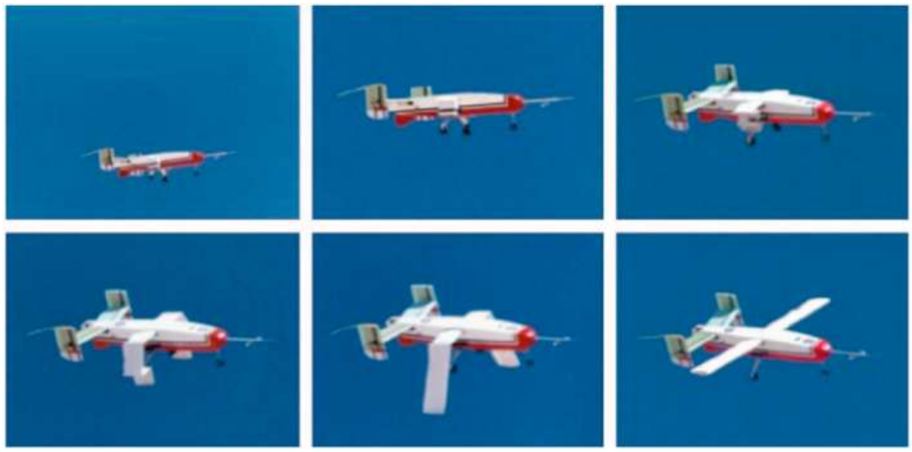

Fig. 9. NASA's morphing-wing UAV- dydren I2000 [49].

Fig. 10. The morphing wing MAV developed by Ifju et al. [50].

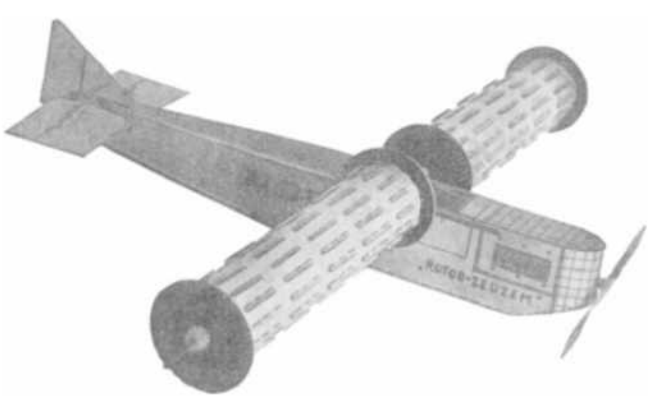

Fig. 11. Magnus-effect UAV with cylindrical wings [52].

Moreover, the sideslip angle and wing's surface roughness may also affect the performance of the Magnus wing. A typical Magnus rotor is usable as long as it is spinning [52]. Fig. 12 depicts the lift generated by the movement of a rotating cylinder [52].

Magnus-effect UASs are generally controlled like a fixed-wing UASs; however, the effects of control surfaces will not be like that of fixed-wings and will be more similar to the helicopter control system [52]. In this type of UAS, in the case of engine failure, the aerial vehicle may continue flying for a short period of time due to the wing's self-rotating phenomenon, which happens in specific types of Magnus wings. In this scenario, the velocity ratio between airspeed and circumferential speed

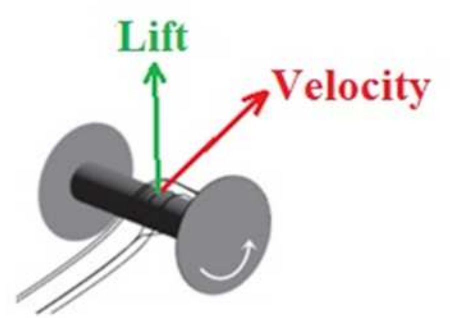

Fig. 12. Lift generated by a rotating cylinder [52].

will be constant because of autorotation; therefore, the lift force cannot be controlled independently from the airspeed. In comparison to other types of fixed-wing drones, the design of the Magnus-effect UAV is more challenging due to the dependence of lift on the direction and speed of airflow and the difficulties with regard to their control and aerodynamics. Moreover, the flow around a circular cylinder in Mangus-effect UASs is complex and consists of tip vortices, and an alternate vortex shedding between the rotor ends [52].

In 2010, Badalamenti conducted a detailed study of the Magnus-effect UAVs. In addition to building a Magnus-effect UAV, he also proposed several alternative design concepts (see Fig. 13) [53]. In 2012, Seifert derived the flight dynamics and aerodynamic modeling of this type of UASs [52]. In 2013, Jiwei et al. patented a new concept, which combined a fixed-wing UAV and Magnus-effect wing [54]. Later, Hou et al. developed a Magnus-effect UAS in combination with a ducted-fan, as shown in Fig. 14 [55]. Fig. 15 shows several examples of Magnus-effect UASs. The rotatable cylinder can also be integrated into the leading edge of conventional wings to generate a higher lift. In Fig. 15(c), a view of this concept introduced by Gligorin and Romer is shown [52].

There are also other concepts of Magnus UASs, including non-cylinder wings, multiple parallel and non-parallel wings, combined Magnus wing and conventional wings, lighter than air wind turbines and so on, which have been reviewed by Seifert [52].

2.3.1. *Challenges and benefits*

As noted above, the significant advantages of a Magnus-effect UASs are high-lift force or relatively high wing-loading and stall resistance in some specific types of Magnus wings [52]. But using Magnus wings and rotors needs additional control mechanisms, which may increase the weight and complexity compared to a conventional wing. In lower

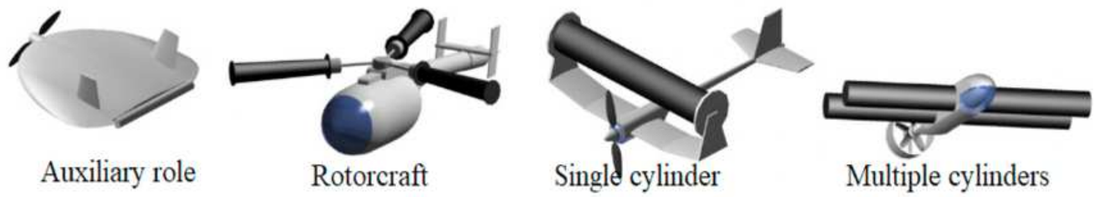

Fig. 13. Conceptual designs of the Magnus-effect UAVs proposed by Badalamenti [53].

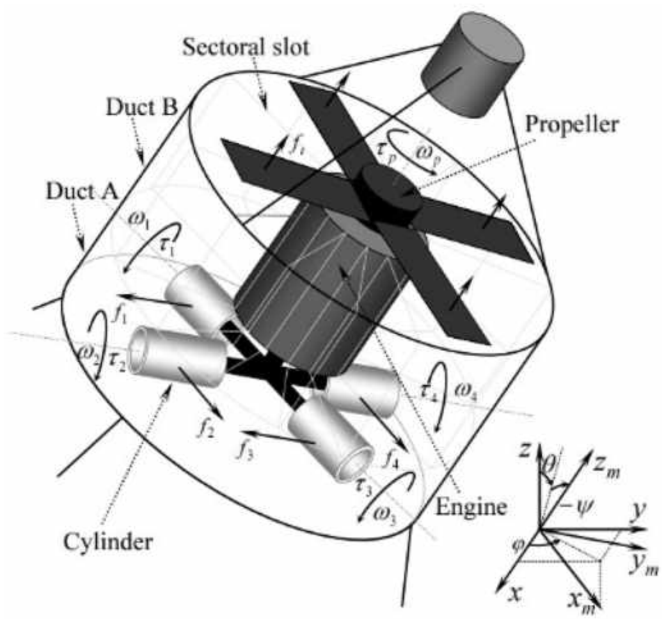

Fig. 14. View of Magnus-effect UAS in combination with a ducted-fan proposed by Hou et al. [55].

airspeed, particularly during takeoff and landing, Mangus rotors are typically spinning at high rates, which eventually influences UAS's lateral motion by precession and nutation gyroscopic effects. The gyroscopic effects may help to increase stability but makes major issues in control. In Magnus rotors, the nutation gyroscopic effects might be observed as tumbling, as the yaw and roll angles are expected to oscillate simultaneously.

The design and development of a proper flight control system to handle the gyroscopic forces for future Magnus-effect UASs is essential. Moreover, there is a need for other control surface mechanisms to control the roll in this type of drone. A potential solution for controlling the UAS in the roll axis is to turn the Magnus rotors at different speeds, but in cases where this is not possible, some extra control surfaces should be considered instead of the removed ailerons [52].

It should be noted that for Mangus-effects UASs, there is not enough information for their design, aerodynamic modeling and flight dynamics fundamentals [52].

Even though a Magnus rotor is a lifting device, in a specific range of low Reynolds number and low-velocity ratios, we may have a negative side force called negative Magnus force, which depends on the surface roughness. In the design of a Magnus UAS, the negative Magnus force can be an issue due to the break down of the lift force in specific ranges of low Reynold number and velocity ratio [52]. This is a stall-like phenomenon in Magnus UASs, while unlike the fixed-wing drones, the stall is independent of angle of attack, but it may happen in a critical range of Reynolds number and velocity ratio. The negative Magnus force is an important issue, especially in MAVs, because of their low Reynolds numbers [52]. When it comes to power and energy consumption, the overall efficiency of a Magnus UASs will probably always be lower than a fixed-wing. Moreover, the high lift force will only be useful if the Magnus rotor's weight and its control mechanism can come close to that of an equal-sized wing [52].

2.4. *Paraglider UASs*

Unmanned paragliders are usually constructed in a manner similar to the manned versions. In these UASs, the parachute generates lift like a wing. In paragliders, a motor usually with a fixed-pitch propeller is placed in a body that is attached to the parachute with suspension ropes (see Fig. 16(a)) [58]. These cost-effective UASs can be used for transporting heavy cargo and usually have a long-endurance. Moreover, in addition to high stability, they have high robustness againstdisturbances. However, this type of aerial vehicle's mathematical modeling is difficult due to swing motion caused by the separation between the parachute's center of gravity (CG) and that of the cargo's CG.

The thrust generated by the propeller has a significant effect on the pitch angle. In paragliders, the ropes' flexibility leads to the motion in the yaw and pitch axes, and since the parachute is full of air, any change in the airflow speed and shape of the wing affects their flight [58]. The control mechanism for these UASs is accomplished using ropes attached to the parachute. These ropes change the direction of airflow over the parachute by way of turning it. As a result, the lift and drag forces generated by the parachute change, and the paraglider moves in the desired direction. Li et al. in 2019, investigated the design, modeling, control, and testing of an unmanned paraglider, as shown in Fig. 16(b) [58].

2.4.1. *Challenges and benefits*

Paraglider UASs have an appropriate configuration for heavy transportation and long-distance delivery missions because of their low cost, compact structure, inherent stability, and adaptability to different environments (the additional mass of the parafoil canopy exists) [58]. These drones are mainly flying at a low speed and in an environment

Fig. 15. Examples of Magnus-effect UASs (a) four Magnus wing with the rough surface [56], (b) four Magnus wing with blades [57], and (c) Gligorin's concept of combined fixed-wing and Magnus rotor [52].

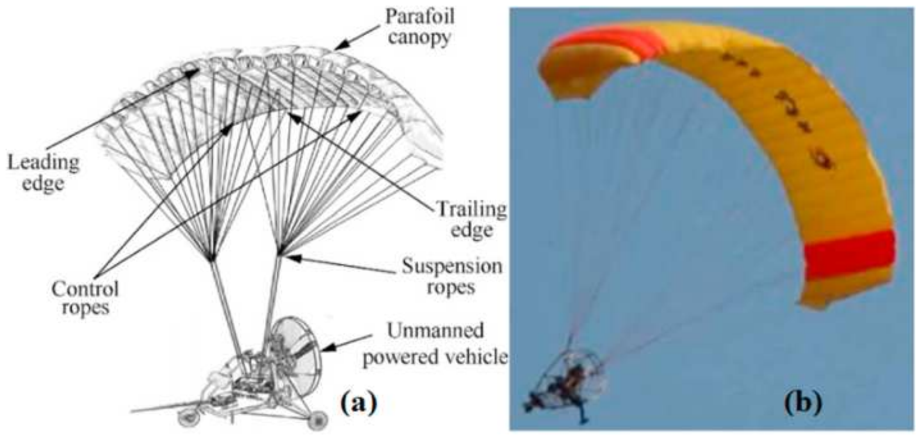

Fig. 16. (a) Structure of an unmanned paraglider and (b) paraglider made by Li et al. [58].

with high uncertainty, where the disturbance's magnitude is close to their flight speed, which affects their flight efficiency. Moreover, due to the nonlinear and time-varying dynamic characteristics and high coupling degree, the only input controls are the control rope and the propeller thrust. In these UASs, the control inputs' dimensions are smaller than outputs, which makes the control algorithms more stable, reliable, and adaptive [59]. Paraglider UASs have plenty of applications in surveillance and reconnaissance missions. They also have been used for contaminated gas sampling in environmental pollution and volcanic eruption [60].

3. Vertical takeoff and landing UASs

Generally, the Vertical Takeoff and Landing (VTOL) UASs do not need a runway for takeoff and landing. These types of UAVs employ their propulsion systems for vertical takeoff and landing and hovering flight [5]. In the following, different VTOL types are discussed.

3.1. Mono-rotors

The control of mono-rotor UASs and the suppression of gyroscopic and reaction torque of the rotor is challenging because of using only one rotor. Therefore, numerous solutions have been proposed to overcome these problems, which eventually led to the invention of different types of VTOL UASs. This category of UASs is divided into four sub-categories as follows: ornicopters (semi-flapping wing), thrust vectoring, moving mass controlled, and ducted-fan. There are also some unconventional mono-rotors which are studied in following sections.

3.1.1. Ornicopters

This class of UASs has semi-flapping wings or cyclic blades. Ornicopters are tail-less helicopters that can fly as a result of the periodic oscillation of their blades. The tail in a helicopter consumes much energy. Helicopters are noisy and offer limited control capability against

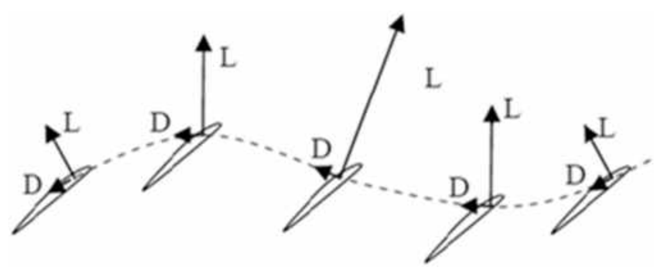

Fig. 17. Cyclic motion of blades in ornicopters and aerodynamic forces [61].

external forces such as wind. To mitigate these problems, Holten, in 2002, proposed a design that employed only one rotor to fly without any tail-fan or tail-rotor [61]. In this UAS, the blades oscillate vertically and in circular motions in addition to rotational spin. Hence, besides the lift, they also produce a drag force, where it can be manipulated to control the UAV and to eliminate the effect of reaction torque. Fig. 17 depicts the aerodynamic forces of an ornicopter, which is similar to an airfoil with an oscillating trajectory. In the ornicopters, a strong downward flapping motion leads to a forward tilt of the lift vector that creates propulsion, and the upward flapping has the opposite effect [61].

The transitional motion of the ornicopters causes some disturbances in the flight. Various ideas have been advanced to address this problem, including the use of a pair of additional blades (four blades), three blades, and asymmetric blades [62]. In these UASs, just like the helicopters, swash-plate is responsible for generating periodic and conventional controls. The rotation of the swash-plate turns the plane of the blades asymmetrically towards the main axis. As a result, the change in the flapping angle will not produce a force on the horizontal plane. This makes the lateral control and periodic control to become independent of each other [62]. Fig. 18(a) and (b) depict, respectively, examples of an ornicopter having asymmetric blades and a swash-plate mechanism.

In 2002, Holten derived the aerodynamics and dynamic modeling of an ornicopter UAS [61]. Heiligers et al. in 2005, designed and manufactured a radio-controlled ornicopter with no reaction torque [63]. Wan and Pavel in 2014, described the basic principles of the ornicopter's forced flapping and feasibility of the ornicopter concept with respect to the required power, stability, performance, and oscillatory loads [62].

3.1.1.1. Challenges and benefits.

Tail-rotor in helicopters is an essential part to cancel out the reaction torque of the main rotor. This rotor also can enhance helicopter maneuverability. However, it has many drawbacks, such as high power consumption and marginal control authority under unfavorable wind conditions. Moreover, it is noisy, vulnerable and dangerous. Researches indicate that about half of the helicopters' accidents are related to their tail rotor's failure [62]. Ornicopters are types of helicopters without reaction torque, where this eliminates the need for a tail rotor. Ornicopters also have some disadvantages, including a small flight envelope and worse stability and handling qualities in yaw direction than helicopters [64].

3.1.2. Thrust vectoring

This group of UASs often are made of a brushless motor, which is simultaneously able to produce clockwise (CW) and counter-clockwise (CCW) rotation (Contra rotating motors). Two CW and CCW blades are used in this type of UASs to produce the required lift while do not generate any gyroscopic and reaction torque. In thrust vectoring drones,

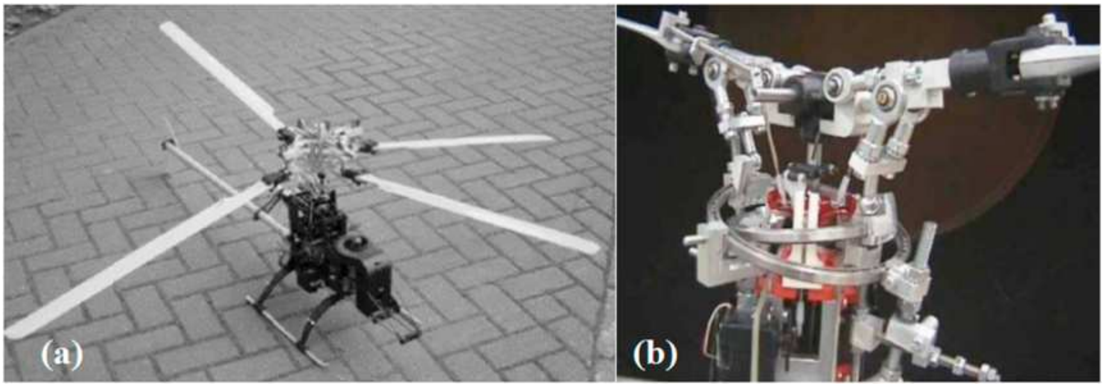

Fig. 18. An ornicopter with (a) asymmetric blades, and (b) swash-plate mechanism [62].

the motor is often mounted on a servo motor actuator, which can tilt it in different directions. The change in the thrust vector enables the longitudinal and lateral motion, and by changing the speed of the rotors, it is possible to have a motion in the yaw axis. It is also possible to use swash-plate instead of servo mechanism to buid coaxial helicopters.

Considering the absence of the reaction torque and using the thrust vectoring control mechanism, these UASs have very simple mathematical model, wherein hovering conditions, they can be easily considered as a mass and a force. It should be noted that the aerodynamic study of the two coaxial blades is a challenging issue because of the interference of airflow passing through their surface. Giorgi et al. in 2017, conducted a numerical study on the performance of contra-rotating propellers for an unmanned aerial vehicle [65]. This type of UASs is simpler than other single-rotor drones. Their control is easier, and considering the empty space under these drones, they are suitable to carry payloads. However, if one of the blades or propellers is lost, it is impossible to control them. So, they have a lower security margin. Few examples of this kind of drone have been designed and made, such as Bombardier OL327, EADS Dornier SEAMOS (and GEAMOS) [66], and Kamov KA-137 [67]. In Fig. 19, views of thrust vectoring UASs are shown.

3.1.2.1. Challenges and benefits. Coaxial mono-rotors are an attractive UAS platform due to their small dimension, aerodynamic symmetry, and high thrust-to-weight ratio. For a similar weight, a coaxial mono-rotor's size can be 35–40% smaller than a helicopter. The coaxial mono-rotors can easily cancel out the yaw moment and side forces commonly seen in helicopters. These drones also do not require extra mechanisms to eliminate reaction torque, as seen in Ornicopters. Thus, the mono-rotors are much more effective in fast forward flights. These advantages make them an ideal configuration for operation in confined environments, such as indoor and cluttered outdoor [70]. Another feature of a coaxial helicopter is using a stabilizer bar, which attaches to the top rotor hub, and passively stabilizes the UAS. However, it strongly influences the rotor dynamics, especially the fixed-pitch coaxial configuration, as the upper rotor is not linked to any servo. As a result, the upper rotor's cyclic pitch control is solely induced by the stabilizer bar [71].

3.1.3. Moving mass controlled

This group of drones is similar to Thrust Vectoring UASs, but the method used in these UASs for changing the vector of thrust is based on the displacement of the center of gravity. In this type of drone, there are one or more moving masses that are controlling the CG of the UAS [72]. One of the main challenges of these configurations is the nonlinearity of the system that happens due to the changes in the moment of inertia. In the past, moving mass mechanisms have been used widely in submarines, underwater vehicles, rotating projectiles, satellites, spacecraft, and balloons [73], but they are recently applied in multirotor drones [74].

In this type of UAS, the moving mass mechanisms which are used to move the center of mass can be designed in a variety of shapes, such as the pulley, rails, gear, etc. The motion in the yaw axis is generated by velocity difference in the blades, but other motions are based on shifting the center of gravity. In moving mass controlled UAS, the thrust vector is often constant except in yaw maneuver. With moving the CG along the lateral axis, the thrust vector will create a torque around the longitudinal axis, and by moving the CG along the longitudinal axis, a torque will be created around the lateral axis, which eventually will result in roll and pitch motions [75–80]. It should be noted that this type of drone does not have the complexity of the UASs with more blades or swash-plate. However, the nonlinear coupling of the equations and the variability of the matrix of the moment of inertia and the CG with respect to the time make the modeling more complicated.

In 2008, Bermes et al. proposed a new design of the steering mechanism for a mini coaxial helicopter and studied the dynamics of this UAS [77]. Schafroth et al. in 2008, studied the stability of this type of drone [78]. Bermes and Sartori, in 2008, discussed the control mechanism of a coaxial helicopter with the center of gravity steering [79]. In Fig. 20(a) and (b), views of the moving mass controlled mono-rotor and its mechanism are shown, respectively.

3.1.3.1. Challenges and benefits. One of the main objectives of designing mono-rotors is to have a small size drone. Because of using only one rotor, this configuration is more suitable to reduce the size of the drones.

Fig. 19. Views of (a) contra-rotating brushless motor and its blades, (b) a thrust vectoring mono-rotor with a camera mounted on [68], (c) EADS Dornier SEAMOS mono-rotor [67], and (d) Skybotix's CoaX autonomous commercial micro-helicopter [69].

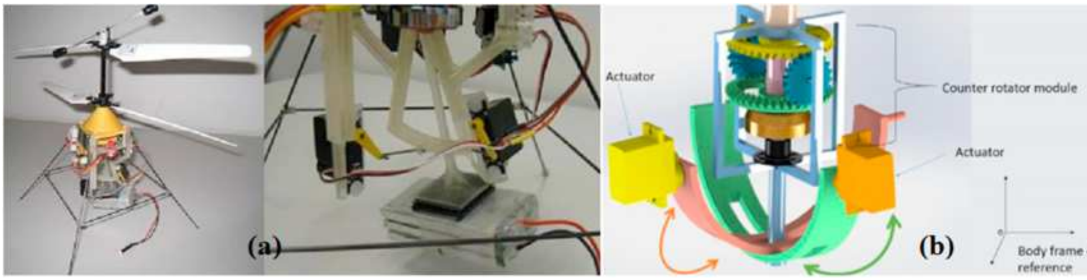

Fig. 20. Views of (a) a moving mass controlled mono-rotor designed by Bermes et al. [77] and (b) moving mass mechanism in a mono-rotor [80].

Although the swash-plate is a reliable mechanism for mono-rotors, it would need very small mechanical parts in smaller drones, and it is much more complicated than moving mass controlled mechanisms. Generally, moving mass controlled mono-rotors have a reliable and easy to control mechanism while consuming much more energy [81]. This type of mono-rotors may provide high maneuverability, while their dynamic is more complicated. In these UASs, shifting the center of gravity will increase the coupling between the flight axes (pitch, roll, and yaw) by creating non-diagonal terms in the moment of the inertia matrix (I). Moreover, in the cases where the moving masses' velocities are high, the terms of linear and/or rotational accelerations of the moving masses may not be neglectable [82].

3.1.4. Ducted-fan UASs

This class of drones consists of a duct with a fan (or propeller) that controls the vehicle using control surfaces embedded at the end of the duct [5]. This type of drone can also be categorized as tail-sitters; however, they are classified in this category since their flight relies on their propellers only, and they do not use wings or canards. The thrust required for these drones is provided by a fan or propeller and sometimes by a coaxial fan or propeller. Several fins are incorporated into the fan outlet that drives the vehicle by guiding the airflow. Landing and takeoff maneuvers are possible with an increase or decrease in fan or propeller speed. Following the differential rotation of two or all four fins equally, the air will circulate like a vortex and cause a yaw motion.

As can be seen in Fig. 21, if the two fins in the y-axis remain at 0°, a roll motion can be created following the simultaneous movement of the two fins in the x-axis direction. Similarly, pitch movement can be obtained by reversing this process. If only one fan is used in these drones, an initial installation angle should be taken for the angle of all the fins so that the airflow rotates in the opposite direction of the torque generated by the propellers [83]. The efficiency of the propeller in this type of drone can be improved by applying a duct. Moreover, a smaller propeller will be needed to generate thrust force compared to a duct-free drone. In these drones, also the duct can be designed for having a higher efficiency at higher speeds. Generally, these UASs have less noise compared to other types and can be used in hybrid drones, such as tilt-rotor UASs. However, along with all of these benefits, the ducted-fan UASs have more complex aerodynamics than duct-free propellers. In these drones, to achieve high efficiency, the distance between propeller and duct should be very short, and they need a motor with a greater revolution. Furthermore, at a high angle of attack, stall may happen for some parts of the duct that consequently will generate more aerodynamic drag.

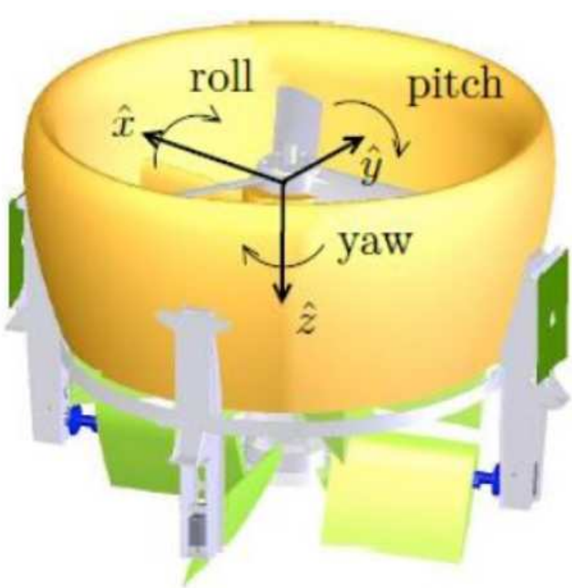

Fig. 21. Structure of a ducted-fan VTOL mono-rotor [83].

In Fig. 22(a), the ducted-fan VTOL UAS developed by AD&D Hornet is shown [84]. In 2006, Eriksson designed, analyzed, and tested a ducted-fan UAV. In this work, the performance of the designed ducted-fan UAS was determined by the lift capacity, the position accuracy, and wind tolerance [83]. Moreover, a commercialized ducted-fan drone (T-Hawk) has been designed by Honeywell and the US Defense Advanced Research Agency (DARPA) (see Fig. 22(b)). Finmeccanica Selex ES also designed and manufactured a ducted-fan UAS for target acquisition and over-the-hill surveillance, as shown in Fig. 22(c) [85].

3.1.4.1. Challenges and benefits. In ducted-fan UASs, the presence of duct reduces the lift losses initiated from the tip leakage flow. It also can control the flow speed and pressure distribution in the rotor section. Moreover, it can provide protection for high-speed rotating blades, higher propulsive efficiency, and low aero-acoustic emissions [87]. Generally, UASs with ducted-fan structures can generate more thrust than a duct-free rotor with the same blade size. These ducted-fan rotors' characteristics will provide a compact body design for UAS with strong mobility and high efficiency [88]. Ducted-fan UASs, due to their configuration, can perform missions in confined, hazardous, and cluttered environments. However, these UASs have complex aerodynamic structures compared to other types of aerial vehicles [89]. For ducted-fan UASs flying in turbulent and crosswinds conditions, a duct stabilizing torque will be generated due to the lateral momentum drag. This torque will resist tipping into the wind and strongly affects the flight envelope of UAS. A small leading-edge radius in ducted-fan UASs would cause a flow separation, which affects drone performance in static or crosswind orientations. This phenomenon during the hovering flight mode would also reduce the drone's static performance by decreasing the lift produced by the duct, which will consequently increase the required power [87].

3.1.5. Unconventional concepts

Some kinds of mono-rotors UASs are known as All Rotating Aircraft, consisting of a rotor and a structure with flaps to reduce the tendency of spinning over itself due to the propeller momentum preservation. In this concept, all of the body rotates with the rotor, and there is no effort to

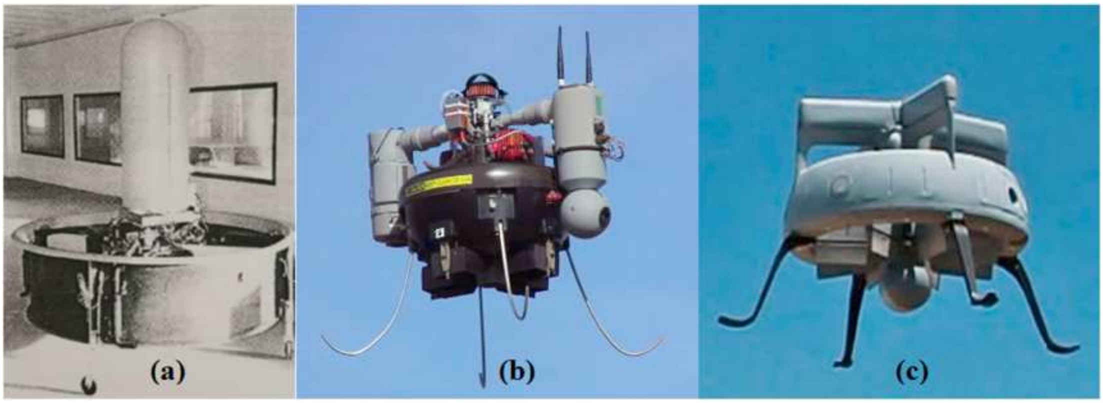

Fig. 22. Views of ducted-fan developed by (a) AD&D Hornet [84], (b) Honeywell [86], and (c) Finmeccanica Selex ES [85].

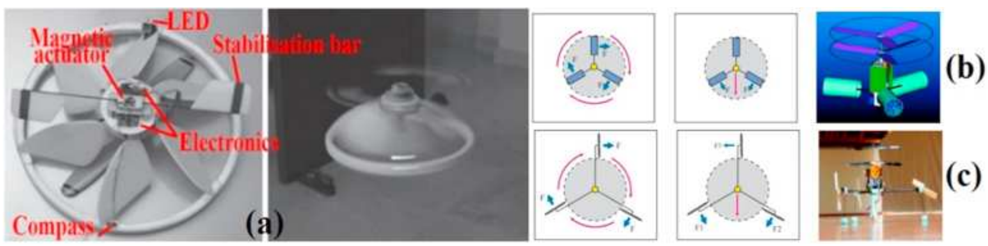

Fig. 23. Views of unconventional mono-rotors (a) all rotating mono-rotor developed by Toledo et al. [90] (b) coaxial mono-rotor with Magnus rotors for attitude control [81], and (c) coaxial mono-rotor with three rotors for attitude control [81].

oppose the reaction torque. In Fig. 23 (a), an all rotating mono-rotor view using the H-∞ controller developed by Toledo et al. is shown [90]. Bouabdallah et al. in 2006, introduced a concept of mono-rotor using Magnus rotors for attitude control. Based on their claim, this concept is more efficient than other conventional mono-rotor UASs and has easier control (see Fig. 23(b)). They also developed a prototype of a mono-rotor using three other rotors for attitude control (see Fig. 23(c)) [81].

3.2. Multirotors UASs

Multirotors UASs consist of two or more rotors and propellers. The flight mechanism of these drones is based on the generation of lift by propellers. These drones are controlled by altering the speed of the rotors [5]. Among multirotors drones, quadrotors are very popular, and over thousands of them have been built over the past few decades beacause of their ease of construction and control [5].

These drones can fly with high (not higher than common fixed-wing or hybrid drones) or low speeds, perform vertical take-off and landing, and hover flight. Multirotors UASs can be used for indoor or outdoor missions [5]. Since their endurance is short, they are more suitable for short-range travel or short-time missions [91]. Multirotors are ideal for specific missions, and their configuration depends on the mission requirements. For example, if the drone is supposed to perform a maneuverable mission, the mono-rotor, moving mass controlled bi-rotor, or quadrotor configurations can be considered. But when it comes to efficiency, the quadrotors may not be suitable choices. Although the rotary wings have simple control systems and are very maneuverable, their main disadvantage is power consumption. Furthermore, weight and energy are some of the critical challenges in multirotors [5].

Multirotors can be found as fixed rotors, tilt-rotors, ducted fans, coaxial rotors, moving mass controlled, and Dyson fans. In the following subsections, different kinds of multirotors will be studied based on the number of rotors.

3.2.1. Bi-rotors

Bi-rotors drones are composed of two motors, which rotate in opposite directions to neutralize each other's reaction torque [5]. The basis of motion inthis category of drones is thrust vectoring. Each rotor and its blade are deployed on a servo motor that tilts it around the lateral axis; therefore, they can be categorized as tilt-rotor drones too. In this type of UAS, the yaw can be obtained similar to mono-rotors by creating difference between the two rotors speed. In this case, the yaw and roll motions are coupled. Another way is to rotate the motors equally but in the opposite direction; in this case, only the yaw will be obtained. Pitch motion is achieved by a simultaneous increase/decrease in tilt angle of rotors [92,93]. In Fig. 24(a) and (b), the view of thrust-vectoring and motions of VTOL bi-rotors are shown, respectively.

Chalupa et al. investigated the mathematical model of the Vertical Take-Off and Landing (VTOL) bi-rotor [94]. This type of drone performs better than helicopters because they do not require a stabilizing horizontal tail; Moreover, their stability is higher than mono-rotors and helicopters. Numerous cases of this type of drone have been made and tested. In 2011, Papachristos et al. developed a design and control mechanism for an unmanned Tilt-Rotor aerial vehicle [95]. Agarwal et al. in 2013, designed and built a prototype of a VTOL bi-rotor [93]. In 2020, in partnership with Trek Aerospace Inc, NASA has developed a VTOL bi-rotor with a ducted fan assembly [96]. Another novel concept of bi-rotors is being developed by Darvishpoor et al. based on moving mass control. They have used two rotors in the middle of a square frame and four moving masses for controlling the attitude [82]. In Fig. 25, views of bio-rotors drones are shown.

3.2.1.1. Challenges and benefits. Although multirotors drones with more than four rotors are more reliable in motor failure, multirotors with three or two rotors may prefer when high efficiency is desired. It has been indicated that a large single rotor is more efficient than multiple small rotors with equal rotor areas. Therefore, bi-rotors and tri-rotors are more efficient than multirotors with more than four rotors. However, bi-rotors are underactuated systems, and there is always a need for

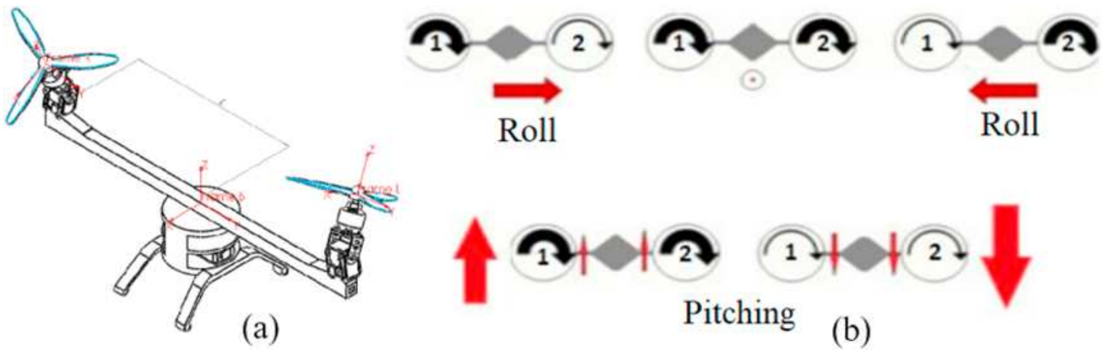

Fig. 24. Views of (a) thrust-vectoring [92], and (b) motion of a VTOL bi-rotor [93].

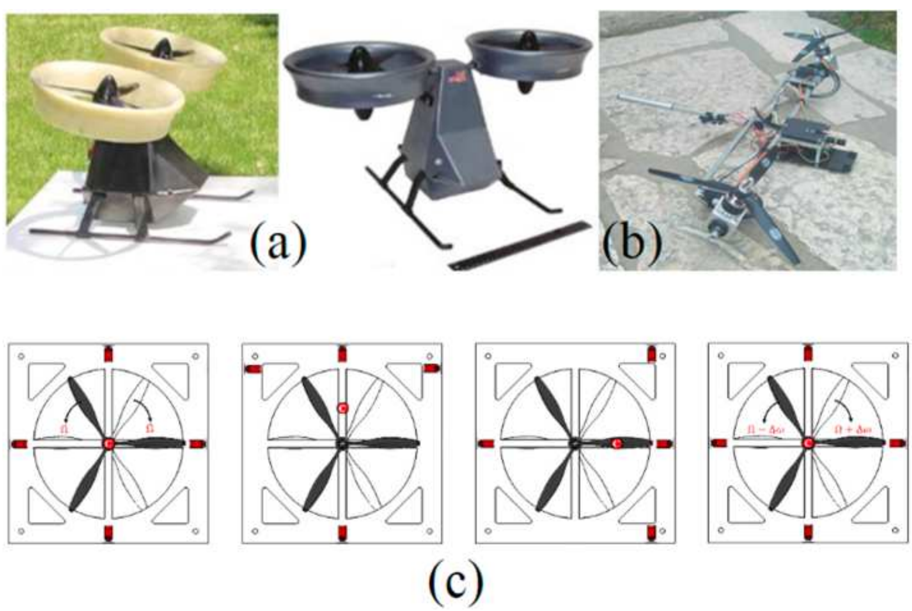

Fig. 25. Views of (a) ducted-propeller bi-rotor developed by NASA and Trek [96], (b) VTOL bi-rotor developed by Papachristos [95], (c) moving mass controlled bi-rotor developed by Darvishpoor et al. [82].

other mechanisms like tilt rotor or moving masses to stabilize and control them [97].

3.2.2. *Tri-rotors*

This category of UAS consists of three motors that are usually located on the sides of an equilateral triangle. Reaction torques of two motors are neutralized together, and the torque of the third motor, which is mounted on a servo motor, is used to maintain the drone balance [5]. In Fig. 26, the flight mechanisms of tri-rotors are shown [98]. The motors of tri-rotor UASs, similar to other VTOLs, have the same speeds during takeoff and landing. Fig. 26(a) indicates that with increasing or decreasing the speed of each rotor, the altitude can increase or decrease, respectively. In Fig. 26(b), the roll control is shown, that in this mode, the rotor speeds of the two front rotors are varying differently. The pitch

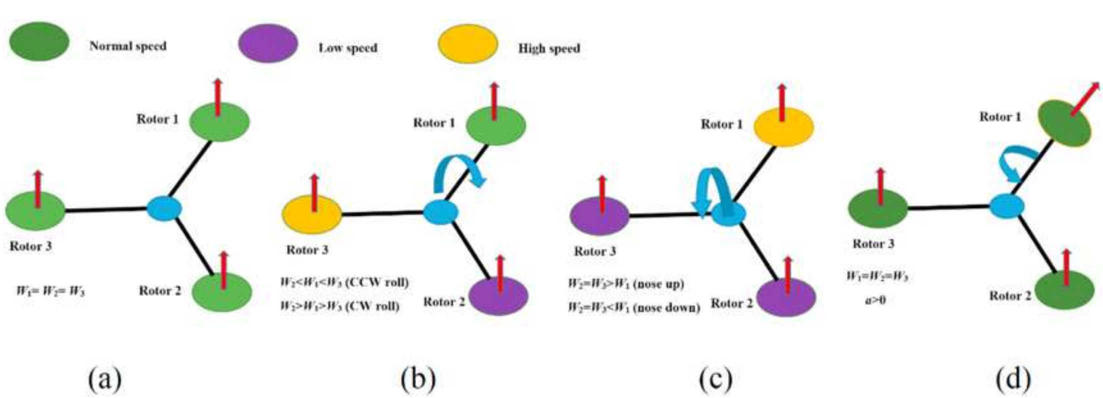

Fig. 26. Scenarios for (a) altitude, (b) roll, (c) pitch, and (d) yaw control of tri-rotors [98].

control is indicated in Fig. 26(c). In this flight scenario, the two front rotors have the same angular velocity, and the speed of the rear rotor is varying for pitch control. Regarding the yaw control, as shown in Fig. 26 (d), by using the yawing moment from the reaction torque and also from the tilt angle, yaw control can be achieved [98].

There are many commercial and non-commercial examples of the VTOL tri-rotor. In 2008, Escareño et al. conducted a simulation and control design of a tri-rotor drone [99]. In 2015, Sai and Tun derived the flight dynamics modeling of a tri-copter UAS [98]. Kastelan et al., in 2015 also developed a tri-copter unmanned aerial vehicle with three tilting motors [100]. In Fig. 27, views of some commercial and non-commercial examples of the VTOL tri-rotor drones are shown.

3.2.2.1. Challenges and benefits. Tri-rotors, compared to quadrotors and other multirotors, are smaller in size, less expensive, and have less complexity. They also have more flexibility and great agility. They can fly for a longer time due to the reduction in the number of motors. These characteristics make tri-rotors drones an ideal configuration for deployment in various missions [102]. Tri-rotors UASs' dynamics are nonlinear and highly coupled, making their control system design more challenging compared to quadrotors. Due to the asymmetric configuration of these drones, their yaw control is also problematic. Furthermore, pitch, roll and yaw moments are highly coupled in these drones, and their attitude control is challenging compared to quadrotors due to Coriolis gyroscopic and terms [102].

3.2.3. Quadrotors

Since their emergence, quadrotors have quickly gained popularity among drones designers because of their ease of construction and control. Plenty of research has been conducted on this type of drone. This study investigates some of the drones that are developed based on this configuration with different flight mechanisms. A common set of quadrotors are made with fixed rotors. This conventional type of quadrotor consists of four motors and propellers mounted on four vertices of a square frame. The motors belonging to this category rotate in pairs opposite to each other to counteract the reaction torque caused by the rotation of the motor and the propellers. This vehicle moves in such a way that the two propellers facing each other rotate in the same direction and opposite to the other couple propellers (their pitch is opposite to that of the other two propellers). To increase or decrease the altitude, the speed of the motors should be increased or decreased simultaneously. Quadcopters can also rotate around the yaw axis with an increase in clockwise rotors speed and a decrease in counter-clockwise rotors speed and vice versa [103]. Fig. 28(a) shows the motor speeds on the yaw maneuver. In quadcopters, if the torques of the

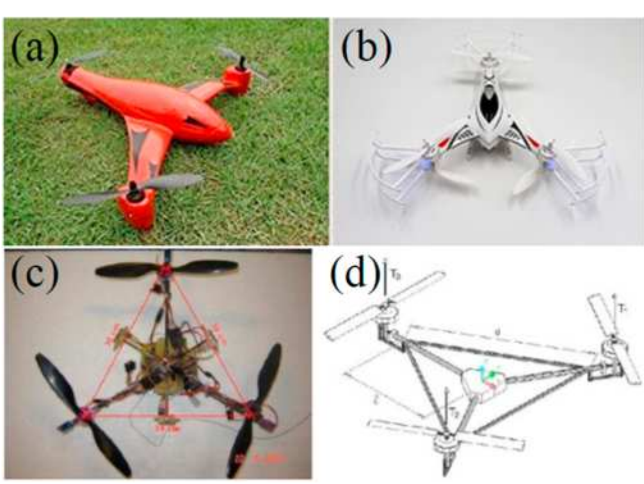

Fig. 27. Views of commercial tri-rotors (a) FlyFly Hobby RC Tri-rotor, (b) DK CX-33S RC [101], and (c & d) tri-rotor developed by Escareño et al. [99].

opposite motors are not equal, the drone will rotate about the longitudinal and lateral axes. Fig. 28(a)-28(c) illustrate the speed condition of the motors in yaw, roll, and pitch motion, respectively.

45-degree rotation of quadcopter around the z-axis creates another common structure of this type of drone, which is called X structure. X structure also flies in the similar way as the (+) structure. Numerous researches have been conducted on the linear and nonlinear dynamical modeling of the quadrotors using various methods. One of the comprehensive activities in this field is the research done by Sabatino in 2015 [104]. This type of drone has plenty of advantages, among other configurations, such as low cost, high maneuverability, easy control, simple dynamics, and applying a fixed-pitch propeller. On the other hand, the disadvantages of this type of drone include low endurance due to the use of electric motors and the limited capacity of batteries for them (high capacity batteries are not lightweight enough yet) and the dangers of using them in urban environments [104]. A comprehensive review is done by Amezquita-Brooks et al. on the modeling and control of the quadrotors in order to represent a standard design model [105]. Several drones have been developed with a quadrotor structure. Rones, in 2017, designed and prototyped a quadrotor with a ducted structure for propellers [106]. In 2018, Rivellini developed a ducted quadrotor drone with embedded fans, which increases safety and makes it appropriate for daily use, specifically in urban environments [107]. In Fig. 29 (a) and (b), views of quadrotors designed by Rones and Rivellini are shown, respectively.

There are also some configurations of quadrotors that are made coaxially. In this type of drone, eight rotors are arranged coaxially coupled in the form of a quadrotor. The performance of this drone is similar to that of quadrotors, except that there must be a $\Delta\omega$ decrease or increase in rotational speed of coupled coaxial motors so that their rotation around their common axis generates torque. Similarly, there must be a speed difference between the other motors whose torque is required to perform the maneuvers, as described in the quadrotor section. It should be noted that the flight mechanism and the dynamic modeling of this configuration of drones are similar to the quadrotors. Chen et al. in 2011, presented the modeling and neuro-fuzzy adaptive attitude control for these types of quadrotors [108]. These coaxial quadrotors have greater stability than other quadrotors due to the neutralization of the torques generated by each rotor by the coupled coaxial rotor [109]. Numerous examples of this type of quadrotor have been developed. In Fig. 30(a)-30(c), views of coaxial quadrotors are shown.

Like mono-rotors and other multirotors, quadrotors have also been developed with tilt-rotor structure. Unlike fixed-rotors, these types of quadrotors are mounted on a mechanism that enables them to be tilted. In 2019, Ji et al. developed the mathematical modeling of a general tilting quadrotor considering parametric uncertainties and external disturbances [112]. The overall flight mechanism of this type of drone is generally similar to quadrotors; however, thrust vectoring may be used for pitch maneuver rather than an increase or decrease in motors speeds. In these drones, like other tilt-rotors, the motors are driven by servo motors. Generally, the tilt-rotor quadcopters have higher maneuverability and efficiency; however, they have more complex control and dynamics compared to quadrotors [113].

In 2013, Şenkul and Altuğ modeled a novel tilt-roll rotor quadrotor UAV [114]. Nemati and Kumar, in 2016, studied the dynamics of a tilt-rotor quadrotor and worked on the control and hardware requirements of these drones [113]. In addition to these studies, various experimental and commercial tilt-rotor quadcopters have been developed. In 2018, Bin Junaid et al. proposed a tilting mechanism to enhance the performance characteristics of conventional quadrotors. They also presented the design, modeling, simulation, and prototyping of a dual-axis tilting quadcopter [115]. In Fig. 31, views of tilting quadcopters are shown.

In addition to thrust vectoring for controlling quadrotors, one of the other proposed mechanisms is the use of moving mass control. In 2016,

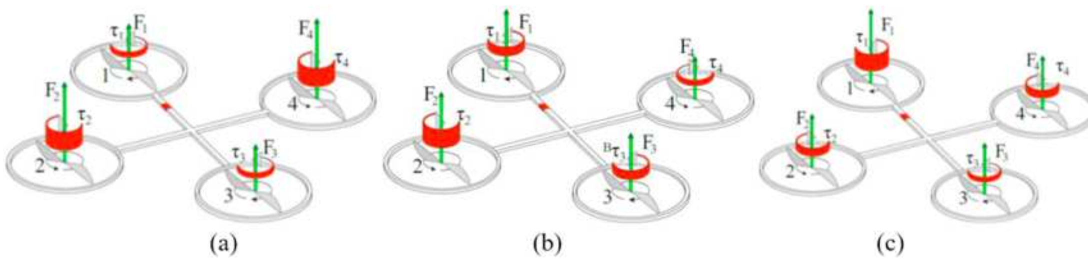

Fig. 28. Views of motors speeds in a quadrotor for (a) yaw, (b) roll, and (c) pitch motion [103].

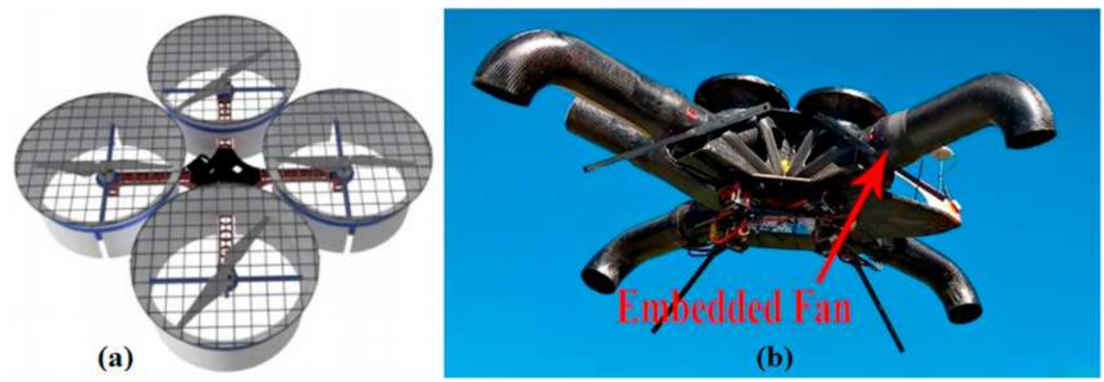

Fig. 29. Views of (a) Ducted-fan quadrotor developed by Rones [106], and (b) ducted quadrotor drone with embedded fans developed by Rivellini [107].

Fig. 30. Views of coaxial quadrotors developed by (a) Tashreef et al. [110], (b) Haddadi and Zarafshan [109], and (c) Saied et al. [111].

Fig. 31. Views of (a) XRay tilt-rotor quad DIY ARF FPV [116], (b) Tilt-rotor quadrotor designed by Ben Junaid et al. [115], and (c) Inspire 1 Pro tilt-rotor quadrotor developed by DJI [117].

Haus et al. presented a novel concept of attitude control for large multirotor drones based on moving mass control [74] (see Fig. 32). Haus et al. in other studies besides the modeling of quadrotors with moving mass control, investigated the control [118], stability and feasibility [75], and other design parameters [119] of this kind of drone. In this type of quadrotors, several rails are mounted on the arms of the drone that allow the servo motor to move along it. To perform the pitch motion, the masses on the quadrotor's arms are moved along the longitudinal axis that consequently changes the center of mass. In this motion, due to the difference in the arm length of the thrust force generated by propellers, the torque cannot be neutralized, and the quadrotor will rotate around lateral axis. For roll maneuver, the masses move along the transverse arms, and the yaw maneuver is generated similar to conventional quadrotors. Generally, in this type of quadrotor, the maximum power of the motors is used, which increases its efficiency. However, in addition to requiring a reliable moving mass control mechanism, these quadrotors have a more complicated control, manufacturing process, and mathematical model compared to other types. These happen due to the variable center of mass and moment of inertia [75].

For quadrotors, some unexplored ideas based on the use of the Dyson fan have been proposed by researchers. Dyson fan was patented in 2009 by a designer under the same name. A patent was also filed in 1981 by

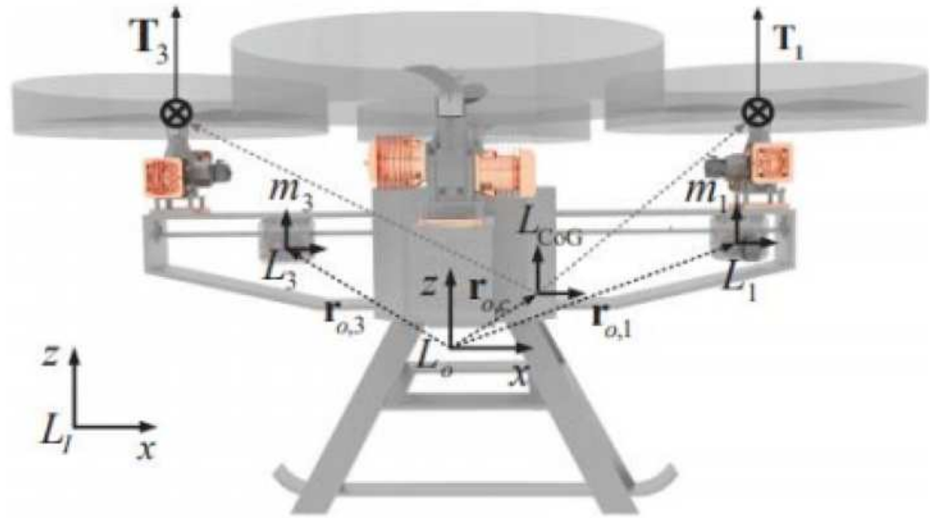

Fig. 32. Quadrotor designed by House et al. [74].

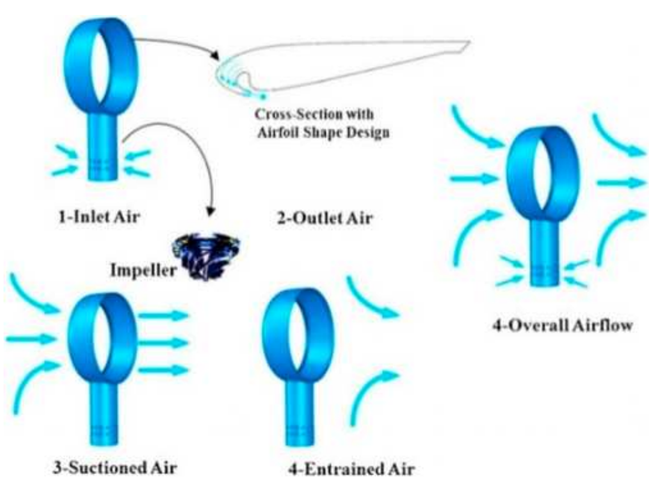

Fig. 33. Views of airflow motion steps from a Dyson fan [121].

Toshiba [120]. In this type of fan, a compressor guides the air to a ring. The curve of the ring is designed in such a way that air flows over it and continues horizontally. In Fig. 33, schematic views of airflow motion steps from a Dyson fan are demonstrated [121].

Dyson fan has high noise pollution and low efficiency. For this reason, the idea of designing an unmanned aerial vehicle based on the Dyson fan has not yet materialized. Due to the increasing safety of UASs with removing the propellers and the proper maneuverability and hovering capability of quadrotors, combining a quadrotor with a Dyson fan can be very suitable for urban spaces. In Fig. 34, concepts of Dyson fan quadrotors are shown [122,123].

3.2.3.1. Challenges and benefits. In recent years, quadrotors have received extensive attention from drone designers and scholars worldwide due to their simple structure, easy operation, low energy consumption, and hovering flight capability. The design of a control system for trajectory tracking of quadrotors is challenging because of their control characteristics, such as strong coupling, nonlinearity, and sensitivity to disturbance. Quadrotors have six degrees of freedom, including three attitude angles and three-position variables. However, these drones only have four control inputs, making them a typical underactuated system [124]. Quadrotors have short endurance because of using electrically powered motors. Recently, researchers have focused on the fuel-powered version of these UASs. Compared to fixed-wing drones, quadrotors are less efficient and have a lower cruise speed, and their maximum altitude is limited. These drawbacks make them inappropriate for long-endurance missions. Due to their VTOL and hover flight capability, they are among the best configurations for a short time and indoor missions.

3.2.4. Penta-rotor and higher

The flight mechanism of multirotors having more than four rotors is similar to those of the previous four categories. Reaction torque is not considered a problem for drones with even rotors; however, a similar approach is used for drones with odd rotors as introduced for a monorotor or tri-rotor drone. In Fig. 35, views of hexarotor drones are indicated.

3.2.4.1. Challenges and benefits. Compared to other multirotors, using more than four rotors increases the payload capacity, dynamics complexity, and energy consumption. Even though having multiple rotors increases drones' safety in the case of motor failure, they are less efficient compared to drones that use fewer rotors with equal propeller

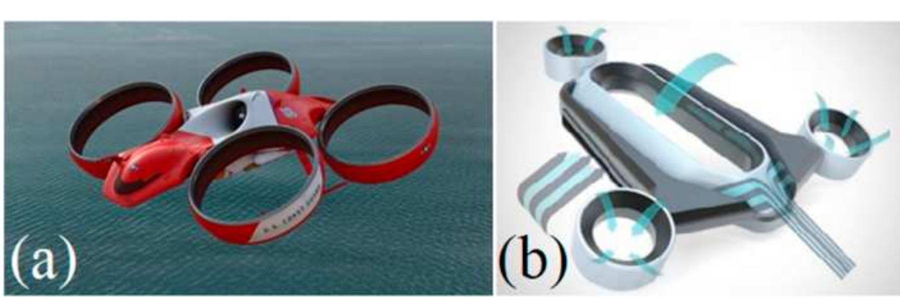

Fig. 34. Views of (a) a Dyson fan bladeless drone [122], and (b) HERA conceptual design based on Dyson fan [123].

Fig. 35. Views of (a) Typhoon H hexarotor developed by Yuneec [125], and (b) a tilted-rotor hexarotor developed by Ryll et al. [126].

area. While UASs with an even number of rotors do not need any extra mechanism, the UASs with odd rotors may need additional mechanisms to counteract the sole rotor's reaction torque. However, using more rotors makes the control algorithms more complex. This configuration, obviously like other multirotors, benefits from vertical takeoff and landing and hover flight. They are more popular for applications that need to carry heavy payloads because of having more payload capacity. These UASs are so popular in agricultural applications, industrial inspection, delivery, firefighting and longtime monitoring, but the high energy consumption is one of their major problems.

3.3. Coanda-effect UASs

The Coanda effect that is described by Henri Coanda in 1932 is the tendency of flow to stay attached to a convex surface. In Coanda-effect UASs, passing flow through the surface leads to a static pressure drop that will create a lift force. The first dome-shaped UAS was developed by Collins in 2002 that was called Coanda UAV [127]. In this kind of drone, generally, a propeller sucks the air into the duct installed on the upper part of UAS and then guides the high-speed airflow over its surface. This high-speed airflow through this convex surface is accelerated and causes a static pressure drop, which forms the major part of the lift force for flight [127]. To avoid rotation of this UAS, some fixed fins are implemented on the outer surface of the body, which changes the airflow direction. This creates a torque that is in the opposite direction of the torque generated by blades. Moreover, in order to control the UAS, a number of moving control surfaces are added to its body that can be used for controlling the drone. In these UASs, there are some controllable stabilizing fins that can be used for directional control around the yaw axis. In Fig. 36, views of UAS with the Coanda effect are shown.

In contrast to the ducted fan and fixed-wing UASs, in the Coanda effect drones, the equipment and supplies can be placed inside the body. This type of UAS also produces less sound pollution and is safer and more convenient than multirotors and helicopters for use in urban areas. However, it has relatively more complex aerodynamics, and its dynamic is highly dependent on the shape of the body. Nedelcut, in 2010, reviewed different kinds of Coanda effect UASs in detail [130]. In 2013, Collins studied the aerodynamic modeling of a Coanda-effect UAS [131]. In 2015, Haque et al. developed a new Coanda-effect UAS using two rotors without ducts to generate lift force and achieve maneuverability in a more efficient manner (see Fig. 37) [132].

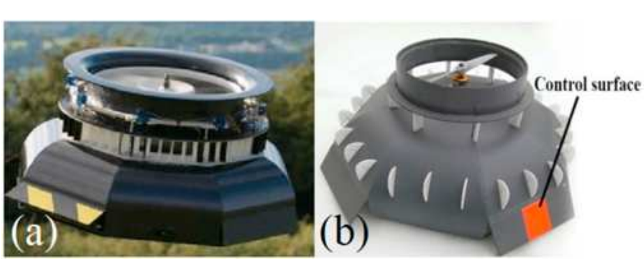

Fig. 36. Views of (a) Coanda-effect UAV [128], and (b) control surfaces in a Coanda-effect UAV [129].

Fig. 37. Views of Coanda-effect UAS developed by Haque et al. [132].

3.3.1. Challenges and benefits

The lift force in the Coanda-effect UASs is produced by deflecting and guiding the generated airflow along the body's outer side. Therefore, the inside of the body would be appropriate for placing the cargo. In these UASs, the airflow necessary to create lift forces is not dependent on the altitude or the angle of attack, unlike fixed-wing UASs, which makes them more stable during the flight. The Coanda-effect UASs are not as vulnerable as conventional fixed-wings or helicopters to impacts against ceilings, walls, etc., so they may bump into obstacles without losing altitude or being damaged [133].

3.4. Lighter than air UASs

Lighter than air UASs includes balloons and airships. In these aerial vehicles, light gases such as hot air or hydrogen are used in bulk (voluminous) chambers to reduce the overall density of the system. Various mechanisms can be used to control these UASs, including the moving mass mechanism or propeller (see Fig. 38) [134]. Balloons are mainly used for meteorological and research purposes, some in the atmosphere, and some under near-space conditions. Recently, unmanned balloons have also been used to provide internet services. In this kind of UAS, usually, the altitude of the balloons is controlled only, and there is no control over their position due to the type of applications and the weather. Therefore, it can be said that they are usually offline-controlled. There is a kind of lighter-than-air UAS called jellyfish, categorized as bio-based because of simulating jellyfish behavior.

In airships, the thrust is usually provided by ducted fans or propellers. In some cases, (micro) jet thrust mechanisms are used to generate the required thrust and control the airship. These kinds of mechanisms can also adjust the flight altitude of the airships. Besides, the airships can use elevators and rudders for better control and wind resistance [134,135]. Features of lighter-than-air UASs include low power consumption, high endurance, and relatively simple dynamics and control. The challenges of using these aerial vehicles include large dimensions, risks of hydrogen use, and problems with material selection

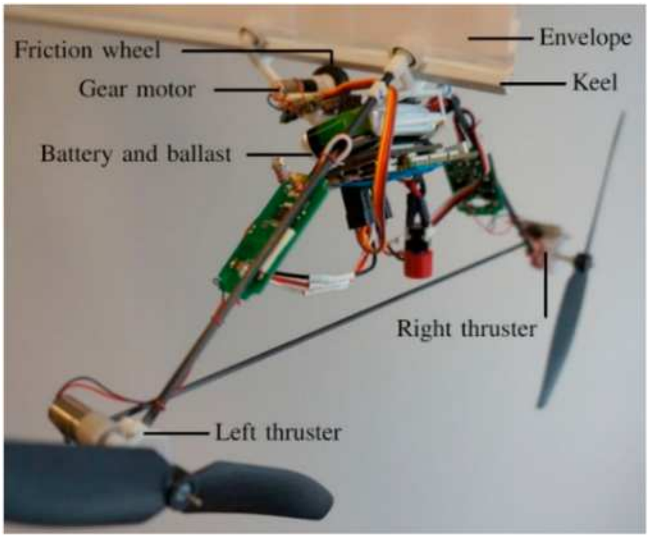

Fig. 38. View of an actuation mechanism for an unmanned airship [134].

and balloon design. A number of these UASs have been manufactured and used for various applications, such as meteorology, imaging, or advertising (see Fig. 39). In 2006, Gammon et al. derived the mathematical modeling and flight dynamics of the tri-turbofan airship for autonomous formation control research [135].

The airships can be found in different shapes and configurations. They can vary in the shape of the balloons and actuators. Some concepts came up by adding wings to the balloons that can work with various kinds of light gases like hydrogen or hot-air (see Fig. 40). Liao and Pasternak, in 2009, have reviewed the progress and developments in the airships with a focus on their structure [140]. Li et al. in 2011, have also reviewed the researches about dynamics modeling of airships [141].

In airships, the most flexible part is the hull. Airships are categorized into three main sub-categories based on their hull structure, including rigid airships, semi-rigid airships, and non-rigid airships. Airships with a rigid hull structure have multiple balloons or non-pressurized gas cells to generate lift. There is an inflated envelope in non-rigid and semi-rigid airships as a hull, where the hull shape is maintained by pressure level more than the surrounding air pressure. Unlike non-rigid ones, semi-rigid airships have a rigid keel along the bottom of their envelope to distribute suspension loads on to the envelope. Among the discussed airships, nowadays, the non-rigid airships are the most favorable configurations. By inflating or deflating the airbags inside the hull (ballonets) across altitudes, this type of airship maintains a sufficient pressure difference between the surrounding air and the internal lifting gas [141].

3.4.1. Challenges and benefits

Unmanned airships are known for their low energy consumption and the ability to provide communication for commercial and military missions. Compared to other UASs such as fixed-wing and helicopters, these lighter-than-air drones need much less power since the buoyancy balances the gravity. Also, solar panels can be integrated into this type of UASs to provide the required energy. Winds can highly affect the airship motion due to their large volume, slow speed and low-maneuverability [142]. Generally, depending on the interaction of aerostatics forces between the airship and air, which provides the most of the required lift, the flight behavior of these UASs is changing. In airships dynamics analysis, the aerodynamic computation becomes an important issue since their aerostatics is simple to derive. In dynamic modeling of airships, their flight characteristics, which can be strongly affected by atmospheric turbulence, should also be considered [141].

3.5. Helicopter UASs

Helicopters consist of a rotor with one or more blades that are controlled by a swash-plate and a fan-tail or stabilizing propeller. In helicopters, the thrust force is generated by the propeller. To overcome the reaction torque resulting from the rotation of the propeller, usually, a tail with a propeller or fan is applied to produce a resistant torque. Moreover, the speed of this fan determines the yaw motion. In helicopters, pitch and roll motions can be achieved by using a swash-plate. A mechanism in the helicopter provides the ability to tilt the rotating plate at longitudinal and lateral axes. In Fig. 41(a), a view of the swash-plate function is indicated.

In 2010, Salazar proposed mathematical modeling and simulation for a helicopter with a tail rotor [143]. Muhammad et al. in 2015, modeled and simulated the dynamics of a micro coaxial helicopter [144]. Generally, helicopters have high maneuverability and, due to applying fuel engines, have a high endurance compared to typically

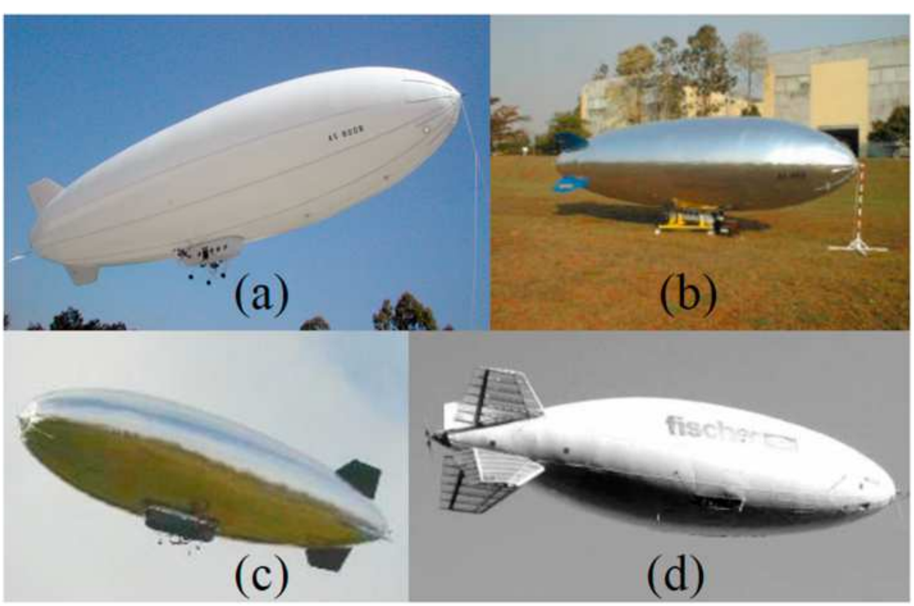

Fig. 39. View of (a) AS-800 B Airship [136], (b & c) AS-500 Airship [137,138], and (d) Lotte Airship [139].

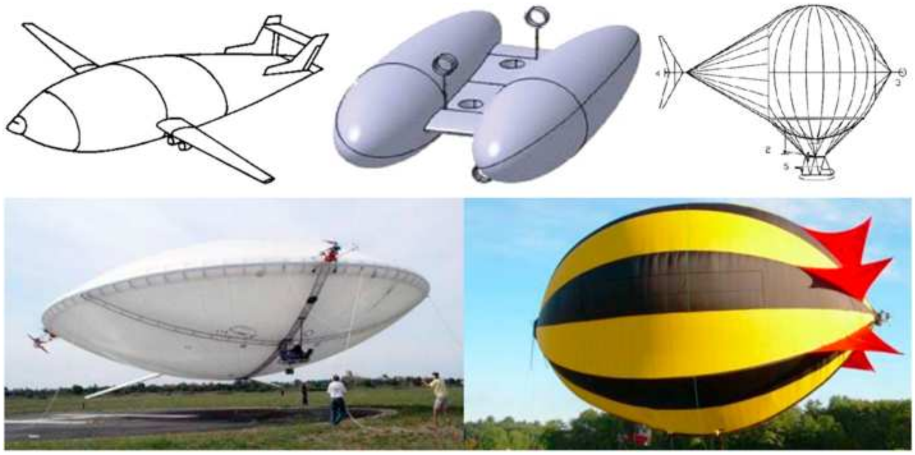

Fig. 40. View of different concepts of unmanned airships [140].

Fig. 41. View of (a) swash-plate function [149], (b) unmanned tandem-rotor helicopter developed by DPI UAV Systems [85], and (c) SY260H coaxial unmanned helicopter [150].

electrical multirotors. However, they have more complex dynamics and control and relatively higher noise pollution. In most cases, the gyroscopic effects of the propeller with high mass and momentum of inertia complicate their control [145,146]. Almost all types of manned helicopters have also been developed in an unmanned version. In Fig. 41(b) and (c), views of unmanned helicopters are shown [85,144]. Different studies have been conducted on the aerodynamics and modeling of the helicopters. Conlisk, in 2001, reviewed modern helicopters' aerodynamics with different shapes and numbers of rotors [147]. In 2013, Brocklehurst and Barakos studied and covered the different tip shapes in helicopter rotors [148].

3.5.1. Challenges and benefits

Like other VTOL UASs, helicopters have remarkable capabilities to perform vertical taking-off and landing and hovering flight in complex and unknown environments at low altitudes and speeds. Because of these advantages, helicopters have a variety of military and civil applications. Unmanned helicopters are recognized as multi-input, multi-output, underactuated nonlinear systems with a strongly coupled dynamic [151]. These drones have the most challenging control systems due to their complex swash-plate mechanism, gyroscopic effects, and stabilizing tail-rotor.

3.6. Wing-rotor UASs

Instead of a propeller or a combination of wing and tail, these drones consist of a rotary-wing that forms the entire UAS's body. The terms "rotating body" or "rotating aircraft" can be used for this type of UAS, and they are also known as All Rotating Aircrafts. The main idea of mono-rotors is inspired by the Maple Seeds that are called Samara.

3.6.1. Single-wing rotor UASs

Single wing-rotor, half-wing rotor, or wing and rotor, which is also called Monocopter, consists of a wing and a rotor attached to it [5]. Following rotor rotation and thrust generation, the wing rotates around the center of gravity and produce the required lift force. The center of gravity of this UAS usually lies somewhere between the wing, control board, and batteries. Generally, the single-wing rotor UAS is designed in such a way that the center of gravity is out of the wing. The distance of generated thrust force from the center of gravity creates a torque that will rotate the drone around its vertical axis. The rotation of the drone subsequently rotates the wing that generates the lift force [152].

The flight altitude of this type of drone can be controlled by an increase or decrease in the speed of the motor. In single-wing rotor UASs, a mechanism is applied to tilt the rotating wing that is called cyclic pitch (see Fig. 42) [152]. During each rotation of this kind of drone, the angle of attack is changed through the control surface embedded in the wing to produce more lift when the wing is in the forward phase and less lift when it is in the backward phase (and vice versa) [152,153].

In 2015, Matiè et al. proposed a mathematical model for a monocopter based on unsteady blade-element momentum theory [155]. One of the most important features of this type of UAS is its inherent stability in hovering flight and static flight. This drone has simple mechanisms, few actuators, simple shape and configuration, and has

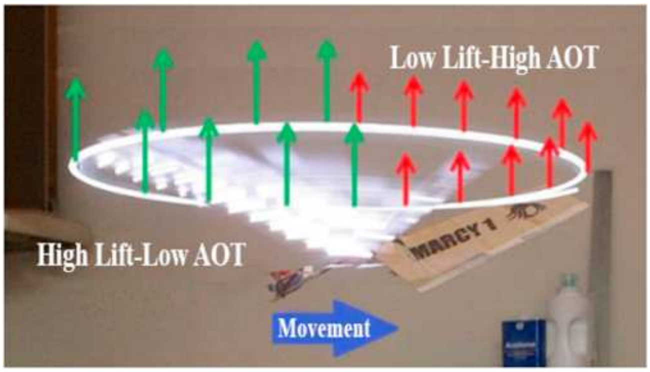

Fig. 42. Cyclic pitch mechanism in Single-wing rotor drone [154].

more endurance than other types. However, it cannot be easily aerodynamically modeled because of flight at low Reynolds numbers [152, 153]. The first mono-copter was designed by the Defense Advanced Research Projects Agency (DARPA), inspiring by the free flight of maple seeds. It should be noted that these drones also can be categorized as bio-inspired UASs. In 2014, Safaee et al. developed a novel version of wing-rotor UAS using some new elements like winglet and fly bar, to decrease the cone angle of flying and reduce the sided turbulence motion of the system [152]. In Fig. 43(a)–43(c), views of the single-wing rotor drones are shown.

3.6.2. Two-wing rotor UASs

The structure of this UAS is similar to the single-wing rotor, except that it uses two wings to fly instead of one wing. Both wings are equipped with control surfaces for control. The mechanism of the two-wing rotor UAS is similar to the single-wing rotor, with this difference that one wing being in the forward-swept phase and the other being in the backward-swept phase. Therefore, the angle of attack located in the backward-swept phase must be exactly the opposite of the other wing if a “symmetric wing” is used. This drone generates more lifting power and, at the same time, has a more complex control algorithm. In Fig. 44, a view of a two-wing rotor UAS is shown.

3.6.2.1. Challenges and benefits. Wing-rotors are considered as all-rotating powered flight unmanned vehicles. Due to their simple, concise structure and less moveable parts, these kinds of drones are easy to manufacture and maintain [159]. Wing-rotor UASs have vertical takeoff and landing, as well as the hovering flight modes where these features allow them to operate in the confined environment [160]. The significant advantage of wing-rotors is that they are passively stable [159]. The most important challenge in wing-rotors is the difficulty of determining the orientations of the drone. The solution is to use the absolute heading angle with respect to the magnetic or true north. The absolute heading allows these unmanned systems to have the proper pitch and roll control. Due to the spinning, these drones do not have

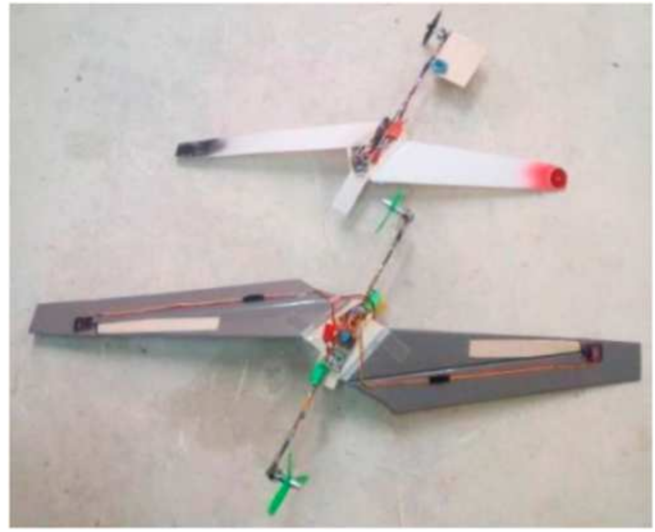

Fig. 44. An example of a two-wing rotor UAS [158].

obvious roll and pitch axes. These drones can orientate and define these two axes (roll and pitch) by heading measurement. Once these axes are defined, the wing’s control surface can be controlled with high precision for the rolling and pitching motion. There are multiple solutions to obtain the heading direction of a wing-rotor UASs, such as magnetometer reading, and using extended Kalman filter beside gyroscope, magnetometer, and accelerometer as inclinometer [153]. Besides the absolute heading angle, the rotating speed of these drones is an important parameter for their flight control. The rotating speed allows the drone to reach and maintain the optimal cruise speed to achieve maximum efficiency. It also allows the control system to detect and correct some unsafe occurrences such as stalling and over speed [153].

3.7. Cyclocopter UASs

This class of VTOL drones uses multiple wings or fins mounted on a rotating axis as a series of pedals to generate lift force [5]. In cyclocopters, the rotors move like watermill or bicycle pedals. At first, these UASs required an initial speed and were hand-thrown; however, newer ones fly vertically. Generally, in some of the unmanned aerial vehicles, cyclic rotors can be used instead of propellers [5,161]. Different types of multirotors can be potentially developed in this configuration, as illustrated in Fig. 45.

In Fig. 46, a concept view of a cyclic aircraft is shown. As can be seen, the two displayed pedals are rotated using the engine power. The angle-of-attack of fins is controlled by the control mechanism. Accordingly, this aircraft can be controlled almost like tri-rotors, except that the generated reaction torque by the pedals can be neutralized by a rotor embedded in the tail.

Generally, no lift force is produced if the angle of attack of all fins is

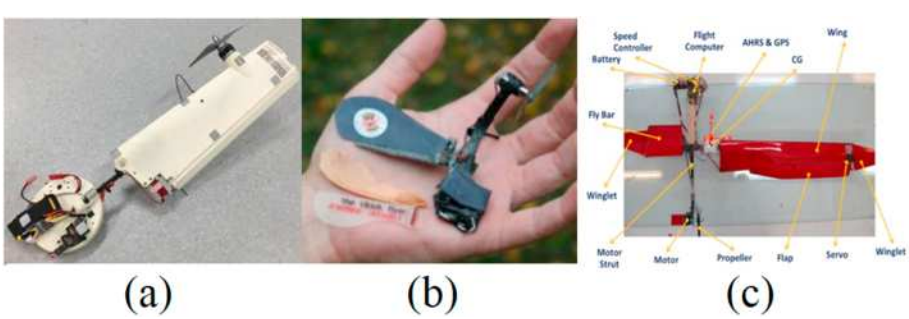

Fig. 43. Views of designed and prototyped single-wing rotor drones by (a) Shaohui [156], (b) Ulrich et al. [157], and (c) Safaee et al. [152].

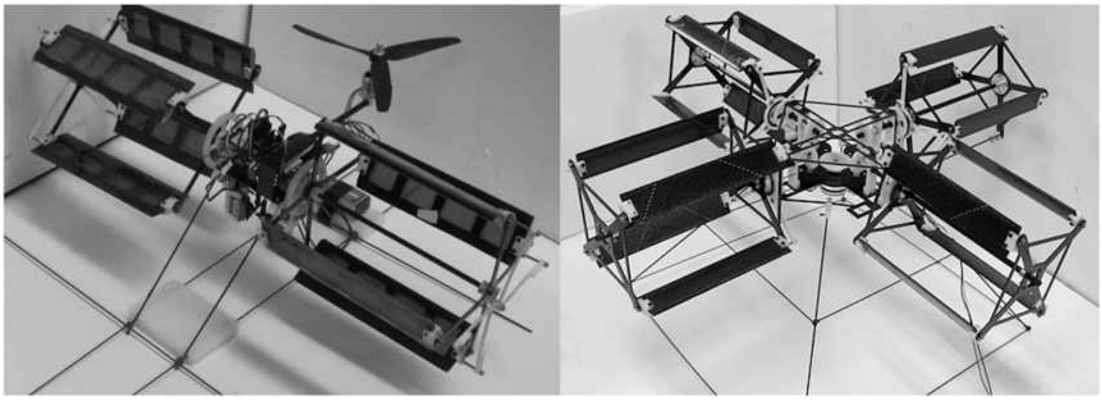

Fig. 45. Views of cyclic drones [161].

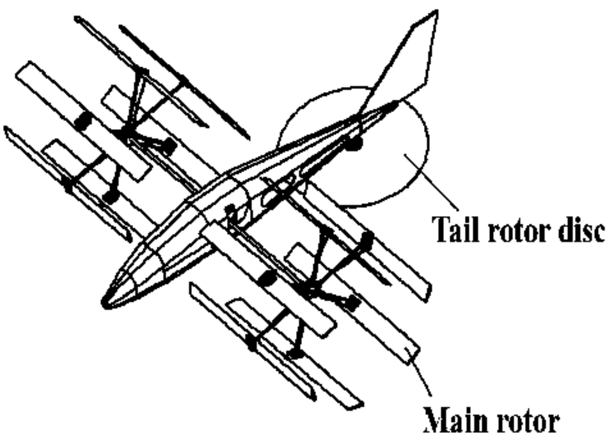

Fig. 46. concept view of a cyclic aircraft [162].

the same. Therefore, the angle of attack of the fins, as shown in Fig. 47 (a), in the backward-swept phase, is reduced by a mechanism in such a way that the generated lift by the set of fins will be positive [162]. Fig. 47(b) indicates the status of the fins of a cyclocopter in a complete cycle. Cyclocopters perform better in generating lift force, with relatively less noise pollution. However, they have a more complex operating mechanism and also complex dynamic and aerodynamic modeling [163]. Furthermore, they have a low cruise speed and high vibration.

Mcnabb, in 2001, conducted a study on the modeling of a cyclocopter and compared the simulation results with experiments [164]. In 2006, Yu et al. derived the dynamic modeling of a cyclocopter [162]. Besides these studies, in 2013, Adams et al. developed and tested a small-scale cyclocopter that was utilizing a novel cam-based passive blade pitching mechanism [165]. Benedict et al. in 2014, designed a micro twin-rotor cyclocopter capable of autonomous hover [166] (see Fig. 48(a). In 2016, Shrestha et al. proposed control strategies for a twin-cyclocopter in forward flight (see Fig. 48(b)) [161].

3.7.1. *Challenges and benefits*

Cyclocopter UASs have many advantages, such as higher aerodynamic efficiency (in terms of power loading), maneuverability, and high-speed forward flight capability in comparison with a conventional helicopter with the same disk loading (thrust per unit actuator area) [166]. Cyclocopters have a uniform aerodynamic loading on their blade, and favorable unsteady phenomena such as the leading-edge vortex formation enable their blades to operate at very high lift coefficients and low rotational speeds to produce the same thrust [167]. In cyclocopters, by changing the phase of cyclic blade pitching, a full 360 deg instantaneous thrust vectoring can be achieved. This enables them to be gust tolerant and more maneuverable, and easily transit from hover to high-speed forward flight [167]. Cyclorotor UASs can obtain the required thrust at a significantly lower rotational speed than an equivalent conventional rotor [168]. They can perform the hovering flight like multirotors. However, they have more complex flight mechanisms and control design compared to multirotors or unmanned helicopters.

4. Hybrid UASs

Hybrid UASs are combinations of VTOL and HTOL aerial vehicles. This category of drones has the benefits of both groups simultaneously with greater efficiency and performance. In the last few decades, hybrid UASs have attracted the attention of researchers and companies. The development of hybrid UASs is still in its infancy, and there is a considerable space for design philosophy, dynamics modeling, control, guidance, navigation, and robustness of these types of drones. Hybrid drones have much more complex flight dynamics than fixed-wing and

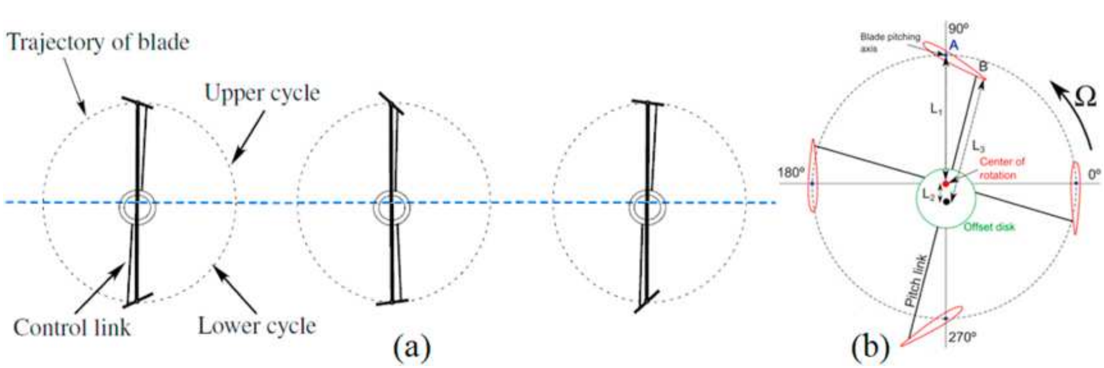

Fig. 47. Views of (a) angle-of-attack of fins to generate lift force [162] and (b) the status of the fins of a cyclic aircraft in a complete cycle [163].

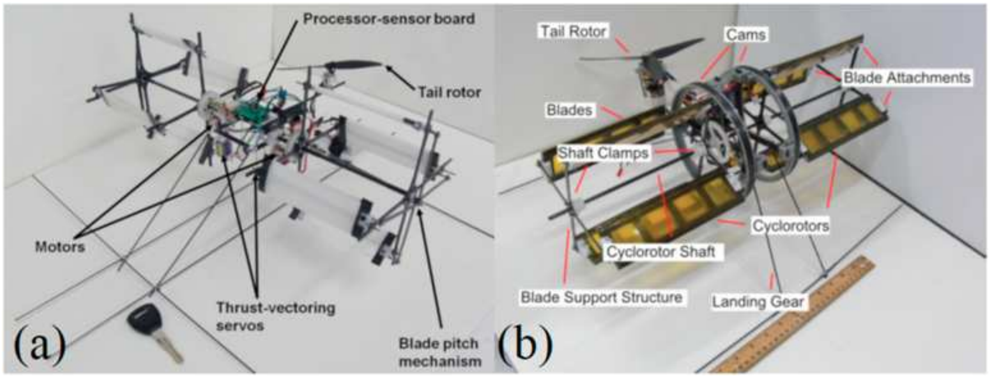

Fig. 48. Views of cyclocopter developed by (a) Benedict et al. [166], and (b) Shrestha et al. [161].

multirotors drones, specifically during their transition phase [21]. In the following sections, we will review the different types of hybrid drones. A major group of hybrid UASs uses tilting mechanisms to switch between HTOL and VTOL configurations, including tilt-body, tilt-wing and tilt-rotor UASs, while another approach is using non-tilting solutions, such as dual-system and rotary-wing UASs.

4.1. Tilt-hybrid UASs

In this category of UASs, all or part of the body is designed to be capable of tilting so that the drone can perform landing and takeoff phases vertically and the cruise phase horizontally, similar to HTOLs.

4.1.1. Tilt-body UASs

Unlike tilt-rotors and tilt-wings, in this category of drones, the whole body experiences a 90-degree rotation to perform a hybrid flight. Tail-sitters form an important category of the UASs, introduced by Nikola Tesla, a prominent American-Croatian scientist in 1928 [169]. However, the first XFY-1 and XFV-1 aircraft were manufactured by Convair and Lockheed in the 1950s [21]. As their name implies, tail-sitters have a vertical rocket-like landing and takeoff phase and fly in the cruise phase horizontally. Their mechanisms in cruise flight can be similar to those of fixed-wings or can be performed using other methods. As shown in Fig. 49, the structure of a typical tail-sitter aerial vehicle consists of two contra-rotating rotors at the nose of the body and the control surfaces required to control the UAS. At the bottom of the UAS, there is a tail, which besides its stabilizing role in cruise flight, acts as the aircraft support in the landing and takeoff phases.

Flight of hybrid UASs consists of three phases, namely landing/ takeoff, the transition phase, and the cruise phase. The transition phase is accomplished using control surfaces embedded in the tail and wing and the cruise phase is performed, similar to fixed-wings. The equations of motion of this type of drones are similar to those of fixed-wings. In addition to the benefits of fixed-wings, including long endurance, they will not require a runway for landing and takeoff. However, like other hybrid drones, the transition phase of this UAS has its own complexities [5,21]. Various types of UASs have been developed as a result of combining this type of drones with other aerial vehicles. For example, as indicated in Fig. 50(a), Kubo and Suzuki, in 2008, attempted to model and design two-tail tail-sitter controllers [172]. In 2015, Wang et al. simulated and modeled an agile tail-sitter drone with four tails and rotors on them (see Fig. 50(b)) [173]. Even a version of these UASs with morphing wings was developed by Ke et al., in 2016 (see Fig. 50(c)) [174].

The Flexrotor tail-sitter designed by Aerovel Company uses a variable pitch propeller to create roll/pitch torque in the hovering phase and vertical landing and takeoff. As shown in Fig. 51, two small rotors are employed at the end of the wings, which are rotating in opposite directions to prevent yaw rotation in these phases [21,175].

Several attempts have been made to combine ducted fans with tail-

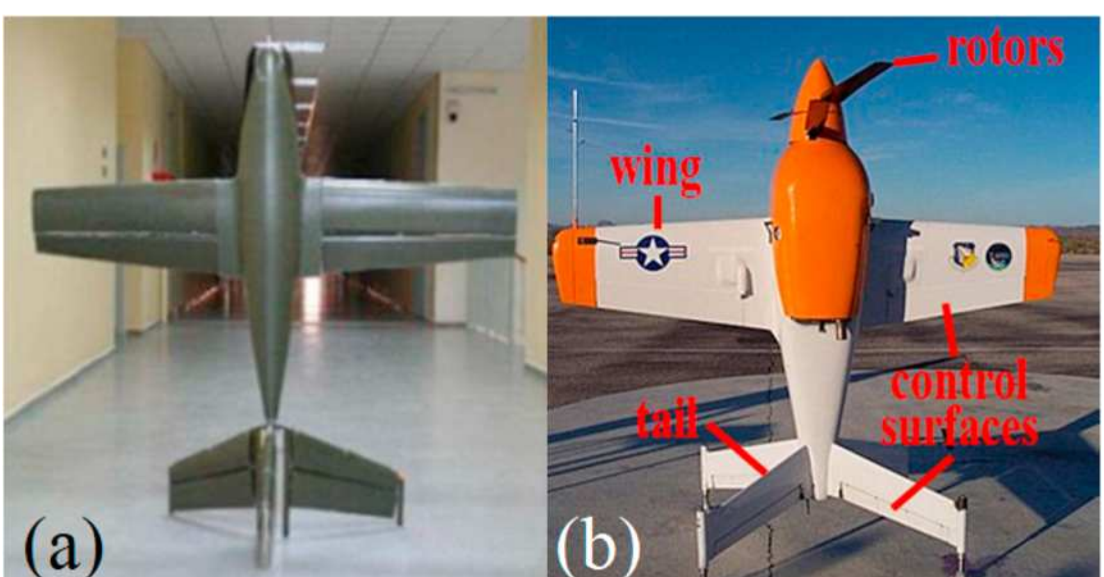

Fig. 49. Views of (a) a hybrid unmanned tail-sitter [170], and (b) the overall structure of a tail-sitter UAS [171].

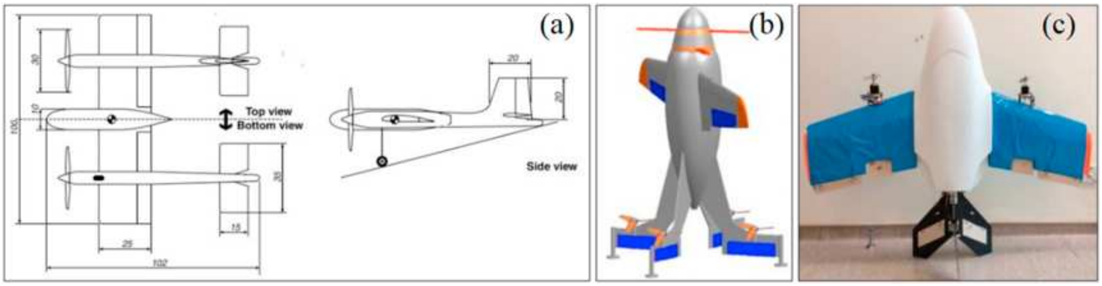

Fig. 50. Views of (a) tail-sitter developed by Kubo and Suzuki [172], (b) tail-sitter designed by Wang et al. [173], morphing wing tail-sitter developed by Ke et al. [174].

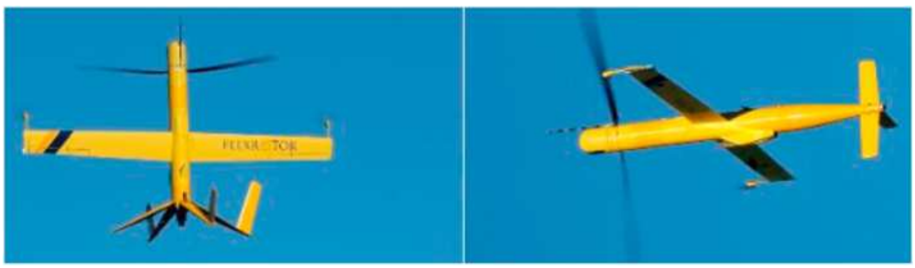

Fig. 51. Flexrotor tail-sitter made by Aerovel Company [175].

sitters. Integrating a ducted fan into the tail-sitter UASs allows the use of individually controlled ducted-fan fins alongside with control surfaces to control the drone. In 2009, Zhao explored the idea of a ducted-fan tail-sitter. Finally, after modeling, simulating, and designing the controller, it has led to the construction of a prototype that is a combination of a ducted-fan mono-rotor and a fixed-wing (see Fig. 52) [176]. Jung et al., in 2013, attempted to design, simulate, model, and control these ducted-fan drones (see Fig. 53) [177].

Besides researchers, private sectors like MartinUAV company have also developed Ducted-fan tail-sitter (see Fig. 54).

Barth et al. in 2018, proposed another type of tail-sitters by turning the tail into support, and eliminating its operating and stabilizing role. They have used two fixed rotors to generate thrust and two control surfaces, and a vertical tail to control the drone, leading to increased UAS maneuverability [179]. In Fig. 55, a view of the designed UAS by Barth et al. is shown. Compared to other hybrid UASs, tail-sitters have a

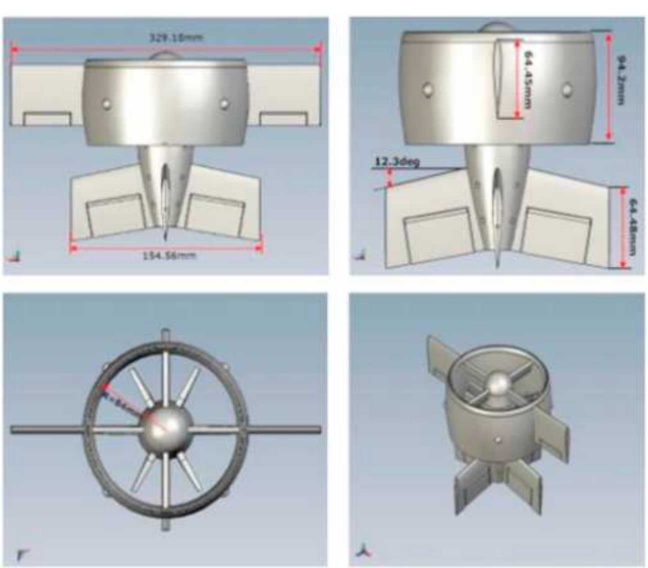

Fig. 52. Ducted-fan tail-sitter, designed by Zhao [176].

more complex and challenging structure. In this type of drone, the dimensions, size, and type of propeller and airfoil must be carefully selected for both the takeoff/landing and cruising phases. On the other hand, to reduce airflow disturbance in the landing and takeoff phase, a wing with a high aspect ratio and a narrow chord is required. However, this choice in the cruise phase reduces the cargo-carrying capacity [179]. Also, in cases where a rotor is used, the transition phase is accomplished by a process called stall and tumble that can leave the UAS completely out of control. Furthermore, they are unstable in the vertical flight phase and can hardly land on a moving base. Instead, there are plenty of options available for designers to design a wing or tail. If more than one rotor is used, higher speeds can be achieved in the cruise phase. For this reason, most tail-sitters are still in the design phase and rarely used massively [21].

The performance of another batch of tilt-body UAS is similar to that of tail-sitters, except that the tail and wing are combined. This drone is called a semi-tail-sitter. Unlike tail-sitters, which usually use a rotor, semi-tail-sitters apply two or more rotors (often with fixed pitch). Flying wings form a significant part of these drones. In this new combination, the thrust to weight ratio increases due to the use of more than two rotors. In this type of UAS, the destructive effects of the wing on the tail are eliminated, and the weight is reduced due to the removal of the tail. However, in addition to the disadvantages and challenges of tail-sitters due to tail removal, control operations are performed with their own complexities that are requiring a range of specific solutions in most cases [21]. Semi-tail-sitters are considered to be relatively new flying concepts, with little work being done on their modeling and control. In 2015, Hochstenbach et al. conducted research on the design, control, and prototyping of a semi-tail-sitter called VertiKUL (see Fig. 56(a)) [180]. This semi-tail-sitters UAS consists of four rotors in quadrotor configuration and two fixed wings. It does not use control surfaces to control the drone and performs transition, cruise, and takeoff only by using its rotors [180]. In 2019, Garcia-Nieto et al. developed a model with a tilt-rotor structure consisting of two tilt rotors on a delta wing-body. This drone that has a flying wing concept uses tilt rotors with no built-in control surfaces (see Fig. 56(b)) [181].

In 2011, Transition Robotics company developed a similar design called the Quadshot, which utilizes four rotors in the quadrotor configuration, as well as wings with control surfaces for flight, such as

Fig. 53. Ducted-fan tail-sitter, developed by Jung et al. [177].

Fig. 54. Ducted-fan tail-sitter, developed by MartinUAV company [178].

Fig. 55. Tail-sitter UAS, developed by Barth et al. [179].

VertiKUL. The octagonal model of this UAS has also been developed by this company with two parallel wings known as the Jumpship [182]. In Fig. 57(a) and (b), views of Quadshot and Jumpship UASs are shown, respectively.

E-flite has developed a VTOL drone called X-VERT with high maneuverability that uses control surfaces to control the UAS in both horizontal and vertical flight modes [183]. Chengdu Aircraft Research & Design Institute (CADI) in China and also Google have designed and prototyped VTOL drones with flying wing concepts. In flying wings, the body and wing are integrated, and the drone is controlled by control surfaces embedded in the body. These UASs often use fixed-pitch rotors. The drone developed by the Chengdu Institute uses two fixed rotors for thrust production, while Google uses four rotors for thrust production [184–186]. Views of these commercial VTOL drones are indicated in Fig. 58.

In 2018, Reyes successfully modeled, simulated, designed, and built

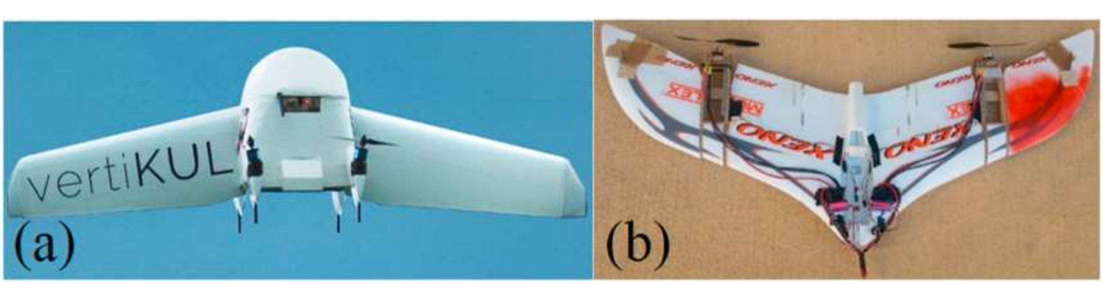

Fig. 56. Views of (a) VertiKUL semi-tail-sitter [180] and (b) Semi-tail-sitter developed by Garcia-Nieto et al. [181].

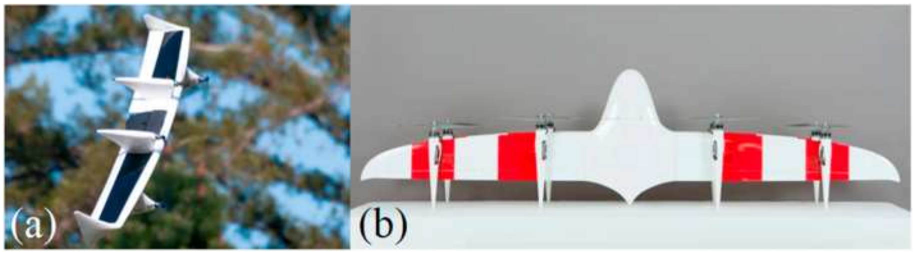

Fig. 57. Views of (a) Quadshot, and (b) Jumpship semi-tail-sitter [182].

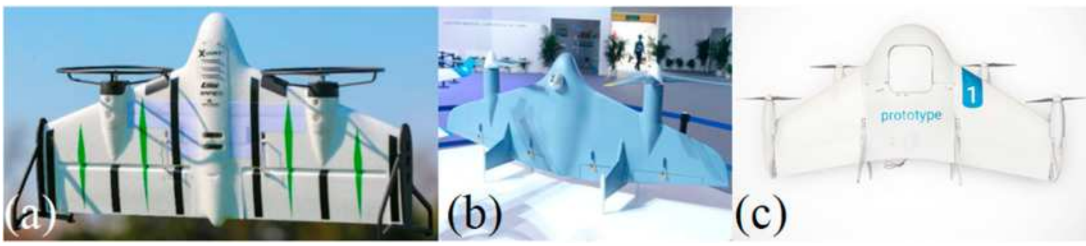

Fig. 58. Views of (a) X-VERT manufactured by E-flite Co. [183], (b) VD200 flying wing [184], and (c) Google X-wing [186].

a semi-tail-sitter with four asymmetric rotors (see Fig. 59) [187].

Some efforts have been made to design and manufacture unmanned semi-tail-sitters with some kind of planar wings. In this category, short and wide wings with a low aspect ratio similar to flying wings are used instead of conventional wings. In 2008 Garcia et al. [188] and in 2011, Ta et al. [189] attempted to design, model, control, and build this type of UAS. Ta et al. used fixed rotors, while Garcia et al. used tilt rotors to control the drone (see Fig. 60). In the design of these two UASs, the vertical tail is designed as long fins on the wing. Also, the fins embedded at the base of the body help to provide a stable vertical flight and also play the role of a horizontal tail in the cruise phase.

Some new hybrid drones are created as a result of combining these UASs with different types of wings. For example, Stone, in 2004, designed a tail-sitter drone by incorporating T-shape wings [190] (see Fig. 61(a)). A semi-tail-sitter has been developed by combining a quadrotor with two fixed wings. This UAS consists of two parallel wings with four rotors that act as a quadrotor in the takeoff phase and as a fixed-wing with two parallel wings in the cruise phase. Commercial versions of this model have been developed by Xplus and ATMOS [21] (see Fig. 61(b) and (c)).

4.1.1.1. Challenges and benefits. Over the last two decades, tilt-body UASs were commonly adopted in developing tactical UASs with the increasing maturity and cost reduction of miniature drone development [21]. Ducted fan and tail-sitter drones have an unstable vertical flight, low cruising speed, low payload capacity and low endurance. In contrast, the models which use a combined configuration of multirotors have high cruising speed, high controllability and stability. Tail-sitter drones can quickly take-off and land vertically. However, they have reduced efficiency in horizontal flight and vulnerable to crosswinds like semi tail sitter drones. One of the differences between these types and semi-tail-sitters is that semi-tail-sitters have more efficient cruise flight than multirotor-combined tilt-body drones. Ducted-fan tail-sitters have more efficient rotors (or fans), and there are various design options for their wing shape [21]. The major challenge in tilt-body drones, like other hybrid drones, is their complex dynamics and control, especially during the transition phase.

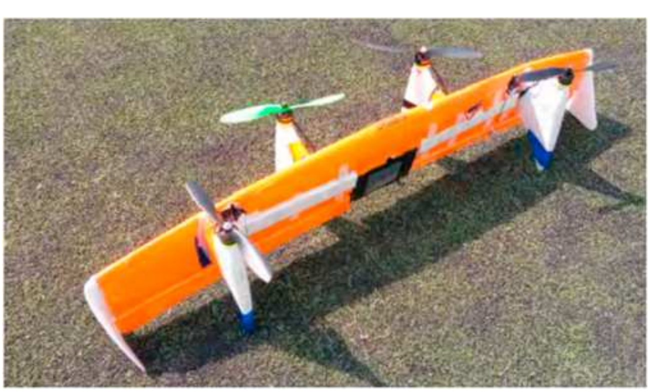

Fig. 59. Semi-tail-sitter, developed by Reyes [187].

4.1.2. Tilt-components UASs

In hybrid UASs with tilt components (or hybrid tilt-rotor drones), the initial orientation of the body is maintained during flight, and only parts of the aerial vehicle, mainly wings and rotors, rotate [5]. One of the most popular types of hybrid drones with tilt components is tilt-rotors. In this category of UAS, all or part of the rotors are tilted, and other parts, such as wings and body, are fixed in all phases of flight. Tilt-rotors, along with most multirotor configurations, have been researched and tested. There are also other types that have been proposed by combining them with fixed-wing or ducted-fan UASs. This category of UASs takes advantage of fixed-wing configurations, including high endurance, and does not require a landing and takeoff runway [5]. Compared to other hybrid drones, they have a simpler transition mechanism; however, they require a more complex structure and have a lower aerodynamic efficiency. Like tilt-wings, selecting suitable actuators with acceptable performance is very challenging in tilt-rotors [21].

4.1.2.1. Tilt-rotors. Tilt-rotors act like multirotors in the takeoff phase, as reviewed in the previous sections, and after the transition phase, they fly as fixed-wings in the cruise phase. The rotors will handle thrust generation, and control surfaces will be used to control the UAS. The original idea of this type of aerial vehicle was first introduced by the Bell Helicopter Company in 1993 [21]. Subsequently, other examples were developed by other companies and researchers. For instance, in 2009, Yanguo and Huanjin designed a flight control system for a small unmanned tilt-rotor drone [193]. In Fig. 62, a view of this drone has been shown.

In 2013, AgustaWestland Corporation designed and manufactured a

Fig. 60. Views of semi-tail-sitter designed by (a) Ta et al. [189], and (b) Garcia et al. [188].

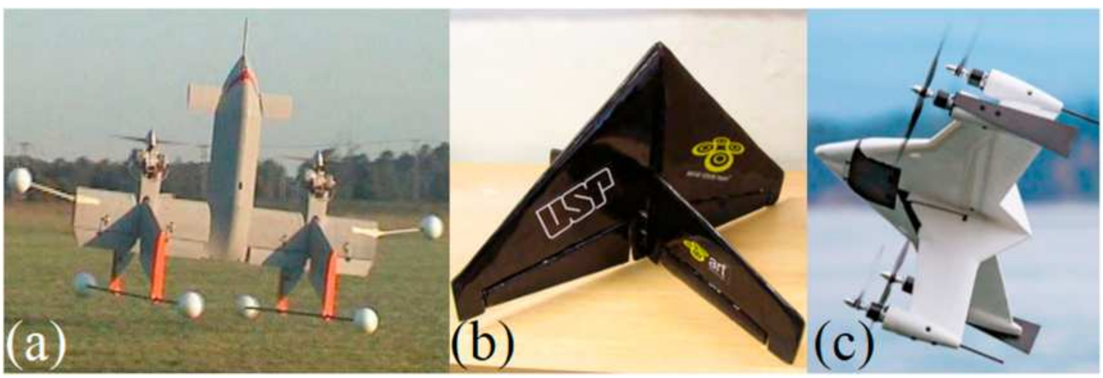

Fig. 61. Views of Semi-tail-sitter designed by (a) Stone [190], (b) Sampaio et al. [191], and (c) Xplus and ATMOS [192].

Fig. 62. Tilt-rotor drone designed by Yanguo and Huanjin [193].

tilt-rotor drone by combining a delta flying wing with two ducted fans inside the wings [194]. These type of tilt-rotor drones are more stable in hovering mode; however, the effect of rotor rotation on the body results in some problems, especially in the transition phase [194]. In Fig. 63, a view of this drone is indicated.

Various hybrid tilt-rotors have also been developed using three rotors. For example, in 2014, Carlson proposed a combination of a tilt-rotor with a flying wing. In this drone, a third motor is positioned at the center of the body near the end, which helps the two other motors in the takeoff process and provides a yaw control (see Fig. 64(a)) [195]. The control surfaces installed on the wings perform roll and pitch maneuvers. In this type of drone, the rear motor does not participate in the horizontal flight phase, but it is mounted with a 10-degree slope to provide part of the horizontal force needed in the transition phase [195]. Similar work was conducted by Aktas et al., in 2014 [196]. They applied two coaxial ducted-fans rotors, in place of the third motor, to generate lift for vertical flight mode (see Fig. 64(b)) [196]. BirdsEyeView Co. has developed another similar version with co-axial rotors (see Fig. 64(c))

Fig. 63. Tilt-rotor drone developed by AgustaWestland [194].

Fig. 64. Views of tilt-rotor drones designed by (a) Carlson [195], (b) Aktas et al. [196], and (c) BirdsEyeView Co [197].

[197].

Quantum-Systems company also developed a commercial model of this type of tilt-rotor drones with three tilt rotors. A third motor is mounted on the aircraft tail, which is used in all three phases of flight [198]. Various examples have been designed with a standard fixed-wing structure with a horizontal and vertical tail, as shown in Fig. 65 [199].

The tilt-rotor UASs have also been developed in the quadrotor configuration. The Phantom Swift made by Boeing is similar to Murillo et al.'s in general, except that it uses a tilting ducted-fan instead of a tilt rotor and two non-coaxial fans instead of two coaxial fans (see Fig. 66 (a)) [200]. Moreover, Quantum Systems company has designed a commercial drone that uses four motors for the takeoff phase. In this UAS, two rear motors are not involved in the horizontal cruise phase, and the front motors generate horizontal thrust (see Fig. 66(b)) [201].

4.1.2.1.1. Challenges and benefits. Nowadays, tilt-rotor UASs are popular among drone designers because of their flight efficiency, stability, and controllability. However, tilt-rotors have complexities and challenging issues in their design, specifically in their transition mode. This is due to the fact that the transition between vertical and horizontal configurations necessitates a different control strategy. In tilt-rotor drones, degradation of stability is usually found at high-speed in cruise flight, and the equations of motion are highly coupled and nonlinear [5]. These UASs can be easily equipped with ducted rotors or co-axial rotors. It is also easy to combine different multirotor configurations with conventional fixed-wing or flying wings to easily benefit from each configuration's advantages.

4.1.2.2. Tilt-wing UASs. This category of UASs is designed with a fixed-wing structure with tilting capability. In these drones, wings and connected motors rotate about 90°, but the rest of the body parts remains fixed. Appearance of this type of aerial vehicle dates back to the 1960s and 1970s when Boeing developed its first tilt-wing manned aircraft [5,21]. Like other hybrid UASs, the flight in this type of drone consists of three phases, namely vertical landing and takeoff, the transition phase, and the horizontal cruise phase. In the vertical landing and takeoff phases, the wings are positioned at an angle of 90° so that the thrust produced by the rotors is applied opposite to the force of weight. After the transition phase, the UAS will continue to fly as a fixed-wing aerial vehicle. In the hovering flight, they act like the bi-rotors that were mentioned earlier [21].

Like other hybrid drones, the transition phase is one of the most challenging steps. These UASs have nonlinear flight dynamics in transition mode that should be considered during the design of a suitable controller. Compared to tilt-rotors, tilt-wings may bring up bigger challenges to designers and engineers because of the need for stronger actuators [5,21]. Another challenge of these UASs is the exposure of the wing to airflow during landing and takeoff modes. Although the speed of drones in landing and takeoff modes is much slower than that of the cruise, the lift and drag forces in vertical modes should be considered [5, 21].

In recent years, various examples of hybrid UASs, in particular tilt-wings, have been made and studied. Dickeson et al. in 2007, developed a tilt-wing UAS and studied its aerodynamics and flight efficiency. Moreover, they proposed a control system for this drone (see Fig. 67(a)) [202]. In 2012, Ostermann et al. proposed a control concept for a tilt-wing UAS during low-speed maneuvering. They used variable pitch rotors instead of fixed-pitch rotors in order to have easier control in the hovering mode, along with the ailerons (see Fig. 67(b)) [203].

Fig. 65. Views of tilt-rotor drones designed by (a) Quantum-Systems [198], and (b) Nimbus Co [199].

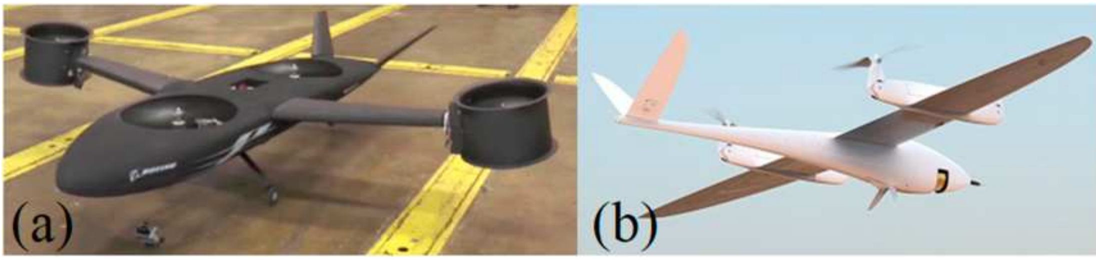

Fig. 66. Views of tilt-rotor drones designed by (a) Boeing [200], and (b) Quantum-Systems Co [201].

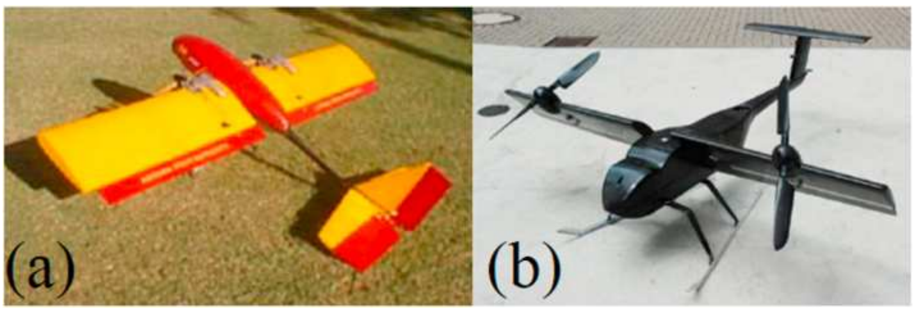

Fig. 67. Views of tilt-wing drones designed by (a) Dickeson et al. [202], and (b) Ostermann et al. [203].

Cetinsoy et al. in 2012, attempted to model, design, and control a quad tilt-wing UAV. They used four tilt-wing and rotors in the quadrotor configuration for their design, which turns into a twin fixed-wing in the cruise phase [204]. A view of this quad tilt-wing drone is shown in Fig. 68.

Besides researchers, private sectors also designed and manufactured different types of tilt-wing UASs. For example, Acuity Technologies company designed and manufactured a tilt-wing UAS, called AT-10, that only a part of the wing is tilted to reduce disturbance and drag effects (see Fig. 69(a)) [205]. Some examples have also been developed using more than four rotors but in the fixed-wing configuration, such as NASA's tilt-wings, which uses ten electric rotors on tilting wings [21]. With these rotors mounted on a 3 m wingspan, the drone can carry up to 28 kg payload and have a vertical landing and takeoff (see Fig. 69(b)) [206].

A special type of tilt-wing drone shown in Fig. 70 has been developed by Low et al. in 2017, by integrating a tailless flying wing configuration with a single-axis rotor [207]. In this UAS, the wing acts as a propeller in the vertical takeoff phase and generates lift force through rotation, such as the wing-rotor, as previously mentioned. In the cruise phase, the wing is fixed, and the drone continues to fly like a fixed-wing UAS. In this phase, the rotors will be responsible for generating thrust and the needed torque to control the drone [207].

As indicated in Fig. 71, Iridium Dynamics has designed a drone called Halo 240-E Inspection that uses rotary wings. In the vertical takeoff phase, these wings are responsible for generating vertical thrust, such as the rotary mono-rotors. In this phase, the entire body rotates with the wings, and the drone's tail is also used as a propeller. After the transition phase, the wing and tail become fixed and will provide the lift force like fixed-wings [208].

4.1.2.2.1. Challenges and Benefits. Compared with the tilt-rotors, tilt-wing UASs generally have a more sophisticated and complicated design in on-board components such as tilting drive train. Also, in low-speed operation, like hover, takeoff, and landing, the wings of a tilt-wing UAS need to be directed upward, making them more vulnerable to crosswind. Therefore, developing a tilt-wing UAS requires additional effort in designing control mechanisms to handle the attitude stabilization [21]. These UASs can perform vertical flight similar to rotary-wings and fly with high speed for long-duration missions like fixed-wing UASs [5].

4.2. Non-tilt hybrid UASs

In this set, although the UAS has a hybrid configuration but it does

Fig. 68. Tilt-wing drone developed by Cetinsoy et al. [204].

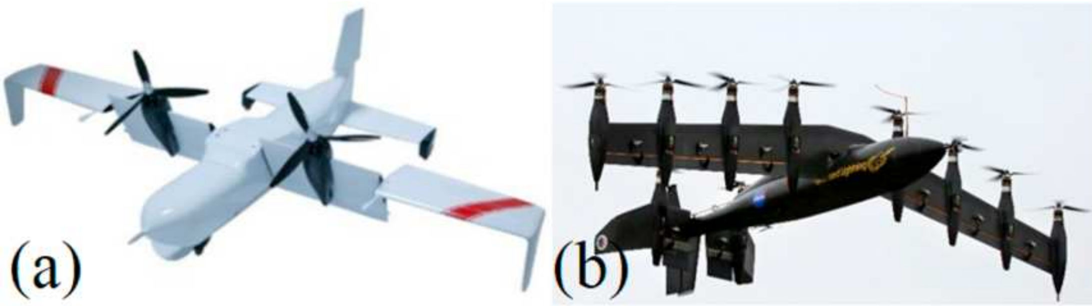

Fig. 69. Tilt-wing drones designed by (a) Acuity Technologies company [205] and (b) NASA [206].

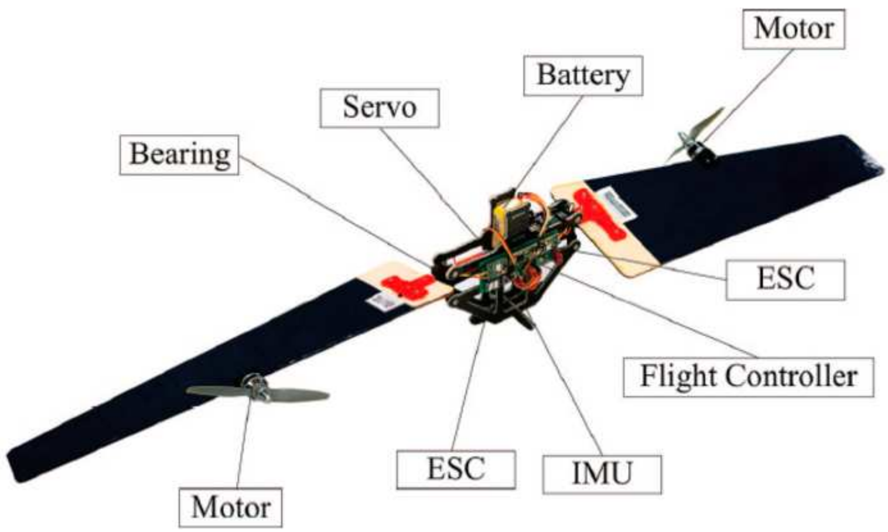

Fig. 70. View of tilt-wing drone developed by Low et al. [207].

Fig. 71. Rotorcraft developed by Iridium Dynamics [208].

not need rotation and transition phase to be converted from VTOL to HTOL. There are two types of non-tilt hybrid UASs, including dual systems and rotary wings, that are discussed below.

4.2.1. Dual system

These drones have the characteristics of the HTOL and VTOL drones simultaneously. In dual systems, during each phase, one system is activated, and the other is deactivated. A class of drones that uses dual fuel is also called dual systems, which should not be confused with this type of UASs. Generally, this UAS is composed of a combination of multirotor and fixed-wing configurations. Although they do not have a complex transition phase compared to tilt-wings or tilt-rotors, the unnecessary use of a system in each phase imposes an extra burden on the system and does not allow the designer to utilize all the capacity of the motors. These UASs are not very popular among designers despite the simplicity and feasibility of using different wing designs, and not many of them have been developed. In Fig. 72, the structure of a typical dual system drone is shown [209].

One of the most old-fashioned examples of drones with dual systems was developed in 2000 by Sikorsky Dragon. This UAS uses two ducted propellers for vertical flight and another motor with a duct for the cruise flight. The control surfaces are also embedded in the wing and help to

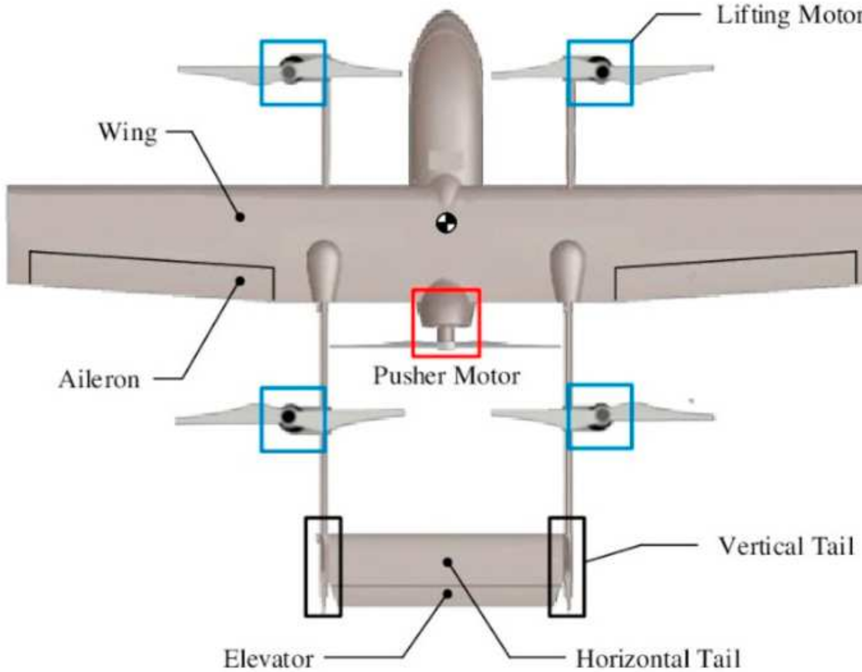

Fig. 72. Structure of a typical dual system drone [209].

control the drone [84]. In Fig. 73, views of a hybrid drone with dual systems developed by Sikorsky Dragon is shown.

An example, called HADA, has also been developed through combining helicopter and fixed-wing configurations that act as a helicopter in the takeoff mode and like a fixed-wing in the cruise. In this phase, the motor embedded in the drone tail is responsible for thrust generation (see Fig. 74) [211].

Similar concepts have been developed, inspired by the quadrotor configuration with a fixed rotor for the takeoff phase. For example, ArcturusUAV has built a commercial prototype of this drone (see Fig. 75 (a)) [212]. Aletky has also proposed a similar design using coaxial motors with a V-shape wing combination (see Fig. 75(b)) [213]. Examples have also been developed with other designs of wing and tail.

The Airborne company has also designed a dual system drone combining a fixed-wing and bi-rotor configurations. In this UAS, the vertical flight is performed as a bi-rotor, and the cruise is fixed-wing (see Fig. 76) [214].

4.2.1.1. Challenges and benefits. In dual systems, the tilting mechanism is not a part of the drone, so dual systems, compared with tilt-hybrid UASs, have simplified mechanical design and enhanced reliability. However, during cruise flight, the multiple non-operational rotors for vertical lift generation cause extra aerodynamic drag due to their fixed mounting. Furthermore, this configuration is not mass-efficient because the VTOL rotors are not involved in cruise flight. But their simple structure and dynamics make the control design easy. Also, unlike tilt-hybrid drones, there is no transition mode.

Fig. 74. HADA dual system aircraft [186].

4.2.2. Rotary-wing

In a group of UASs with dual systems, the wing is involved in both the vertical and horizontal flight modes. In other words, the wing provides

Fig. 73. Hybrid drone with dual systems developed by Sikorsky [84,210].

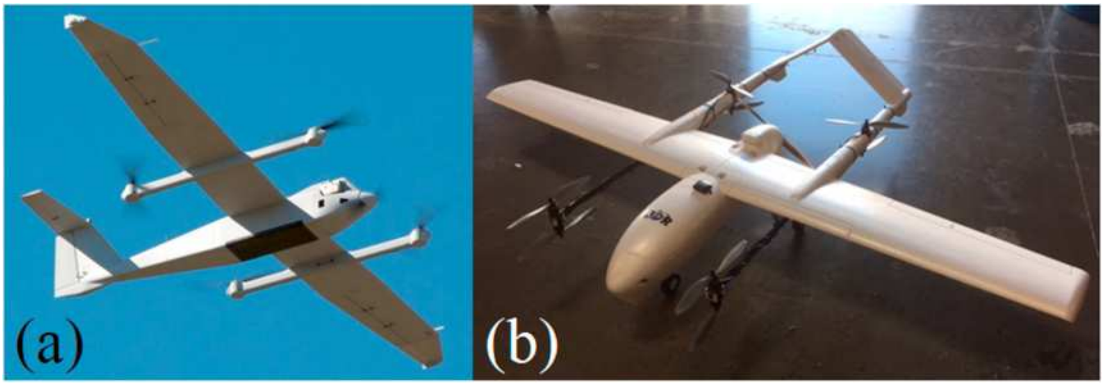

Fig. 75. Dual system drones developed by (a) ArcturusUAV [212], and (b) Aletky [213].

Fig. 76. The dual system UAS combines the capabilities of an aircraft and helicopter to provide a wide range of missions, developed by Airborne [214].

the required lift in the takeoff phase as a rotor and as a fixed-wing in the cruise phase. This group of drones is called rotary-wings. In cruise mode, the wing is fixed, and the rotation mechanism of the wing is deactivated. For this reason, they are classified in the hybrid category, although the wing participates differently in both phases. In Fig. 77, views of a rotary-wing are indicated [215].

As indicated in Fig. 78, Boeing has also developed an example of this type of drone called the X-50. However, the rotary-wing UASs have complex dynamical modeling and aerodynamics due to their instability in transition mode [5,21].

4.2.2.1. Challenges and benefits. Rotary-wing UASs have been studied in a few kinds of research, and most of them have been stopped. It should be noted that none of the above-mentioned projects have succeeded in completing the transition flight. The main reason for this is that the unique rotary-wing feature poses critical challenges to a qualified solution to balance the design complexities in aerodynamics and mechanics.

5. Bio-based UASs

The drones in this category are somehow linked to living avians or insects, either directly inspired by birds and insects and mimic their flight mechanism or that living species form a part of their flight mechanism. Accordingly, this category is divided into two classes, bio-inspired and bio in the loop.

5.1. Bio-inspired UASs

Bio-inspired drones include those designed based on nature or the ones that mimic the flight of living birds. As discussed above, from this classification, drones that are inspired by the maple seed known as Samara, have been considered as wing-rotor VTOLs. These bio-inspired drones are classified as flapping-wing and non-flapping-wing drones.

5.1.1. Flapping-wing drones

The flapping-wing drone category has been very popular over the past ten years among micro-drones designers [216–220]. This category of UAS uses flapping motion to generate the required aerodynamic forces, such as lift and thrust, instead of the conventional methods. Flapping wings generally have a twist on their wing in addition to transitional movement. These drones are often built in two types, namely twisting-wing and fixed-wing (non-twisting), where twisting-wings are more efficient and complex. Flapping wing drones are designed in three classes, namely, Pico, Nano, and Micro Air Vehicles (PAV, NAV, and MAV). Flapping wing PAVs are inspired by insects, MAVs are inspired by birds, and NAV flapping wings are inspired by species between very small birds and huge insects, such as hummingbirds and dragonflies [5,220]. In Fig. 79, views of three classes of flapping-wings are shown. Flapping-wing drones also can be designed and fabricated in three different configurations, namely, monoplane, biplane, and tandem [5,221].

Flapping-wing drones are able to fly by applying the aerodynamic forces resulting from the oscillatory motion of wings coupled with twisting. Aerodynamic analysis of these drones has indicated that flapping motion is the most efficient method in generating aerodynamic

Fig. 77. Views of NLR The stop-rotor rotary-wing drone [215].

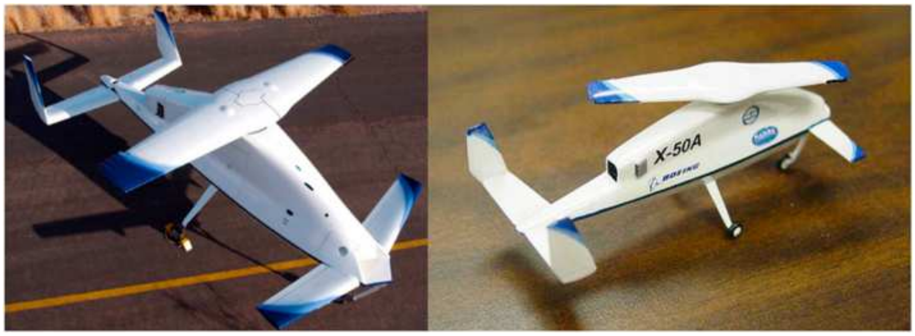

Fig. 78. Views of Boeing X50 Dragonfly rotary-wing drone [5,21].

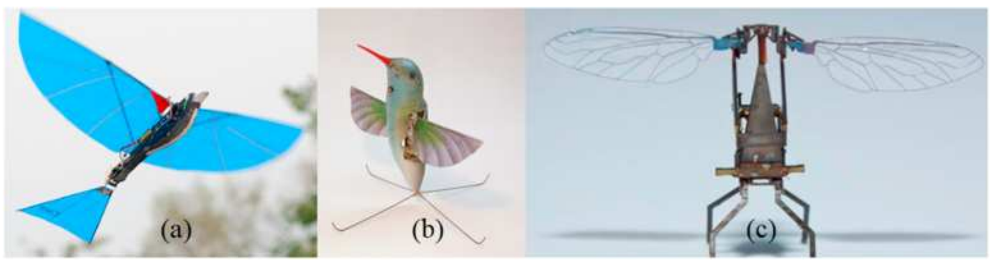

Fig. 79. Views of (a) MAV [222], (b) NAV [223], and (c) PAV flapping-wing drones [224].

forces at the low Reynolds numbers [5,225]. Generally, flapping-wing drones have light and flexible wings, as seen in avians and insects, which shows that the weight and flexibility of wings are important for their flight stability and aerodynamic proficiency [5]. This flexibility of the wing creates the twist-angle that provides the necessary angle of attack to generate sufficient lift during flapping [5,218]. In Fig. 80, different insects' wings are shown that can be inspired for wing shapes of flapping-wing drones [226].

There are plenty of actuation mechanisms that have been designed for flapping-wings, which are dependent on the type and class of these bio-inspired drones [227]. These actuation mechanisms are 4-bar, 5-bar, and 6-bar mechanisms. For example, for flapping wings at MAV class, a variety of actuators have been applied, and most of them are similar to the commercial flapping-wings, such as Slowhawk2 [228], Kinkade [229], and Kestrel [230]. Delfly NAV has been powered by a DC electric motor coupled to a gearbox and linkage mechanism using conventional pin joints (see Fig. 81(a)) [231,232]. At this scale, Keennon et al. have designed and fabricated a flapping wing NAV like a hummingbird, which is capable of flying in hover mode (see Fig. 81(b)) [223]. This flapping-wing NAV applies an actuation mechanism composed of strings and rollers, while still using a geared down motor to generate power at the right frequency [223].

Different types of flapping-wing drones have been designed by researchers and private sectors [233]. Researchers at the Delft University of Technology have designed and prototyped models based on insect flight but with using a tail, which they called them DelflyI and DelflyII (see Fig. 82(a)) [231,232]. Festo company has also developed a penguin, seagull, dragonfly, butterfly, and bat-inspired flapping-wing drones, which are shown in Fig. 82(b–f) [234].

There is also a different version of flapping-wing drones developed by Jones and Platzer, which uses a hybrid flapping-fixed-wing design. In this drone, the flapping-wing is generating thrust and the fixed-wing producing the necessary lift [235]. In Fig. 83, a view of the flapping-fixed-wing drone developed by Platzer et al. is indicated [236].

Some of the other flapping-wings come with four and more wings in various configurations such as tandem or perpendicular and cross (X-wing) (see Fig. 84 and 85) [237].

A comprehensive study was conducted on the aerodynamics of the flapping-wings by Shyy et al. [226]. They also worked on the aerodynamics of the low Reynolds number flyers like birds, bats, insects and flapping-wing MAVs [238]. In 2010, Shyy et al. reviewed the recent progress in flapping-wing aerodynamics and aeroelasticity [239]. Orlowski and Girard, in 2012, reviewed the researches on the dynamics, stability and control analysis of flapping-wing micro air vehicles [240]. In 2019, Phan and Park studied the progress in the bio-inspired flapping-wing drones, including their aerodynamics, mechanism, modeling

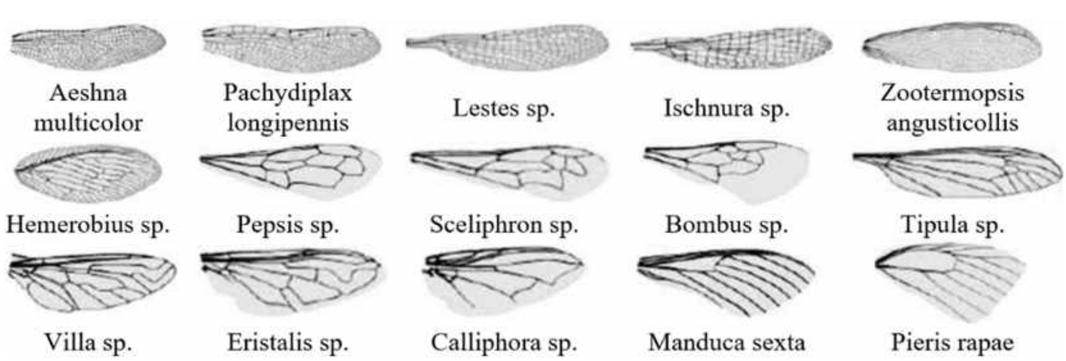

Fig. 80. Views of insects' wing shape [226].

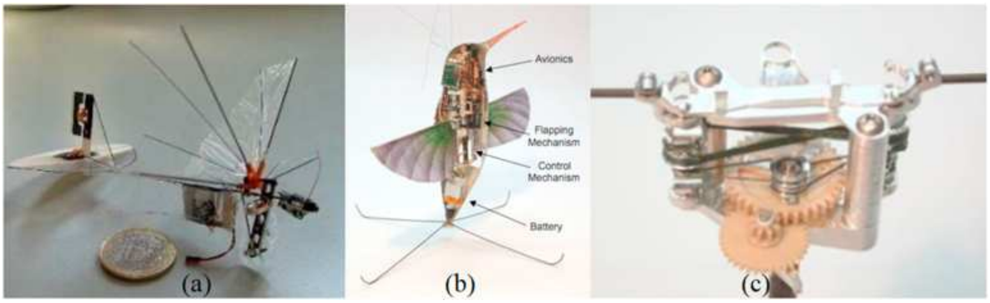

Fig. 81. Views of (a) Delfly flapping-wing [232], (b) hummingbird-inspired NAV, and (c) flapping-wing mechanism for hummingbird-inspired NAV [223].

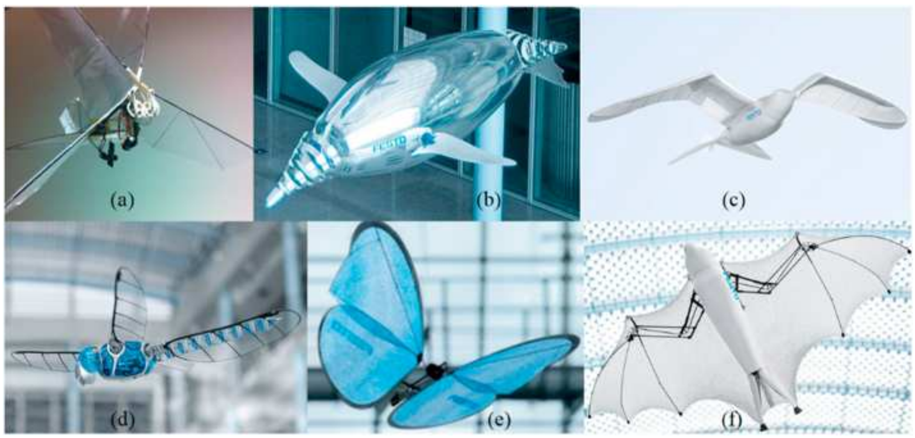

Fig. 82. Views of (a) DelflyII flapping-wing [232], and Festo (b) penguin-inspired, (c) seagull-inspired, (d) dragonfly-inspired, (e) butterfly-inspired, and (f) bat-inspired flapping-wing [234].

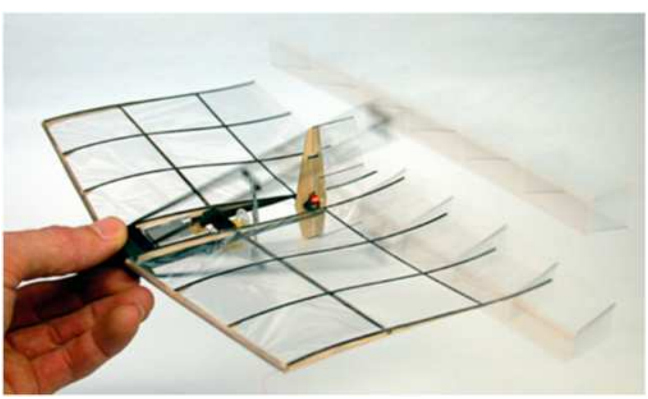

Fig. 83. View of flapping-fixed-wing drone developed by Platzer et al. [236].

and control [237].

5.1.1.1. Challenges and benefits. The designs of fixed-wing drones encounter more fundamental challenges in flight control and lift generation as their sizes become smaller than a few centimeters. Flapping-wing UASs, in comparison with fixed-wing and multirotors drones, have merits and challenges. Due to the Reynolds number effects, micro air vehicles and conventional manned air vehicles have different aerodynamic characteristics such as lift, drag and thrust. Studies have shown that in low Reynolds number, fixed-wing drones have a lower efficiency than flapping-wings. However, flapping-wings have lower weight, can fly at low speeds, and are sensitive to wind force [239]. Insect-size flapping-wings have the ability to hover and a quick transition to forward flight. These characteristics make flapping-wing an ideal configuration for search and rescue, law enforcement, and military missions. Flapping-wings have an extremely limited payload capacity. Therefore, their control calculations' processing power needs to be as low as possible [240]. These UASs, due to their small size, hovering capability, high maneuverability at low speeds, and small acoustic signature, are one of the best solutions for indoor missions. Moreover, they are more efficient in power requirements at low speeds than either fixed-wing or multirotor UASs [241].

As noted before, there are two types of flapping-wing UASs; bird-like and insect-like flapping-wings. There are significant differences between the flight mechanisms of a bird and an insect. Birds apply their tail as a control surface, while insects do not have a tail and mainly rely on their wings to produce control forces by actively modifying wing kinematics

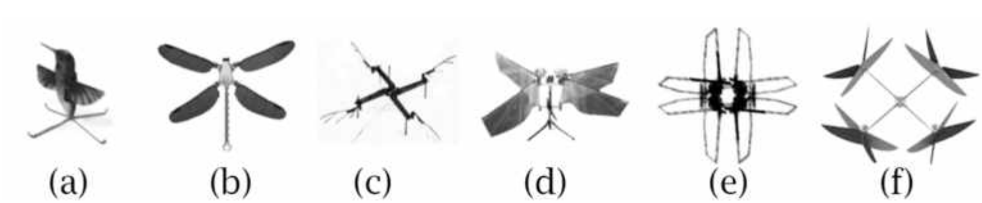

Fig. 84. Different configurations of wings in flapping-wing drones; (a) two-wing, (b) tandem, (c) perpendicular, (d) two-pair, (e) four-pair, and (f) eight-pair [237].

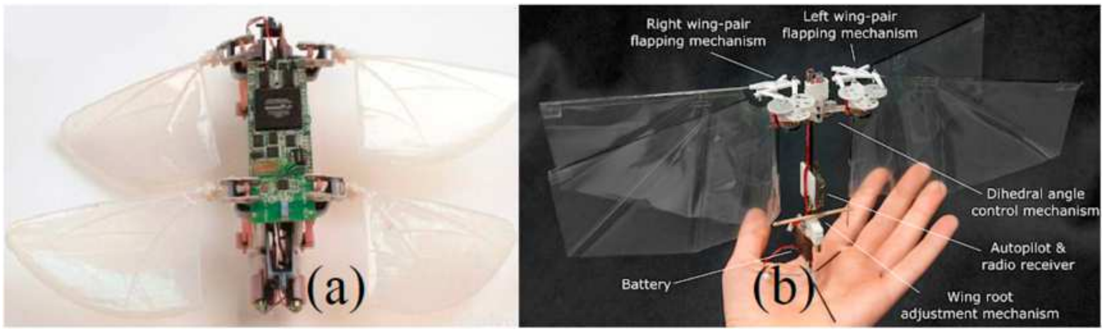

Fig. 85. Views of flapping-wing drones, (a) TechJect Dragonfly and (b) Delfly Nimble [237].

during flapping motion. In addition, usually, the birds are not capable of hover flight while most of the insects are. Therefore, the insect-inspired drones may have more advantages, but their design is more challenging because of the lack of stabilizing tail, smaller size, and manufacturing processes [237].

5.1.2. Non-flapping-wing drones

In the category of non-flapping-wings, the only example is the jellyfish-inspired UAS designed by the Festo company. This drone is designed based on the mechanism of the jellyfish in the water to generate thrust by moving its arms for flying. The jellyfish-inspired UAS consists of a light gas-filled balloon, like helium, with several mechanical arms at the bottom. An oblique gear is mounted in the center of the drone. First, the force is transmitted to the oblique gear and then to a row of eight gears. These gears provide the required power by the eight axles. Each of them activates a crank, which in turn causes one of the robot's eight arms to move. According to the creators, the antenna structure is derived from the functional anatomy of the fish fin. Together, these arms produce a forward motion similar to that of jellyfish. The control of this flying object is affected by moving the center of gravity. For this purpose, a pendulum that can move in two directions has been considered. The pendulum is located in the upper part of the robot, making it fit for the movement (motion). The center of mass of the robot, as well as the robot itself, move along the pendulum. The robot moves in any spatial direction using a peristaltic motion. This bio-inspired drone is lightweight, relatively quiet, and safe and can hover and fly vertically. Alongside these benefits, it has a complex flight mechanism. Fig. 86 shows this drone discussed above [5,234].

5.2. Bio in the loop (cyborg)

In this category of UASs, part of the flight mechanism consists of living things. Most efforts in this area focus on controlling living birds and insects. Some of the activities have focused on practicing and training birds for flight [5]. Some of the activities have also been done on direct control of birds. This is done by sending control signals to the brain, neural network, or muscle and has already been tested on some insects and birds [5]. The mechanism for motion of the musculoskeletal system is based on the transmission of commands by the nerves to the muscles. These include a series of low-voltage electronic signals that can be generated by external devices and sent to the muscle, nervous system, or brain. The necessary electrodes are inserted into the body of the bird or insect by surgery and assume control of the bird organs [5]. In the training method, the bird is trained on how to fly. It can be controlled by finding its origin or destination or by using actuators that do not require surgery, for example, stimulating bird or insect by light, sound, or impact. For example, in 2009, Bozkurt et al. have attempted to control a witch moth using balloons [242].

In this type of UASs, energy consumption is very low, and important phases of the flight, including detection and obstacles avoidance, can be performed by living birds. Nevertheless, the challenges facing such bio-drone include medical complexities, surgeries, and other impediments, such as violations of animal rights and environmental laws, along with the possibility of the bird being lost in the process of flight or disrupting the mission by the living organ. Some few researches have been done on insects; however, less research has been performed on birds and flying insects due to their complexity. For example, in various studies, Sato et al. have attempted to study how to control insects and several flying insects [243–246]. Researchers at Shandong University, China, are also working on controlling pigeons using brain signals [247]. In Fig. 87 (a)-87(c), views of controlled flying insects and birds are demonstrated.

Before reviewing the drones' applications, it would be helpful to review the different configurations of the UASs, which were discussed in this paper. Fig. 88 illustrates a view of all categories of UASs.

Fig. 86. Views of Jellyfish-inspired UAS developed by Festo [234].

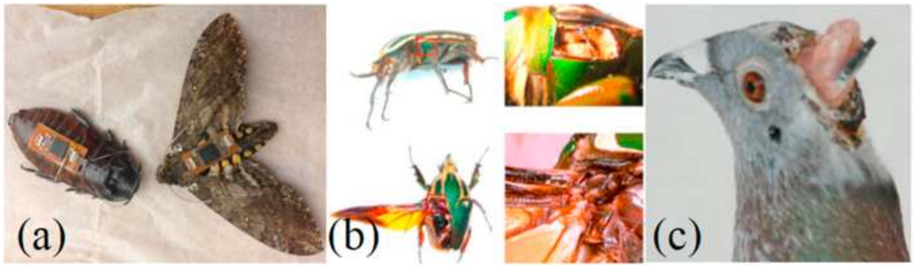

Fig. 87. Views (a) remotely-controlled flying insects [246], (b) surgery of a beetle to embed control actuators [246–248], and (c) brain-controlled pigeon of Shandong University [247].

6. Applications and capabilities of different UAS configurations

In this section, applications of UASs and their requirements are discussed in order to underscore which configuration is best suited for a particular application.

6.1. UAS's specifications

In order to demonstrate the applications of the UASs, it is necessary to examine their specifications. Each application requires its own specifications. Typical specifications which determine the fitness of a UAV for a specific application include; structural simplicity, scalability, ability to utilize different Sources Of Energy (SOE) such as solar, electrical, chemical and hybrid energies, operational altitude and range, endurance, cruise speed, ability to hover, maneuverability and cargo-carrying capacity.

Table 2 provides a qualitative comparison of the specifications described above for different types of UASs. In each section, two categories are considered as the lowest and highest bound of each characteristic and other categories are ranked between them with Low, Medium and High designations. For example, the highest level in structural simplicity is considered to be a fixed-wing UAS, while the lowest level for structural simplicity is taken as flapping-wings and helicopters. All other categories would then fall between these two (lowest and highest) categories. The highest level in a variety of SOE belongs to fixed-wing UASs, where they can fly using solar, electrical, chemical, and hybrid fuels. On the other hand, there are flapping-wing drones that normally use electrical power only or paragliders, which typically use chemical energy. With regard to scalability, the highest level is assigned to fixed-wing UASs again. As mentioned before, they are constructed in NAV, MAV, μUAV and UAV configurations. Also, flapping-wing UAVs can be of PAV, NAV, MAV, and μUAV types, so both of these categories can be considered the highest in scalability. The paragliders, which can be found only in UAV size, are considered the lowest in scalability. The highest level in operational altitude belongs to lighter than air and fixed-wing UASs, which can fly at altitudes as high as 25 km, and the lowest

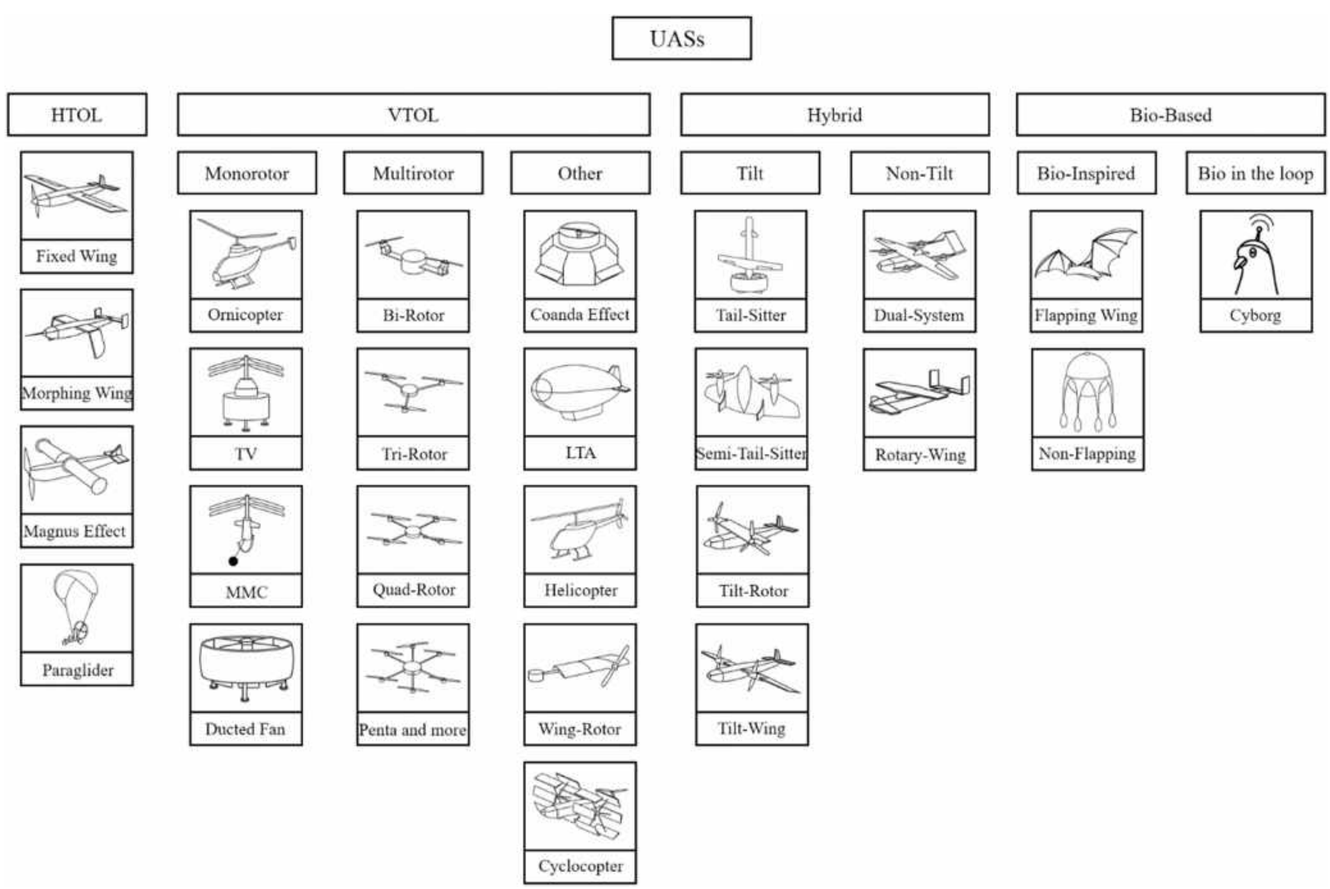

Fig. 88. Different categories of UASs.

Table 2
Qualitative comparison of various UASs.

Category		Sub-Category	Structure Simplicity	Variety of SOE	Scalability	Max Altitude	Max Range	Endurance	Cruise Speed	Need for Runway	Hover Flight	Maneuverability	Cargo Capacity
HTOL		Fixed-wing	H	H	H	H	H	H	H	Y	N	M	H
		Morphing wing	L	H	H	H	H	H	H	Y	N	M	H
		Magnus-effect	L	H	M	H	H	H	H	Y	N	M	H
		Paraglider	M	L	L	M	H	H	L	Y	N	L	H
VTOL	Mono-rotor	Ornicopter	L	M	M	L	M	M	L	N	Y	M	L
		Thrust vectoring	M	M	M	L	L	L	L	N	Y	H	L
		MMC	L	L	M	L	L	L	L	N	Y	H	L
		Ducted-fan	M	M	M	L	L	L	L	N	Y	M	L
	Multirotors	Bi-rotor	H	M	M	L	L	L	L	N	Y	H	L
		Tri-rotor	H	M	M	L	L	L	L	N	Y	H	L
		Quadrotor	H	M	M	L	L	L	L	N	Y	H	L
		Pentarotor and higher	H	M	M	L	L	L	L	N	Y	M	L
	Others	Coanda-effect	M	M	M	L	L	L	L	N	Y	M	L
		Lighter than air	M	H	L	H	M	M	M	N	Y	M	H
		Helicopter	L	M	H	M	M	M	M	N	Y	L	M
		Wing-rotor	M	M	M	M	M	M	L	N	Y	M	L
		Cyclocopter	L	M	M	L	L	L	L	N	Y	M	L
Hybrid		Tilt-rotor	M	H	M	H	H	H	H	N	Y	M	H
		Tilt-wing	M	H	M	H	H	H	H	N	Y	M	H
		Tilt-body	M	H	M	H	H	H	H	N	Y	M	H
		Dual systems	M	H	M	H	H	H	H	N	Y	M	H
		Rotary-wing	M	M	M	M	H	H	H	N	Y	M	H
Bio-Based		Flapping-wing	L	L	H	L	L	L	L	N	Y	M	L
		Non-flapping-wing	L	L	M	L	L	L	L	N	Y	M	L
		Bio in the loop	L	L	–	L	L	L	L	–	–	–	L

level belongs to flapping-wing UASs, which normally fly at elevations below 1 km [5].

In the same manner, different categories of UASs can be organized with respect to other specifications, qualitatively. The results are summarized in Table 2, where H, L, M, Y, and N denote high, low, medium, yes and no, respectively. It should be noted that bio in the loop UASs cannot be evaluated with regard to specifications like scalability. In that case, a '-' designation appears in the table.

Each of the sub-categories in categories can be compared relatively by the same method. Fig. 89 illustrates a qualitative comparison between the sub-categories of each category based on Table 2. It has been tried to show each configuration's advantages compared to other configurations of its own type, so the charts do not show the exact values of specifications.

The following sections review the applications of UASs and their required specifications. The primary objective is to determine the most suitable configuration for a given application.

6.2. UAS's applications and required specifications

UASs have applications in a wide range of civilian and military operations, where they perform both outdoor and indoor tasks in diverse environments extending from underwater (amphibious UASs) to space-related missions. They can be equipped with various sensors and cameras to perform surveillance, reconnaissance, research, operational and intelligence gathering assignments [5]. The applications of UASs can be classified in different ways. It can be based on the type of the mission (civilian or military), type of flight zone (indoor and outdoor) and environment (underwater, on the water, ground, air, space) [5]. Nowadays, besides military applications, they are routinely employed in fire-fighting activities, disaster assessment and mitigation, search and rescue, and multimedia and motion picture industries. They are also applied in all types of aerial surveillance, including policing, counter-terrorism operations, large scale public outdoor events, important objects and VIP security, ground and sea traffic, and environmental pollution control and monitoring. Telecommunications, crop monitoring, animal surveillance, fisheries protection, mineral exploration, ground mapping and photography, meteorological observation, pipeline and power line inspection, freight carrying, mailing and delivery, etc., are few other areas of applications of UASs.

A comprehensive classification of the drone's applications is presented by Hassanalian and Abdelkefi, which pairs the above-mentioned applications and classifications [5] (see Fig. 90). Shakhatreh et al. have classified applications of drones into search and rescue, remote sensing, construction and inspection, precision agriculture, delivery of goods, real-time monitoring of road traffic, surveillance and wireless coverage [249].

Due to the similarity in the requirements and the nature of missions, the applications of UASs are assessed in terms of the following categories; Inspection, Survey and Mapping, Agriculture and Environment research, Search and Rescue (SAR) Missions, Mailing and Delivery, Military Missions, Marine and Underwater Missions, Space Missions and Miscellaneous Applications (see Fig. 91).

6.2.1. Inspection, survey and mapping

Drones are a valuable tool for data collection in a variety of applications, such as surveillance, inspections, mapping, and 3D modeling. UASs are considered a low-cost device compared to classical manned aerial photography. New applications in the short and close-range domain are introduced regularly by researchers [250]. For example, rotary and fixed-wing drones are able to perform photogrammetric data acquisition with different types of cameras. Besides typical

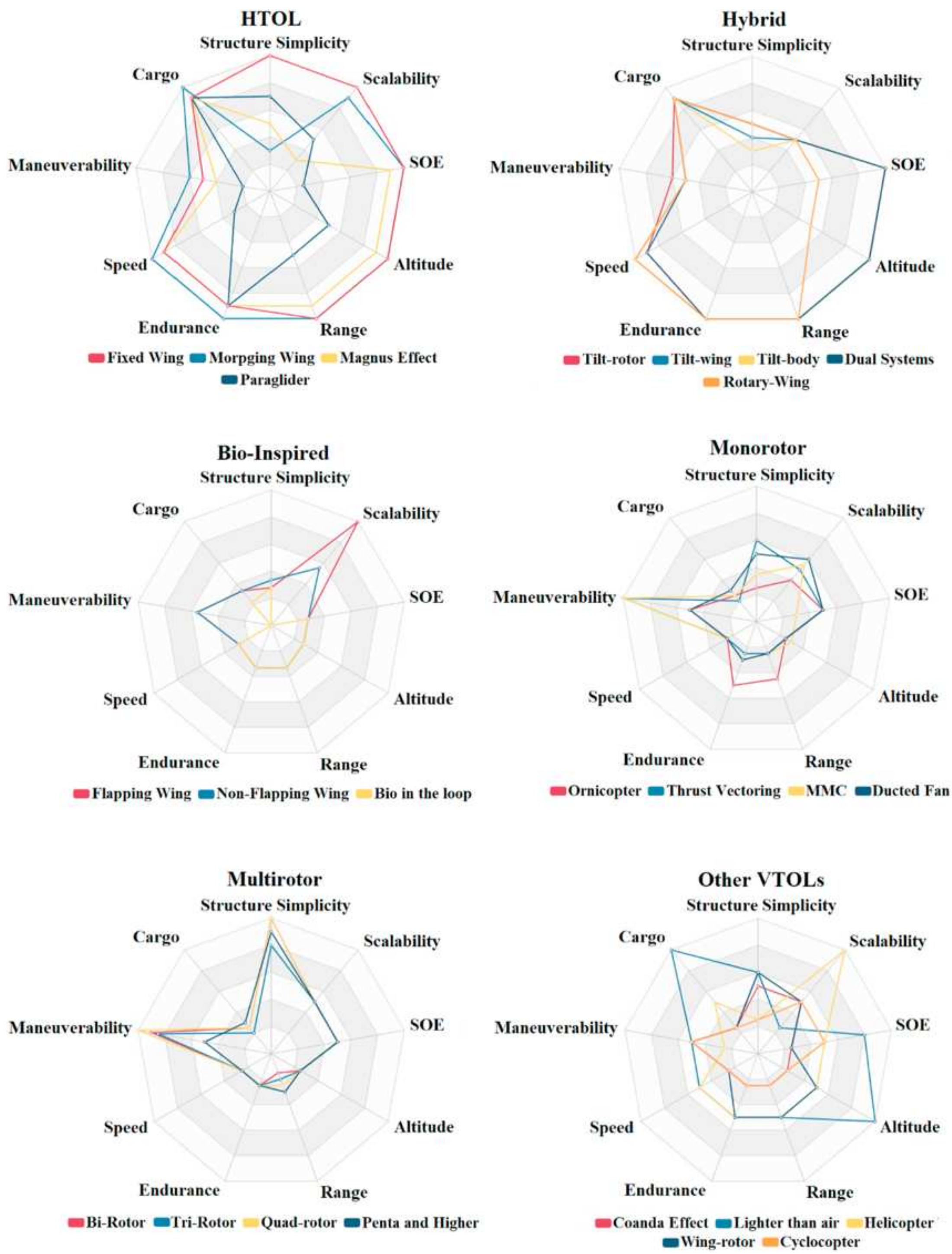

Fig. 89. Qualitative comparison of each category's specifications.

photogrammetric workflows, drones can create contours, 3D digital surfaces or terrain models, textured 3D models, and vector information for a vast area [250]. Nex and Remondino, in 2014, reviewed the state of the art of UAS for geomatics applications, considering different UASs platforms, applications, and case studies. They also showed the latest developments in UAS image processing [250].

The main required specifications of drones for mapping based on Nex and Remondino are acceptable payload capacity, wind resistance, autonomous flight, high endurance and portability [250]. Mapping is one of the popular applications in archeology, agriculture, forestry, and architectural and environmental areas. These requirements are common for inspection and survey missions. Thus, the drones designed for mapping missions are also usable for inspections and survey missions.

The sheer number of drones for these types of missions are broad. Some commercial UASs use fixed-wing configurations, mainly flying wing platform with manual launch capability. For example, South Group has developed a hand launch flying wing UAS, known as SKYCRUISER A22, for surveying and mapping missions with about 1-h endurance and up to 80 km flight range [251]. Also, Unmanned System Group has developed a flying wing with twin wing-mounted vertical tails, called Supercam S100, which is designed for aerial surveillance in a wide range of weather conditions and search protocols, including complicated land

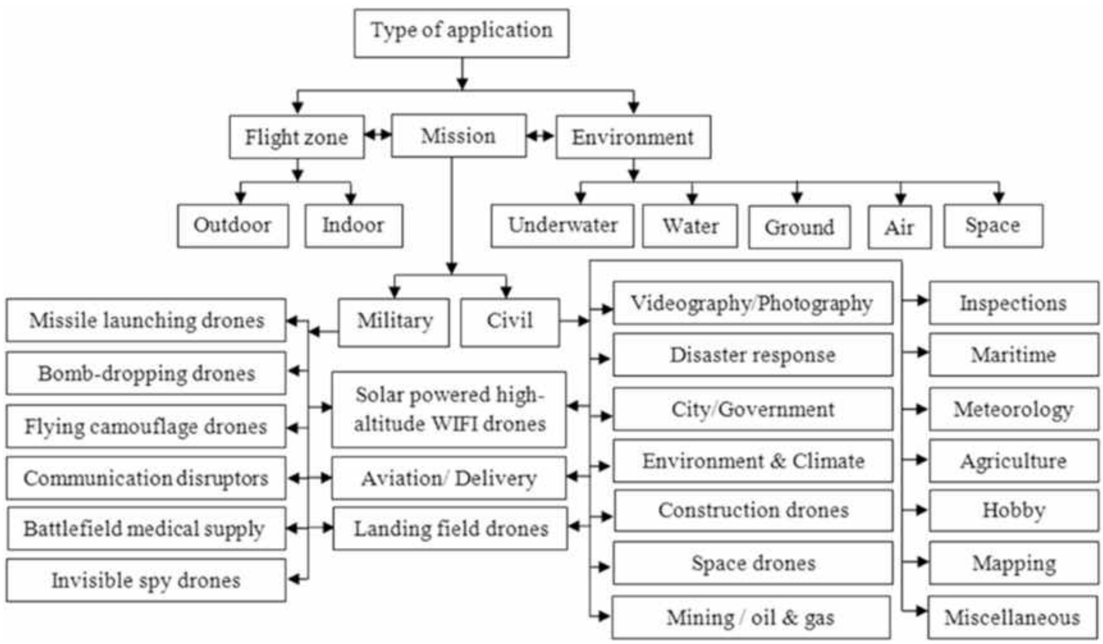

Fig. 90. The classification of drones' applications presented by Hassanalian and Abdelkefi [5].

relief and water's surface [252]. Moreover, there is a similar drone, eBee, developed by SenseFly Company, which uses a flying wing configuration and manual launch system and is designed for agriculture-related missions. This drone has about 1-h endurance and flies at 400 ft above ground level, which is a high operational altitude compared to small multirotors [253]. A solar-powered version of these UASs has been developed by UAV Instruments Spain Company, called CIES for photogrammetry, remote detection, recognition and activities involving precision agriculture [254]. EasyMapUAV has developed a flying wing with two rotors and tree wing-mounted vertical tails (Masterfly) for photogrammetric missions and reconnaissance missions [9]. In Fig. 92, views of the flying wing UASs for inspection, survey and mapping are shown.

There are also some versions of classical fixed-wing UASs for these types of missions. For example, Satlab has introduced a fixed-wing UAS (SLA-1) with twin tail boom empennage for mapping and survey missions [256]. Topcon Company has also introduced a typical fixed-wing UAS for high accuracy aerial mapping and modeling [257]. Aeromao developed a fixed-wing drone with a V-shape tail and parachute landing for mapping, surveying, 3D modeling, photogrammetry, agriculture, mining and construction missions [258]. Fig. 93 depicts these three fixed-wing UASs.

Lighter than air UASs are also one of the configurations that are applicable to these types of missions. For example, Skyshot Helikite developed by Allsopp Helikites Ltd is a semi-kite balloon that is used in photogrammetry, surveying and mapping missions. This balloon resists

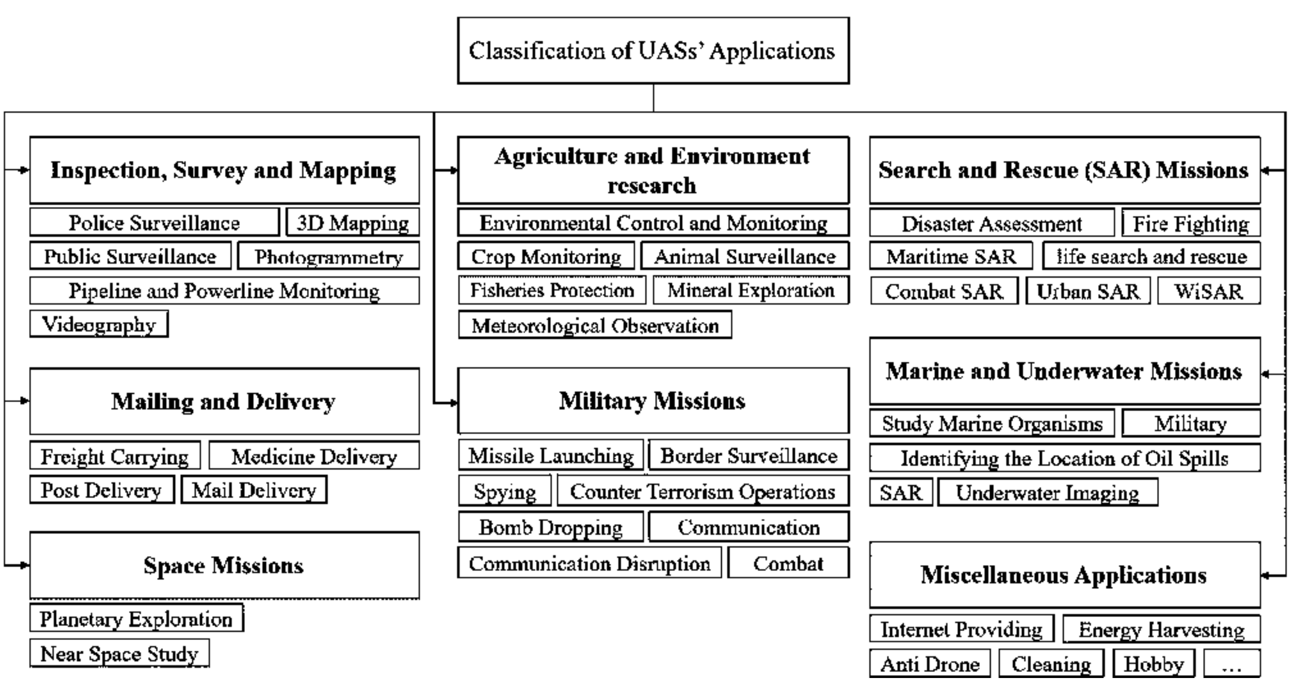

Fig. 91. Classification of UASs' applications.

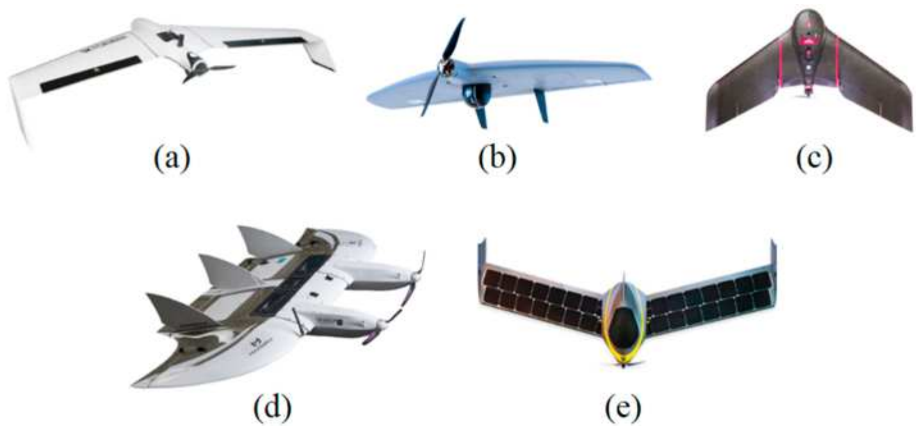

Fig. 92. Views of flying wing UASs for inspection, survey and mapping; (a) SKYCRUISER A22 [251], (b) Supercam S100 [252], (c) eBee SQ [253], (d) MasterFly [255], and (e) CIES 2.2 [254].

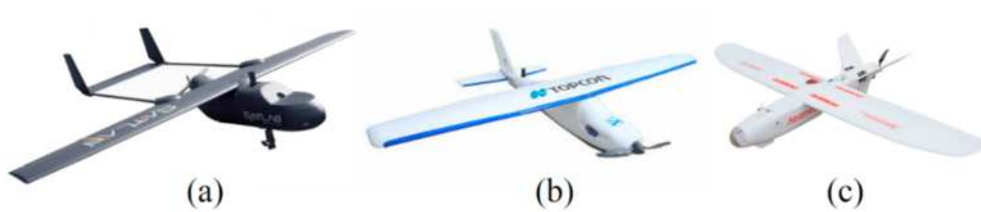

Fig. 93. Pictures of fixed-wing UASs for inspection, survey and mapping (a) SLA-1 [256], (b) SiRIUS Pro [257], and (c) Aeromapper [258].

wind gusts of up to 35 mph speed [259] (see Fig. 94(a)). Another example is Halo, which is an unmanned balloon designed for photography with up to 3 h of endurance (see Fig. 94(b)) [260].

One of the popular configurations for mapping, inspection and surveying missions is multirotors. There are many commercial and research drones of this kind in service today. For example, Satlab Company has developed a heavy lift hexarotor photogrammetry UAS [261]. Italdrone has made a heavy-lift long-endurance octarotor for photogrammetry, filming, 3D reconstruction and inspection [262]. Ascending Technologies has prototyped an unconventional hexarotor for photography, videography, inspection and survey missions [263]. ECA Group has designed and manufactured a mini co-axial Birotor UAS propelled by a gasoline engine and dedicated to inspection and survey missions, which has up to 2 h of endurance [264]. Applied Airborne has built a coaxial tri-rotor for a survey and mapping [265]. Another example is MetaVista Inc.'s quad-rotor drone that runs on liquid hydrogen and is powered by an 800W PEMFC provided by Intelligent Energy (EI). MetaVista's HYCOPTER drone achieved the Guinness World Endurance record time of 10 h and 50 min on January 21, 2019 [266]. Fig. 95 depicts several multirotors UASs.

Helicopters have also been used as UASs to conduct survey and inspection missions. For example, Flying-Cam has developed an unmanned electric helicopter equipped with a Lidar for photogrammetry and Surveying [267]. Another unmanned helicopter designed by Alpha Unmanned Systems uses a liquid fuel-powered engine, which increases the endurance of the UAV up to 2 h and makes it suitable for conducting civil, agriculture, mapping, surveillance and military missions [268]. Views of these two unmanned helicopters are shown in Fig. 96.

Another popular class of drones is the hybrid configuration that includes: tilt-rotor, tilt-body and dual systems. The main reason for the popularity of hybrid drones is their high endurance, high payload capacity, as well as the ability to vertically take-off and land. There are

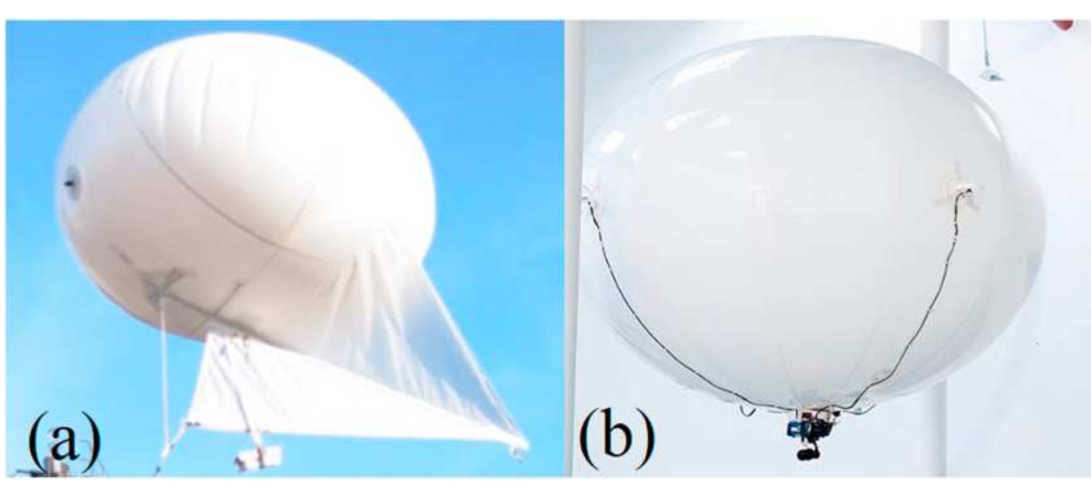

Fig. 94. Lighter than air UASs for photography, (a) Skyshot Helikite [259] and (b) Halo Balloon [260].

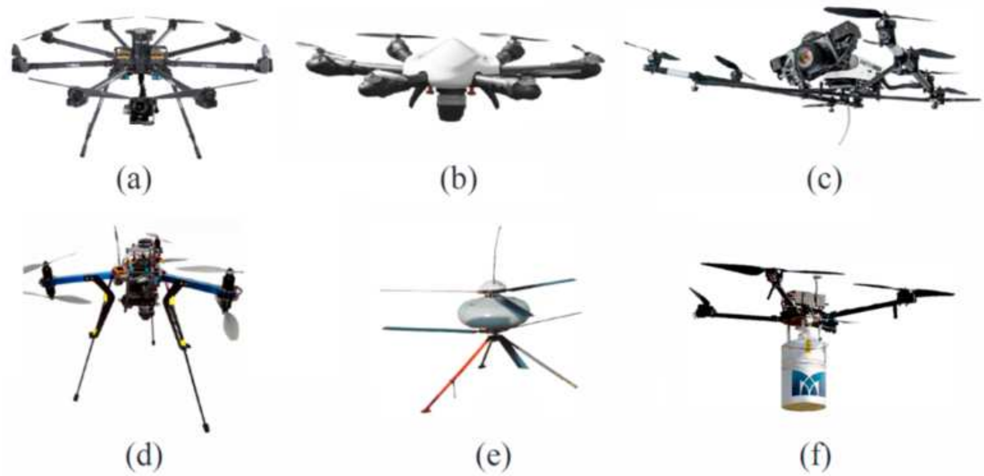

Fig. 95. Several multi-rotors developed for mapping and inspection missions; (a) Italdrone BIGONE8HSE [262], (b) Satlab SLM-2 [261], (c) Ascending Technologies AscTec Falcon 8 [263], (d) Applied Airborne X-Mapper PPK [265], (e) ECA Group IT180 5 TH U [264], and (f) MetaVista's HYCOPTER drone [266].

Fig. 96. Unmanned helicopters developed for mapping and inspection missions; (a) Flying-Cam SARAH [267] and (b) SNIPER UAV Helicopter [268].

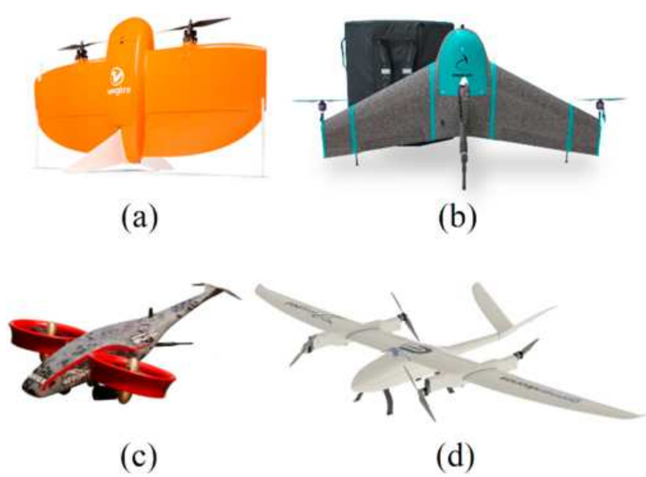

Fig. 97. Hybrid UASs developed for mapping and inspection missions; (a) Wingtraone [269], (b) Marlyn [270], (c) Navig8 [271], and (d) German drones Songbird [274].

many examples of hybrid UASs which have been used for inspection, survey and mapping missions. For example, Wingtra has used a tail sitter tilt-body UAS for surveying, high-resolution mapping, mining and agricultural operations. By using a hybrid configuration, they achieved a performance ten times greater than multi-rotors [269]. Another example is Atmos UAV's Marlyn mapping drone that has a hybrid configuration with a combination of a quadrotor and a fixed-wing UAS for mapping, surveying, mining, environmental and agriculture activities [270]. 4Frontrobotics has developed a ducted twin tilt-rotor UAS that is able to carry a 5 kg payload for indoor and outdoor inspection, mapping and aerial imaging [271]. Quantom Systems uses tilt-rotor UASs called Tron and Trinity UASs for agriculture, 3D reconstruction and surveying, which are described in the tilt-rotor section [272,273]. Moreover, Germandrones has designed a tilt-rotor UAS with a payload capability of 2 kg and flight endurance of 1-h, which is a fixed-wing UAS with a V-shape tail in cruise flight mode [274]. Fig. 97 illustrates several hybrid UASs discussed above.

Yet, another popular class of drones is dual system hybrid UASs. There are many commercial UASs with a dual system configuration. For example, V-TOL Aerospace Company has designed a dual system hybrid UAS with a combination of a fixed-wing and a quadrotor configuration for mapping missions [275]. A joint tail boom version of such a UAS has been developed by South Company for 3D modeling and aerial mapping

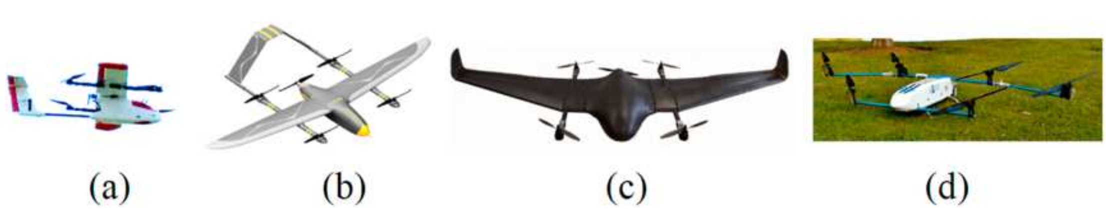

Fig. 98. Dual system hybrid UASs for mapping and inspection missions; (a) V-TOL Aerospace Goshawk Hybrid [275], (b) South Skycruiser MF2500 [276], (c) DeltaQuad Pro [277], and (d) HAMR's unconventional dual system hybrid UAV [278].

Fig. 99. Applications of multi-rotors in environmental protection [282–284].

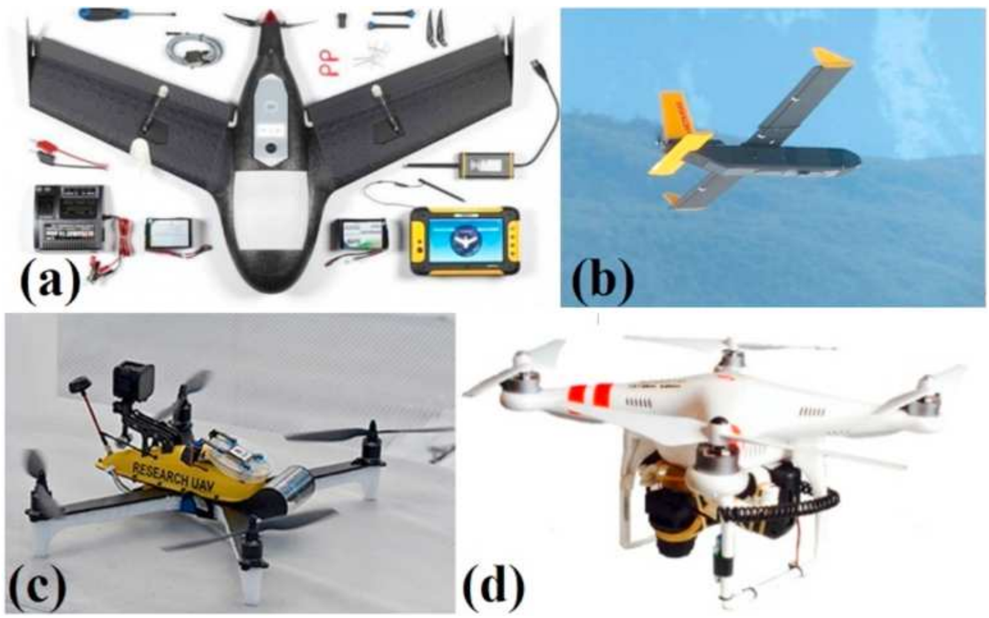

Fig. 100. UASs developed for tasks related to environmental protection; (a) flying wing UAS used by Linchant et al. to count elephants [287], (b) fixed-wing UAS used by Van Andel et al. [290] (c), quadrotor developed by Pirotta et al. [286], and (d) quadrotor used by Harvey et al. for georeference imagery [288].

Fig. 101. Several taxidermy drones (a) OstrichCopter [291], (b) Robosparrow [292], and (c) PigeonBot [293].

[276]. A tail-less version has been built by DeltaQuad Company for autonomous mapping, geospatial, agriculture and forestry operations [277]. Another unconventional dual system hybrid UAS has been made by HAMR Company, which uses six rotors for the VTOL phase and a fuel-powered engine for horizontal cruise flight. Using this configuration, HMAR UAS can carry up to 7l lbs of payload for about 3.5 h, which makes it suitable for 3D modeling, mapping and surveying activities [278]. Fig. 98 depicts dual system hybrid UASs for mapping and inspection applications.

6.2.2. Agriculture and environment research

Environmental missions are summed up in surveying and inspection. Most of the UASs developed for environmental protection are equipped with cameras and enable scientists to study, monitor and track wildlife and the effect of climate change in the national parks, forests, oceans and deserts. UASs are used for investigation and monitoring occurrences of natural disasters like forest fires, avalanches, etc. [279]. For example, Oliveira-da-Costa et al. have studied the effectiveness of drones in detecting Amazon dolphins. In their study, they showed that compared to visual surveys, the use of aerial drones could provide a more reliable, cost-effective and accurate estimate of Amazon river dolphin populations [280]. Colefax et al. in 2019, have also worked on the reliability of marine faunal detection in drone-based monitoring. Based on their study, drones provide an effective tool for monitoring large marine fauna off coastal beaches [281]. Fig. 99 shows the applications of multi-rotors in environmental protection activities.

The most popular configurations in environmental protection are fixed-wing and quadrotor drones. Hartman et al. used quadrotors to study the relationship between sociality and position in a group of male Risso's Dolphins (Grampus griseus) [285]. Pirotta et al. developed an

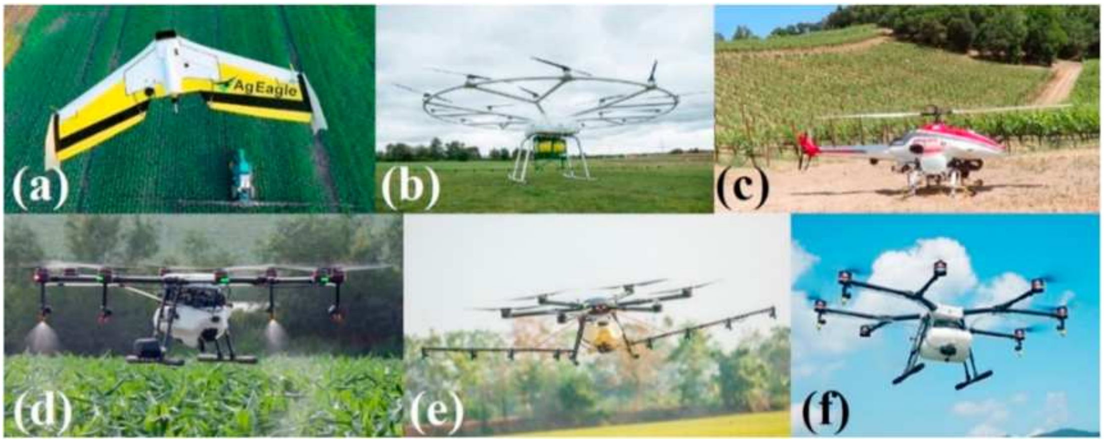

Fig. 102. Views of agriculture drones [297–302].

economical custom-built quadrotor for assessing Whale health [286]. A similar study was conducted by Linchant et al. who applied a fixed-wing flying wing drone to count the elephant populations [287]. Harvey et al. utilized a quadrotor equipped with an infrared camera to provide high-resolution georeferenced imagery of the Waikite geothermal area in New Zealand [288]. Gemert et al. introduced nature conservation quadrotor drones for automatic localization and counting of animal populations. In their study, they used automatic object recognition techniques to accomplish their objectives [289]. Van Andel et al. have also used a typical fixed-wing drone for locating Chimpanzee nests and identifying fruiting trees [290]. Fig. 100 depicts drones utilized for environmental protection programs.

In some cases, the dead or taxidermied bodies of animals are used in the structure of the UAVs to track the animal's behavior. In some cases, this was to calm animals down and prevent them from being frightened. It also has some military applications such as espionage. These types of bio-drones have been used in many projects. Jansen used the taxidermy of animals as flying platforms for drones [291]. In his works, the dead bodies of animals, such as cat, rat, and ostrich, were used as the structure of the quadrotor drones [291]. In 2013, Anderson et al. applied a taxidermized dead bird animated by off-the-shelf robotics to study the behavior of the swamp sparrow species [292]. In 2020, Chang et al. developed a biohybrid morphing wing called PigeonBot with real feathers of pigeon to understand the underlying design principles [293]. Fig. 101 provides several of the bio-drones discussed above.

UASs are also applicable in agriculture, specifically in irrigation and spraying, soil and field analysis, planting, crop monitoring and health assessment [294]. Applications of drones in precision agriculture have been reviewed by Mogili and Deepak [295]. Ahirwal et al. also conducted a study in reviewing the implementation of drones in agriculture [294]. Marinello et al. conducted a technical analysis of UASs in agricultural operations. In that study, they used technical specification sheets of over 250 commercially available models. Based on their research, the main requirements of UASs for agriculture are medium endurance (about 30–45 min), medium payload capacity (about 300–1000 g), and camera-carrying ability [296]. The common configuration in these types of applications are multi-rotors and fixed-wing UASs, but there are some versions of helicopter configuration, as well. Fig. 102 depicts drones developed for agriculture usage.

6.2.3. *Search and rescue (SAR) missions*

Rapid response is essential to any search and rescue mission; that is why the UASs are more suited than manned aerial vehicles to this kind of mission [5]. Drones are agile and fast and can be controlled autonomously to perform missions that are hard for human operators to execute [303]. Search and rescue operations can take advantage of UASs to survey the environment and collect evidence [303]. In search and rescue missions, there are sets of constraints, such as the limited time to perform the mission, potential loss of human lives, and unfriendly operational environments, e.g., disaster scenes, forests, etc. [303]. In recent years, so many designs and concepts have been introduced for search and rescue UAS, including their control, path planning, swarm scenarios and imaging and human identification algorithms as well as their configurations. UAS potentially can be used in various natural and man-made disasters and emergencies like storms, floods, droughts, earthquakes, volcanic eruptions, fires and accidents.

There are four types of search and rescue missions performed by drones, which are classified based on their environment, including wilderness, maritime, combat, and urban [304]. In the wilderness search and rescue missions, the goal is often to find lost persons or objects. In these kinds of missions, medical drones can help by providing urgent medical care at the hard to reach areas and by transporting injured patients quickly [304]. Drones with vertical takeoff and landing capability can be appropriate for these types of missions. In maritime search and rescue missions, the main objective is to find people lost at sea. In the maritime missions, there are challenges, such as unstable weather conditions, limited fuel or battery capacity, and uncertainty and dynamicity of survivor locations, which affect the success of these missions [304]. Drones in combat and urban search and rescue missions have similar objectives to the previous ones but in different

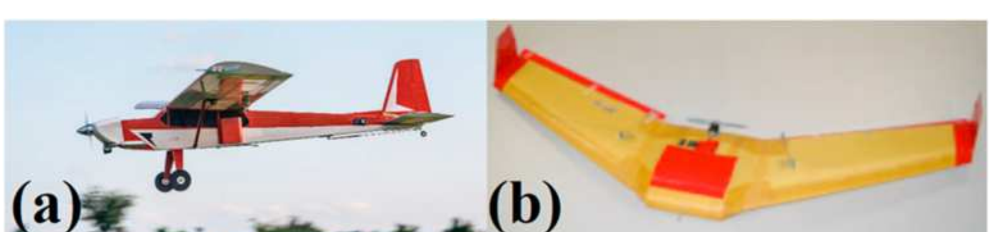

Fig. 103. Fixed-wing search and rescue UASs; (a) UAV designed by Erdos et al. [305] and (b) flying wing developed by Goodrich et al. [306].

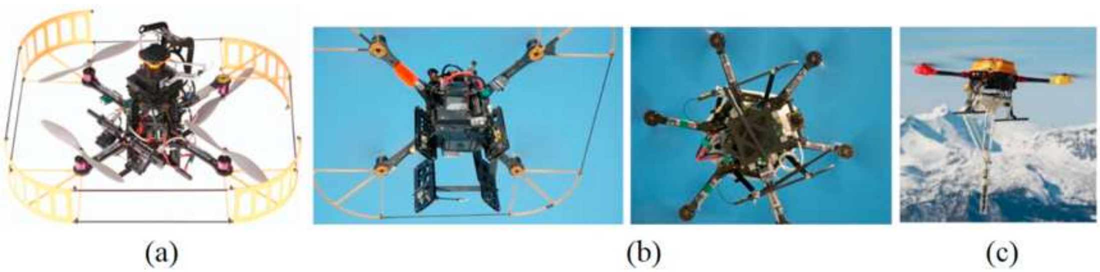

Fig. 104. Several multirotor UASs developed for SAR missions; (a) quadrotor developed by Tomic et al. [307], (b) different multirotors used by Scherer et al. [308], and (c) quadrotor developed by Silvagni [309].

Fig. 105. The mono-rotor developed by Wang et al. for SAR missions [310].

environments [304]. Some projects in SAR missions have been carried out using fixed-wing UASs. For example, Erdos et al. have introduced a typical fixed-wing design for search and rescue missions [305]. Goodrich et al. used a flying wing UAS for wilderness search and rescue missions [306]. Fig. 103 gives views of fixed-wing search and rescue UASs described above.

Another configuration that has been used widely in SAR missions is multirotor, specifically quadrotor configuration. Tomic et al. have developed a fully autonomous quadrotor for indoor and outdoor urban search and rescue [307]. Another similar work is done by Scherer et al. using an autonomous Multi-UAV system, including multiple multi-rotors for conducting SAR missions [308]. Silvagni et al. developed a quadrotor for search and rescue operations in mountain avalanche events [309]. Fig. 104 depicts several multirotor UASs developed for SAR specific missions.

Furthermore, Wang et al. have developed a coaxial mono-rotor for the SAR application aimed at retrieving physical information about the trapped environment and providing accurate location information of the victims (see Fig. 105) [310].

Several multirotor drones have been designed and built by the RTS group for Marine SAR (MSAR) missions. Yeong et al. in 2015, reviewed the literature on using UASs in marine search and rescue operations

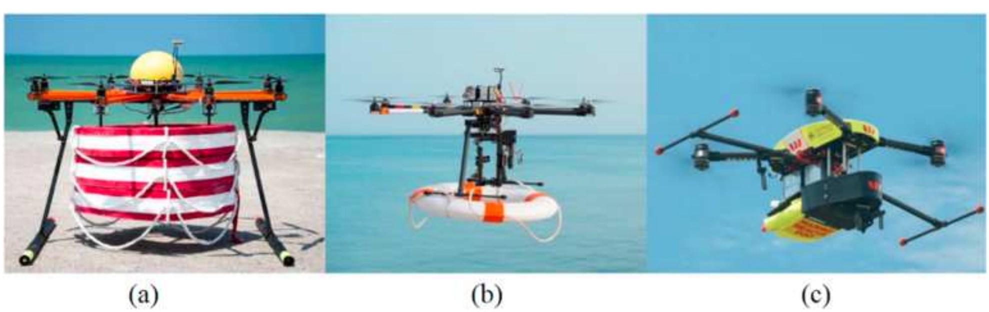

Fig. 106. Several MSAR multirotor drones [312–314].

Fig. 107. Views of unmanned helicopters; (a) helicopter developed by Qi et al. for SAR missions [315] and (b) emergency aid delivery helicopter developed by UAVOS Company [316].

Fig. 108. DroneAmerica's fixed-wing firefighting UAS [317].

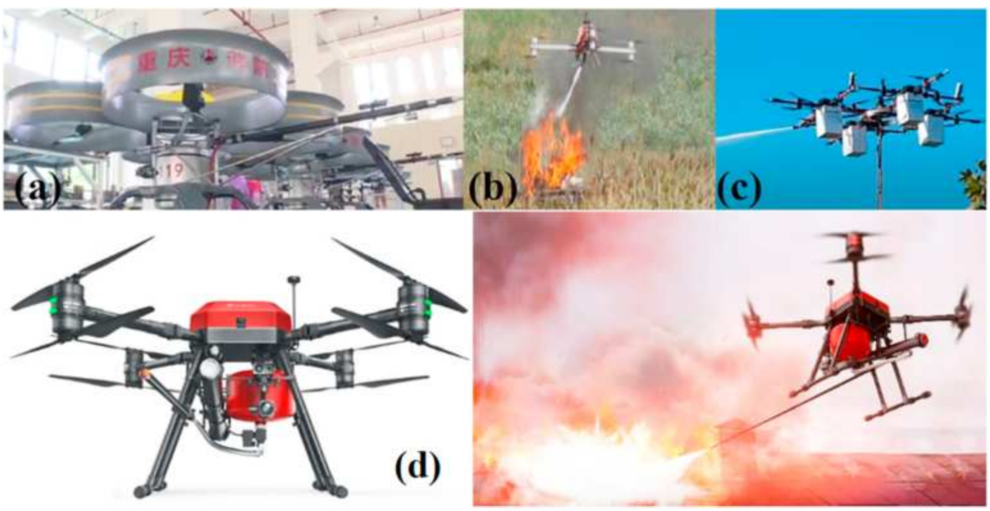

Fig. 109. Firefighting multirotor drones; (a) CGGAEM ducted-fan firefighter [320], (b) tri-rotor coaxial firefighter [322], (c) Aerones's multirotor firefighter [321], and (d) Walkera's coaxial quadrotor [319].

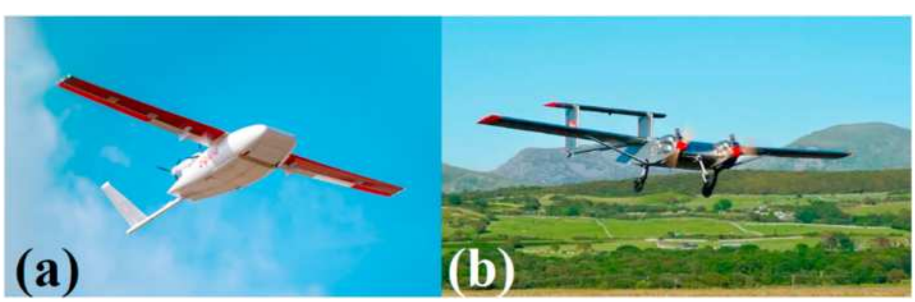

Fig. 110. Fixed-wing delivery drones; (a) Zipline's drone [323] and (b) Solent Transport's drone [324].

[311]. Fig. 106 shows various MSAR multirotor drones.

Qi et al. have used an unmanned helicopter for post-earthquake search and rescue. They tested its applications in detecting damaged buildings and helping ground rescue teams in the aftermath of the Lushan Ms 7.0 earthquake (see Fig. 107(a)) [315]. UAVOS Company has also successfully completed tests of its gasoline-powered emergency aid cargo delivery unmanned helicopter (see Fig. 107(b)) [316].

There are also some versions of firefighting UASs which are developed by different researchers and companies, such as Drone America's amphibious fixed-wing air tanker UAS, which can be used during fire suppression missions [317]. Fig. 108 depicts DroneAmerica's fixed-wing UAS.

Multi-rotors are also a popular group of UASs for firefighting missions. Vyshnavi et al. developed an automatic CO_2 extinguisher firefighting quadrotor [318]. Walkera Company has built a coaxial quadrotor for firefighting missions, which was equipped with a fire extinguishing tank [319]. Chongqing Guofei General Aviation Equipment Manufacturing (CGGAEM) Company has designed and manufactured a ducted-fan firefighting quadrotor which has been tested in various missions [320]. Aerones Company also has proposed a

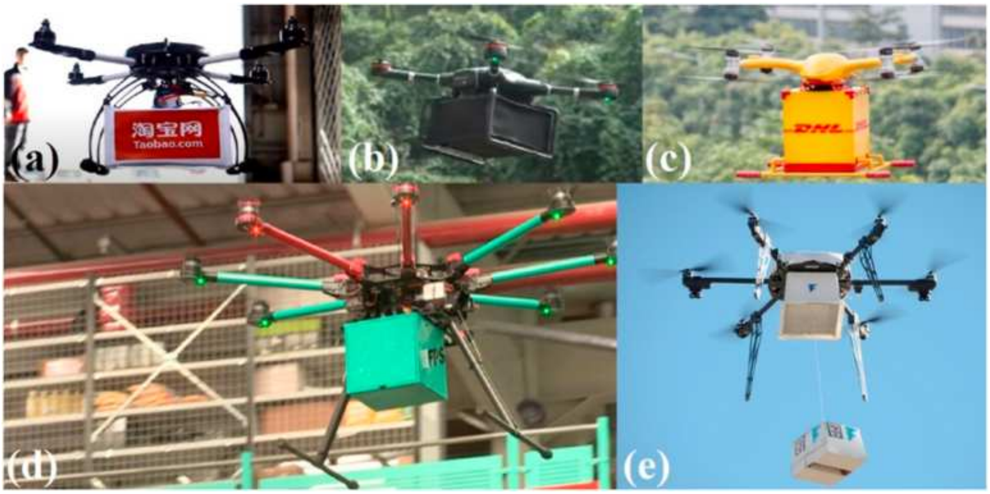

Fig. 111. Multirotors delivery drones; (a) Alibaba Tabao's quadrotor [325], (b) SF-Express's quadrotor [326], (c) DHL's coaxial quadrotor [327], (d) FPS's octocopter [328], and (e) Flirtey's hexacopter [329].

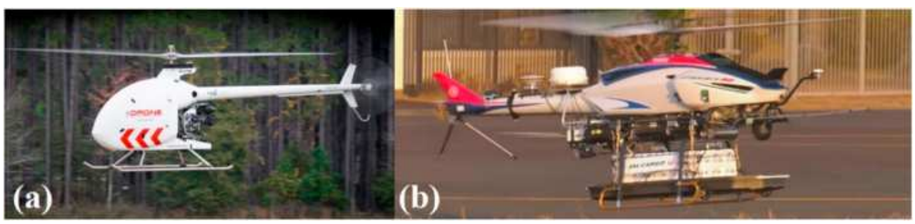

Fig. 112. Unmanned delivery helicopters; (a) DDC helicopter [330] and (b) Yamaha's helicopter [332].

Fig. 113. Views of hybrid delivery drones; (a) Google X's dual system drone [333], (b)Wingcopter's tilt-rotor drone [334], and (c) DDC's dual system drone [336].

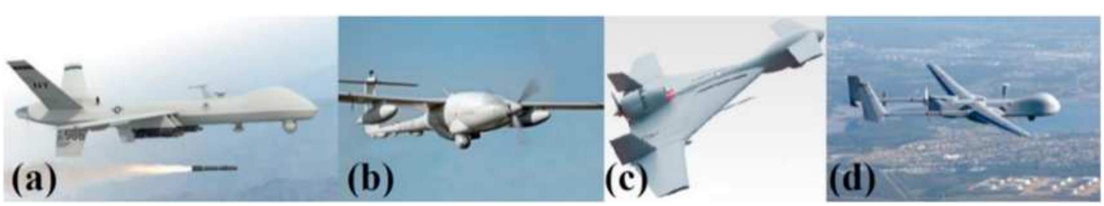

Fig. 114. Views of different fixed-wing military UASs, (a) V-tail [338], (b) T-tail [339], (c) delta wing [340], and (d) twin tail boom [341].

firefighting multirotor with sixteen coaxial rotors, which is powered by wire and can carry a high-pressure water hose [321]. In Fig. 109, views of these firefighting multirotor drones are illustrated.

6.2.4. Mailing and delivery

Drone delivery service is of interest to many companies all over the world, including Amazon, Google and DHL. Fixed-wing UASs are also a suitable configuration for mail and delivery service. Zipline company has been using a fixed-wing UAS for delivering medical products during the COVID-19 outbreak. The company tested delivery drones for distributing test kits in Ghana (see Fig. 110(a)) [323]. Solent Transport Company has also developed a fixed-wing UAS with a twin tail boom, which is able to carry 100 kg of medical supplies (COVID-19 related) to a destination 1000 km away (see Fig. 110(b)) [324].

While Zipline and Solent Transport are using fixed-wing drones for the delivery of goods, few others have opted for multirotor drones and specially quadrotor configuration instead. For example, Alibaba [325] and SF-Express [326] are using quadrotor drone configuration for their delivery service. DHL mail service is also using a coaxial quadrotor for shipping and delivery [327]. Other multi-rotors are also popular for these types of missions. For example, two companies – FPS and Flirtey, operate octocopters and hexacopters, respectively, for their delivery

Fig. 115. Views of armed military quadrotors, (a) Duke Robotics military quadrotor [342], (b) Turkey's armed quadrotor [343], and (c) RPG-combined quadrotor [344].

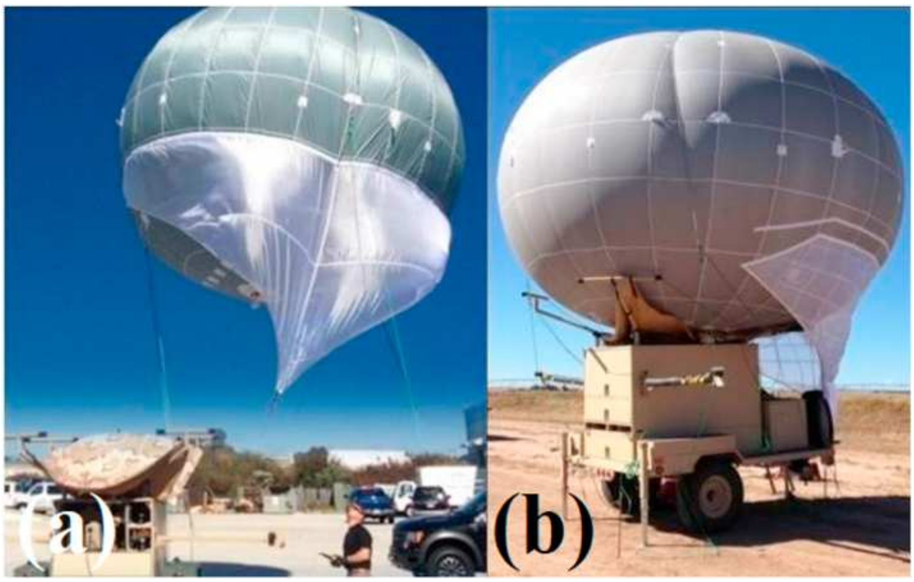

Fig. 116. Views of unmanned military balloons [345].

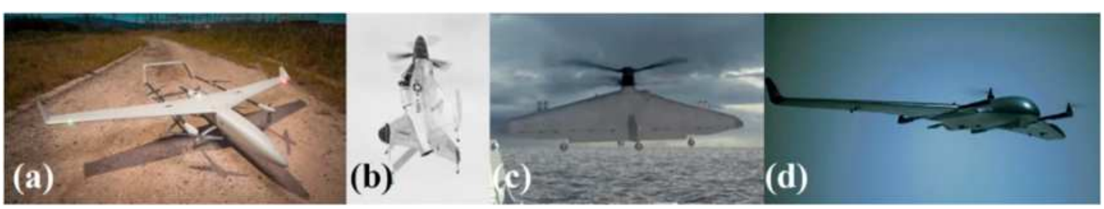

Fig. 117. Views of hybrid military UASs; (a) dual system hybrid drone ALTI [346], (b) tail-sitter designed by Navy and Convair [347], (c) semi tail-sitter military drone concept [348], and (d) dual system military UAS Bat-2 [349].

Fig. 118. Views of unmanned military helicopters; (a) Northrop Grumman MQ-8 Fire Scout [350], (b) Black Hornet PRS nano military unmanned helicopter [351], and (c) CAMCOPTER S-100 unmanned military and civil helicopter [352].

service [328,329]. Fig. 111 shows multi-rotors used as delivery drones.

Helicopters are also popular configurations that have been employed for delivering goods. Drone Delivery Canada (DDC) Company has developed an unmanned helicopter with a cargo capacity of 180 kg and an operational range of 200 km (see Fig. 112(a)) [330]. Yamaha has developed a similar unmanned helicopter with a flight range of 90 km (see Fig. 112(b)) [331].

Google is working on a dual system hybrid UAS for delivery service. Google's UAS is equipped with twelve rotors having an unconventional configuration for vertical takeoff and landing, and two rotors on a wing

Fig. 119. The flapping wing military drone, Skeeter [353].

for horizontal cruise flight [333]. Another similar hybrid tilt-rotor drone is that developed by Wingcopter Company intended for delivery of insulin, vaccine and COVID-19 test kits in Africa. This drone configuration allows an endurance of 72 h for a 3.5 kg of payload capacity [334,335]. Moreover, a dual system hybrid UAS has been prototyped by DDC Company by combining a quadrotor and fixed-wing configurations, which can carry a payload that weighs 11 kg payload and a delivery range of up to 60 km [336]. Fig. 113 depicts several hybrid delivery drones used by various companies.

The main challenge for delivery drones is their limited flight endurance and cargo capacity. These two factors have a direct impact on costs. In electrical powered UASs, increasing the number of batteries will not increase flight endurance, so an optimized limited number of batteries should be used to reach maximum flight endurance [337].

6.2.5. Military missions

UASs in the military are used for dropping munitions, missile launching, communication, communication disruption spying, medical activities and so on. The most popular configuration for the military missions is fixed-wing UAS. Fixed-wing UASs are being used in almost every military mission, specifically in operational and combat assignments. Due to the nature of the application, their configuration may differ with respect to wing shape, tail and propulsion system. In fact, some have morphing wing and flying wing configurations. Fig. 114 depicts several fixed-wing UASs developed for military-type operations.

Recently multi-rotor drones, specifically quadrotors, have been employed in operational and combat missions alongside their applications in imaging. Some versions and products are weaponized by arming quadrotors with light and heavy weapons (see Fig. 115) [342–344].

Balloons are also popular VTOL UASs for military missions. The lighter-than-air systems are designed to provide semi-persistent ISR (Intelligence, Surveillance and Reconnaissance) functionality at high altitudes (up to 300 m). They can be used for border security and strategic asset surveillance using different sensors and cameras [345]. Fig. 116 shows a number of unmanned military balloons in operation today.

Fig. 117 depicts several hybrid configurations, including tail-sitter and dual systems that have been deployed by the military.

Helicopters are also popular configurations in military applications, including operational missions. Their VTOL and hovering flight capabilities and easy-to-deploy characteristics make them suitable for optical and laser imaging, communication, border guarding, military support and other military missions. They are being used in different shapes and sizes (see Fig. 118) [350–352].

The range of military missions is quite diverse, and their requirements and UASs' specifications and configurations differ from one mission to another. So it is not possible to narrow down the main required specifications until all mission requirements have been identified in detail, which is outside the scope of this review. But it can be concluded that almost every configuration of UASs is being used or can be utilized in military missions and operations, including the bio-based drones. For example, Defense Science and Technology Laboratory (DSTL) of the ministry of defense of the United Kingdom has funded a dragonfly inspired spying drone, which is specially designed for covert operations (see Fig. 119) [353].

6.2.6. Marine and underwater missions

Some drones are intended to perform missions on the water and underwater. These amphibious drones can be used to study marine life, identify the location of oil spills, and for other military or civilian applications [5]. Because of the lack of space for horizontal take-off and landing, most of these drones are designed based on VTOL configurations but also possess some versions of HTOL configurations as well. These drones can be launched from boats, submarines and ground or beaches. A comprehensive survey of these types of drones has been given

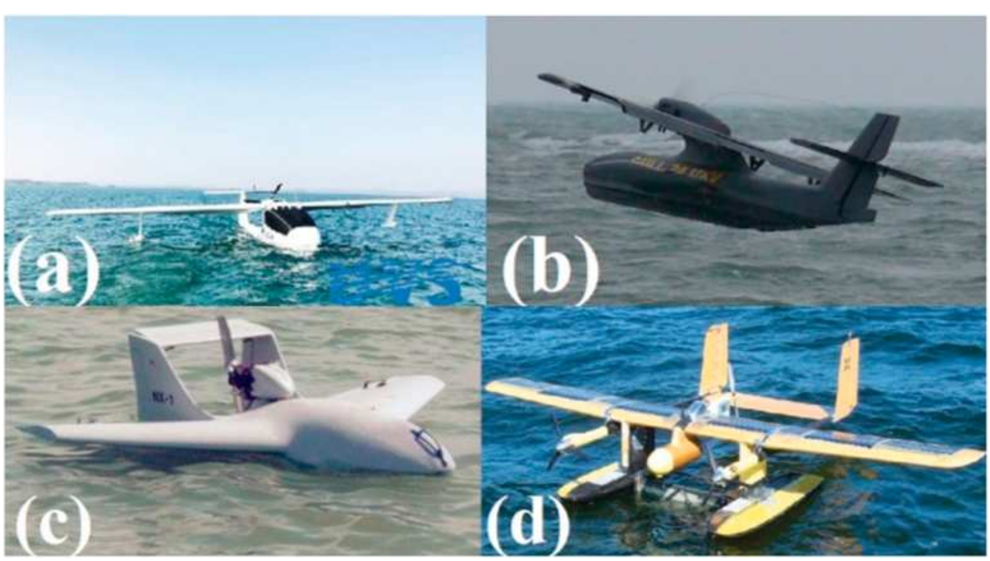

Fig. 120. Views of fixed-wing marine drones; (a) UVS's drone [356], (b) GULL's drone [357], (c) DRS Technologies' drone [358], and (d) solar-powered fixed-wing seaplane developed by Eubank et al. [359].

Fig. 121. Views of underwater HTOL drones; (a) fixed-wing underwater drone developed Weisler et al. [360] and (b) morphing wing underwater drone developed by Siddall et al. [361].

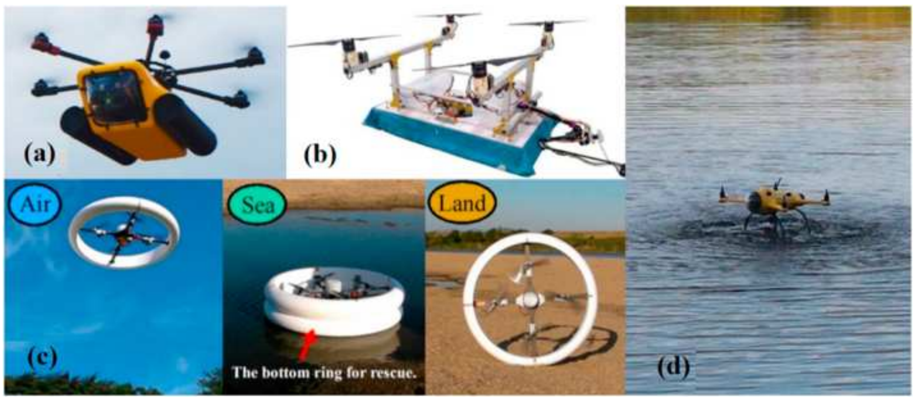

Fig. 122. Views of seaplane multirotors; (a) HexH2O [364], (b) quadrotor developed by Esakki et al. [363], (c) quadrotor developed by Kawasaki et al. [366], and (d) QuadH2O [365].

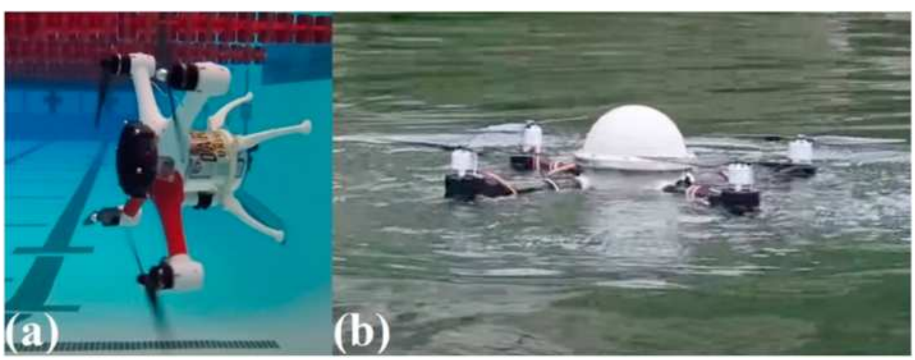

Fig. 123. Views of underwater multirotors; (a) quadrotor developed by Rawashdeh et al. [367] and (b) quadrotor developed by Johns Hopkins University's researchers [368].

Fig. 124. Hybrid seaplane lifeguard concept introduced by Hazken [369].

by Yang et al. for aquatic-aerial amphibious drones [354]. Another review on the amphibious robots also has been done by Guo et al. [355].

The amphibious UASs can perform operations in both the air and on the water surface. The main application of the seaplane UAS is to seek enemy status reconnaissance and surveillance and marine environment monitoring [354]. Moreover, there are many on the water or seaplane drones with fixed-wing configuration. For example, UVS Company has developed a fixed-wing amphibious drone with an engine in the middle of the wing [356]. Other models have been developed by GULL [357] and DRS Technologies [358]. A solar-powered version of an amphibious

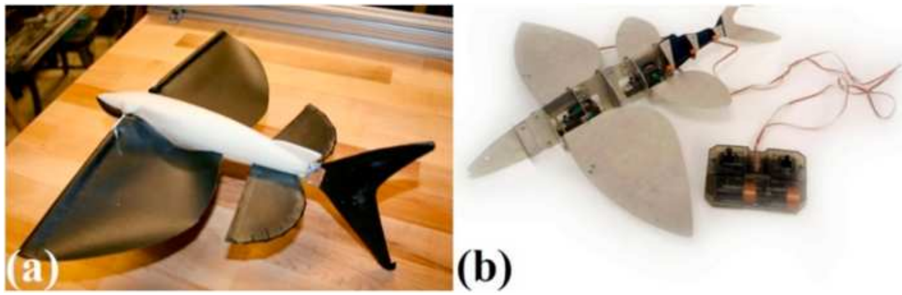

Fig. 125. Views of bio-inspired flapping-wing underwater drones; (a) flying fish developed by Gao and Tachet [370] and (b) flying fish developed by Cherney [371].

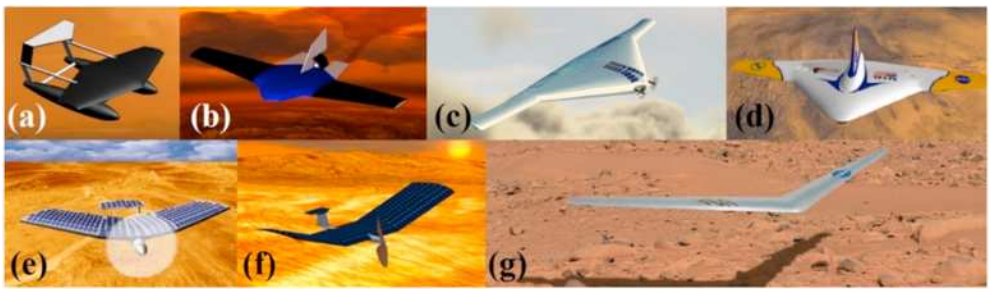

Fig. 126. Views of fixed-wing drones for space missions; (a) Titan exploration drone proposed by Pellerito et al. [381], (b) Venus exploration UAV proposed by Acosta et al. [382], (c) Northrop Grumman's fixed-wing Venus explorer [378], (d) NASA's flying wing Mars explorer [379], (e) solar fixed-wing drone designed by Landis [375], (f) solar fixed-wing Venus explorer drone designed by Xiongfeng et al. [377], and (g) NASA's flying wing Mars explorer [380].

drone has been designed by Eubank et al. [359]. Fig. 120 shows several of these amphibious drones.

Other underwater fixed-wing drones developed by researchers and companies all over the world Include one by the Weisler et al. that is capable of underwater operation (see Fig. 121(a)) [360] and another morphing wing drone with a V-shape tail by Siddall et al. which is inspired by plunge-diving birds (see Fig. 121(b)) [361].

Multi-rotors are also popular for underwater and on the water operations. Waterspout is a coaxial contra-rotating underwater mono-rotor that was designed in 2007 [362]. Esakki et al. developed a simple quadrotor seaplane [363]. QuadH20 Company has also built a hexacopter and a quadrotor seaplane for marine applications [364,365]. Kawasaki et al. have designed and manufactured a quadrotor seaplane with a light ring that keeps it afloat on the water surface and moves on the dry land [366]. Views of these seaplane multi-rotors are shown in Fig. 122.

Multirotors also have been used as underwater drones. For example, Rawashdeh et al. developed an underwater quadrotor, which was able to move in the air and under the water (see Fig. 123(a)) [367]. Researchers at the Johns Hopkins University Applied Physics Laboratory have also developed a similar quadrotor that can sit on a station beneath the water, then launch into the air to perform a variety of missions (see Fig. 123(b)) [368].

A novel concept was introduced by Hazken at the 2016 Red Dot Design Competition, which is for amphibious drones. It is a lifeguard drone and a combination of a water ski board and a quadrotor (see Fig. 124) [369].

Bio-Inspired drones are one of the most useful configurations for underwater operations. These include concepts and prototypes inspired by flying fish. Gao and Tachet have developed a prototype of a compact flapping-wing drone based on flying fish that is capable of swimming underwater and gliding in the air. This drone has many potential applications in ocean exploration, mapping, surveillance, and forecasting [370]. Cherney has designed and prototyped a similar underwater drone [371]. Fig. 125 depicts two bio-inspired flapping-wing underwater drones discussed above.

It should be noted that propulsion systems which are efficient in the air may not be suitable for use underwater. For example, the propellers in multirotors are designed to be efficient in high rpms, but due to the different density of the water, the possible maximum rpm of the rotor in water is much lower than in the air. This makes the multirotors to be less efficient in the water. Therefore, some adaptations might be needed for underwater phase to reach maximum efficiency [354].

6.2.7. Space mission

One of the newer applications of drones involves space missions. Several drone designs and concepts have been proposed by researchers for space explorations. For example, NASA is developing a co-axial drone with a quadrotor configuration for Titan exploration, which will be launched in 2026 and orbits Titan looking for origins and signs of life

Fig. 127. Views of multirotors drones for space missions; (a) NASA's Dragonfly for Titan exploration [372], (b) NASA's coaxial mono-rotor drone for Mars explorations [373], and (c) tri-rotor drone designed by Young et al. [384].

Fig. 128. Views of hybrid drones for space missions, (a) Collins's hybrid drone for Martian exploration [385], (b) NASA's concept for Mars explorer hybrid UAS [387], and (c) hybrid Mars explorer designed by Aguirre et al. [386].

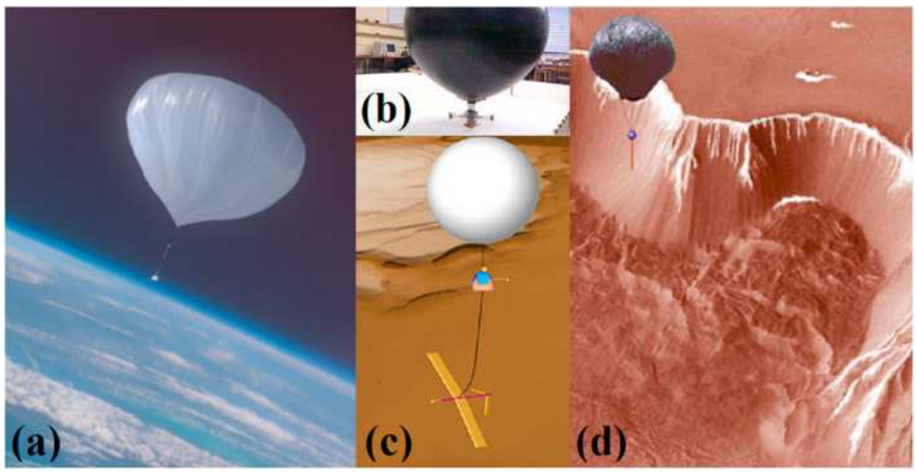

Fig. 129. Views of Balloons for space missions; (a) Zero2Infinity's near-space balloon, (b) University of Wales's balloon [391], (c) NASA-funded robotic balloon Stratosail [391], and (d) Mars solar hot air balloon [392].

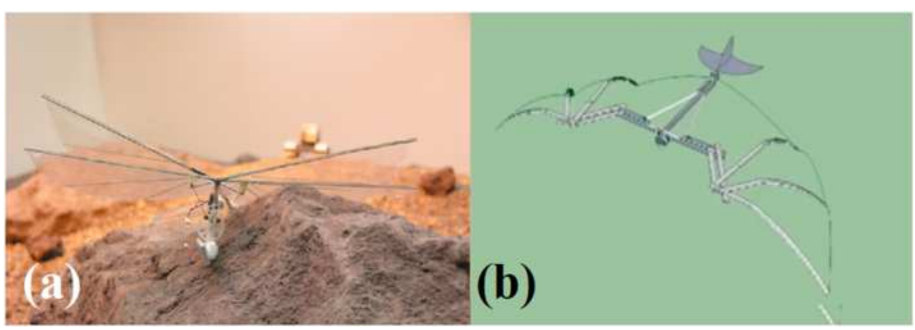

Fig. 130. Views of flapping-wing drones for space missions; (a) drone developed by Zegers et al. [393] and (b) MLABs' flapping wing Mars explorer [394].

[372]. They also have developed a coaxial mono-rotor with counter-rotating blades for Mars explorations, which has passed the tests and will be launched in July 2020 to demonstrate the viability and potential of heavier-than-air vehicles use on Mars [373]. Another concept presented by NASA for the Mars mission utilizes a tilt-body hybrid configuration [374].

Some concepts are based on fixed-wing configuration. Landis et al. have proposed a fixed-wing drone design intended for Venus exploration [375]. Landis also has another concept that is a solar-powered fixed-wing drone for Venus exploration [376]. Similar works were done by Xiongfeng [377] and Northrop Grumman researchers for Venus exploration [378]. Other flying-wing concepts have been introduced by NASA for Mars explorations [379,380]. Pellerito et al. have designed a fixed-wing UAV for Titan exploration [381]. Acosta et al. have also studied a high temperature and high-pressure fixed-wing space drone for Venus exploration [382]. Fig. 126 depicts several design concepts for the drone exploration of space.

Some concepts and designs have been introduced based on multirotors. Pergola and Cipoll have designed a hexarotor for Mars exploration [383]. Young et al. also have proposed a tri-rotor UAS for Venus exploration [384]. Fig. 127 shows multi-rotor drones for space missions.

The hybrid configuration is among the popular configurations of drones for space missions. For example, Collins has designed a tilt-rotor drone using two tilt-rotors and one ducted fan with a combination of a fixed-wing configuration for Martian exploration (see Fig. 128(a)) [385]. Aguirre et al. have proposed a dual system hybrid drone for Mars exploration (see Fig. 128(c)) [386].

Another concept proposed for planetary exploration is the hybrid balloon-drone model. This concept of the flying vehicle would address several of the limitations drones currently encounter, such as power requirements, weight, and time in flight. For the applications that need static or slow motion, balloon-type drones can be employed with require significantly less power, longer flight time, and greater flexibility [17]. Some versions of balloon drones are introduced by, for example, NASA [388], Global Aerospace [389], Zero2Infinity [390] and so on, for

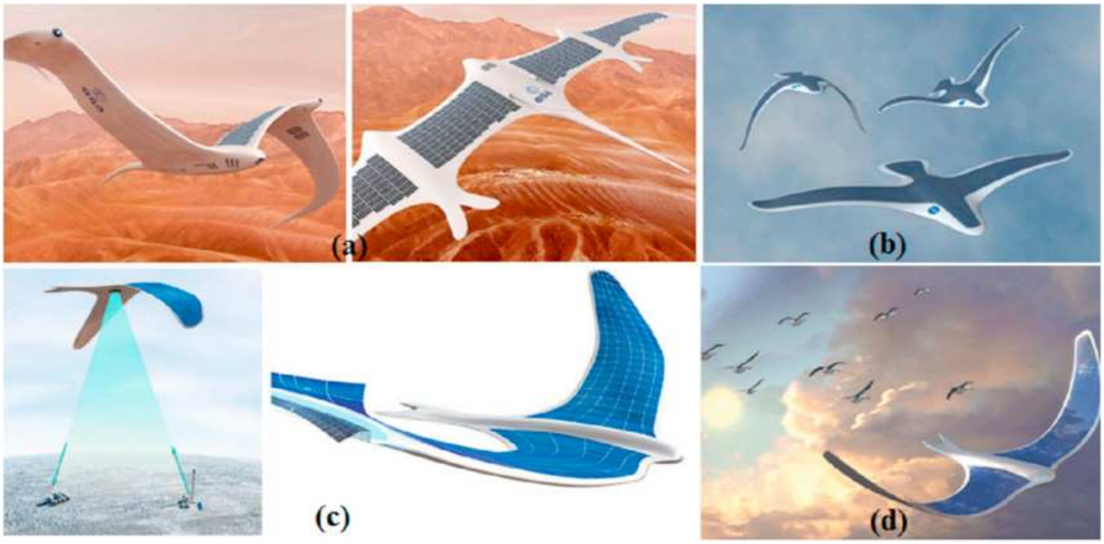

Fig. 131. Views of different concepts of flapping-wing drones for space missions reviewed by Hassanalian et al. [17].

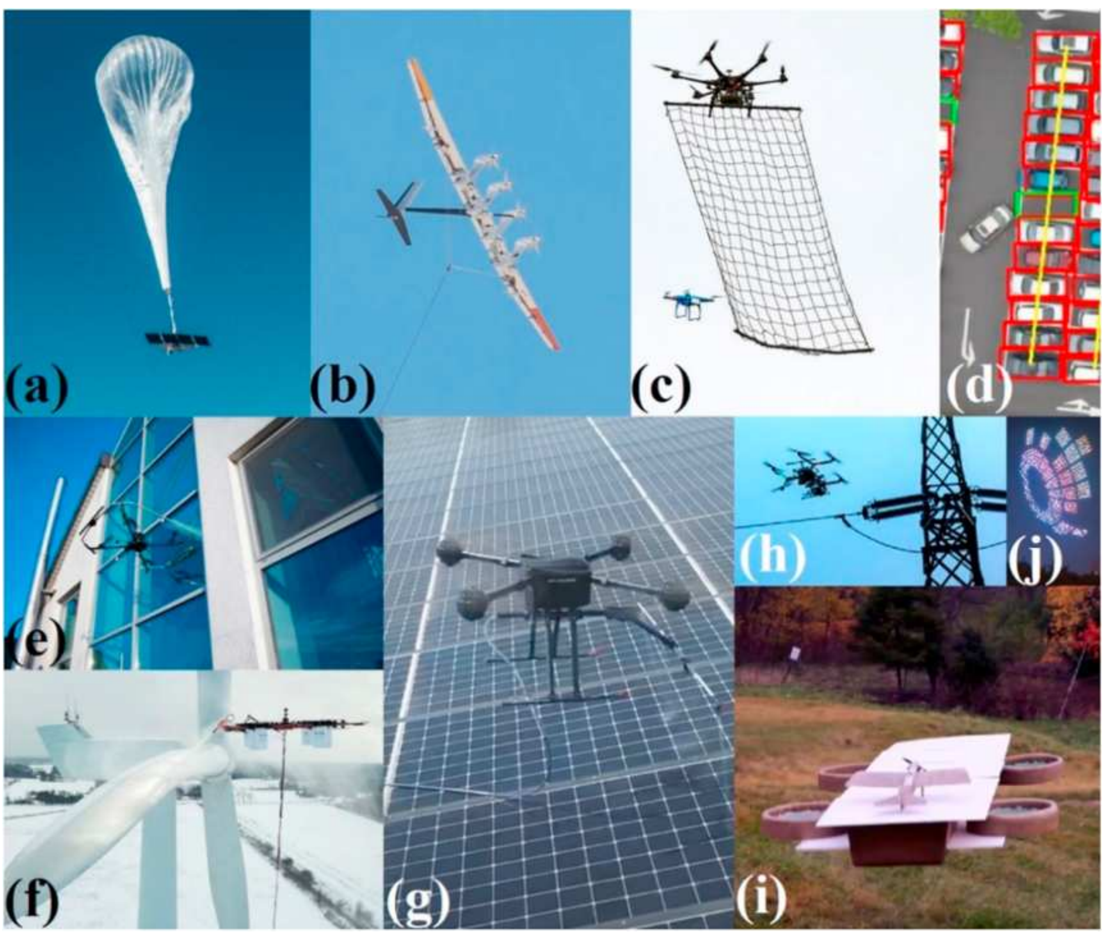

Fig. 132. Other miscellaneous applications of drones; (a) internet providing [395], (b) energy harvesting [396], (c) anti-drone [397], (d) vacant parking space detection [405], (e) window cleaning drone [399], (f) wind turbine cleaning drone [402], (g) solar panel cleaning drone [400], (h) power tower cleaning drone [401], (i) runway for other drones [403], and (j) swarm drone show [404].

near-space missions and planetary explorations. Fig. 129 shows the balloon-type drones proposed for space exploration.

Some researchers have also tried to design flapping-wing drones for space missions. Zegers et al. have proposed a flapping wing aerobot for autonomous flight in the Martian atmosphere. This flapping-wing drone is well suited for the low-density atmosphere of Mars (see Fig. 130(a)) [393]. A research group from Mountain Lake Labs (MLABs) has also designed a bat-inspired flapping wing for Mars exploration (see Fig. 130 (b)) [394].

There are also some other similar concepts involving flapping-wing

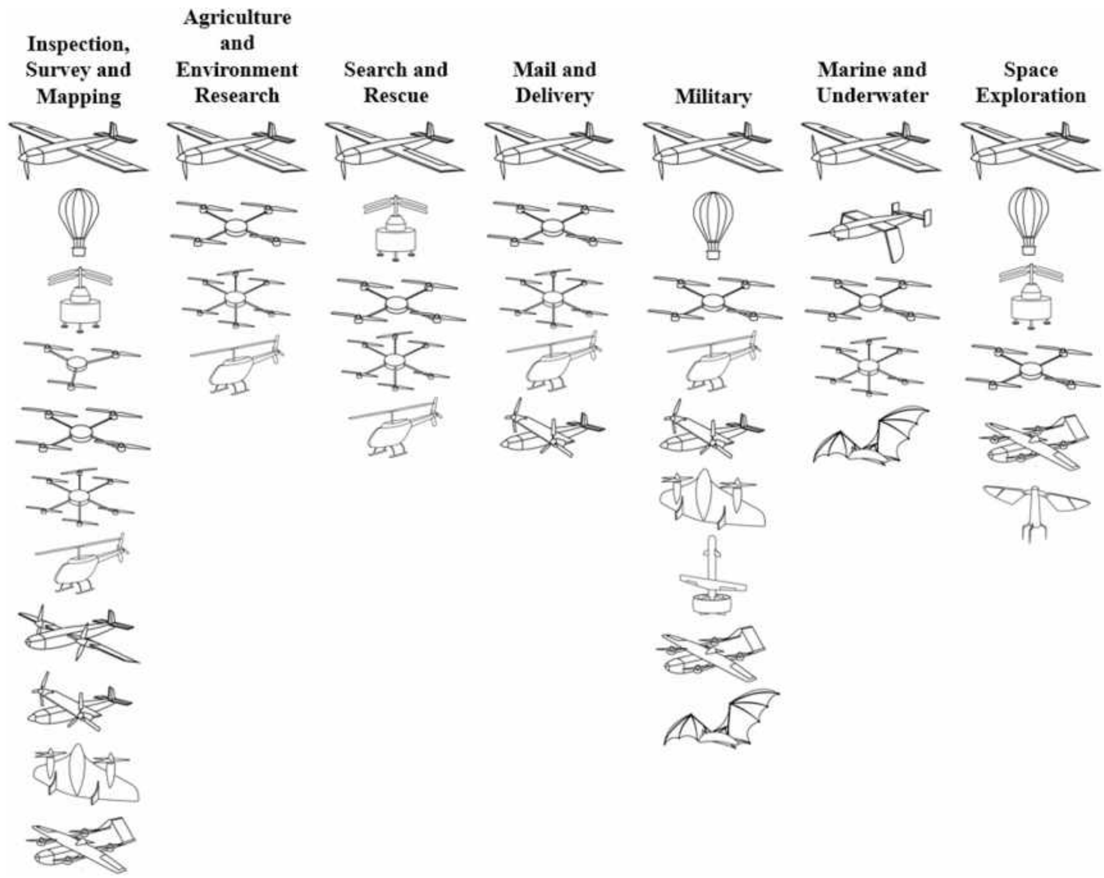

Fig. 133. Popular configurations for each category.

drones intended for space missions. A comprehensive review of the space drones, including their specifications, applications and design challenges, has been given by Hassanalian et al. [17]. The authors discussed and consolidated several concepts, research findings and studies that have been performed on space drones for planetary exploration. Fig. 131 depicts different concepts of flapping-wing drones for space missions reviewed by Hassanalian et al. [17].

Considering the targeted solar body, the design of the space drones is different. For example, the flight and performance of Venus-based drones differ from Martian-based drones. The Martian atmosphere is very thin compared to that on Earth [17]. The range of Reynolds numbers that drones are able to fly in other solar bodies is one of the most design factors that should be considered. On Earth, the Reynolds numbers of drones are on the order of $10^{6,}$ while on Mars, they are on the order of 10^5 [17]. Fixed-wing space drones that would fly in the Martian environment require larger propellers to generate enough thrust due to the lower values of atmospheric density [17].

6.2.8. *Miscellaneous applications*

UASs can be used in unconventional missions. For example, Google is working on expanding internet connectivity with stratospheric balloons. The plan is to extend the internet from the sky instead of ground to expand connectivity to rural areas, fill coverage gaps, and improve network resilience in the event of a disaster [395]. Google is also working on energy harvesting using kites that generate electricity by efficiently harnessing energy from wind resources that are not accessible or cost-effective today [396]. Malou Tech has introduced its anti-drone strategy, which is capturing drones with a net carried by another drone [397]. Gade et al. have introduced a solution for keeping birds away from airports [398]. Drones can also be used for cleaning tall buildings and towers [399] or cleaning solar panels [400], power towers [401] and wind turbines [402]. Moreover, drones have been used as a runway for other drones [403]. One of the most popular applications of drones is for hobby. Many drones are now available for entertainment and activities ranging from racing competition to aerial shows [404]. Furthermore, drones have been used for vacant parking space detection [405]. Fig. 132 shows a number of miscellaneous applications of drones.

Fig. 133 illustrates the popular configurations for each category of applications based on the reviewed examples. The fixed-wing UASs are the most popular configurations among companies and researchers as they have been used for almost any application. The second place belongs to the multirotors and specially quadrotors; even for space explorations, some concepts have been introduced based on multirotor configurations. The helicopters and hybrid configurations are also two of the popular configurations, although the hybrid UASs are predicted to be more popular in the future because of their numerous advantages.

6.2.9. *Summary*

Table 3 summarizes the different applications/missions of UASs and the corresponding requirements and specifications, based on the reviewed examples. Considering the applications' requirements and the specifications of different configurations, summarized in Table 3, some of the most suitable configurations for each application are suggested. Each category of applications contains a wide range of different missions with their own specific requirement. Therefore, the exact decision should be made based on the mission. The column "Suitable configurations" in Table 3 is a simple estimation of the suitable configurations based on the common requirements of the missions in each category. In some categories like military, space, and miscellaneous applications, we have covered all of the currently used configurations, as suggested. Their common requirements are indicated by "Based on mission". For more exact information about different missions and their requirements, the

Table 3
UAS configurations suited to a given application/mission.

Application/Mission	Common requirements	Suitable configurations
Inspection, Survey and Mapping	• Endurance • Payload capacity • Robustness	Fixed-wing Lighter than Air Multirotors Helicopter Hybrid
Agriculture and Environment Research	• Endurance • Payload capacity • Robustness	Fixed-wing Multirotor Helicopter
Search and Rescue (SAR)	• Speed • Maneuverability • Endurance • Payload capacity • Robustness	Fixed-wing Multirotor Helicopter
Mail and Delivery	• Endurance • Payload capacity • Robustness	Fixed-wing Multirotor Helicopter Hybrid
Military	Based on mission	Fixed-wing Morphing wing Multirotor Helicopter Balloon Hybrid Bio-Inspired
Naval	• Endurance • Waterproof • Speed	Fixed-wing Morphing wing Multirotor Hybrid Bio-Inspired (Flapping-wing)
Space	Based on mission	Fixed-wing Multirotor Balloon Hybrid Bio-inspired (Flapping-wing)
Miscellaneous	Based on mission	Based on mission

reader can refer to the previous sections.

7. Conclusions

This review provides an update of advances in the structure, configuration, and flight mechanisms of different types of unmanned aerial systems. Clearly, this research was not intended to be all-inclusive and examine the entire activities in the field. However, it has been our attempt to identify the general framework of progress made to the extent possible. In this paper, a comprehensive concept for the classification of drones based on configuration and flight mechanism is presented. The UASs are classified into four main categories – Horizontal Takeoff and Landing (HTOL), Vertical Takeoff and Landing (VTOL), Hybrid, and Bio-based drones. The sub-categories of each class and their advantages and shortcomings have been critically reviewed. The type of UASs considered included those capable of military and civilian operations, such as search and rescue, environment protection, mail service and delivery, space exploration, and smart cities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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