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Classifications, applications, and design challenges of drones: A review

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A B S T R A C T

Nowadays, there is a growing need for flying drones with diverse capabilities for both civilian and military applications. There is also a significant interest in the development of novel drones which can autonomously fly in different environments and locations and can perform various missions. In the past decade, the broad spectrum of applications of these drones has received most attention which led to the invention of various types of drones with different sizes and weights. In this review paper, we identify a novel classification of flying drones that ranges from unmanned air vehicles to smart dusts at both ends of this spectrum, with their new defined applications. Design and fabrication challenges of micro drones, existing methods for increasing their endurance, and various navigation and control approaches are discussed in details. Limitations of the existing drones, proposed solutions for the next generation of drones, and recommendations are also presented and discussed.

1. Introduction

Drones are flying robots which include unmanned air vehicles (UAVs) that fly thousands of kilometers and small drones that fly in confined spaces [1,2]. Aerial vehicles that do not carry a human operator, fly remotely or autonomously, and carry lethal or nonlethal payloads are considered as drones [3]. A ballistic or semi-ballistic vehicle, cruise missiles, artillery projectiles, torpedoes, mines, and satellites cannot be considered as drones [4]. Advances in fabrication, navigation, remote control capabilities, and power storage systems have made possible the development of a wide range of drones which can be utilized in various situations where the presence of humans is difficult, impossible, or dangerous [5,6]. Flying robots for military surveillance, planetary exploration, and search-and-rescue have received most attention in the past few years [7]. Depending on the flight missions of the drones, the size and type of installed equipment are different [6]. Considerable advantages of the drones have led to a myriad of studies to focus on the optimization and enhancement of the performances of these drones. According to the mentioned characteristics, drones benefit from the potential to carry out a variety of operations including reconnaissance, patrolling, protection, transportation of loads, and aerology [8–12].

Drones often vary widely in their configurations depending on the platform and mission. There are different classifications for the drones based on different parameters. Watts et al. [13] described a variety of platforms. They identified advantages of each as relevant to the demands of users in the scientific research sector. They classified the drones' platforms for civil scientific and military uses based upon characteristics, such as size, flight endurance, and capabilities. In their drones' classifications, they classified them as MAVs (Micro or Miniature Air Vehicles), NAVs (Nano Air Vehicles), VTOL (Vertical Take-Off & Landing), LASE (Low Altitude, Short-Endurance), LASE Close, LALE (Low Altitude, Long Endurance), MALE (Medium Altitude, Long Endurance), and HALE (High Altitude, Long Endurance). In an overview of military drones used by the UK armed forces, Brooke-Holland [14] classified drones into three classes. Class I is subdivided into four categories (a, b, c, and d). The categorization process is initially based on the minimum take-off weight combined with how the drones are intended to be used and where they are expected to be operated. This classification is shown in Table 1.

Arjomandi et al. [15] classified drones on the basis of weight, range and endurance, wing loading, maximum altitude, and engine type. They classified drones as super-heavy with weights more than 2000 kg, heavy with weights between 200 kg and 2000 kg, medium with weights between 50 kg and 200 kg, light/mini with weights between 5 kg and 50 kg, and finally micro drones with weights less than 5 kg [15]. This classification which is defined based on drones' weight is shown in Table 2.

Gupta et al. [3] classified drones as HALE, MALE, TUAV (medium range or tactical UAV), MUAV or Mini UAV, MAV, and NAV. Cavoukian [16] categorized drones as three main types, namely, micro and mini UAVs, tactical UAVs, and strategic UAVs. He divided the tactical UAVs into six subcategories: close range, short range, medium range, long range, endurance, and medium altitude long endurance

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Table 1
The proposed drones' categorization by Brooke-Holland based on their weight [14].

Class	Type	Weight range
Class I(a)	Nano drones	W≤200 g
Class I(b)	Micro drones	200 g < W≤2 kg
Class I(c)	Mini drones	2 kg < W≤20 kg
Class I(d)	Small drones	20 kg < W≤150 kg
Class II	Tactical drones	150 kg < W≤600 kg
Class III	MALE/HALE/Strike drones	W > 600 kg

Table 2
The proposed drones' categorization by Arjomandi et al. based on their weight [15].

Designation	Weight range
Super heavy	W > 2000 kg
Heavy	200 kg < W≤2000 kg
Medium	50 kg < W≤200 kg
Light	5 kg < W≤50 kg
Micro	W≤5 kg

Table 3
The proposed drones' categorization by Weibel and Hansman based on their weight [17].

Designation	Weight range
Micro	W < 2 lbs
Mini	2 lbs≤W≤30 lbs
Tactical	30 lbs≤W≤1000 lbs
Medium and high altitude	1000 lbs≤W≤30,000 lbs
Heavy	W > 30,000 lbs

(MALE) UAVs [16]. Weibel and Hansman [17] classified drones as micro, mini, tactical, medium and high altitude, and heavy types. In Table 3, the proposed classification is indicated.

Australian Civil Aviation Safety Authority (CASA) [18] categorized drones into three classes, namely, micro UAVs with weights less than 0.1 kg, small UAVs with weights between 0.1 kg and 150 kg, and large UAVs with weights more than 150 kg for fixed wing models and more than 100 kg for rotorcrafts [18]. United Kingdom – Civil Aviation Authority (CAA) [19,20] classified drones into three types consisting of small unmanned aircraft (weight≤20 kg), light UAV (20 kg < weight≤150 kg), and UAV (weight > 150 kg). Zakora and Molodchik [21] classified drones based on their weight and range as follows: micro and mini UAV close range, lightweight UAVs small range, lightweight UAVs medium range, average UAVs, medium heavy drones, heavy medium range UAVs, heavy drone large endurance, and unmanned combat aircraft. They also categorized drones based on their missions, namely, (1) attack UAV multiple applications, (2) attack UAV expendable, (3) strategic UAV, (4) tactical UAV, and (5) miniature UAV [22]. In Table 4, the presented drones' classification by Zakora and Molodchik is shown.

Nowadays different types of drones evolved from the advancement

Table 4
The proposed drones' categorization by Zakora and Molodchik based on their weight and flight range [21].

Designation	Weight range	Flight range
Micro and mini UAVs close range	W≤5 kg	25 km≤R≤40 km
Lightweight UAVs small range	5 kg < W≤50 kg	10 km≤R≤70 km
Lightweight UAVs medium range	50 kg < W≤100 kg	70 km≤R≤250 km
Average UAVs	100 kg < W≤300 kg	150 km≤R≤1000 km
Medium heavy UAVs	300 kg < W≤500 kg	70 km≤R≤300 km
Heavy medium range UAVs	500 kg≤W	70 km≤R≤300 km
Heavy UAVs large endurance	1500 kg≤W	R≤1500 km
Unmanned combat aircraft	500 kg < W	R≤1500 km

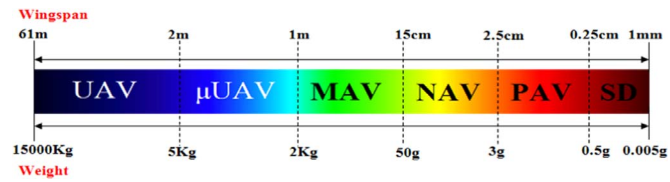

Fig. 1. Spectrum of drones from UAV to SD.

in miniaturization of electronic components, such as sensors, microprocessors, batteries, and navigation systems [23]. A wide variety of drones were used for military and civilian purposes. Drones range in size from vast fixed-wing unmanned air vehicle (UAV) to smart dust (SD) which consists of many tiny micro-electro-mechanical systems including sensors or robots. In Fig. 1, the spectrum of different types of drones is presented.

As shown in Fig. 1, there is a spread spectrum of drones from UAV class with maximum wing span of 61 m and weight of 15,000 kg [24] to smart dust (SD) with minimum size of 1 mm and weight of 0.005 g [25]. Between UAV and SD at both ends of the defined spectrum, there are various types of drones, which are called micro drones, such as micro unmanned air vehicle (μUAV), micro air vehicle (MAV), nano air vehicle (NAV), and pico air vehicle (PAV) [7]. In this study, we offer a new classification for drones which covers other types of classifications with better and more comprehensive categorization. The rest of this study is organized as follows: the unconventional classification of drones is presented in Section 2. In Section 3, the various applications of these drones are investigated and discussed. Design and manufacturing methods and their challenges are, respectively, studied in Sections 4 and 5. Different propulsion systems and actuators for drones, and their power supply and endurance are shown in Sections 6 and 7, respectively. Control and navigation, and swarm flight of drones and conclusions are, respectively, presented in Sections 8–10.

2. Classification of drones

In the recent decades, due to the development of a smaller air drone called micro air vehicle, the demands for intelligence missions have been increased [26]. Therefore, nowadays, there is a serious effort to design and fabricate air drones that are very small for special missions. These efforts have resulted in the development of different types of small drones with various shapes and flight modes. In Fig. 2, a comprehensive classification of all of the existing drones is shown, where HTOL is the abbreviation of Horizontal Take-Off and Landing.

Generally, drones can be categorized by their performance characteristics. Features including weight, wing span, wing loading, range, maximum altitude, speed, endurance, and production costs, are important design parameters that distinguish different types of drones and provide beneficial classification systems. Furthermore, drones can be classified based on their engine types [15]. For example, UAVs often apply fuel engines and MAVs use electrical motors. The types of propulsion systems which are used in drones are different based on their models. The offered classification of drones in Fig. 2 shows different models of drones as a function of their configuration. The indicated flowchart in Fig. 2 also considers the bio models of micro and nano air vehicles, which are defined as live controllable birds or insects and flying taxidermy birds.

2.1. Classification of UAVs

The main aspects that distinguish UAVs from other types of small drones (such as MAVs and NAVs) include the operational purpose of the vehicle, the materials used in its fabrication, and the complexity and cost of the control system [27]. UAVs vary widely in size and configuration. For example, they may have a wing span as broad as a Boeing 737 or smaller than a radio-controlled drone [2]. Different

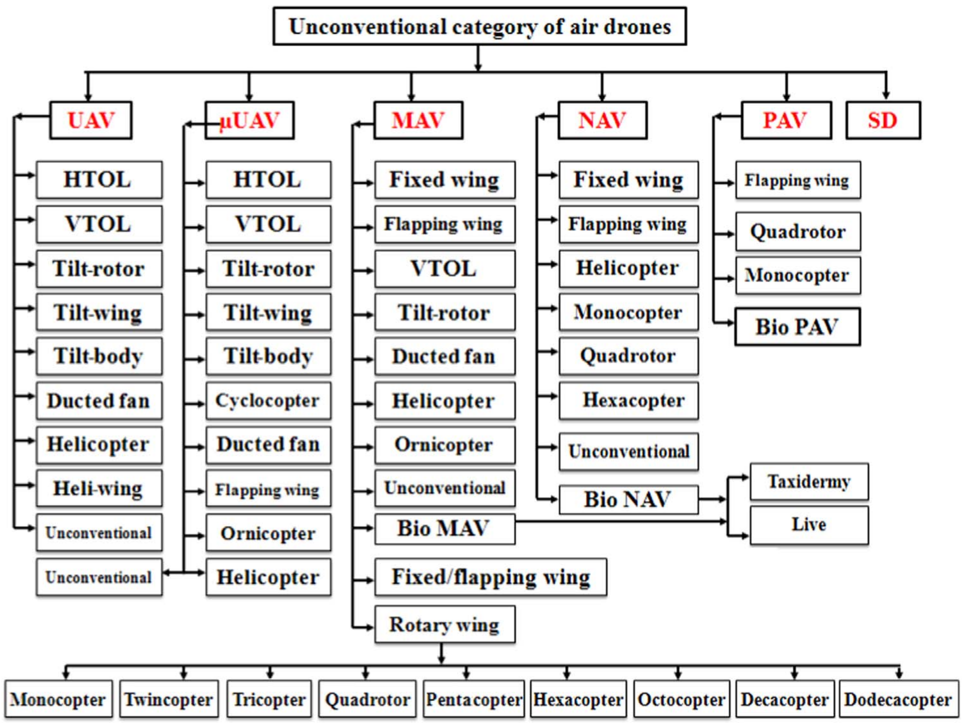

Fig. 2. Different types of air drones.

mission requirements created various types of UAVs. For this reason, it is often useful to categorize UAVs in terms of their mission capabilities [15]. As indicated in Fig. 2, UAVs can be considered as HTOL (horizontal take off landing), VTOL (vertical take-off landing), hybrid model (tilt-wing, tilt-rotor, tilt-body, and ducted fan), helicopter, heli-wing, and unconventional types. In Fig. 3, different types of unmanned air vehicles are presented. In Table 5, the characteristics of different types of UAVs shown in Fig. 3 are provided.

2.1.1. HTOL and VTOL UAVs

After many years of development in HTOL drones, there are four configurations for these UAVs, which are specified by lift/mass balance and by stability and control. They are tailplane-aft, tailplane forward, tail-aft on booms, and tailless or flying wing UAVs [37]. The mentioned configurations may have the propulsion systems at the rear of the fuselage (see Fig. 3(a)) or at the front side of the UAV. Fixed wing VTOL UAVs, often use a vertical propulsion system at the front of their fuselage, as shown in Fig. 3(b), and have cross wings. This type of drones can take off and land vertically and do not need runway for takeoff.

2.1.2. Tilt-rotor, tilt-wing, tilt-body, and ducted fan UAVs

For hovering flight mode, the VTOL drones are more efficient than HTOL ones. They have limitations in cruise speed because of the stalling of the retreating blades, but usually for longer range missions, UAVs with higher cruise speed are required [38]. However, the ability of vertical take-off and landing is valuable. Due to these limitations, the idea to have a type of drone which combines the capability of both VTOL and HTOL types was introduced [39]. Therefore, nowadays, there are different types of hybrid drones including tilt-rotor, tilt-wing, tilt-body, and ducted fan UAV, as shown in Fig. 3(c), (d), (e), and 3(f), respectively [40]. In tilt-rotor UAVs, at first, rotors are vertical in vertical flight, but for cruise flight they tilt forward through 90°. In tilt-wing UAVs, the engines are usually fixed to wings, and tilt with wing. In this type of drone, the angle of the whole wing is changed from zero to 90°in order to convert its flight modes from horizontal to vertical. Both of these configurations flew successfully as drones, but the tilt-rotor UAV was the most efficient in hover flight and the tilt-wing UAV was the most efficient in cruise flight.

The free wing tilt-body UAV, as shown in Fig. 3(e), is a new kind of drones, distinct from fixed wings and rotary wings. It is neither fixed wing nor rotary wing nor any combination of the two. In this type of drones, the wing is completely free to rotate in pitch axis and the fuselage is a lifting body. Both the left/right wing pair and the central lifting body are free to rotate about the spanwise shaft, free with regard to the relative wind, and free with regard to each other [41–46]. The tilt-body is also an unconventional attachment of a boom type to a fuselage such that it changes its incidence angle relatively to the fuselage in response to external commands. The merits of this type of drones are short take-off and landing (STOL), low speed loitering, and reduced sensitivity to center of gravity (CG) variation [41].

The ducted fan UAVs, are drones where their ‘thrusters’ are enclosed within a duct. The thruster of these drones is called ‘fan’. This fan is composed of two contra-rotating elements for minimizing the rotation of the body by a resultant torque. Ducted fan UAVs cannot only take off and land vertically, but can also hover and be controlled by two counter rotors and four control surfaces (vanes) [38,47]. Even though the transition into, and back from cruise flight is easy, flow separation from the duct is a concern [38].

2.1.3. Helicopter and heli-wing UAVs

Nowadays, researchers design and fabricate different types of unmanned helicopters for vertical takeoff, landing, and hovering flight. There are four types of helicopter UAVs, namely, single rotor, coaxial rotor, tandem rotor, and quad-rotor [38,48]. Heli-wing UAVs are other types of drones which use a rotating wing as their blade. They can fly as a helicopter vertically and also fly as a fixed wing UAV, as shown in Fig. 3(h) [49,50].

2.1.4. Unconventional UAVs

UAVs that cannot be placed in previous defined categories are considered as unconventional UAVs. Bio-inspired flying robots are usually placed in this group. For example, the FESTO AirJelly [51] which was inspired from jellyfish, as shown in Fig. 3(i), is considered as

Fig. 3. Different types of UAVs, (a) HTOL [28], (b) VTOL [29], (c) tilt-rotor UAV [30], (d) tilt-wing UAV [31], (e) tilt-body UAV [32], (f) ducted fan UAV [33], (g) helicopter [34], (h) heli-wing [35], and (i) unconventional UAV [36].

Table 5
The characteristics of different types of UAVs [28–36].

Name	Manufacturer	**Weight**	**Wing span**
[a] RQ-4 Global Hawk	Northrop Grumman	14,628 kg	39.9 m
[b] SkyTote	AeroVironment	110 kg	2.4 m
[c] Bell Eagle Eye	Bell Helicopter	1020 kg	7.37 m
[d] UAV Quad Tilt Wing	của GH Craft Ltd	23 kg	2 m
[e] Specs (Model 100–60)	Freewing Tilt-Body technology (USA)	215 kg	4.9 m
[f] V-bat	MARTINUAV	31 kg	2.74 m
[g] MQ-8 Fire Scout	Northrop Grumman	225 kg to 1430 kg	8.4 m
[h] Boeing X-50 Dragonfly	Boeing and DARPA	645 kg	2.71 m
[i] Air Jelly	Festo	–	–

unconventional UAV. This drone glides in air thanks to its central electric drive unit and an intelligent adaptive mechanism. This drone is able to perform this task because it consists of a helium-filled ballonet. AirJelly is the first drone with peristaltic drive. This new drive concept, with propulsion based on the principle of recoil, moves the jellyfish gently through the air [51,52]. There are other unconventional UAVs that fly differently than conventional UAVs including the FESTO flying penguin [51].

2.2. Classification of μUAVs

A μUAV or small UAV (SUAV) is an unmanned aerial vehicle small enough to be man-portable. It is usually launched by hand and does not need a runway for take-off [53]. μUAVs are larger than micro air vehicles (MAVs), but can be carried by a soldier, and smaller than UAVs that cannot be carried and launched by hand. μUAVs vary widely in their configurations. As shown in Fig. 4, μUAVs can be categorized as HTOL, VTOL, hybrid model (tilt-wing, tilt-rotor, tilt-body, and ducted fan), helicopter, ornithopter (flapping wing), ornicopter, cyclocopter, and unconventional types.

HTOL, VTOL, tilt-rotor, tilt-wing, tilt-body, ducted fan, helicopter, and unconventional μUAVs are similar to UAV models but often have smaller size and weight compared to them, as shown in Fig. 4(a), (b), (c), (d), (e), (f), (g), and (k), respectively. In Table 6, the characteristics of some μUAVs shown in Fig. 4 are provided.

2.2.1. Ornithopter μUAVs

An ornithopter, is derived from the Greek words of ornithos meaning bird and pteron which means a wing, that is flying by opening and closing its wings. The idea of inventing bird wings to fly refers back

Fig. 4. Different types of μUAVs, (a) HTOL [54], (b) VTOL [55], (c) tilt-rotor [56], (d) tilt-wing [57], (e) tilt-body, (f) ducted fan μUAV [58], (g) helicopter [59], (h) ornithopter [60], (i) ornicopter [61], (j) cyclocopter [62], and (k) unconventional μUAV [63].

Table 6
The characteristics of different types of μUAVs [54–60,62].

Name	Manufacturer	**Weight**	**Wing span**
[a] Q-11 Raven	AeroVironment	1.91 kg	1.3 m
[b] HeliSpy II	Micro Autonomous Systems LLC, USA	2 kg	–
[c] ITU Tilt-Rotor	Turkish UAV research	–	–
[d] QUX-02	Japan Aerospace Exploration Agency	3.4 kg	1.38 m
[f] T-Hawk	DARPA	–	–
[g] Sniper 032	Alpha Unmanned Systems	–	1.8 m
[h] SmartBird	FESTO	450 g	1.96 m
[j] Cyclocopter ADEX	Korean Aerospace Research Institute	–	–

to ancient Greek legends about Daedalus and Icarus. Roger Bacon, in his writings in 1260 CE, was among the first to propose the idea of advanced flying. Leonardo da Vinci, around the year 1490, began to study the flight of birds. He concluded that humans are too heavy to fly with wings attached to their arms. As a result, he thought about a machine which allowed he pilot to move big wings by means of hand axels, foot pedals, and a system of pulleys [64,65]. The first ornithopter was built around 1870 in France by Gustav Trouvé who flew for about 70 m in an exhibition in France [64,66]. Recently, researchers designed and fabricated some flapping wing drones. For example, FESTO designed a flapping wing, called Smart-Bird with a wing span equal to 1.96 m can fly like a seabird [67].

2.2.2. Ornicopter μUAVs

An ornicopter is a helicopter without a tail rotor, but with wings that flap like bird wings, as shown in Fig. 4(i). The name, ornicopter is a contraction of the words ornithopter and helicopter. In other words, ornicopter is a helicopter that flaps its wings like a bird to get into the air [68]. Aeronautical engineers at Delft University of Technology [68,69] thought that by flapping a helicopter's main rotor blades like the wings of a bird, they can dispense with the tail rotor and avoid the drawbacks of the NOTAR (NO TAil Rotor) system and increase the freedom of movement by flapping like a bird [70].

2.2.3. Cyclocopter μUAVs

The cyclocopter or cyclogyro are μUAVs that use cycloidal rotors which consist of airfoils rotating around a horizontal axis to generate lift and thrust forces, as shown in Fig. 4(j). They can take off, land, vertically, and hover like a helicopter. The cyclocopter wing resembles a paddle wheel, with airfoils replacing the paddles [71]. Bin et al. [72] from the National University of Singapore first built a cyclogyro μUAV that could hover and turn on the end of a tether [72].

2.3. Classification of MAVs

MAV airplanes are micro planes usually with a length smaller than 100 cm and a weight lower than 2 kg [73]. These drones are grouped

Fig. 5. Different types of MAVs, (a) fixed wing [6], (b) flapping wing [83], (c) fixed/flapping-wing [84], (d) rotary wing [85], (e) VTOL [86], (f) ducted fan [87], (g) tilt-rotor, (h) helicopter [88], (i) unconventional, (j) ornicopter [89].

into nine categories: fixed wing, flapping wing, VTOL, rotary wing, tilt-rotor, ducted fan, helicopter, ornicopter, and unconventional types. These drones can carry visual, acoustic, chemical, and biological sensors [74], as shown in Fig. 5. Different types of micro air vehicles are attracting various disciplines including aerospace, mechanical, electrical, and computer engineering [75]. The Defense Advanced Research Projects Agency (DARPA) program limits these air drones to a size less than 150 mm in length, width, or height and weighing between 50 and 100 g [7,76], but after the advent of NAVs and PAVs, the definition for MAV was changed. Therefore, in this review, the dimensions of these drones are considered between 15 cm to 100 cm and weight between 50 g to 2 kg. The smaller dimension of MAVs, compared to UAVs, provides them with the broader performance range [6].

The first comprehensive research on MAV was performed in 1993 at RAND Institute [77,78]. In the past decade, due to the quick advances in microtechnology, MAVs have drawn a great deal of attention. As a result, in subsequent years, several research investigations were carried out on the micro planes [79,80]. In addition to their small sizes, these types of planes are capable to fly at low speeds. MAVs are mainly flying at low altitudes for various applications, such as monitoring of dangerous locations, tracking of the specific targets, or mapping. Flying of MAVs at low altitude places them within the atmospheric boundary layer, a particularly turbulent regime which makes them sensitive to these atmospheric disturbances [81]. Therefore, design and fabrication of these air drones should be accurately carried out. Conceptual design of micro air vehicles usually differs from that of conventional UAVs design due to nontraditional flight missions and decreased time required for design, production, and evaluation of these drones [82].

As for VTOL, tilt-rotor, ducted fan, helicopter, ornicopter, and unconventional MAVs, they are similar to μUAV models but have smaller size and weight compared to them, as shown in Fig. 5(e), (f), (g), (h), (i), and (j), respectively. The features of a few of the MAVs shown in Fig. 5 are indicated in Table 7.

Table 7
The characteristics of different types of MAVs [6,83–86].

Name	Manufacturer	Weight	Wing span
[a] Inverse Zimmerman	Isfahan University of Technology	430 g	43.2 cm
[b] Thunder I	Isfahan University of Technology	350 g	70 cm
[c] NPS flapping-wing	Naval Postgraduate School	14 g	23 cm
[d] Apollo	IdeaFly	1200 g	35 cm
[e] VTOL UAS	Cranfield Aerospace Solutions	–	–
[f] GFS 7	JL Naudin	526 g	60 cm

2.3.1. Fixed wing MAVs

Fixed wing MAVs, as shown in Fig. 5(a), often consist of rigid wing, fuselage, and tails which use a motor and propeller as their propulsion system and can cover a wide range of possible operational environments including jungle, desert, urban, maritime, mountains, and arctic environments [90,91]. Because of their small dimensions compared to UAVs and low required power, fixed wing MAVs are quite covert, have low radar cross-section, and are very difficult to detect [26,90]. Furthermore, advances in micro fabrication technology allow these drones to be produced in large quantities and with low cost. Fixed wing MAVs often apply a low-aspect ratio wing which is specified by a three dimensional flow field [92]. Fixed wing MAVs which fly in environments, such as urban or forested areas, require short wings with low aspect ratios since drones with longer wings are quite delicate and likely to hit obstacles [93].

Because of the MAVs applications, such as data gathering or patrolling, having high endurance and range is very important. It should be mentioned that both of these features are proportional to lift to drag ratio. Usually, fixed wing MAVs with more lift/drag values perform better than those with lower values. Mueller's group [74,94] demonstrated the importance of camber and wing shapes (planform) by performing wind tunnel investigations. They indicated that cambered plates provide better aerodynamic performance [95]. Fixed-wing MAVs have longer range and endurance and can fly at higher altitude than flapping and rotary wing MAVs which usually perform indoor missions with slower flight speed [96]. There are different types of planforms which are: rectangular, tapered wings with swept leading edges, Zimmerman, inverse Zimmerman, and elliptical [91,97].

2.3.2. Flapping wing MAVs

Flapping wings are usually designed in three classes, namely, MAV, NAV, and PAV. The design of flapping wing MAVs (FWMAVs) are inspired from birds, PAV flapping wings are inspired from insects, and NAV flapping wings are inspired from organisms between very small birds and huge insects, such as hummingbirds and dragonflies [98,99]. Flapping wing MAVs consist of the flexible and flapper wings which use an actuation mechanism for their flapping motion. Most of the flapping wings have flexible and light wings as observed in birds and insects which indicate that the flexibility and weight of wings are important for their aerodynamic proficiency and flight stability [100–102]. The research on natural and manmade flapping wings showed that these types of air vehicles have more complexities compared to fixed and rotary wings mainly due to their complex aerodynamics [103]. Therefore, birds, bats, and insects have been investigated by biologists and drone researchers for years, and active study in the aerospace engineering community, motivated by interest in flapping wings, has been rapidly increasing [104].

Biologic inspiration indicates that flying with flapping wings presents unique maneuverability advantages. There are fundamental challenges for fixed and rotary wings to fly reliably when their sizes are reduced. When the wing area is reduced, a flow transition to low Reynolds number occurs which reduces the aerodynamic wing efficiency [7]. In Table 8, the range of Reynolds number for different classes of micro drones and the proposed wing configurations, such as fixed wing, flapping wing, and rotary wing for each range are shown [105].

Reynolds number is one of the main parameters that determines the lift and drag of the air vehicles. For very small drones, it will most likely involve a laminar flow but for larger drones that have higher Reynolds numbers, mixed laminar and turbulent flows occur with possible transition. Furthermore, it can be seen that for Reynolds numbers in the range between 10^4 and 10^6, the drones exhibit a flow phenomenon which is called laminar separation bubble (LSB) [105]. These LSBs usually create additional drag as they displace the outer inviscid flow. Drones which are operated at low Reynolds number, employ different ways to generate aerodynamic forces. For example, fixed wing drones with low aspect ratio exhibit three dimensional flows and laminar turbulent transition. Flapping wings generate unsteady flows which determine the lift and drag. Fixed and rotary wing drones that operate at low Reynolds number, are prone to flow separation resulting in a drag increase and loss of efficiency. Even without flow separation in these types of drones, the low Reynolds number results in lower lift-to-drag ratios from O(100) to O(1) [105,106].

A flapping wing has the potential to benefit from the advantages of other micro drone types [107]. The hovering ability of insects, coupled with the ability for a quick transition to forward flight, provides an ideal drone for search and rescue and other applications [108,109]. Flapping wing MAVs can be designed and fabricated in three configurations, namely, monoplane, biplane, and tandem [110]. The monoplane flapping wings apply a single pair of wings to generate lift same as birds, as shown in Fig. 6(b). The tandem ones have two sets of wings, with one wing behind the other, flapping independently same as dragonflies as presented in Fig. 6(b). The biplane configuration, shown in Fig. 6(c), has two superimposed pairs of wings, with one wing set over the other, and does not exist in nature [110–112]. In Table 9, manufacturer, weight, and wing span of shown flapping wing drones in Fig. 6 are provided.

2.3.3. Fixed/flapping-wing MAVs

Research in low Reynolds number unsteady aerodynamics and flapping-wing propulsion has developed an unconventional flapping-wing propelled micro air vehicle. Fixed/flapping-wing MAVs are hybrid designs which use fixed wings for lift and flapping wings for propulsion, as shown in Fig. 5(c). In this type of micro air vehicles, the drone usually consists of a low aspect ratio fixed-wing with a trailing pair of higher aspect ratio flapping wings which flap in counterphase [84]. The flapping-wing part increases efficiency, provides a mechanically and aerodynamically balanced platform, and quenches stall over the fixed wing by entraining flow [84]. This type of drone also can be seen in dragonfly with tandem wings, where they apply two pairs of wings to increase the lift and thrust forces.

2.3.4. Rotary wing MAVs

One of the important merits of MAVs when compared to other drones, such as UAVs, is their small dimensions, which allow them to fly in confined spaces [113]. This is particularly true for rotary wing MAVs that can hover and have a high maneuverability [114]. As shown in Fig. 5(d), having rotary blades or propeller-based systems they are called rotary wing drones. Unlike the fixed wing models, these drones can fly in every direction, horizontally, vertically, and also can hover in a fixed position [38]. These characteristics make them the perfect drones for surveying hard-to-reach areas, such as pipelines, bridges, etc [115,116]. Rotary wing drones, similar to helicopters generate lift from the constant rotation of the rotor blades [38]. In this type of MAVs, several blades may be used. Thus, nowadays, researchers designed and fabricated different types of drones ranging from one to twelve motors.

Table 8
The range of Reynolds number for different types of micro drones [105].

Type	PAV	NAV	MAV	μUAV	UAV
Reynolds number	10^3–10^4	10^4–5×10^4	5×10^4–2×10^5	2×10^5–5×10^5	5×10^5–2×10^6
Configuration	Flapping	Fixed, rotary, flapping	Fixed, rotary, flapping	Fixed	Fixed

Fig. 6. Different configurations of FWMAVs, (a) monoplane, (b) tandem, and (c) biplane [112].

Table 9
The characteristics of flapping-wing drones with different configurations [110–112].

Name	Manufacturer	Weight	Wingspan
[a] Slow Hawk 2	Kinkade R/C	397 g	106.7 cm
[b] BionicOpter	FESTO	175 g	63 cm
[c] Butterflys spy drone	Israel Aircraft Industries (IAI)	12 g	20 cm

Those consisting of one motor and blade are known as mono-copters which were inspired from whirling seeds that fall from some trees [117,118], as shown in Fig. 7(a). Rotary wing MAVs with two, three, four, five, six, eight, ten, or twelve motors are called twin-copters, tri-copters, quad-rotors or quad-copters, penta-copters, hexa-copters, octo-copters, deca-copters, and dodeca-copters [119,120]. Among the rotary wing MAVs, the quad-copters and hexa-copters are the best known drones [27]. Different types of rotary wings are presented in Fig. 7. In Table 10, the characteristics of some rotary wings presented in Fig. 7 are given.

Table 10
The characteristics of rotary wing drones with different configurations [121,122,124,125,127].

Name	Manufacturer	Weight	Wingspan
[a] Monocopter	Massachusetts Institute of Technology (MIT)	175.5 g	40.64 cm
[b] OVIWUN	Trek Aerospace Inc	–	–
[d] Aeryon Scout	Aeryon Labs of Waterloo, Ontario, Canada	1700 g	80 cm
[f] ZALA 421-21	ZALA AERO	–	–
[h] Distributed Flight Array	Raffaello D'Andrea	–	–

2.4. Classification of NAVs

In addition to the micro air vehicles, DARPA started another program on nano air vehicles (NAVs) [129,130] defined as extremely small and lightweight drones with a maximum wing span length of

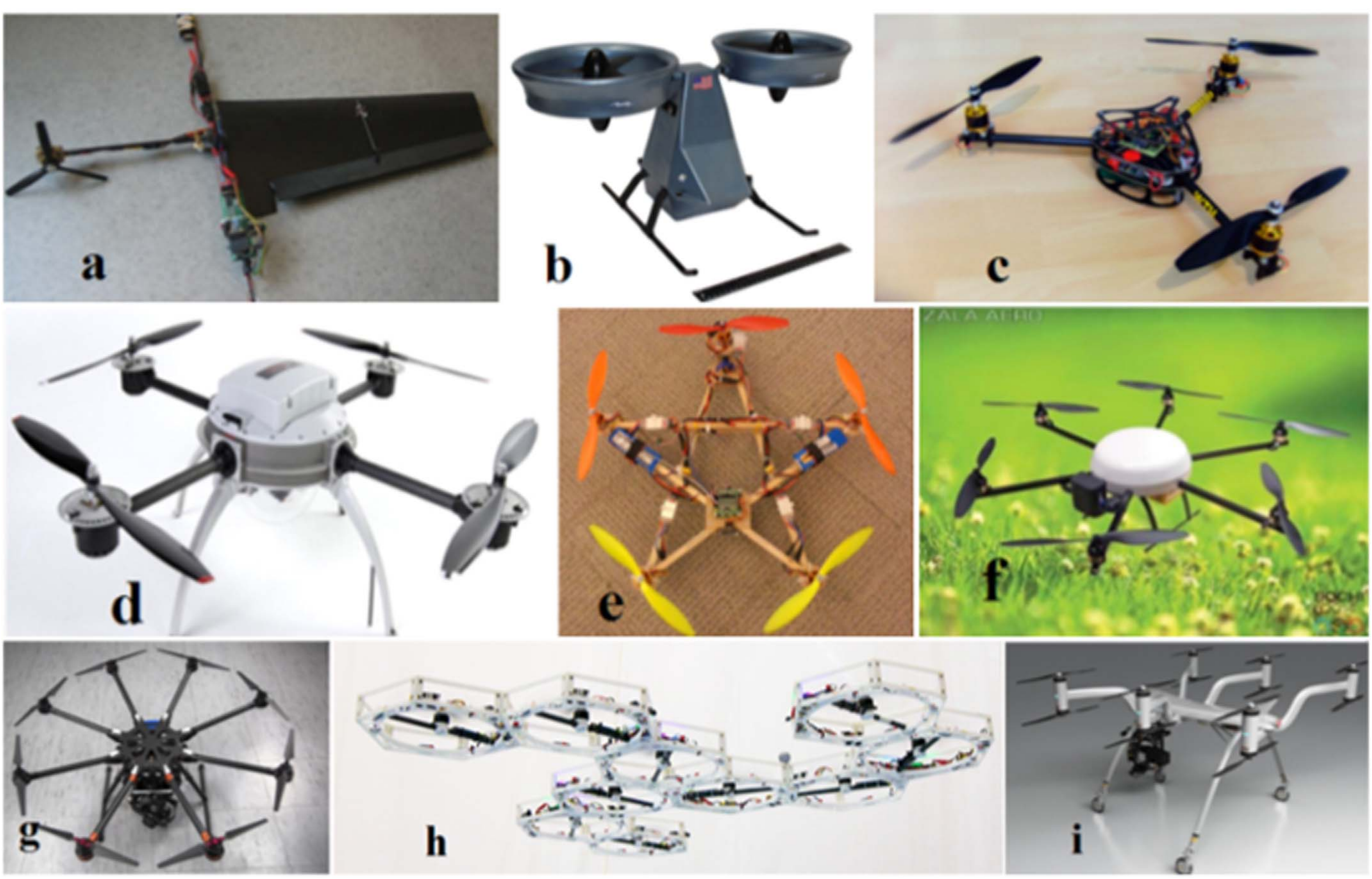

Fig. 7. Different types of rotary wing MAVs, (a) mono-copter [121], (b) twin-copter [122], (c) tri-copter [123], (d) quad-copter [124], (e) penta-copter, (f) hexa-copter [125], (g) octo-copter [126], (h)deca-copter [127], (i) dodeca-copter [128].

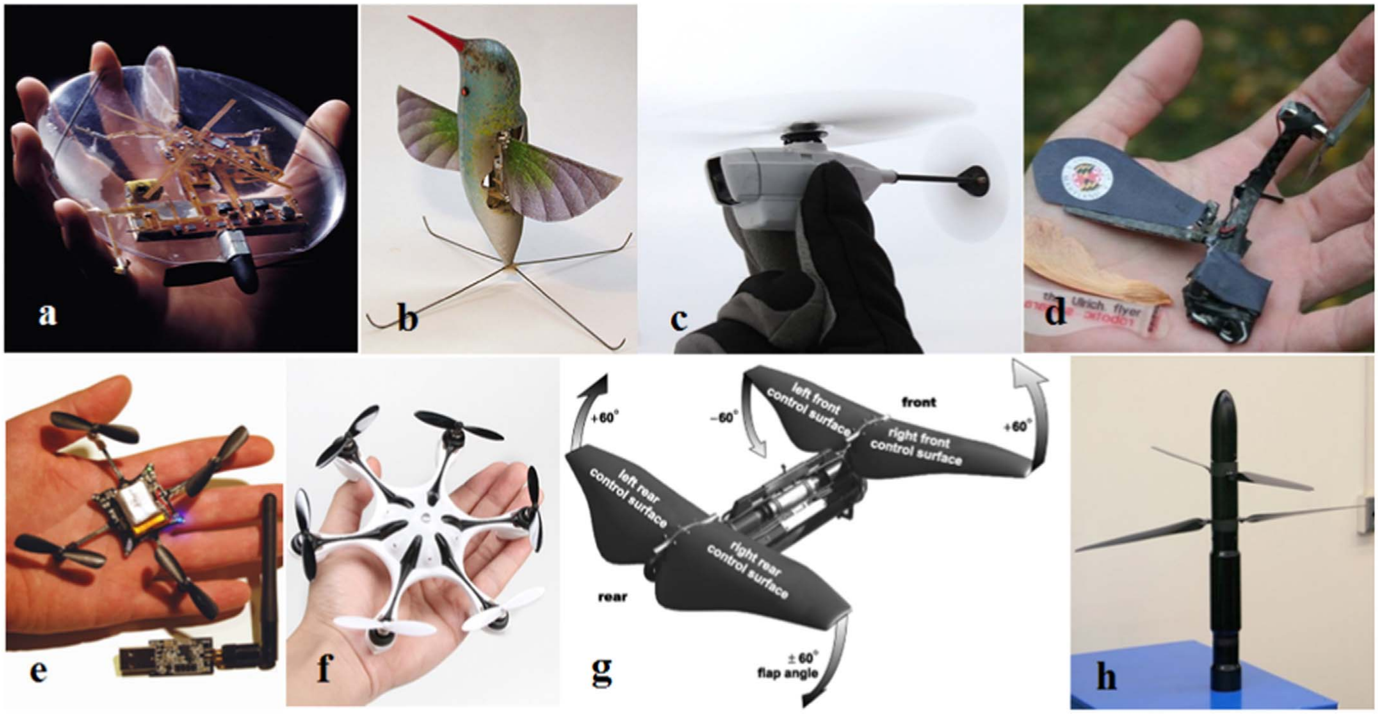

Fig. 8. Different types of NAVs, (a) fixed wing [133], (b) flapping wing [134], (c) helicopter [135], (d) monocopter [136], (e) quadrotor [137], (f) hexacopter [138], and (g and h) unconventional [139,140].

Table 11
The characteristics of different types of NAVs [133–139].

Name	Manufacturer	Weight	Wing span
[a] Black Widow	AeroVironment	56.5 g	15.2 cm
[b] Nano Hummingbird	AeroVironment	19 g	16 cm
[c] Black Hornet Nano	Prox Dynamics	16 g	10 cm
[d] Robotic samaras monocopter	University of Maryland	–	7.5 cm
[e] CrazyFlie Nano Quadcopter	Bitcraze	19 g	9 cm
[f] Mini X6 Micro Hexa-copter	HobbyKing	52 g	13 cm
[g] Entomopter	Georgia Tech Research Institute	50 g	15 cm

15 cm [129] and a weight less than 50 g [131]. These types of drones have a range less than 1 km and a maximum flight altitude around 100 m [130,132]. There are different configurations for NAVs, such as fixed wings, rotary wings, and flapping wings which are depicted in Fig. 8. The features of a few of the NAVs shown in Fig. 8 are indicated in Table 11.

2.5. Classification of PAVs

In the past few years, researchers tried to design and fabricate drones in insects' sizes [141–144]. To this end, a new class of drones was defined which is recognized as pico air vehicles (PAVs) [142]. Because of their small sizes and low weights, there are just a few types of PAVs. Quadrotors and flapping wings are the designs used in the PAV class. Between the mentioned types, recently, flapping wing PAVs received more attention than rotary wings (quadrotor) because flapping insects showed amazing flight performances, such as hovering, abrupt acceleration, and rapid turning [141]. Many researchers worked on microrobotic drones. Shimoyama et al. [143] were the pioneers who worked on microrobotic flight. They proposed a conceptual design for a microrobot with an external skeleton and elastic joints like in insects. While different approaches were pursued by various groups to design flying microrobots, Dickinson et al. [144] tried to build an insect size drone with a wing span of about 25 mm and weighing about 100 mg. In order to investigate the butterfly flight, Tanaka et al. [141] developed a tiny and light butterfly type flapping wing whose weight, wing span, and frequency were equal to 0.4g, 140 mm, and 10 Hz, respectively. Wood et al. [142] started the “RoboBee” project to design and manufacture flapping wing PAVs. Different types of pico air vehicles are depicted in Fig. 9. In Table 12, the characteristics of the two fabricated pico air vehicles in Fig. 9 are shown.

2.6. Smart dust

Nowadays, the combination of nanotechnology, wireless sensor networks, and micro-electro-mechanical systems (MEMS) has an important role in a wide variety of applications, such as climate control, building safety, and environmental monitoring [150]. One of the interesting examples of a sensor network technology is the ‘smart dust’ project which consists of hundreds to thousands of tiny micro-electro-mechanical systems that can be used for light, temperature, vibration, magnetism, or chemicals detection [151]. These robots are usually distributed over some areas to perform their defined tasks. For example, smart dust nodes can be moved by winds or can even remain suspended in air for monitoring of weather conditions, air quality, and many other phenomena [152].

The concepts for smart dust emerged from a workshop at RAND in 1992 and a series of DARPA studies in 1990 [153,154] and then later expanded by Warneke et al. in 2001 [151]. Pister and his coauthors [151,155] tried to design a wireless communication system for sending and receiving data from smart dust systems. Smart dust usually consists of many dust motes and each mote contains one or more sensors, a power supply, analog circuitry, bi-directional communication, and a programmable microprocessor [156]. Depending on the power source, which can be based on solar cells or thin film batteries, the size of the dust motes can vary from 1 mm to 3 mm [155]. These dust motes can be applied for both commercial and military applications. As for military applications, dust motes usually contain acoustic, vibration, and magnetic field sensors which can be delivered to the

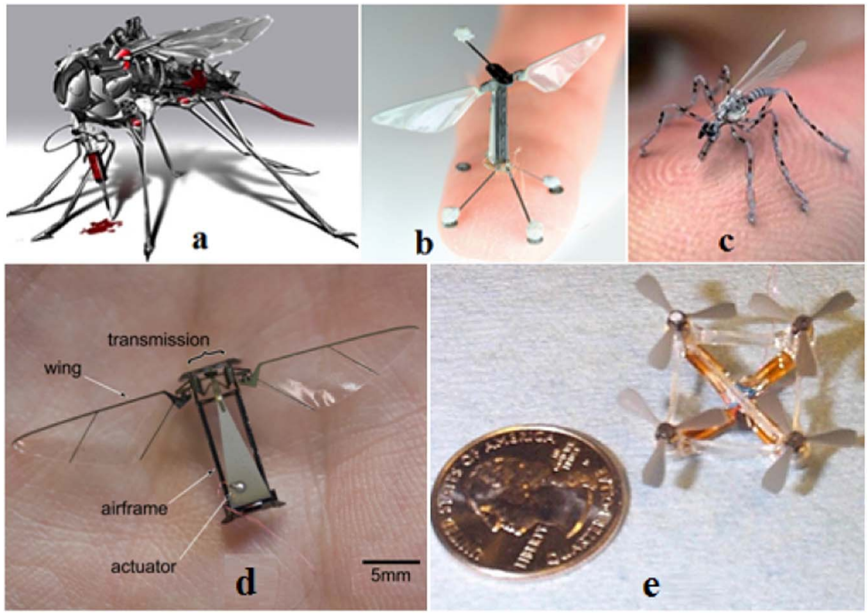

Fig. 9. Different types of PAVs, (a, b, c, and d) flapping wing [145–148], and (e) quadrotor [149].

Table 12
The characteristics of different types of PAVs [148,149].

Name	Manufacturer	Weight	Wing span
[d] RoboBees	Harvard University	0.5g	3 cm
[e] Mesicopter	Stanford University	1.5g	1.5 cm

target area by unmanned air vehicles (UAVs) or micro air vehicles (MAVs). Recently, there is an effort to incorporate chemical and biological sensors to dust motes [155]. In Fig. 10, schematic views of smart dust are shown.

2.7. Bio-drones

Because of the importance of reconnaissance and patrolling in civil and military applications, applying new instruments for these tasks has received much attention. Sometimes, huge and enormous drones, such as Global Hawk are designed and developed to perform these missions. As mentioned before, however, micro drones with smaller dimensions and weights could attract the attention of military and civil centers. There are different techniques for the design and fabrication of small drones. One of these techniques is the inspiration from birds and insects. There are other techniques which propose the use of live or dead birds and insects for reconnaissance and patrolling or other missions instead of design and fabrication of artificial drones [163,164]. Therefore, some live insects or birds that can be controlled by using some electrical chips on them can be utilized. Next, the different types of bio-drones will be discussed. In this review, the bio-drones are divided into two categories, namely, taxidermy and live drones.

2.7.1. Taxidermy bio-drones

One of the innovative ideas that was presented in the recent years is using the dead bodies of animals or birds as flying platforms for drones. In other words, the taxidermy bodies of animals and birds were applied as structural part of drones and are combined with other parts, such as electrical batteries and sensors. Jansen [165] was the pioneer of using taxidermy bodies of animals as flying platforms. He applied the dead bodies of different animals including cat, rat, ostrich, etc, in order to fabricate quad-copters (Orvillecopter and OstrichCopter), tricopter (Ratcopter), etc. Even though the dead bodies of cats and rats are not relevant examples of flight efficient structures, applying the same concept for the taxidermied birds can be considered as new platforms for flapping wings. Scientists at Duke University with cooperation of engineering students and a taxidermist applied a taxidermied dead bird animated by off-the-shelf robotics to study the behavior of the swamp sparrow species. They programmed simple Picaxe computer chips and built a tiny linear motor to fit inside the cavity of the bird named Robosparrow [166]. Even though this taxidermy bird was used for biology studies, it gives researchers new ideas to use taxidermy birds as drones. Different types of taxidermy bio-drones are presented in Fig. 11.

2.7.2. Live bio-drones

Development of low power radio systems and miniaturization of digital circuits coupled with neurophysiology studies and dynamics of birds and insect flight can provide the capability to control the birds' and insects' flights. According to advances in microfabrication technology and considerable progress in understanding of insect flight, researchers started to build insect size robots. However, because of the limitations in current technology and knowledge of insect flight, fabrication of tiny flyers which can fly well in real environments is a difficult task. Nowadays, the smallest micro drone is the microrobotic-fly which was built at Harvard Microrobotics Laboratory with 60 mg total weight [167]. Even though these tiny drones are rapidly evolving, they are currently struggling with difficulties in replicating the mechanical efficiencies and power densities of existing power sources.

Recently, some researchers [168] have attempted to solve the mentioned problems by merging synthetic control and communication systems into living insects with the aim to control free flight. Also, scientists from the Robot Engineering Technology Research Center at Shandong University of Science and Technology in China could attach an electronic chip to the brain of a pigeon which allowed them to remotely control the pigeon movements. They used hair-thin electrodes which were implanted in the brain of the pigeon in locations responsible for movement [164]. Furthermore, the birds can be equipped with some sensors, such as GPS, modems, and camera and released in the target area to carry out the mission without having control on their motions. Different types of live bio-drones are presented in Fig. 12.

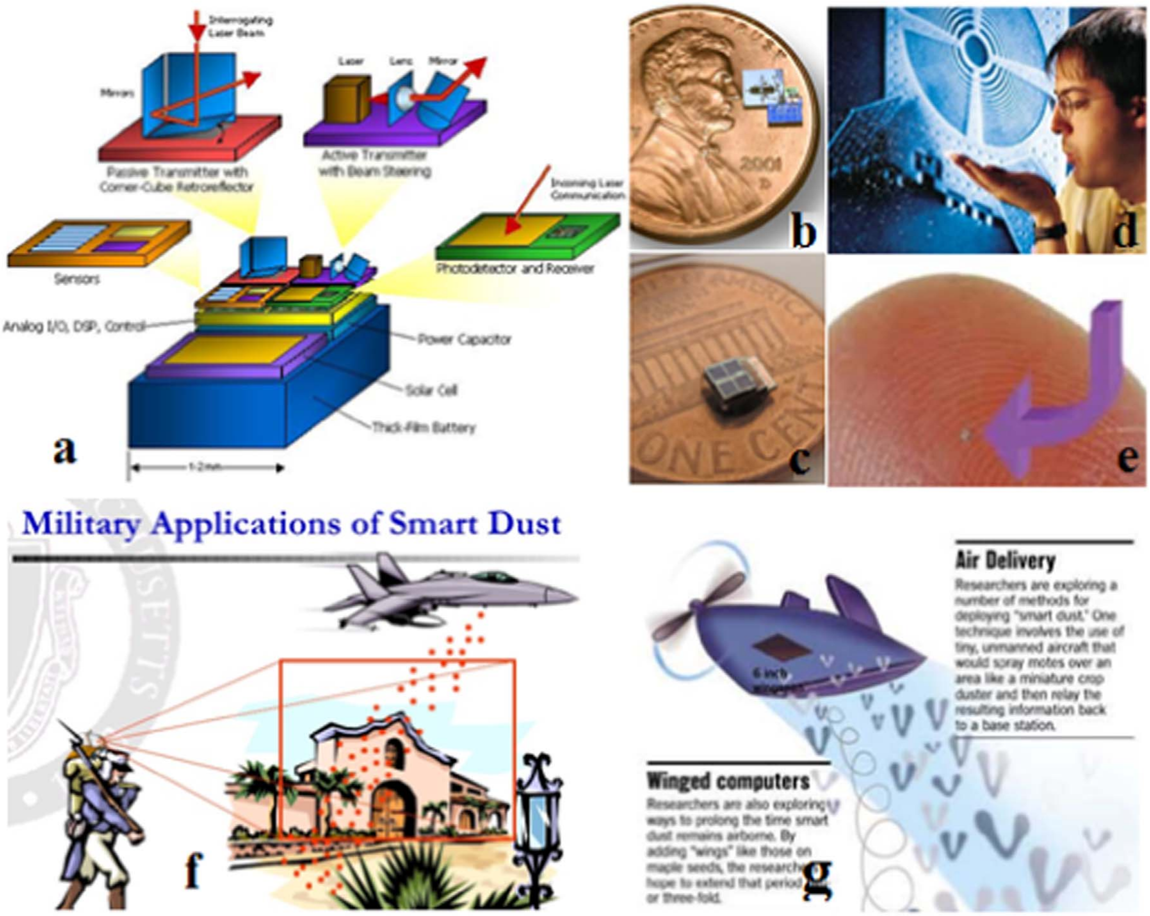

Fig. 10. (a) Structure of smart dust motes [157], (b, c, d, and e) smart dust motes [158–161], and (f and g) smart dust application [162].

2.8. Hybrid drones

Nowadays, some efforts are made to design and fabricate drones with different abilities that can be applied in various environments. Different drones were invented having the ability to walk and move on the ground and water or swim and dive under water. A hybrid tank-quadcopter was created by a company named 'B' that in response to the flip of a switch, can transform the drone from a dirt-barreling tank into a sky-flying quadcopter (Fig. 13(a)) [173,174]. DALER robot is a drone that flies and walks [175] which consists of a flying wing with adaptive morphology that enables the robot to perform both the long distance flight and walks in target environments for local explorations. This

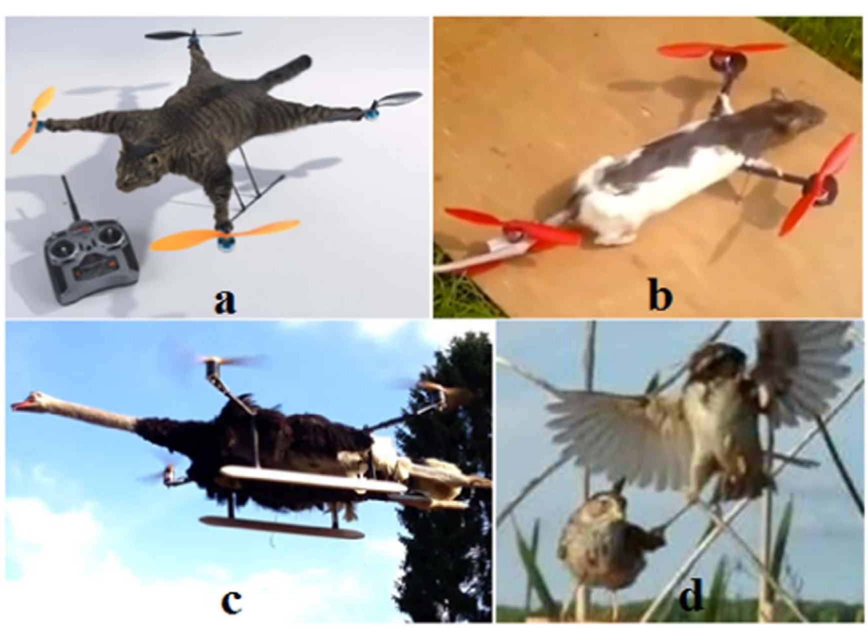

Fig. 11. Taxidermy bio-drones (a) Orvillecopter, (b) Ratcopter, (c) OstrichCopter, and (d) Robosparrow [165,166].

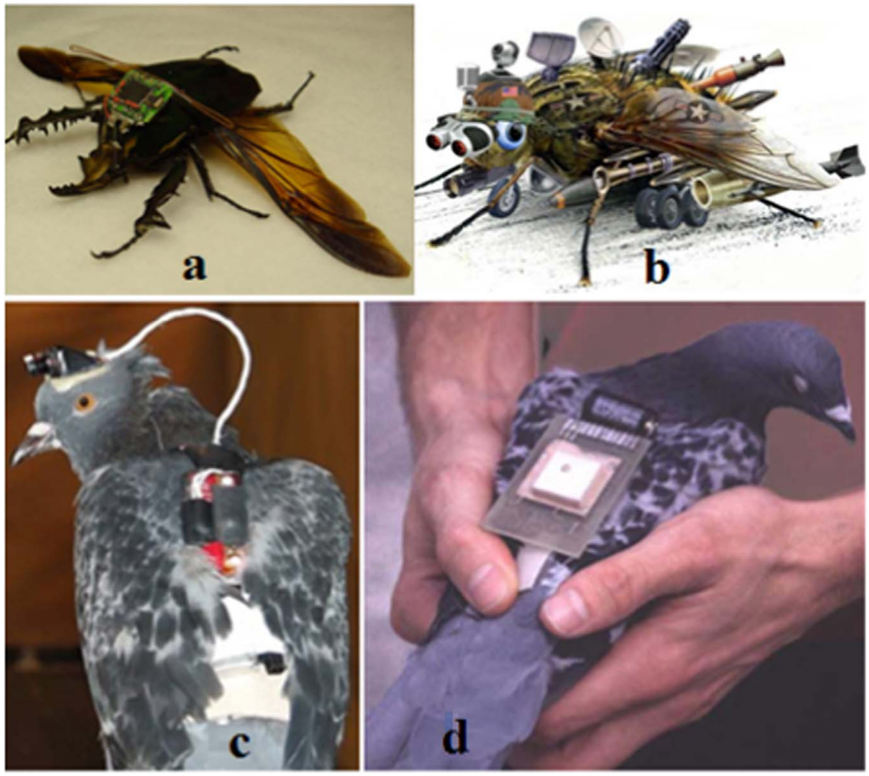

Fig. 12. Live bio-drones (a) controlled beetle [169], (b) schematic of controlled insect [170], (c and d) controlled pigeon [171,172].

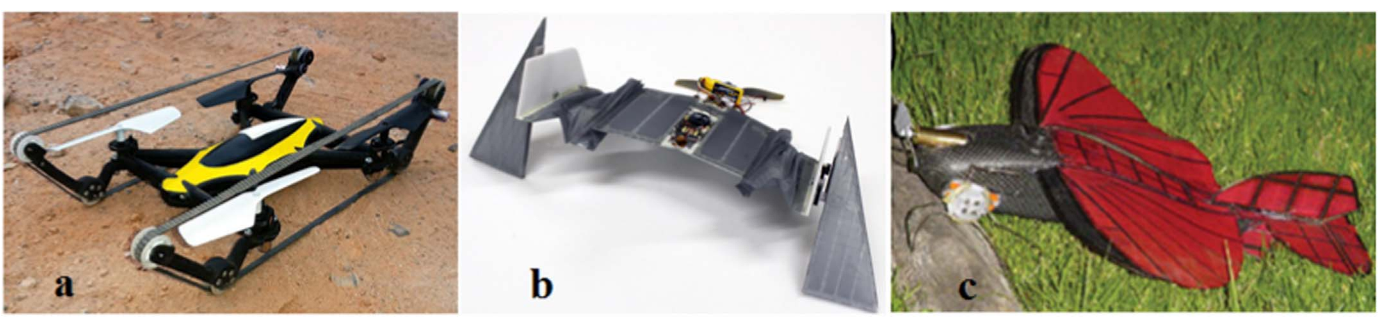

Fig. 13. Air-ground hybrid drones: (a) tank quadcopter [174], (b) DALER robot [175], and (c) MALV [5].

drone was inspired from the vampire bat Desmodusrotundus which can perform aerial and terrestrial locomotion with limited trade-offs (Fig. 13(b)) [175,176]. Furthermore, the micro air-land vehicle (MALV) which was designed by Bachmann et al. [5] is another drone which can fly and walk over rough terrain using passively compliant wheel-leg running gear(Fig. 13(c)). Parrot Hydrofoil is a drone that is considered as a remarkable hybrid robot in both air and water (Fig. 14(a)) [177,178].

Researchers from Rutgers University developed a flying and diving drone to aid search-and-rescue operations, defuse underwater mine threats, and monitor oil spills, (Fig. 14(b)) [179]. In addition, there is another type of hybrid drone named HexH20, which has the capability to fly and dive underwater (Fig. 14(c)) [180]. Researchers from the Aerial Robotics Laboratory of Imperial College London designed a multimodal flapping wing MAV which was inspired from an amphibious bird that can fly, dive into the water, and retake flight. This Aquatic Micro Air Vehicle (AquaMAV) is supposed to monitor the water quality, and do search and rescue operations and underwater explorations (Fig. 14(d)) [181]. In Figs. 13 and 14, the air-ground and air-water hybrid drones are presented. In Table 13, characteristics of different types of hybrid drones shown in Figs. 13 and 14 are provided.

3. Applications of drones

The applications of drones cover a wide range of civil and military applications. Drones can perform both outdoor and indoor missions in very challenging environments [182]. Drones can be equipped with various sensors and cameras for doing intelligence, surveillance, and reconnaissance missions. The applications of drones can be categorized in different ways. It can be based on the type of missions (military/civil), type of the flight zones (outdoor/indoor), and type of the environments (underwater/on the water/ground/air/space). In Fig. 15, a flowchart of different types of drones' applications is shown [183,184].

As shown in Fig. 15, drones have a variety of applications in our daily life. Drones can have more than two-hundred applications in future according to their types [183,184]. For example, these drones can be used for search and rescue missions, environmental protection, mailing and delivery, performing missions in oceans or other planets, and other miscellaneous applications [185]. These drones can provide a rapid overview around the target area without any danger. Drones equipped with infrared cameras can give images even in the darkness [186]. For instance, because of their reduced dimensions, micro drones

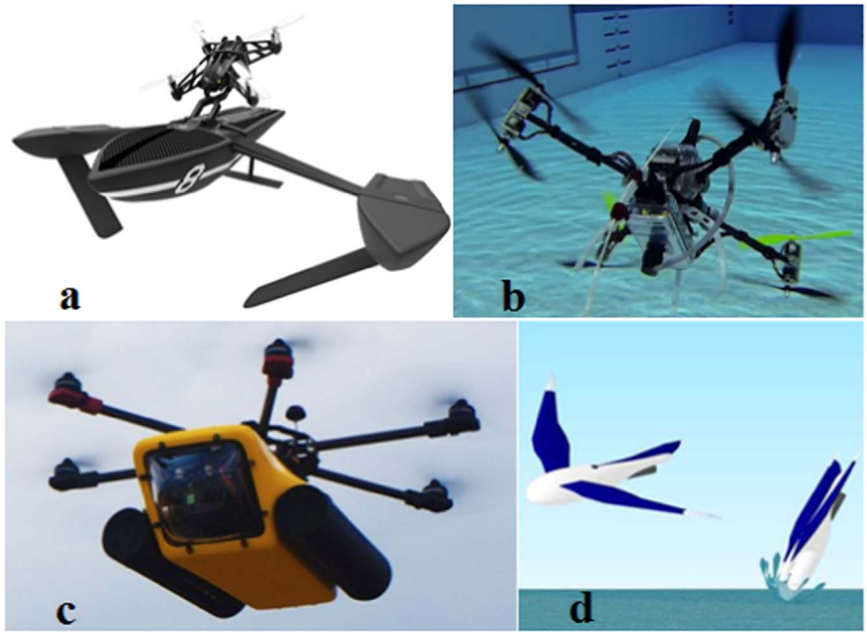

Fig. 14. Air-water hybrid drones: (a) Parrot Hydrofoil [178], (b) Rutgers University drone [179], (c) HexH20 [180], and (d) AquaMAV [181].

Table 13
The characteristics of different types of hybrid drones [5,174,175,178–181].

Name	Manufacturer	**weight**	**Wing span**
[13-a] B-Unstoppable	Bgobeyond	84 g	23.5 cm
[13-b] DALER	Laboratory of Intelligent Systems (EPFL) and (NCCR)	393 g	72 cm
[13-c] MALV	Supported by U.S. Department of Defense	118 g	30.5 cm
[14-a] Parrot Hydrofoil	Parrot	247 g	34 cm
[14-b] Rutgers University drone	Supported by the Office of Naval Research	2000 g	90 cm
[14-c] HexH20	QUADH20	4700 g	74 cm

can be used for reconnaissance inside buildings. As reported in [130,187], small drones are currently the only way to "look" inside buildings in the battlefield. They can carry specific sensors to locate biological, nuclear, chemical, or other threats [188]. Next, some of the civil applications of the drones are discussed.

3.1. Search and rescue missions

One of the important applications of drones is using them in search and rescue missions [189]. In search and rescue operations, every second is vital. In order to function as efficiently as possible, it is important to be able to obtain a rapid overview of the situation. While manned airplanes and helicopters need time to be ready for doing the mission, drones can be put into action immediately without any loss of time [190]. Because of the important role of drones in search and rescue missions, they attracted the attention of many researchers. To

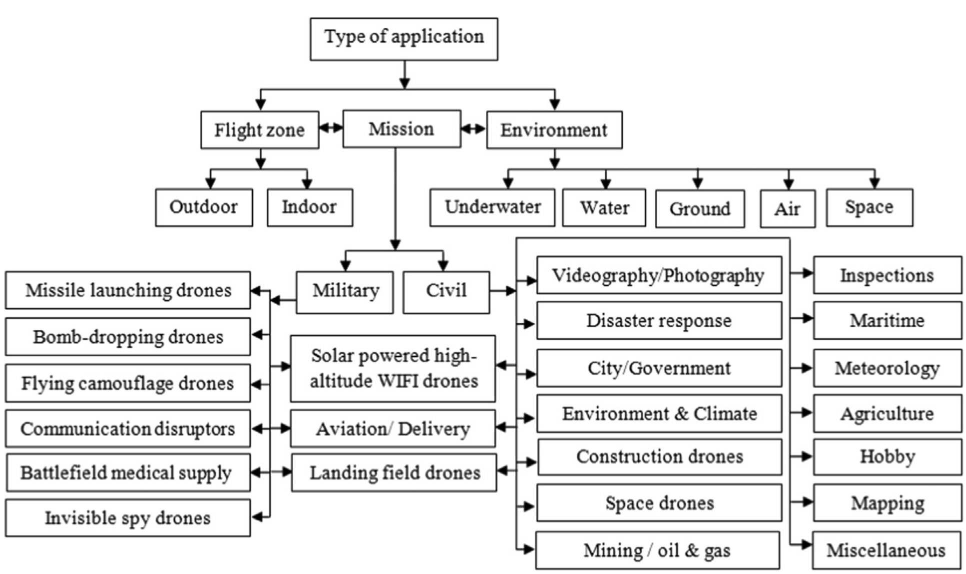

Fig. 15. Classification of drones' applications.

Fig. 16. Application of drones' in search and rescue missions [191–194].

Fig. 17. Application of drones' in environmental protection.

this end, several drones were designed and fabricated for performing this type of missions [191–194]. In Fig. 16, different concepts of search and rescue drones are depicted.

3.2. Environmental protection

Although drones are considered as a vital part of military missions, they are also being increasingly used for performing environmental actions, such as managing national parks and agricultural lands, tracking wildlife in different areas, observing the effects of climate change, and monitoring the biodiversity of different ecosystems from rainforests to the oceans [195]. These drones can be used for recognition and investigation of natural disasters including forest fires, avalanches on mountains, etc [196,197]. In Fig. 17, some types of drones which are used for environmental protection are shown.

3.3. Mailing and delivery

Recently, drone delivery service became an interesting topic for different companies around the world. For example, Amazon and

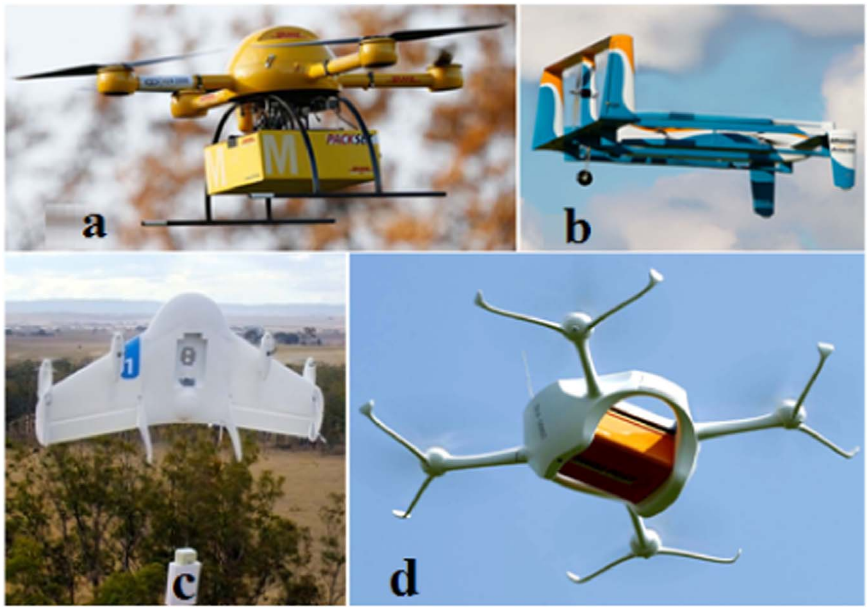

Fig. 18. Application of drones' in mailing and delivery [198–200].

Google in the U.S [198,199], DHL post service in Germany [200], and many other companies are using drones to deliver packages to customers. For delivery, the designed drones land and take off vertically and have the customer address to carry the cargos. In Fig. 18, some delivery drones are presented.

3.4. Space drones

One of the environments in which drones can be used, is space and the exploration of other planets, such as Mars. In planetary explorations, because of the advantages of drones compared to other robots, there is a tendency to design and fabricate some drones that can fly and perform missions in space environments. For example, NASA is building drones to explore other planets [201,202]. Different types of drones were designed and fabricated in order to carry-out space missions and planetary explorations [201–204]. In Fig. 19, some examples of space drones are shown. It should be noted that design and fabrication of space drones should be done based on that environment. For example, because of the amount of gravity on Mars, the weights of drones differ from their weights on Earth. Indeed, the weights reduce by 61.5% [205].

3.5. Marine drones

As shown in Fig. 14, drones can be applied in the marine environments to study marine organisms, identify the location of oil spills, and for other military or civil applications [206–208]. Because of the lack of a runway in marine vehicles, such as submarine and boats, most of the drones are launched vertically in these environments. Launching drones from underwater was introduced at first by U.S

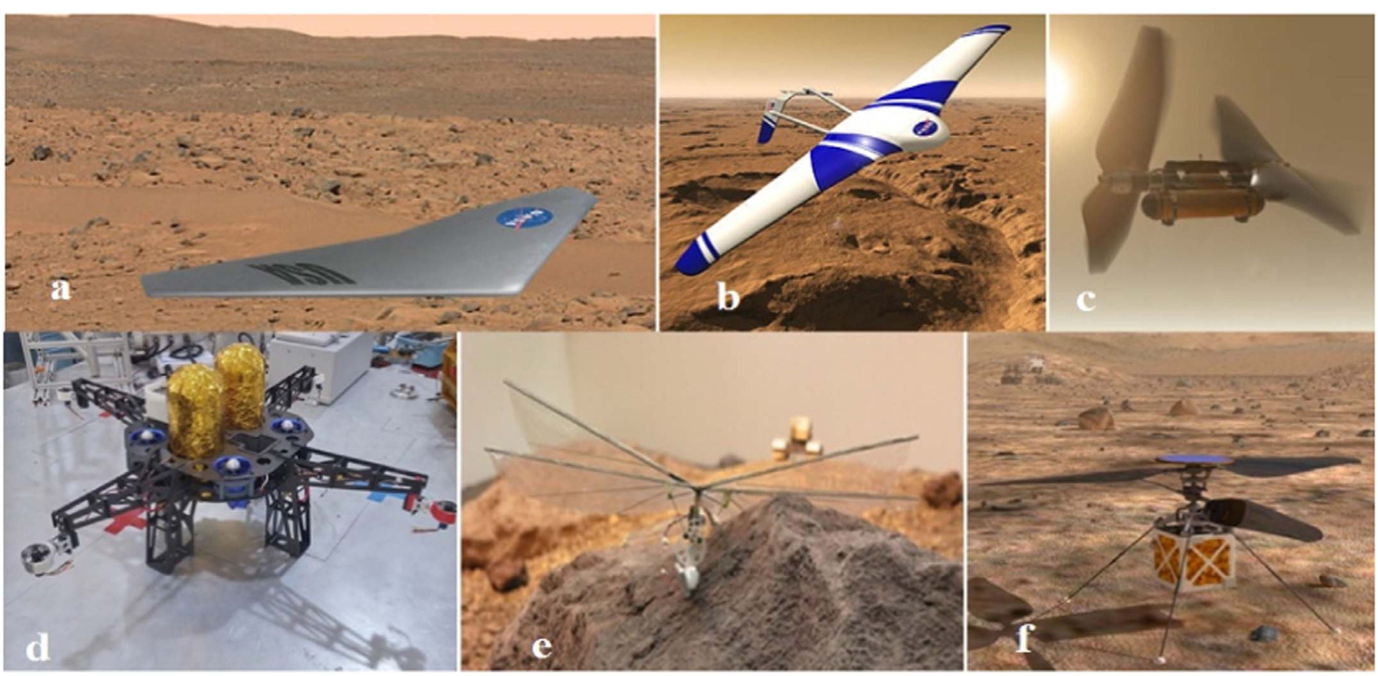

Fig. 19. Application of drones' in space [201–204].

Fig. 20. Drones' in marine environments, (a) TacMAV [209], (b) Scan Eagle [210,211], (c) Volans [212,213], and (d) Cormorant [214,215].

Table 14
The characteristics of marine drones [209–215].

Name	Manufacturer	Weight	Wingspan
[a] TacMAV	Applied Research Associates Inc.	363 g	53 cm
[b] Scan Eagle	Boeing	27 kg	3.7 m
[c] Volans	GABLER	–	–
[d] Cormorant	Lockheed Martin	–	13 m

researchers in 2005 [209]. Nowadays, there are different types of drones including Scan Eagle [210,211], Volans [212,213], Cormorant [214,215], etc, which are launched from submarines. The successful launch of these drones from submarines offered a pathway to perform critical intelligence, surveillance, and reconnaissance missions. In Fig. 20, different types of launched drones from underwater and submarines are shown. The features of marine drones shown in Fig. 20 are indicated in Table 14.

3.6. Drones' miscellaneous applications

Despite of the conventional applications of drones, they can be used in some non-ordinary missions. As an example, Tokyo's Metropolitan Police Department unveiled its new anti-drones which are used to take down naughty or offensive drones from the sky. In this type of application, if a suspicious drone is detected, at first the operator is warned. In case the operator is not found or the flight continues despite the warning, an interceptor drone is scrambled to catch the suspicious drone, as shown in Fig. 21(a) [216]. Moreover, drones can be used as a runway for another drone (Fig. 21(b)) [217], can be applied to guide (or scare) birds away from airport runways (Fig. 21(c)) [218], can be used to clean windows, gutters, and solar panels (Fig. 21(d, e, and f)) [219], and for other applications, such as hobbies, as shown in Fig. 21(g and h) [220].

4. Design methods and challenges

The design of drones regardless of their flight class, type, size, and defined mission involves three steps, namely, conceptual design, preliminary design, and detailed design [224–227]. Each step requires increasingly sophisticated sizing, aerodynamic, aeroelastic, structural, propulsion, stability, control, electronic, and fabrication analysis [6,7,91]. It should be noted that, despite the progress in drone technology, there are some gaps in their design.

One of the important tasks in the design process of all types of drones is sizing which results in the optimum values of their dimensions and weights [6,91]. The sizing process of drones is usually composed of five steps: (1) defining the mission, (2) setting the flight mode based on the type, (3) determining the wing shape (planform) and aspect ratio, (4) constraint analysis, and (5) weight estimation [6,7,91]. In the definition of the mission, the analysis of the route is conducted resulting in the determination of the flight time, cruise speed, and turning speed. After that, the determination of the flight modes, shape of the wing and its aspect ratio are determined based on the type of mission. Then, to determine the appropriate wing loading and thrust loading of drone, a constraint analysis is carried out in which the kinematic and dynamic equations of the flight are simulated. Along with the afore mentioned steps, different methods for weight estimation can be employed. The result of this process is the determination of the geometry and dimensions of the drones and also the calculation of some aerodynamic parameters for each type [91].

The sizing process should be performed as accurately as possible [228]. In Fig. 22, a schematic view of the costs for the design and fabrication of different types of drones is shown [229,230].

The trend shown in Fig. 22 is caused by the practical and experimental issues that arise when scaling a drone, such as increased or reduced power density of propulsion systems, electronic boards, fabrication methods, etc. Small drones (μUAV, MAV, NAV, and PAV), are not merely scaled down versions of larger airplanes [38]. Since all the characteristics of larger airplanes have to be retained in a small volume, the challenges and complexity in their design and fabrication increase significantly. In recent years, although scientists tried to design insect size drones, the miniaturization progress of these drones has slowed down due to the physical and technological challenges posed by the decreased size [130,231]. The important problem in these types of drones is related to the low Reynolds number which results from their low speed and small sizes [90,232]. Generally, flight in this regime of flow is more difficult. Because of this, researchers started to study the flight of insects [233–235]. Next, some challenges for designing some types of micro drones are discussed.

4.1. Challenges in fixed wing micro drone design

Among the different types of micro drones, fixed wings are the most developed and the easiest ones to design and fabricate. This is due to

Fig. 21. Drones' miscellaneous applications, (a) anti-drones [216], (b) runway drone [217], (c) drones which scare birds away from airport runways [218], (d) windows cleaning drones [219], (e) gutters cleaning drones [221], (f) solar panels cleaning drones [222], and (g and h) hobby drones [220,223].

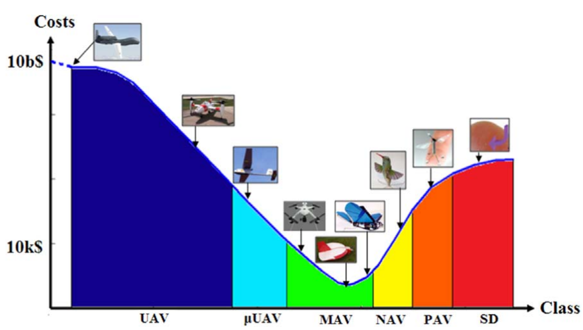

Fig. 22. A schematic view of the costs for design and fabrication of different types of drones.

the fact that there are different methods for larger fixed wing airplanes which can be applied with some modifications in aerodynamic and geometric characteristics [236]. A wide variety of fixed wing drones was developed by various organizations and researchers across the world [7,91,237,238]. These drones have different flight speed, altitude, and endurance depending on their defined mission [91]. These kinds of drones in comparison with other types, such as rotary wings or flapping wings require relatively higher speeds for flight. For example, the cruise speed of fixed wing MAVs typically ranges from 6 to 20 m/s [7,130]. It should be mentioned that this type of drones cannot hover or fly slowly and flying in indoor spaces is very challenging for them. These drones can be used in various types of missions where the high speed is required, such as flying over water and forests.

Fixed wing drones usually require a thrust loading less than one and less power to fly than a helicopter with the same weight in hovering mode [239,240]. In larger drones, the lift over drag ratio is more than 30 [239]. This value is rapidly decreased for smaller drones and consequently Reynolds number decreases [241]. Due to the decrease in the velocity, and dimensions, the operating Reynolds number is reduced and consequently the efficiency of the drone is also decreased [99]. Therefore, the advantage of large fixed wing drones becomes less pronounced when the lift over drag ratio is reduced to less than 10 [130]. Several fixed wing drones were designed and fabricated, but none of them are in the PAV or NAV classes with dimensions less than 10 cm. Generally, to design fixed wing drones, researchers used trial and error methods which increase the cost and time of the design process [242–244]. Because of using trial and error methods in designing fixed wing drones, their design cannot be considered optimized due to uncertainties in weight estimation, sizing, selection of the best wing shape and aspect ratio for maximum endurance.

4.2. *Challenges in flapping wing design*

To design bio-inspired flapping wing drones, some methods are based on empirical formulae [245–256]. These formulae were established based on allometrical data extracted from biological avian flight [7]. The pioneers of these researches include Pennycuick [246,247], Rayner [248,249], Tucker [250,251], Lighthill [252,253], and Spedding [254]. Their empirical formulae related the design parameters of flapping wings, such as wing area, weight, and wing loading to the flapping frequency, flight speed, and required power for flight. In addition to that, these formulae related the geometry of the wing including the area and wing span to the weight of the FWMAV. These empirical formulae were used for sizing of FWMAVs by some researchers, such as Beng [255] and Beasley [256]. In his design, Beasley [256] utilized the biological mimicry for sizing the flapping wing. Indeed, by using the geometric scaling factors for Passeriformes [257], the fixed span, weight, flapping frequency, wing area, and aspect ratio of the MAV were determined from the logarithmic relationships [256]. Other methods based on statistical and experimental sizing and testing were applied. As an example, Gerard and Ward [110] designed their flapping wing MAV based on existing FWMAVs, such as Luna and DelFly.

There are other methods which were utilized for sizing of NAV and PAV flapping wings. For instance, Whitney and Wood [103] proposed a conceptual design process for insect-sized flapping wings with a primary focus on hovering flight. Many assumptions were considered in their method including linear and lumped representations to model the dynamics of the vehicle and the blade-element method to model the aerodynamic forces. In their method, after developing a dynamic model for the flapping wings, they used energy methods to determine the fractions of the actuation mechanism and mass of the battery. Combining this sizing methodology with derived limits on wing structural-inertial efficiency, the range of feasible designs and the limits of performance of the flapping wing PAVs were specified.

Most of the mentioned sizing methods were based on allometric formulae extracted from natural birds and insects which were applied directly for sizing of artificial flapping wings without taking into account the impacts of other parameters including the used materials for the wing membranes. Using the empirical formulae of natural birds and insects, non-optimized micro drones are designed. Therefore, these empirical formulae should be revisited and probably some correction factors are needed [7].

After sizing and during design process of flapping-wing drones, different aerodynamic and structural analyses can be performed on them [258]. Usually, in natural and manmade flapping wings, their aerodynamic, structural and flight dynamics intersect with some of the richest problems, such as unsteady three dimensional separation, transition in boundary layers and shear layers, unsteady flight environment, aeroelasticity and anisotropic wing structure, and nonlinear and adaptive control [259]. There are different theories which are used to model the aerodynamic forces of the natural and manmade flapping wings, such as quasi-steady, strip theory, unsteady, and Navier–Stokes methods. It should be mentioned that the type of analysis is dependent on the type of flapping wing, its configuration, and flight modes. For instance, the complexity of aerodynamic analysis is increasing for flapping wings in tandem wing configurations. This wing configuration has been used by nature's flyers, such as dragonflies. Studying the unsteady flow interactions between two wings is more complex than the case of a single wing; however, two pairs of wings can provide increased lift and thrust and gust resistance [260].

Many researchers, such as Azuma [261], Lighthill [262], Maxworthy [263], Norberg [257], Pennycuick [264], Spedding [265], and Weis-Fogh [266] opted to use a quasi-steady aerodynamic model [99]. This model is centered on a slow wingtip speed relative to the overall velocity of the body [267]. This theory is constructed based on the instantaneous velocity, wing geometry, and angle of attack when the steady-state aerodynamic model is used. Using a quasi-steady model greatly simplifies the aerodynamic model because it allows neglecting the wing motion and flow history, or in other words, the wake effects caused by unsteady motion [99]. Although this approach can greatly reduce the complexity of the modeling, it falls short in accounting for the unsteady effects seen in flapping motion [267]. Many animals and systems exhibit flight that can be accurately modeled by the quasi-steady approximation but others, like many insects, have very high flapping frequencies that generate unsteady contributions to the aerodynamics of the flight [268]. Based on the theoretical analyses of Ellington [269] and the experimental measurements of some tethered insects [270,271], it has been indicated that the quasi-steady model is insufficient to predict the required lift to support insect body weight [99].

Another common theory was used to model the flapping motion of natural and manmade flapping wings, is strip theory [107,272]. This theory is based on dividing the wing into multiple sections and creating an integral function to account for the effects of each strip into an accurate aerodynamic model. This strip theory can be used to determine the average lift and thrust through the cycle of the flapping motion of the system [273]. Strip theory was utilized by many researchers in order to study the performance of flapping wings [107,255,268,273–275]. Benedict et al. [275] wrote a code in C++ for the strip theory. He considered the same assumptions which were implemented by DeLaurier [107]. His code was written to calculate the aerodynamic parameters using the unsteady strip model. Zakaria et al. [273] applied the strip theory to computationally study the unsteady aerodynamics of the commercial flapping wing (SlowHawk 2). Beng [255] wrote a Matlab code for the strip theory and applied it for Pterosaur replica to evaluate his code with the obtained result by DeLaurier [107] and Kamakoti et al. [274]. Hassanalian et al. [272] developed the strip theory in Scilab to study the wing shape and dynamic twist design of bio-inspired nano air vehicles for forward flight. In this study, the wing shapes of seven insects were chosen to be analyzed for their aerodynamic performance and ability to perform forward flight missions [272].

Aerodynamics of birds and insects during the flapping flight can be also modeled within the framework of unsteady Navier–Stokes equations [99]. In this method, nonlinear physics with multiple variables, such as velocity and pressure, and time-varying geometries are among the aspects of interest [99]. This theory is applied and developed by many researchers. Liu and Kawachi [276] and Liu et al. [277] conducted unsteady Navier–Stokes simulations of the flow around a wing of a hawkmoth, to study the unsteady aerodynamics during the hovering flight. They modeled a realistic geometric wing and flapping kinematics of the considered insect and observed the features of the Leading Edge Vortex (LEV) and the spiral axial flow during translational motions [99]. Their results are consistent with those observed by Ellington et al. [278]. Also, using 3D Navier–Stokes computations, Viieru et al. [279] and Shyy and Liu [280] investigated the Reynolds number effect on the LEV for hovering flight.

Beside the discussed methods, different experimental approaches can be carried-out to study the aerodynamic of flapping wings. As an example, for flow field investigations, particle image velocimetry (PIV) is usually applied by researchers [259]. The combination of different aerodynamic theories and applying the experimental study in parallel can be proposed as the best way to have more realistic results.

4.3. Challenges in rotary wing design

Rotary wing drones are designed based on the number and positions of their motors. These drones can fly with high speeds and perform the vertical take-off, landing, and hovering flight [38,281]. Micro rotary wing drones can fly in indoor spaces and are perfect for patrolling [282,283]. Generally, the endurance of these types of drones is restricted due to the required higher power for the hovering flight mode [130]. There are many challenges in designing these drones when their size and weight are decreased. For instance, when they have low thrust loading and the efficiency of rotors is low [284]. Despite these disadvantages, rotary wing drones can fly with high and low speeds and also can perform hovering flight based on the defined mission [285].

Based on the number and position of the motors, there are different configurations for rotary wing drones [38,286]. Each one of these configurations is suitable for specific types of missions. To this end, the selection of each configuration depends upon the mission requirements. For example, if the drone is supposed to perform a maneuverable mission, the quadrotor or hexacopter drones should be considered. Generally, for rotary wing drones, weight is an important criterion. Nowadays, there exist several prototypes of these types of drones in different dimensions. Although the rotary wings have simple control systems and they are very maneuverable, their main disadvantage is the power consumption [287,288].

4.4. Challenges in tilt-wing and tilt-rotor design

Since the beginning of the 21st century, many researchers and companies tried to invent effective flying drones with improved performance and capabilities [289]. In the past few years, tilt-rotor and tilt-wing drones were developed because of their excellent performance [290]. These drones have the capabilities to carry out the vertical flight capabilities of rotary-wings with the high speed long duration flight of fixed wing drones [291]. In other words, the tilt-rotor and tilt-wing drones' configurations have the potential to alter the air transportation by providing a combination of vertical take-off and landing capabilities with efficient high-speed cruise flight [292,293]. These types of drones have a bright future in military and civilian applications [294]. Although, fixed wing drones suffer from the requirement of runways or additional launch and recovery systems for take-off and landing, tilt-rotor and tilt-wing drones could solve these issues [295]. These drones can perform a vertical take-off and landing (VTOL), hovering, and high cruising speed flight by changing the angle of the rotor or wing by a tilt actuation mechanism [296]. Among different types of these drones, tilt-rotors have attracted many designers because of their energy efficiency, stability, and controllability in various missions [297,298].

The design procedure of tilt-rotor drones is a combination of fixed and rotary wing drones which has their same challenges [38]. One of the challenging issues in tilt-rotor drone design is their transition mode. This is due to the fact that the conversion of flight modes between vertical and horizontal configurations necessitates a different control strategy [299]. However, because of the complexity in transition mode, further studies of these drones are needed [293,300]. In these drones, degradation of stability is usually found at high-speed in forward flight mode and the involved equations of motion are highly coupled and nonlinear [292]. Researchers made several studies on the dynamic and control models of these types of drones [301–304]. However, most of them applied linearization techniques which make their results inaccurate due to the neglect of the present nonlinearities [290]. Most of the researches on tilt-rotor and tilt-wing drones have been done on dual tilt-wings, such as HARVee [305] and dual tilt-rotors including Bell Eagle Eye, BIROTAN and Smart UAV of KARI [292]. A cyclicrotor control is required in dual tilt-rotor drones which increases the mechanical complexity [291].

Different control methods were offered to perform autonomous transition maneuvers for tilt- and wing-rotor drones [287–290]. Çetinsoy et al. [291] invented a new drone called SUAVI which can perform vertical take-off and landing like a helicopter and also is capable to fly like an airplane. In their work, their analysis was missing the transition maneuver which is the most interesting phenomenon in this kind of drones [306]. Naldi and Marconi [307] offered an optimal transition maneuver for the tail-sitter V/STOL. Some numerical trajectories at simulations levels which show the transition maneuver were applied. In most of the tilt-rotor drones, as performed in several studies [291,308–310], the control problem of the transition maneuver was analytically considered and the hovering and cruise flights were investigated separately. Therefore, for the hovering and cruise flight modes, the controllers are extracted individually, using a switching condition but without developing any analysis between the mentioned flying modes.

4.5. Proposed solutions for design challenges

To overcome the mentioned challenges for different types of micro drones, developers and designers of drones should consider various parameters in the design process which can result in developing optimized drones. As discussed in the previous sections, each type of drones and their design methods have advantages and disadvantages. Therefore, by using theoretical, statistical, revised allometrical, and bio-inspiration methods, a comprehensive methodology can be proposed which finds solutions for the drawbacks of previous methods. Various types of drones can be introduced by taking inspiration from nature [311]. In current design theories of drones, the ability to transform and change the configuration can be considered as a new field of research. Even though some methodologies are currently in development that can allow for designing of transformers drones, they should be more considered for the design of lightweight, quickly deployable, easily operable, and low storage volume wings for unmanned and micro aerial vehicles [312]. It should be noted that inspiration from nature can introduce some new models to design. For example, inspiration from nature including armadillo, wheel spider, locust, ladybird or even Venus fly trap can give researchers an idea to design and fabricate some drones with cumulative wings, as shown in Fig. 23.

In summary, in the design process of drones, two parts should be considered, the first one is drones' configuration and the second one is their design methodology. Recently, there are some efforts to design drones with unconventional configurations which almost are inspired from nature, such as birds, insects, marine organisms, etc [51]. In Fig. 24, some drones which have the capability to fold their wings are shown.

5. Manufacturing methods for micro drones and challenges

According to the type and class of the drones, there are different methods and materials which are used to manufacture them. Generally, the fabrication process is one of the important steps in the creation of drones. In fact, every step in the manufacturing process affects the final performance of the drone. Thus, in the manufacturing stage of drones, it is important to determine the manufacturing method and the used material to fabricate them. Usually, according to the type and class of the drones, each part of them can be fabricated with different methods and materials, and then they can be assembled [6,7]. It should be mentioned that the selection of the fabrication method is related to the used materials and the selection of the materials is dependent on the type of structural parts of the drones and the required criteria for their weight, strength, stiffness, etc. Next, different methods and materials which are applied in manufacturing of drones are reviewed.

5.1. Manufacturing of fixed wing drones

Fixed wing UAV, μUAV, and MAV drones, usually consist of wing, fuselage, booms, vertical and horizontal tails. Each part of the drone is fabricated with different materials and methods. The applied materials in fixed wing drones can be metallic materials, such as aluminum which are used in huge UAVs, composite materials including kevlar, fiberglass, fiber carbon and other materials including wood, Styrofoam, and plastics (PVC) which are applied in the fabrication of fixed wing MAVs and μUAVs [317]. Nowadays, composite materials are considered as popular materials in the manufacturing process of drones. Unlike metallic materials, the actual material properties of composites are generally not available because their properties are dependent on the manufacturing process [318]. The current materials technology enables the access to different types of composite materials.

Recently, with the advances in the composite manufacturing technology, very complex shaped parts can be easily built. Thus, most of the UAVs are built from composite materials. Moreover, the maintenance and repair processes of UAVs can be performed quickly and easily [318]. Also, composite materials are the most popular technology employed in μUAVs and MAVs structures. Indeed, this type of material provides high accuracy and good quality of surface in these types of drones. Generally, the important advantage of composite material is the possibility of manufacturing airframes with very complicated shapes. The disadvantage of this material is the high cost of the mould preparation [319].

The composite material manufacturing process consists of different steps, such as 3D CAD shape design, CNC mould milling, wet lay-up, prepreg laminating, high temperature curing, and off mould fettling/dressing [319]. There are various fabrication methods for preparing a composite material from continuous fiber and non-metallic matrix material. Some of them are matched die molding, vacuum bagging, filament winding, and resin transfer molding. One of the main features of the vacuum bagging method compared to curing in autoclave is that it is less expensive to set up [318]. In Table 15, a comparison between some conventional used materials in fixed wing drones including aluminum sheet, wood, Styrofoam, plastics (PVC), and carbon fiber is presented.

As shown in Table 15, different factors are listed to compare between the different used materials including stress factors, manufacturability, and cost [321]. It should be noted that each of the mentioned materials are used for a specific part of the drone. For example, balsa wood is usually used to fabricate the fuselage of micro drones with low weight. As presented in Table 15, the only drawback of balsa wood is that its strength is low compared to metal materials, such as aluminum or steel. However, in terms of manufacturability, balsa wood is one of the best materials for micro drones among others. Balsa wood has light weight compared to aluminum, carbon rod, stainless steel, and iron. The cost for manufacturing of balsa is low as it is soft

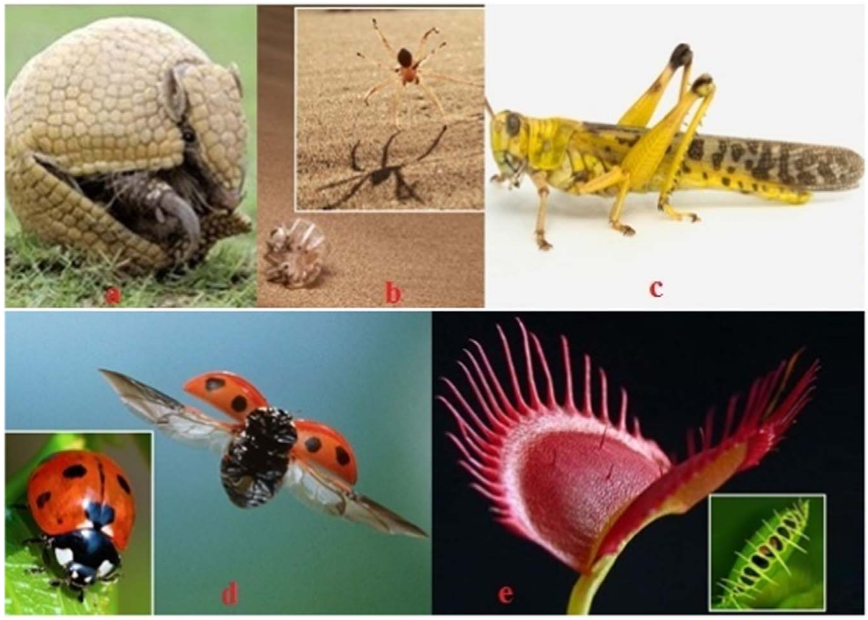

Fig. 23. Views of (a) armadillo, (b) wheel spider, (c) locust, (d) ladybird, and (e) Venus fly trap.

and can be crafted manually without any machine [321,322]. Usually, balsa wood is selected to fabricate the fuselage and tails of drones in μUAV and MAV classes with low weight [6,7].

The wings of fixed wing micro drones are usually fabricated from foam or composite materials. Recently, there are different types of foam that have the lowest density in comparison with other materials [317]. Because of the lowest strength of foam; it is usually used in the fabrication of μUAVs and MAVs. Hotwire cut is the best and easiest way for manufacturing the wings [6,91,323]. Other materials which can be used in drones' structures fabrication are composite materials, such as carbon fiber, fiber glass, etc. Carbon fiber reinforced polymer has higher strength than fiber glass and they are cheaper than spectra fiber. However, carbon fiber can be reinforced by resin matrix under heated condition to achieve their maximum hardness and strength. This increases the complexity of the manufacturing method [321]. Therefore, carbon fiber reinforced polymer is not a suitable material to fabricate the skin of μUAV and MAV classes. In comparison with carbon fiber reinforced polymers, fiberglass is considered as a light-weight, extremely strong, and robust material that can be utilized in drones' fabrication. Although the strength properties of fiberglass are somewhat lower than carbon fiber and it is less stiff, their material is typically less brittle, and its raw materials are much less expensive [324].

5.2. Manufacturing of flapping wing drones

The manufacturing process of flapping wings and the applied materials in their structures are different from other types. The fabrication techniques are dependent on the class of the flapping wings. For instance, the materials and methods which are used for flapping wing PAVs are different from flapping wing MAVs [325]. Flapping wing drones usually consist of wing, fuselage, tails, and

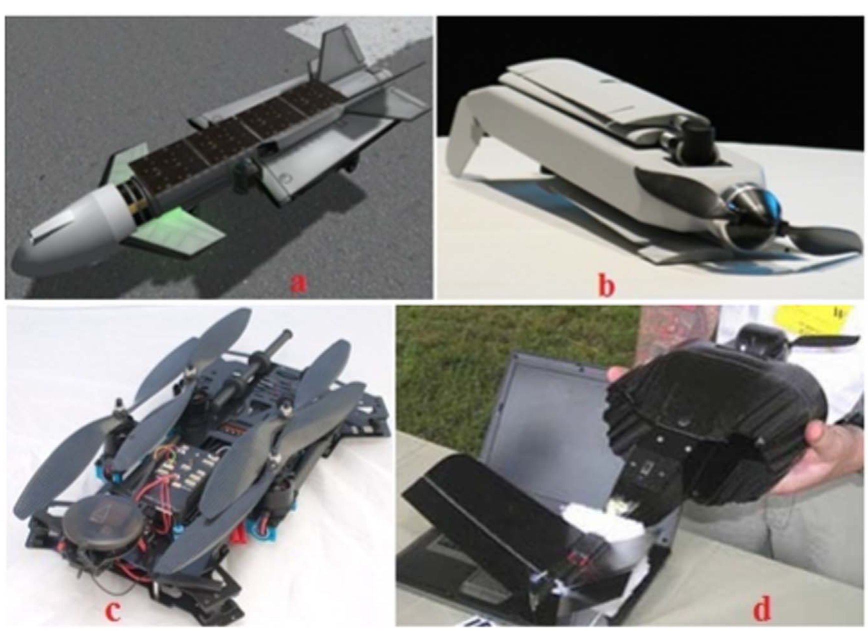

Fig. 24. Views of different types of drones with folding wings [313–316].

Table 15
Comparison between different types of materials [320].

Material	Density (g/cm^3)	Tensile strength @73°F (psi)	Stiffness Mpa	Methods of manufacturing	Price
Aluminum	2.7	30,000	70,000	Forging	Expensive
Wood	0.8	550	10,000	Adhesive bonding	Cheap
Styrofoam	0.18	100	5000	Hotwire cut by CNC	Cheap
Plastics (PVC)	1.15	7000	3000	Vacuum forming	Very cheap
Carbon fiber	1.78	10,0000	50,000	Epoxy resin	Very expensive

actuation mechanism. The wing that constitutes the main part of flapping wing drones consists of a structural part (spars and ribs) and a membrane. The light-weight materials used in the building of the wing and tails of the flapping wing MAVs are foam, wood, composite materials, such as fiberglass and fiber carbon, and flexible membranes, such as mylar or plastic tissues [256]. Composite materials and foam are usually utilized for the fabrication of the fuselage. To have symmetric wings, a well-controlled manufacturing method should be applied for constructing and assembling the wings. In fabricating flapping wing MAVs, usually a practical cut-and-glue method is applied, which is considered as the simplest and cheapest way [111]. However, this method is not accurate because all steps are done by hand and therefore there are many uncertainties. As an example, the ribs, diagonal, and leading edge spars are often not glued symmetrically on the wings [111]. For flapping wing MAVs, conventional manufacturing methods such as, 3D printing, subtractive machining, and molding of applied materials are usually used for the fabrication of the actuation mechanism [23].

There are other methods which are applied for the fabrication of the wings of the flapping wing drones which are more accurate than the hand-made ones. The latter method is usually used in the fabrication of small flapping wings in the NAV and PAV classes. Because their dimensions are reduced, in addition to actuation mechanism and power system selection, there are also some challenges for the manufacturing of the entire drone [23]. At small scales, such as small bird-and insect-size drones, some of the mentioned techniques fail because of the restricted resolution. Nowadays, other methods are proposed and developed. For instance, to avoid the challenges that are inherent in macro-scale nuts-and-bolts approaches, some methods based on folding are being used to create insect-sized drones [23,326]. Also, the fabrication of a wing for an insect-size drone is a challenging task because of the needed flexibility distribution on the wing [327].

5.3. New materials and techniques in drones' fabrication

Nowadays, researchers are trying to introduce new materials for the fabrication of drones which have lighter weight and lower prices. For example, a team of researchers from UC Irvine [328] developed the world's lightest material which is about one hundred times lighter than Styrofoam. This new material can be used in the fabrication of drones. Kolodziejska et al. [329] proposed micro-sandwich structures with areal densities from 0.04 g/cm^2 down to 0.005 g/cm^2 that could potentially be used in the fabrication of wings or propellers of insect-like robots or other micro drones. Self-destructing drones can be made of fungus, bacteria, and wasp spit which are proposed to keep the drones invisible when they are engaged in spying activities [330]. As mentioned above, the manufacturing approaches of drones are different according to the used materials. 3D-printing is one of the recent methods which allows drones to be created quickly and cheaply [331,332]. The fabrication of inflatable drones can be also considered as a new manufacturing method which was proposed by Chinese engineers [333]. These drones have lightweight design and high impact resistance [333]. In Fig. 25, some new materials and manufacturing methods are shown.

One of the solutions is to use bird feathers and insect wings which can be considered as the main material for the fabrication of the micro and nano drones, especially for flapping wing drones. Using these natural wings and structures can help the drones to fly efficiently. Indeed, these types of materials can provide the drones the best flexibility for their wings.

6. Propulsion systems and actuators of micro drones

All of the presented drone configurations need to generate motion. Therefore, there are different ways to make a drone fly [130]. The propulsion system of drones differs according to their shapes and flight modes. For some types of the drones, such as fixed wing UAVs the propulsion system is usually similar to that on conventional aircraft. Thus, these drones do not need a unique propulsion system. Therefore, such drones can avoid the time and expense of developing new systems [334]. On the other hand, some types of drones require new propulsion technology. Thus, they need new designs and concepts. In propulsion systems, power and energy densities are two important factors. Power density is a measure of the power converter and energy density is a measure of the energy in the power source and the conversion efficiency of the engine [334,335]. The propulsion system for a drone is proportional to the weight, size, mission, endurance, etc. The selected system must provide fuel economy (gas or battery), low weight, small size, and high reliability. Generally, for all types of drones, propulsion systems (engines, fuels, and actuators) typically constitute 40–60% of their take-off weight [334]. It should be mentioned that the performance of the propulsion system has an enormous effect on air vehicle performance [335].

For fixed, tilt, and rotary wing UAVs, there are different types of propulsion systems which can be used including fuel engines (gas engine, piston engine, jet engine, gas turbine engine, wankel engine, injected engine, etc.) and electrical motors (brushed and brushless). Between the fuel engines, the gas turbine engines are superior to other alternative engines due to their higher power to weight ratio 3–6 times more than piston engines) and reliability [38,334]. These gas turbine engines can also operate for a long time compared to piston engines [319,336]. However, because of the low cost and the lack of availability of small high-performance gas turbine engines, the small piston engines in current UAVs are more applicable. In other words, alternative propulsion systems may only be desirable when suitable gas turbines are not available [334].

For μUAVs and MAVs, there are four propulsion options, namely, batteries, fuel cells, micro-diesels, and micro gas turbines [8,337]. The last three types usually have the same fuel consumption per unit power, but between them the micro gas turbine engines are smaller and lighter [334]. The most common and easiest way to fly is to use electric motors [130]. These types of motors are usually used because of their reliability, high efficiencies, and controllability. Nowadays, there are two types of electric motors which are used in drones, namely, brushed and brushless. Since brushless motors are smaller and lighter than DC brushed motors, they are considered more appropriate. In this type of motor, there is no iron core and the magnet is placed inside the coil [64]. In addition to the small size and low weight, another advantage of brushless motors rather than brushed is the lack of iron losses that are

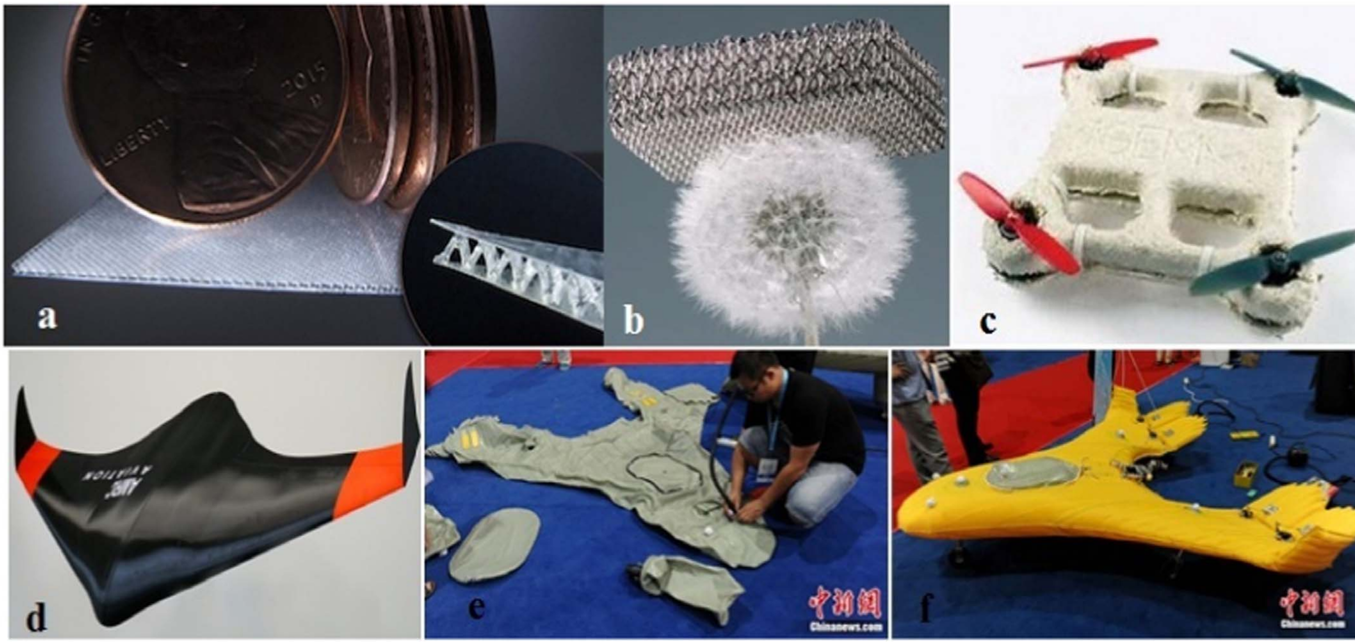

Fig. 25. Views of (a and b) micro-lattice material [328,329], (c) self-destructing drones [330], (d) 3D printed drone [331,332], and (e and f) inflatable drones [333].

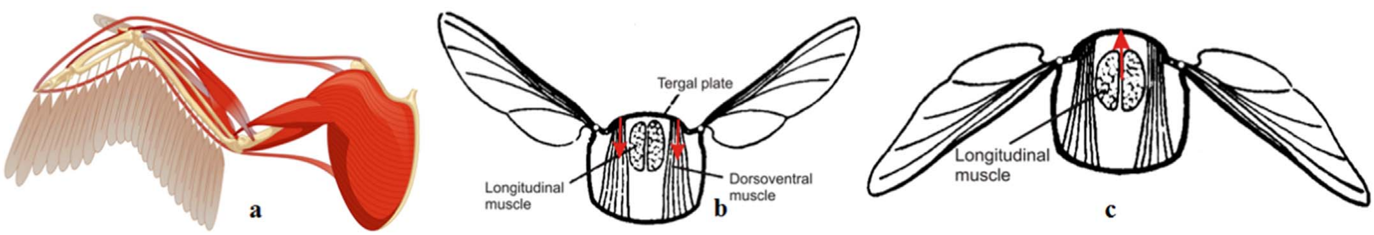

Fig. 26. Views of (a) bird muscle and (b and c) insect muscle [350].

reflected in a higher efficiency. Furthermore, these electric motors are the most suitable propulsion system for the rotary wing drones because more than the half of the electric energy is used to generate lift [130]. In all of the propulsion systems which use a motor or engine, the propeller is the integral part of them.

For flapping wing MAVs and NAVs, the motor is one of the most important parts of a flapping wing which constitutes the flapping wing propulsion system [338]. Flapping wings need a driver source with high energy density and low vibration. Consequently, electric motors are considered as an interface between the electrical and mechanical parts where their inputs are voltage and current and their output is a rotational motion with a specific angular velocity. One of the most important advantages of these motors is the possibility to control their speed in a wide range [64]. The main reasons for the selection of these types of motors are their minimal vibration and noise and low fuel consumption. On flapping-wing MAVs, electric motors are used. Nowadays, out-runner brushless electric motors are one of the best types among brushless electric motors [64,338]. It should be noted that out-runner brushless motors have less speed constant k_v (rpm/V) compared to other types. Hence, they have lower speed and generate more torque [255]. Generally, the main criteria in motor selection for flapping wings are low weight and high torque. Unfortunately, these two factors are interdependent because the heavy motors usually provide more torque [255,339]. Unlike fixed wing MAVs, the flapping-wing drones require more energy [255]. Modern motors rotate very fast but only a small amount of torque is provided. Thus, a gearbox should be used. The main criteria for gears are their low weight and high performance [255,338].

For flapping-wing drones, in addition to the propulsion system, a flapping wing actuation mechanism is required which is dependent on the type of flapping [325,330]. At NAV scale, the Aero Environment company recently designed and fabricated a flapping wing NAV that uses an actuation mechanism composed of rollers and strings, while still using a geared down motor to provide power at the right frequency [340–344]. As for flapping wing PAV, Wood et al. [345,346] developed flapping wings to generate flapping motion by applying piezoelectric actuators. Selecting the appropriate actuator is considered an important part for designing effective flapping-wing drones. Different actuators can be used to perform the mission including electric motors, solenoids, Shape Memory Alloys (SMA) wires, and piezoelectric elements, depending on the type of flapping-wing drones [98,347–349].

For fixed and rotary wing drones, which use engines or motors, the efficiency of the propulsion system is still low and it can be improved by considering new developments in engine technology. For flapping-wing drones, designing propulsion systems by imitating the muscles of birds and insects has great future potential. In Fig. 26, schematic views of the bird and insect muscles are depicted.

7. Power supply and endurance

Engine-powered drones are usually provided with various fossil fuel sources, such as gasoline, methane, and hydrogen. In small drones, and especially in MAVs, the required power is provided by the battery. Over 90% of these drones utilize Li-PO batteries. For micro drones, lithium batteries are the best choice of power due to their low weight [351]. Fossil fuels can produce more energy than batteries, but the available internal combustion engines for use in these drones have extremely low

Table 16
Comparison of different batteries with their specific energy, energy density, and specific power [351].

Characteristic	Ni-Cd	Ni-Mh	Li-Po	Li-S
Specific Energy (Wh/kg)	40	80	180	350
Energy Density (Wh/l)	100	300	300	350
Specific Power (W/kg)	300	900	2800	600

efficiency [38], and the fuel usage may cause stability problems for micro air vehicles. One of the problems that can face MAVs is that they can fly no more than 30 min when using battery or fuel [351]. However, the micro fuel cell is under development and this technology is yet to be used in micro drones [352]. Nowadays, the small Li-Po batteries are the most widely used power sources. In Table 16, features of four types of batteries are compared to each other which show that lithium batteries are better choices [351,353].

The interest to use the micro drones for various missions is increased. The main problem is their low endurance in comparison with larger drones. Flight time depends on the power consumption. Another issue is that the micro drones have limited storage capacity. This has limited their flight endurance up to 30 min [351]. Drones' drag reduction is one of the main factors for increasing the flight endurance. In drones, different geometrical and physical parameters, such as wing shape, wing span, airfoil, cruise speed, weather conditions, etc, can be involved in the reduction of the drag and consequently reduction in power consumption [351,353]. In addition to considering the design parameters for enhancing the drones' endurance, solar panels and piezoelectric energy harvesters can be used as renewable energy sources to enhance the flight endurance or to operate extra sensors and cameras [351,354,355].

The first flight using solar cells was performed in 1974 by the Sunrise airplane [356], followed in 1980 by the Gossamer penguins [357]. Other examples of solar drones are Centurion [358], Pathfinder [359], and Helios [360]. For the micro drones, one of the challenging issues is their high power consumption and limited power capacity due to their weight limitation. Generally, the flight endurance of these micro drones rarely exceeds 20 or 30 min [351]. Nowadays, mounting solar panels on drones is considered as a common method to increase the flight endurance and usually, the battery is used as a backup when the solar cells cannot produce enough power flying in or under clouds or in the dark. In other words, a hybrid source which is a combination of the solar cells and battery is usually used for powering drones [351,361]. Solar cells which are thin, flexible, low weight, and efficient are applied on the wings of different types of drones. Therefore, many examples exist for solar drones, as shown in Fig. 27, and Table 17.

Table 17
The characteristics of solar drones [362–364].

Name	Manufacturer	Weight	Wingspan
[a] VE-100 PAV	Vaero Dynamics Inc.	–	–
[b] Solar-Storm prototype	ENAC	300 g	50 cm
[c] Solarcopter	Queen Mary, University of London	367 g	121.2 cm
[d] Robo Raven III	University of Maryland		

The solar cells must have low weight, must be flexible, and have a high efficiency. Thin film solar cells (TFSC) can be used on the wing surfaces of drones without greatly affecting the aerodynamic efficiency [351]. Major limitations of the solar cells can be their high costs, low efficiency, and their temperature sensitivity. Increased temperatures reduce the power output of solar cells [366,367]. One of the parameters that has a great impact on the maximum power output of solar cells is the amount of solar radiation absorbed by the solar cell [368]. Series and parallel connections of solar cells are used to achieve the required voltage and current in order to improve their performance [369].

As discussed above, the solar systems cannot produce enough power when drones fly in or under clouds or in the dark. Therefore, the drones which use the solar power as their energy source cannot be utilized at night. One solution for this problem is to use laser light from a common power source, such as a portable generator or the electrical grid. This laser beam is directed to a photovoltaic receiver which is installed under the drone [130,370]. In this way, laser power beaming technology can provide drones with unlimited flight endurance to overcome the limitations of most drones [371]. One of the main advantages of wireless power systems is that the energy source is on the ground where power is easier and cheaper to generate [372]. Laser systems do not need to turn off at night and can continuously charge the battery [370]. Even though this system can solve the endurance issues, it has some problems in range of flight. For instance, this system cannot be applied for high altitude UAVs, but it can be a good choice for rotary wing micro air vehicles which have flight range less than 5 km. In Fig. 28, a schematic view of the laser power beaming technology is shown.

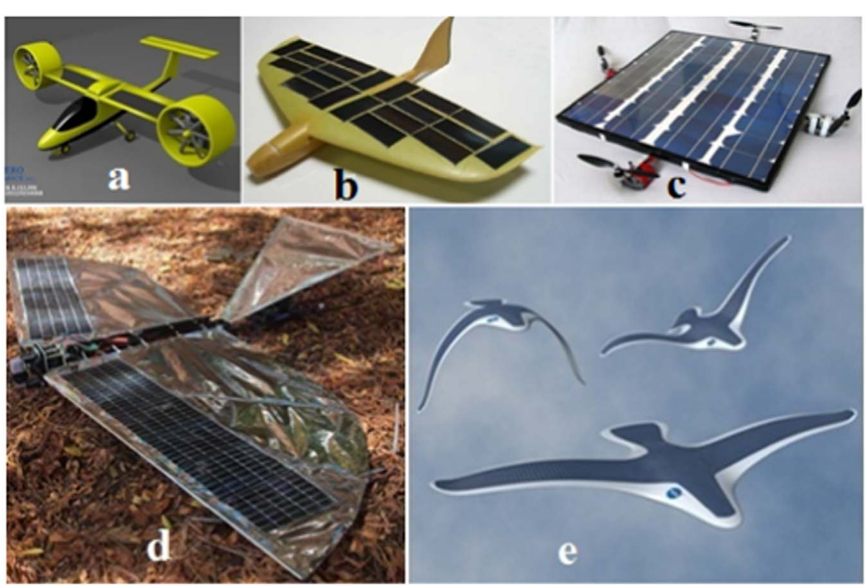

Fig. 27. Views of (a) solar tilt-rotor [362], (b) Solar fixed wing MAV [353], (c) solar quadrotor [363], and (d and e) solar flapping wings [364,365].

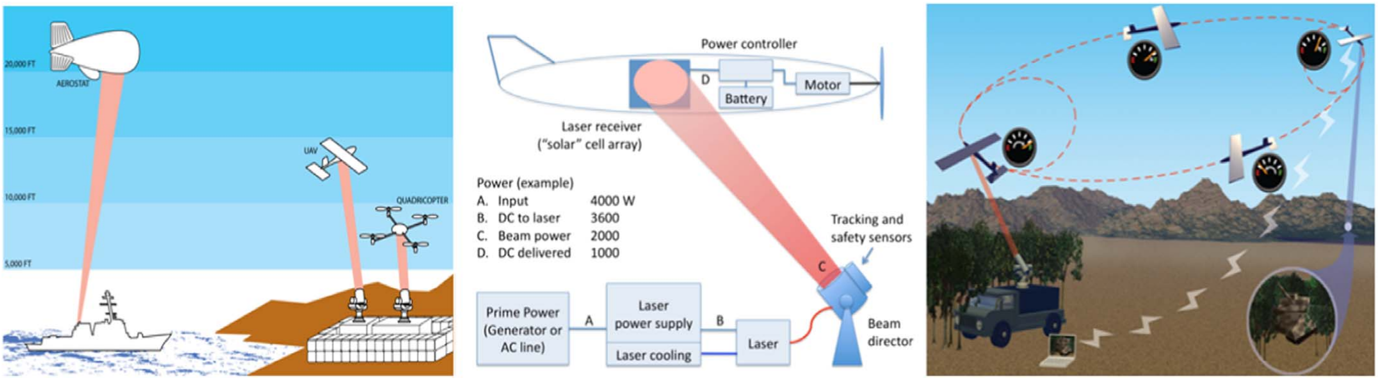

Fig. 28. Views of laser power for drones [370].

An additional method for increasing the endurance of the drones is harvesting energy from flapping motion and morphing. Only one research study was carried out in the past five years by Abdelkefi and Ghommem [355]. They demonstrated that there is an optimum electrical load resistance at which the harvested power can be optimized. They also reported that using the piezoelectric energy harvesting technology from morphing of wings can result in operating many sensors and cameras from wasted mechanical energy [355]. This energy harvesting technology can be improved by considering different types of vibrations, wind, thermodynamic features of the atmosphere, and motion of the drones.

8. Guidance, navigation, and control of drones

Over the past 20 years, several research studies have focused on the guidance, navigation, and control (GNC) for drones, resulting in various techniques and methods. Some researchers have tried to review different GNC systems and subsets [373], such as Ollero and Merino [374] for flight controllers, Chao et al. [375] for autopilots, Goerzen et al. [376] for path planning algorithms, and Valavanis [377] for drones in general. Also, Kendoul [373] has recently performed a comprehensive survey report and organized the large variety of GNC methods. He has provided an overview of GNC systems to increase the autonomous capabilities of drones. The approaches that have been reported are organized into three main categories, namely, control, navigation, and guidance. For each category, methods are grouped at the highest level based on the autonomy level they provide, and then according to the algorithmic approach used, which in most cases is closely associated with the type of sensors used [373]. In Fig. 29, based on Kendoul [373] study, different categories of GNC systems are summarized.

Guidance, navigation, and control (GNC) of drones are traditionally carried out through three methods, namely radio control, video base, and autopilot [378]. One of the most common ways to control and navigate drones is using a radio-control system. In this method, drones are controlled by a radio-system that includes a transmitter along with a receiver. In this navigation system, instructions are transmitted to the drone's electrical components by sending electromagnetic waves [378]. Basically Remote Control (RC) equipment consists of a radio transmitter which includes several radio channels. By using any of these channels, the pilot transmits instructions to the drone [379]. In remote control systems, the transmitter range is different and usually covers a range of about five kilometers. A radio transmitter for drones must have at least 4–6 channels to control their different flight levels. Additional channels can be used for camera controlling. In this system, the receiver is usually used to transmit instructions to the servo motors and speed controller [378].

For navigation systems by video-base, a camera is installed on the drone which is used to take videos and photos when passing regions and sending them to the ground station by video transmitter. Small size, low weight, and high visibility and clarity are considered as the essential features of a video system [378]. In a video base system, the images sent from the video-transmitter and the images received by the antenna are displayed on a screen at the ground station. Antennas can be evaluated by analysis of the output waves. In some cases, amplifiers are used with the antenna which makes it much easier to receive pictures [380]. Nowadays, ultrasonic sensors, color, thermal, or infra-red cameras are used to take information about the surrounding environment of the drones [380]. Small drones often use color cameras which are more useful only in the daytime and cannot provide scale information and depth for the captured environment. In a video base navigation system, computer vision plays an important role in the drone's automation. In these systems, computer vision techniques are used to extract the required information. These captured images are processed for navigation, stabilization, and further information collection [381]. Usually video transmitters can send signals over a certain distance, but in many flights, signals cannot be captured for long distances. The commercial types of transmitters work only within a special radius. When drones are out of range, they show one dead zone and oblige the drones to reduce the flight radius [378]. The best way for guiding, navigating, and controlling the drone is the autopilot system. An autopilot is a set of software and hardware which enables the drones to perform their flight missions automatically. For example, by defining flight plans, direction and speed can be specified in different parts of the flight and the drone automatically obeys this flight plan and tries to perform its mission with minimal errors [378].

Nowadays, several types of autopilots exist, such as Micropilot [382], Piccolo [317], and Paparazzi [317]. Micropilot autopilots have some unique capabilities, such as a weight of 28 g, dimensions of 4 cm×10 cm, and simultaneously control 24 servos, up to an altitude of 12 km, and a radius of 50 km. [382]. In an autopilot system, the flight plan should be uploaded on the system board before flight and at any moment the drone is in contact with the ground station and transmits the data, such as altitude, velocity, etc. From the ground station, different instructions can be sent through RF modem to the drone. After sending instructions, the autopilot sends them to the servo and the drone will perform the desired reaction [378].

In addition to these mentioned methods, researchers proposed new approaches to navigate the drones which can be applied in future for small drones. Bublitz [383] applied Google glass to control a quadrotor drone using head movements. The Google glass can capture the head nods, transform these nodes into flying instructions, and send them over to the drones. Therefore, applying this system, the drone is directly controlled by the commands sensed by the head mounted system while the guidance and navigation tasks are solved by the human pilot. This method can be appropriate for small drones with limited flight ranges which can perform the hovering flight, such as rotary wing MAVs.

Another approach was presented by researchers at the University of Minnesota. They devised a way to use thoughts in order to control the

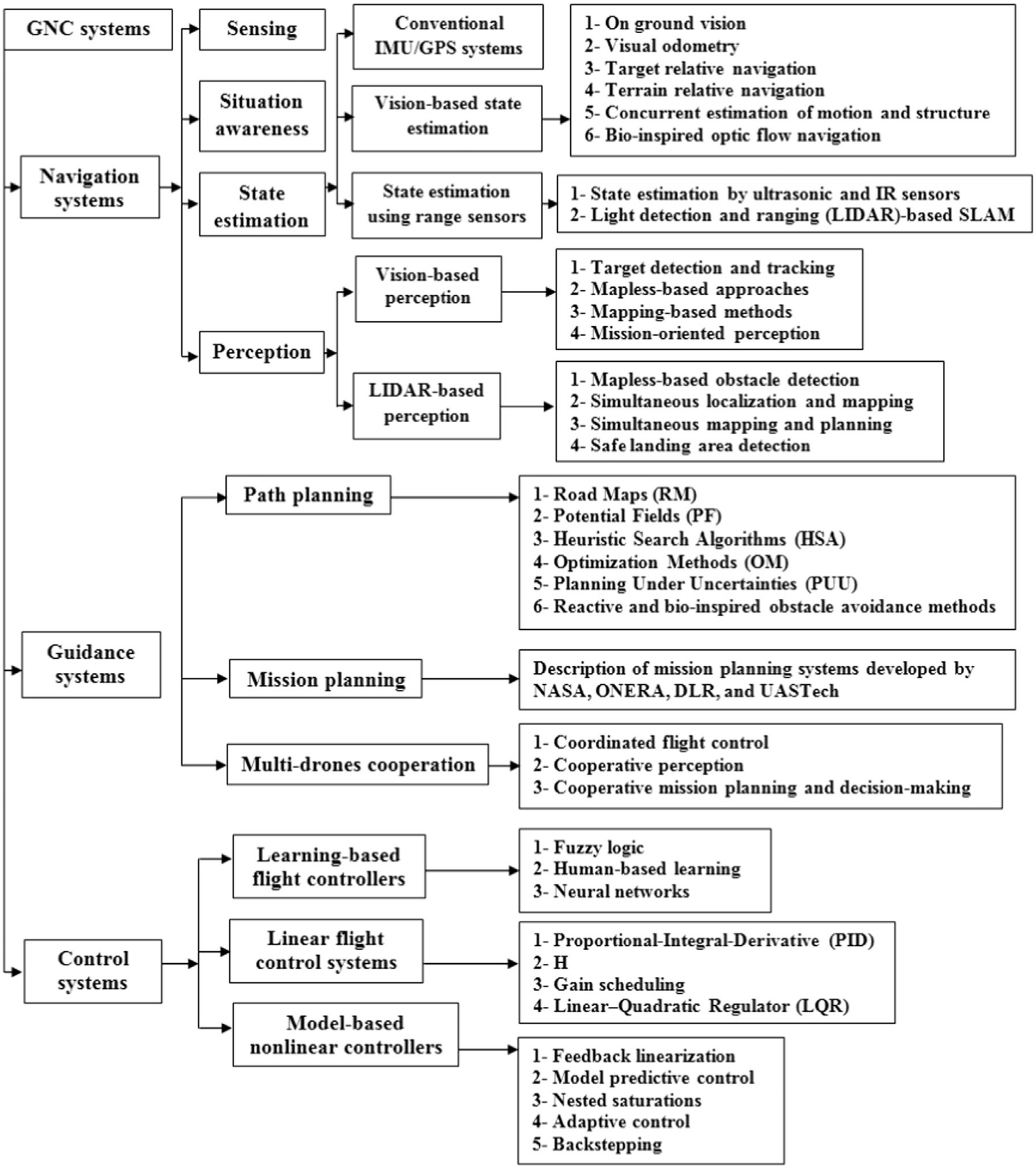

Fig. 29. Classification of GNC systems developed for drones based on Kendoul [373].

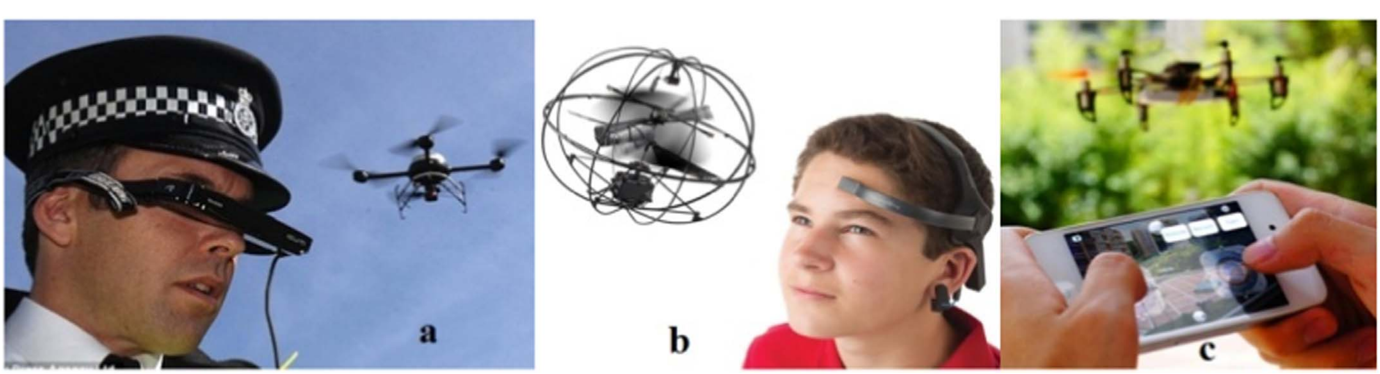

Fig. 30. New methods for navigating the small drones (a) Google glass [385], (b) brain-computer interface (BCI) [386], and (c) smart phone [387].

Fig. 31. Swarm flight of (a and b) fixed wing MAVs [399,400], (c) flapping wing PAVs [401], and (d) rotary wings MAVs [402].

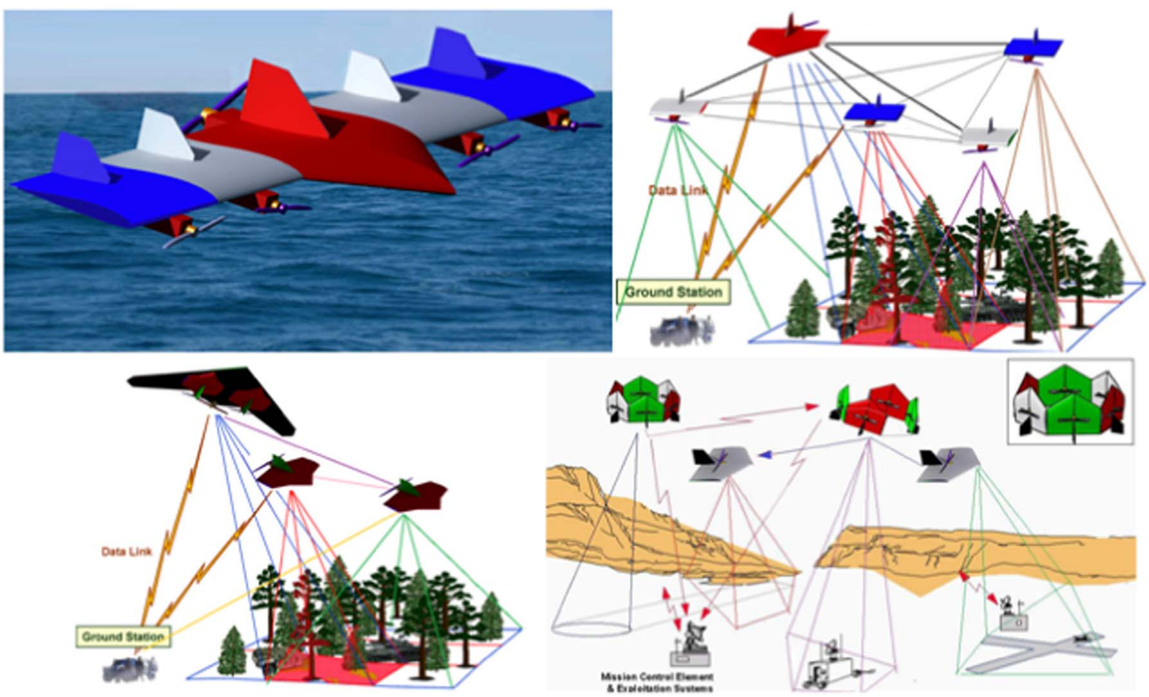

Fig. 32. Some new concepts for separation and swarm flight of drones.

movement of a quadrotor. By using a brain-computer interface (BCI), they made the quadrotor to turn, rise, dip, and even fly through a ring [384]. The used noninvasive technique was electroencephalography (EEG) which can record the electrical activity of the subject's brain through a cap fitted with 64 electrodes [385]. BCI works because of the geography of the area of the cerebrum that governs the movement which is called motor cortex. When there is a movement or the thought about a movement, neurons in the motor cortex produce small amounts of electric current. Thinking about a different movement activates a new set of neurons. In this method, brain signals are recorded by the cap and sent to the quadrotor through WiFi [386]. This method, similar to Google glass, has some limitations and can only be used in small drones. To control and navigate the movement of small drones, smart phones were also utilized [387]. In Fig. 30, different types of these new methods are shown.

Even though these new methods can be applied to control the UAVs, the key differentiating factor here is the quality of communication expressed in terms of lag of the control loop, control bandwidth, and communication loss. Generally, control of drones over short distance results in a negligible lag and high bandwidth with minimal losses, while control over thousands of miles results in severe lag in control, low bandwidth, and significant losses. Therefore, UAVs capable of long distance and endurance flight are typically equipped with augmentation autopilots capable of stabilizing flight in case of loss of the command and control link. Also, the control scheme is organized differently for the same reason.

One of the main parts of the navigation methods of drones is the positioning system. There are different methods for positioning the drones, such as Global Positioning System (GPS) and Inertial Navigation System (INS) [388]. In drones, to detect the position, velocity and altitude, GPS is usually used. To provide the accurate position of the drone, GPS should be in contact with at least 4 satellites simultaneously [378]. The GPS signals are easily affected by external noise or interference [38]. Thus, for drones which are only equipped with GPS, it was observed that some of the drones may lose their GPS connection temporarily for a long time. In these situations, drones have to be landed and their mission is aborted due to safety concerns. Therefore, to avoid this problem, there is a need to design an appropriate method which can estimate the location of the drones when they temporarily lose their GPS connection [389]. The inertial navigation system is the solution for these situations. The INS includes gyroscopes and accelerometers which are used to calculate the position and orientation of the drones. Nowadays, GPS is commonly combined with the INS to avoid the errors in positioning [390,391]. These two types of signals are combined together to produce accurate navigational information. Kalman filter is considered as the common algorithm used to fuse the measurements [392]. In other words, the extended Kalman filter (EKF) is used to estimate the location of the drones that lose their GPS connection temporarily [389].

A new method that can be proposed and considered for navigating and directing the small drones is applying the telecommunication network and internet for sending instructions to drones. The range restriction of the previous methods can be solved by applying this method. According to the increasing expansion of telecommunication networks across the planet and the low altitude flight of the micro drones, this system can be an appropriate method for directing drones, such as MAVs. In addition to its low cost, this system can have a considerable range in comparison with the other control methods. Using drones equipped with this system can be useful for intelligence activities [378].

9. Swarm flight of drones

Using one drone only for a specified mission can be risky because the drone may encounter some technical or other problems, but various missions can be performed with more efficiency by applying multiple drones. Therefore, nowadays due to advances in communication, intelligent software, and processing power, the swarm flight of drones is considered as one of the important topics in drones' studies. A swarm flight of drones has an advantage, if one drone of the swarm is lost in flight, the rest of the drones can carry out the mission. Also, in swarm flight, a combination of various types of drones with different sizes and configurations can make a formation flight.

Swarm intelligence is a novel field of bio-inspired artificial intelligence based on the behavioral models of swarm flight of birds and insects, such as ants, bees, wasps, termites, etc [393]. In nature, there are different types of swarming organisms which are called by different names. For example, a group of ants or bees are called a swarm, but a group of birds are called a flock [394]. A swarm is defined as a configuration of many individuals that have a common goal. Swarm Intelligence is the complex collective, self-organized, coordinated, flexible, and robust behavior of a group which follows a simple rule [395]. Swarming studies of non-aerial vehicles, such as small robots, have been conducted since 1970, but studies of swarming drones did not begin until the early 1990s [188]. Swarm-based drone studies have become very popular in the last few years.

It is the objective of several research groups from different organizations to make drones fly as a group and act autonomously without the interference of humans. Even though researchers from the United States, Germany, Australia, Netherlands, and United Kingdom are at the forefront of swarming research, other countries, such as South Korea and China, also are doing swarming research studies [188]. Reynolds [396] is considered as one of the pioneers of the simulation of a swarm. Others researches on swarm include behavior-rules which is very close to agent-based but often involves artificial-intelligence techniques, graph theory, gradient-vector movement, and mathematically-determined patterns [394]. Nowadays, there are many efforts to develop the swarm-based technology. As an example, the Naval Surface Warfare Center has offered a new approach for formation flight. In their design, they considered the new formation of the drones when a few of them malfunction or have other problems, such as engine failure [397]. In this situation, the other drones become aware of this problem and they find a new formation that allows the rest of the drones to collect the data which the damaged drone was supposed to collect [398]. Researchers from Ecole Polytechnique Federale de Lausanne University [398] developed swarm software for use in disaster situations. They applied micro drones weighing in at 420 g each with a wing span of 80 cm. They developed a software to make the decision as to which flight path is better than another in disaster situations. In Fig. 31, some types of swarm flight of different types of drones are shown.

New designs can be offered for separation and swarm flight. For example, a huge drone can be separated into many micro drones to make a formation flight based on a defined mission. In other words, drones will have the ability to carry and release micro drones that can be designed to conduct swarm flights. These concepts are indicated, in Fig. 32 [403].

It is predicted that the advent of advanced technologies, such as highly capable microprocessors which use multipliers, dividers, high speed compressors, and high precision AD/DA blocks [404–407], radar-absorbing materials, increased data-link rates, high-bandwidth communications, and new navigation systems integrated onto drones will be an invaluable key to carry out very complicated missions [408].

10. Conclusions

Recent researches and studies in the field of flying drones including fixed and flapping wing vehicles were consolidated and deeply discussed. A new classification of these drones was first proposed. This classification includes various classes of drones, such as unmanned air vehicles, micro air vehicles, nano air vehicles, pico air vehicles, and smart dust. These flying drones can be used to carry out various civil and military missions. These possible missions were reviewed including search and rescue, environment protection, mailing and delivery, space exploration. The used design methods and their challenges were also consolidated for all types of drones. Possible solutions for the design challenges were proposed and discussed. In addition to that, the used manufacturing methods and challenges, propulsion systems and actuators, power supply and endurance, control and navigation of drones were reviewed with proposing new ideas to get rid of the existing limitations. The importance of swarm flight and separation of drones was also discussed.

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