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Review Article

Micro- and Nano-Air Vehicles: State of the Art

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Micro- and nano air vehicles are defined as "extremely small and ultra-lightweight air vehicle systems" with a maximum wingspan length of 15 cm and a weight less than 20 grams. Here, we provide a review of the current state of the art and identify the challenges of design and fabrication. Different configurations are evaluated, such as fixed wings, rotary wings, and flapping wings. The main advantages and drawbacks for each typology are identified and discussed. Special attention is given to rotary-wing vehicles (helicopter concept); including a review of their main structures, such as the airframe, energy storage, controls, and communications systems. In addition, a review of relevant sensors is also included. Examples of existing and future systems are also included. Micro- and nano-vehicles with rotary wings and rechargeable batteries are dominating. The flight times of current systems are typically around 1 hour or less due to the limited energy storage capabilities of the used rechargeable batteries. Fuel cells and ultra capacitors are promising alternative energy supply technologies for the future. Technology improvements, mainly based on micro- and nanotechnologies, are expected to continue in an evolutionary way to improve the capabilities of future micro- and nano air vehicles, giving improved flight times and payload capabilities.

1. Introduction

Recently, a large number of studies on micro- and nano air vehicles (MAVs/NAVs) have been published [1–5]. MAVs are defined as small flying systems which are designed for performing useful operations [1]. In 1997, DARPA started a program called "MAV-project" where they presented some minimal requirements. In particular, they set the maximum dimension to be around 15 cm long, and the weight, including payload, to be less than 100 g [6]. Furthermore, flight duration should be 20 to 60 minutes. In addition to the MAV-project, DARPA started another program called nano air vehicles, which focus on the aim "to develop and demonstrate an extremely small (less than 15 cm), ultra-lightweight (less than 20 g) air vehicle system with the potential to perform indoor and outdoor military missions." [7].

In 2005, Pines and Bohorquez [8] published a review on the state of the art of unmanned air vehicles (UAVs), and many of the basic characteristics and challenges identified there are, to a large extent, valid also for NAVs, such as the challenges of maneuverability at low speed in confined spaces.

In [9], NAVs are defined as small air vehicles with an operating range less than 1 km, a maximum flight altitude around 100 m, endurance less than one hour, and maximum takeoff weight (MTOW) of 25 g while MAVs are defined as 5 kg MTOW with endurance around 1 hour and an operative range around 10 km.

In this paper, we will use the definition from [9] when referring to MAV and NAV. When referring to both classes of systems, the term AVS (air vehicle systems) will be used.

1.1. Research and Development of AVS. Many research institutions are actively studying and developing new air vehicles, reducing size and weight while improving performance, and adding more functionality. Examples here are Harvard Micro-robotics Laboratory in the USA [10], Department of Aeromechanics and Flying Engineering from Moscow Institute of Physics and Technology in Russia [4, 11], Aircraft Aerodynamics and Design Group at Stanford University (USA) [12, 13], the Autonomous Systems Laboratory at ETH Zurich (Switzerland) [14, 15], and Deptment of Precision Instrument and Mechanology at Tsinghua University in China [16]. Several companies and agencies also play an

important role in the manufacturing and development of AVS. Examples here are DARPA [7] from USA, Prox Dynamics [2, 17] from Norway, and Syma from USA.

1.2. Applications. AVS applications span a wide range, and the majority of them are military. AVS are capable to perform both indoor missions and outdoor missions in very challenging environments. The main applications are intelligence, surveillance, and reconnaissance (ISR) missions. These systems can provide a rapid overview in the area around the personnel, without exposing them to danger. Infrared (IR) cameras can give detailed images even in the darkness. Furthermore, NAVs, thanks to their reduced dimensions, are perfect for reconnaissance inside buildings, providing a very useful tactical advantage. As reported in [3], such small vehicles are currently the only way to remotely "look" inside buildings in the battlefield.

They can carry specific sensors such as gas, radiation or other sensors used to locate biological, nuclear, chemical, or other threats. They can, for instance, fly inside toxic clouds and transmit data or bring samples back to the base station, and, thus, provide vital information on the composition and extent of gaseous clouds and improve the assessment of danger.

Some of the applications described above can be extended to the civilian field. For example, the police and the fire brigade could use the capability of indoor flights for inspecting unsafe or collapsed buildings [2] in order to search for survivors or simply do a safety check of the building structure.

Since AVS would decrease the time necessary to explore a given area [3], they could be used in disaster cases, such as earthquakes, after hurricanes, or in collapsed mines [1]. In these cases, locating survivors faster increase the probability of saving lives.

However, AVS are not only related to high-risk applications, they can also be used as a support in regular police operations such as traffic control [1], crowd management or ordinary city surveillances.

Mass production of AVS will reduce the cost and, thus, enhance distribution among soldiers and policemen. This could render NAVs to be a natural part of the standard soldiers' equipment. In this case, one of the main features that NAVs must have is that they have to be ready for flight in a few seconds, without any lengthy startup procedures needed.

2. Challenges

AVS are not only scaled down versions of larger aircrafts "*they are affordable, fully functional, militarily capable, small flight vehicles in a class of their own*" [6]. With their reduced size, they have to keep all the features of larger aircraft in a small volume, which increase the complexity and challenges. However, in the last few years, the miniaturization progress of AVS has practically stopped [4] (See Figure 1). This mainly happened since there are several problems. There are both physical and technological challenges that slow down further miniaturization [4].

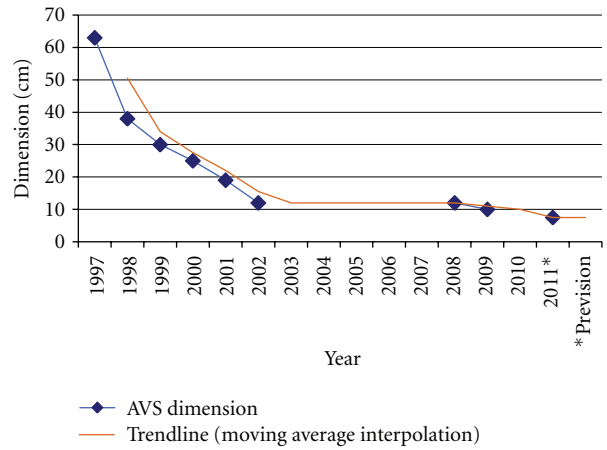

Figure 1: AVS development: dimension reduction; data from 1998–2002 [4] and 2008-2009 [2].

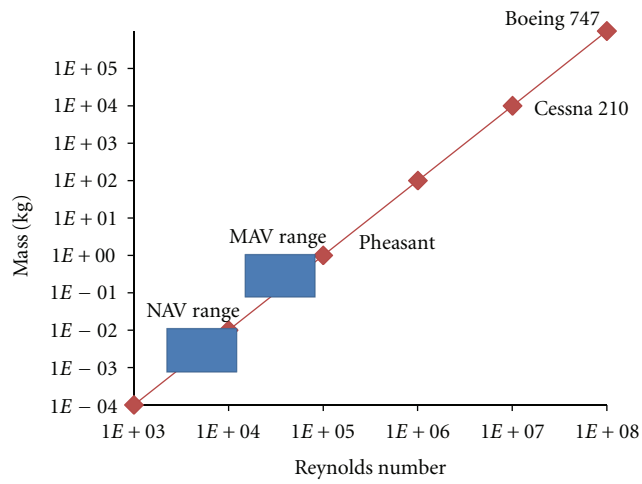

Figure 2: Reynolds number for aerial vehicles, adapted from [19].

The first problem that appears is related aerodynamics related to the low Reynolds number for AVS. This dimensionless number reflects the ratio between the inertial forces and the viscous forces and is defined [18] as

$$\text{Reynolds number} = \frac{\text{fluid density} \times \text{speed} \times \text{size}}{\text{viscosity}}. \quad (1)$$

For AVS, both speed and size are several orders of magnitude smaller than for large aircrafts. This gives Reynolds number, less than one-hundred thousand, which is less than one-tenth of what is common for a full-size aircraft (Figure 2). Flight in this aerodynamic domain is more difficult. Since other physical laws are governing in this domain, a lot of efforts have been made to understand ultralow Reynolds number flight, studying the flight of insects whose size is even smaller than NAV.

Although aerodynamics at low Reynolds numbers are not clearly understood yet [5], it is well know that for

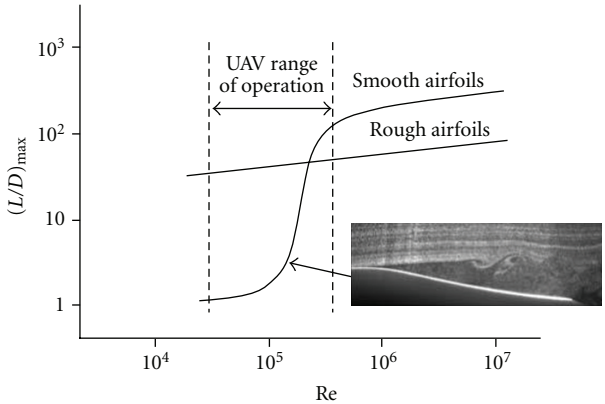

Figure 3: Lift-to-drag ratio variation with Reynolds number, reproduced from [73].

Reynolds numbers under 100,000, the aerodynamics efficiency (defined as lift-to-drag (L/D) ratio) rapidly decreases [19, 20] (Figure 3).

In addition to the physical challenges, given by the intrinsic reduction of physical parameters, there is also a problem of system integration. One can easily be misled to believe that larger aircrafts are much more complex than small AVS. The complexity of AVS becomes apparent if it is considered that they, similar to a larger aircraft, should be fully operational with respect to flight altitude, acceleration, stability, speed, and so forth, while the sensors and signal processing units, as illustrated in Figure 4, have to be integrated in a much smaller volume, with limited weight while keeping the power consumption to a minimum, increasing the challenges beyond that of larger aircrafts.

2.1. Weight Budget and Power Budget. During the design process of AVS, both the weight budget and the power budget should be carefully monitored. In particular, the total mass of the vehicle should be kept as low as possible, since added weight will increase power consumption. The minimum power required to keep a fixed-wing aircraft in level flight can be expressed as [13]

$$P = \frac{TV}{\eta_p} = \frac{W}{L/D}\frac{(2W/S\rho C_L)^{1/2}}{\eta_p}, \tag{2}$$

where T is the thrust, V is the velocity, η_p is the propeller efficiency, W is the weight, S is the wing area, ρ is density, and C_L is the lift coefficient. This means that doubling the weight nearly triples the power consumption. Similarly, for hovering flight, the power requirement is expressed as [13]

$$P = \frac{TV_h}{M} = \frac{W}{M}\left(\frac{W}{2S\rho}\right)^{1/2}, \tag{3}$$

where M is the figure of merit of the rotor and V_h is the induced velocity in hover. Similar to that described above, a doubling of the weight increases the power required by a factor of nearly 3.

An example weight budget for a 197 g MAV can be found in [15]. The details are presented in Figure 5.

A similar budget for a NAV can be found in [12], in which a 15 g vehicle is presented. However, a supercapacitor rather than a battery was used as a power source since no other technologies were able to "*satisfy the power requirement within the weight constraint*". Since the power density of supercapacitors at present is lower than that of batteries (see Section 5.3), the performance falls outside the specification for NAV. A more realistic comparison is, therefore, to replace the 5 g supercapacitor with a 6 g battery as used in [2, 12]. The modified weight budget for a 15 g AVS is, then, as illustrated in Figure 6.

It is interesting to see how the contributions from the various parts scale when the overall weight is reduced. A comparison of the information in Figures 5 and 6 after classifying the various parts in four categories (electronics, motors, battery, and airframe) can be found in Figure 7. It reveals that if the size is decreased, electronics still account for about 13% of the total weight, while motors, actuators and battery increase relatively. This reflects the difficulties of scaling down batteries and motors while maintaining acceptable performance.

When the system is miniaturized, the airframe has the greatest reduction in percentage. This is probably due to the ultralimited weight budget of the NAV that made the developer really optimize the airframe, carefully selecting shape and materials.

A similar comparison has been made for the power budget (Figure 8). It should be noted that, in this case, the MAV power budget has been adapted from [15] while for the NAV budget, we did not find any paper which explicitly reported such information, and for this reason, it was estimated. We used the theoretical estimate for a 15 g NAV found in [21]. For an additional margin to account for various system losses, the value was increased by ~15%, for instance, assuming an efficiency of the electric motor of 85% [22]. The required power was, therefore, increased from the reported 585 mW to 700 mW. With respect to the communication systems, the authors in [16] report an example of a handmade RF communication apparatus that weighs 8 g, which we assume could be adapted to be used in an NAV. The power consumption of this transmitter is reported to be around 500 mW. For the remaining onboard devices, among them a camera [23], the power requirement was estimated to be about 50 mW. Comparing the corresponding power budgets, as seen in Figure 8, we find that by downscaling the weight, the NAV at less than one-tenth of the weight of the MAV, relatively uses less power to generate lift. Since the power consumption of the communication system is dependent on factors like distance, bit rate, data compressions, and so forth, rather than size, the relative requirement in the NAV is significantly higher.

3. AVS Typologies

AVS can be classified into four main typologies depending on their method of propulsion and lift. These are fixed wings,

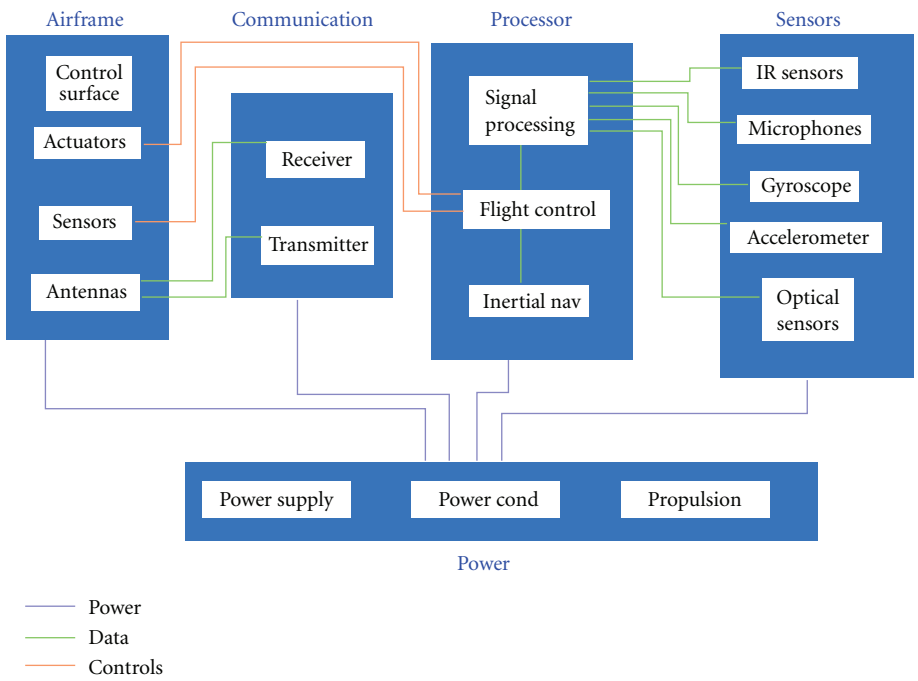

Figure 4: AVS system integration, adapted from [6].

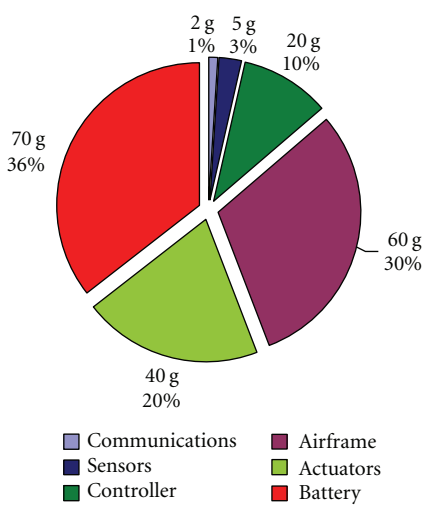

Figure 5: Weight budget for 197 g AVS as presented in [15].

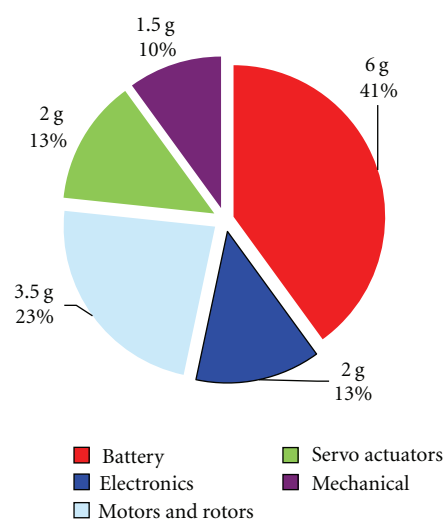

Figure 6: AVS weight budget allocation: the first number is the weight in grams while the second one is the percentage with respect to the total weight of 15 g, adapted from [2, 12].

rotary wings, and flapping wings. The fourth class is without propulsion and is called passive.

In the followings sections, we will briefly review one or more examples from each class, and analyze their main advantages and disadvantages.

3.1. Fixed Wings. Among the different typologies of AVS, fixed wing is the most developed and the easiest to design and build, because "*well-established design methods for larger operational fixed-wing UAV could be applied with some precautions and modified aerodynamic characteristics*" [20]. Several prototypes have already *been proposed to customers* [1]. These kinds of vehicles require relative high speed for flight, typically 6 to 20 m/s. As they are incapable to hover or fly any slower, indoor flight is very challenging and is often avoided. Examples of suitable applications are location of forest fires, searching for people at sea, and missions where low speed is not required.

Fixed-wing aircrafts require a thrust-to-weight ratio less than 1, since wings provide an additional lift [13]. The full

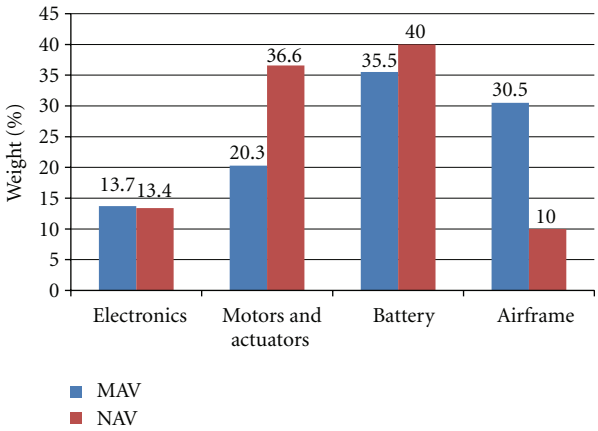

Figure 7: AVS weight budget allocation in percentage with respect to the total weigh calculated for a 197 g MAV and 15 g NAV.

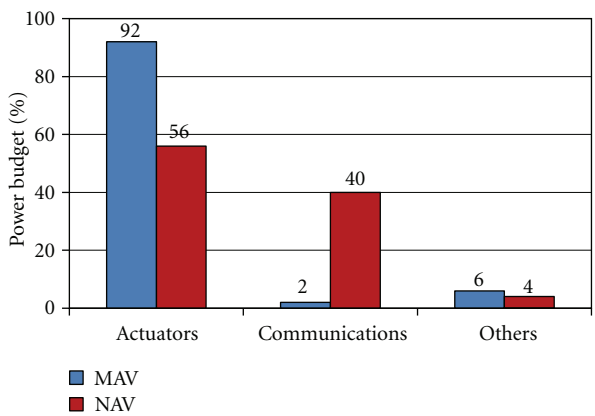

Figure 8: AVS power budget allocation in percentage calculated for a 197 g MAV and 15 g NAV.

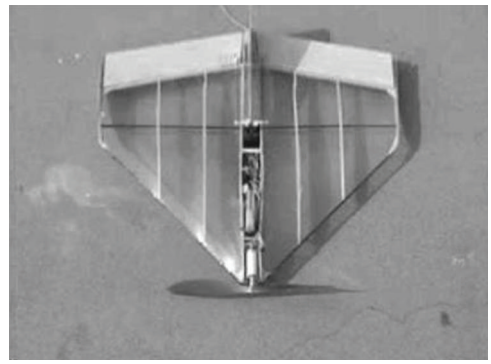

Figure 9: TH360 prototype MAV [16].

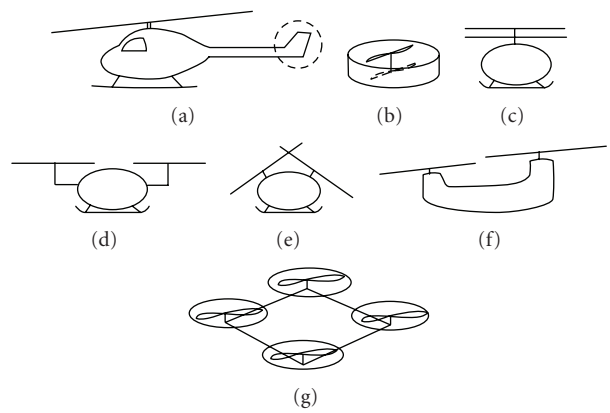

Figure 10: Graphic representation of rotary-wing configurations: (a) conventional configuration, (b) ducted coaxial, (c) conventional coaxial, (d) rotors side by side, (e) synchropter, (f) conventional tandem, (g) quad rotor [27].

Table 1: Performance summary for the first-generation Black Widow MAV [24].

Total mass	56.5 g
Loiter drag	9.4 g
Lift/drag ratio	6.0
Loiter velocity	11.2 m/s
Loiter lift coefficient	0.42
Loiter throttle setting	70%
Endurance	33.4 min

weight is divided by the L/D ratio, and, thus, they require less power to fly than a helicopter with the same weight hovering, where the weight is completely balanced by the propulsion thrust [13]. This efficiency gain is most obvious in larger aircrafts where the L/D ratio reaches values of more than 30. Unfortunately, as we explained in the Section 2, this parameter rapidly decreases as the dimensions and correspondingly, the Reynolds number decrease (Figure 3). For this reason, the obvious advantage of a large aircraft becomes less pronounced when the ratio L/D is reduced to less than 10.

Several prototypes exist, but none are in the NAV range [9]; the existing AVS models have wingspans larger than 15 cm and thus are considered MAVs. In [16], two examples of fixed-wing MAVs are shown. One of these, the TH360 (Figure 9) includes a color video camera that transmits realtime images to the control station. The propulsion is from an electric motor, the wingspan is 45 cm and the total weight is around 120 g.

The main drawback of the system is the limited 5-minute flight endurance. Another fixed-wing MAV, often referred to, is the black widow [24] which was developed in 2001 by AeroVironment Inc. in collaboration with DARPA. The performance of this MAV is reported in Table 1.

Notice that the flight endurance is much longer than for the TH360 in [16] discussed above. The L/D ratio is only 6 for this 15 cm wingspan MAV, which is less than one-fifth of typical commercial airliners.

Rigid wings were used in all of the examples presented above. In contrast, in [25], a flexible-wing MAV is reported and compared with a rigid thin-wing MAV of the same size and shape. The motivation for this comparison is

"*for highlighting the distinct aerodynamic advantages of the flexible wing*." The conclusion is that a "*deformable wing is expected to harvest an intrinsic benefit: a portion of the energy that would normally be lost to the wing-tip vortices and wake, downstream of the MAV, now is stored as elastic strain energy in the wing's structure*" [25]. Following from this, it is found that flexible wings provide better L/D ratio than rigid wings for angles of attack ($\acute{\alpha}$) smaller than 10°.

3.2. Rotary Wings. The second type of MAV typology are systems with rotary wings. These AVS basically have the same structure as macroscale helicopters and, thus, are able to fly at quite high speeds, hover, and execute vertical take-off and landing (VTOL). These features make them perfect for indoor flight and short-range reconnaissance. Due to larger power requirement for hovering and VTOL, the endurance is also the bottleneck for this kind of AVS. With the miniaturization, a lot of challenges arise. Examples are low efficiency of the rotor system and the low thrust-to-weigh ratio [26]. Despite these disadvantages, rotary AVS are the only configuration capable to "*combine acceptable high and low speed characteristic including hovering*" [1]. Furthermore, they are also "*the only controllably hovering object at the moment*" [1].

Based on the number and position of the propellers, there are several possible configurations for rotary AVS. In Figure 10, some of the possible configurations are reproduced from [27].

Each one of these configurations has some specific features that make them suitable for specific types of missions.

Table 2 reports various aspects of the six typologies. Choice of configuration will depend upon the mission requirements. For example, if one wants to build AVS that are easy to maneuver, one should focus more on quad-rotor configuration and discard coaxial, but if we need AVS with low structural complexity, then quad-rotors are not the optimal choice anymore.

In general, when a designer needs to choose the best configuration, he will use a combination between these different selection criteria. In [27, 28], a weight parameter is assigned to each selection criteria to identify which feature is more important.

Several prototypes of these configurations are reported in the literature. In 2004, Epson built a prototype of small ducted coaxial AVS [29].

This "flying robot" had a wingspan of 136 mm and a total weight, including batteries, of 12.3 g. At 3 min, the endurance was the weak point of this prototype.

AVS with an improved flight time of 10 minutes are described in [30]. However, compared to the AVS in [29], the AVS in [30] had a total weight around 110 g and only one rotor, and, in this case, the torque is balanced by changing the angles of the yaw control surfaces [30], so these two systems are not directly comparable.

The T-REX model, provided by ALIGN Corporation [31], is a good example of a conventional configuration rotary MAV. It is an electrical powered AVS with rotor diameter less than 50 cm and a total weight around 340 g.

Table 2: Selection criteria of different rotary AVS typologies [27] (1: bad, 10: very good).

Selection criteria	Conventional (a)	Ducted coaxial (b)	Coaxial (c)
Compactness of folding	1	2	10
Reliability	9	10	8
Controllability	5	5	7
Aerodynamic cleanliness	8	2	8
Maturity of technology	10	8	10
Hover efficiency	10	8	8
Aerodynamic interaction	7	7	7
Vibration	1	2	1
Cruise efficiency	7	6	8
Maneuverability	5	3	3
Ease of payload packaging	10	8	10
Simplicity of structure	8	8	10
Simplicity of control system	6	6	6
Selection criteria	**Side by side (d)**	**Tandem (f)**	**Quad-rotor (g)**
Compactness of folding	2	2	8
Reliability	8	8	9
Controllability	5	5	10
Aerodynamic cleanliness	6	6	2
Maturity of technology	9	10	5
Hover efficiency	10	10	8
Aerodynamic interaction	10	10	7
Vibration	2	2	2
Cruise efficiency	6	6	5
Maneuverability	4	4	9
Ease of payload packaging	10	10	8
Simplicity of structure	8	8	7
Simplicity of control system	6	6	10

Despite that this configuration is the most common for larger aircrafts, it suffers from the disadvantage that it is difficult to control with respect to the quad-rotors configuration. For this reason, a lot of research has recently been put into the control of AVS with quad-rotors. A basic study on control theory presented in [32] shows how quad-rotor AVS could easily be controlled by changing the rotation speeds of the motors. The same principle is used in [12, 14]

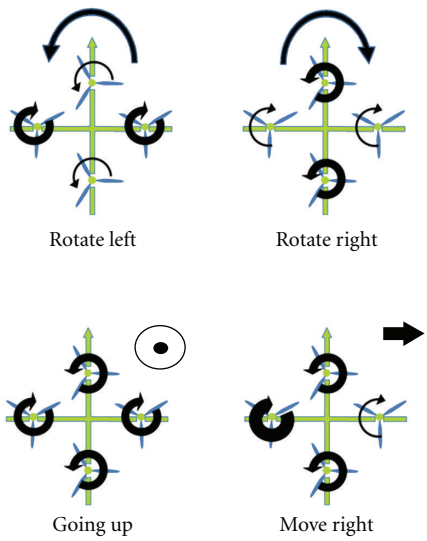

Figure 11: Quad-rotor concept motion description, the arrow width is proportional to propeller rotational speed adapted from [14].

and is illustrated in Figure 11. The torque is cancelled by making two rotors rotating clockwise and two rotors rotating counterclockwise. Despite the simple control systems and the ease of maneuverability of the quad-rotor systems, there are two main disadvantages that could limit their success. In particular, quad rotors mean four motors that are very power consuming [14]. Furthermore, motors are, in general, heavy and difficult to miniaturize. For these reasons this configuration should be avoided when the main target is to maximize flying time.

3.3. Flapping Wings. Both fixed wings and rotary wings provide mature and well-know technologies, but have problems due to the high unsteady effects due to reduction of Reynolds numbers. This motivated researchers to investigate alternative typologies. The basic idea was adapted from nature and uses the same flying technique as insects and birds: flapping wings. Since this idea came up, a lot of studies have been done in order to investigate the efficiency of such methods and the possibility to reproduce them in the laboratory. In fact, the principal motivation seems to be the possibility to "*integrate lift and thrust together with stability and control mechanism*" [33]. However, when we refer to this class of vehicles, we should make a distinction between bird-like vehicles called ornithopters and insect-like vehicles called entomopters. These two subclasses of flapping wings have completely different features. Ornithopters, like the majority of birds, generate lift by flapping wings up and down with synchronized small variations of angle of incidence. This method of thrust generation require forward flight similar to fixed-wing AVS [1]. As a result, ornithopters cannot hover, and they need to obtain an initial airspeed before taking off [1]. Entomopters use the kinematics of insects for flying, meaning a "*large and rapid change of angle of incidence*" [1]. Due to this large angle variation between the upstroke and downstroke, this technique is sometimes also referred to as pitch reversal. Compared to how birds fly, they are able to generate much more lift and, thus, are able to execute VTOL [1] and hovering.

With these two advantages, entomopters are much more interesting to adapt to AVS than ornithopters, and therefore we will mainly discuss Entomopters. Insects generate wing beats by contraction of muscles. The muscles can either generate wing motion through direct attachment or through indirect attachment, where the wing motion is generated, for example, through deforming the shape of the thorax [34, 35] (Figure 12). Large insects with lower beat frequency use both these modes of flying while smaller insect use mainly indirect muscles [35].

Linear actuators are the most suitable means for reproducing this motion. However, none of the available actuators match natural "*muscles over all the main performance characteristics*" [35]. The most promising technology is electroactive polymers (EAP) that is able of providing high energy density and high efficiency. In [36, 37], the possibility of using EAPs to reproduce artificial muscles is investigated. Even though it looks very promising, this technology is still under development and thus not yet widely available in commercial actuators.

A possible concept is to develop a flapping-wings mechanism using rotary actuators such as electric motors. In [34, 35, 38], three different methods for translating rotary motion into flapping-wings motion are presented (one example is shown in Figure 13). All three uses a crank rocker technique, but differ with respect to how they generate the pitch motion of the wing.

Despite this, a recent study [39] has shown that it is also possible to generate stable forward flight using simple motion without any feedback control of the wing movement.

Another important aspect of flapping air vehicles is the shape of the wings. In the literature, many different designs are reported; however, most of them try to reproduce bird or insects wings.

One distinction can be made between smooth wings and rough wings. Several test runs by the authors of [39] show that creating rough wings helps to increase the performance, since they "*are needed to prevent feathering deformation and produce a large up-down body motion*" [39].

Regarding wings, they are in general fabricated using micromachined molds. The molded wings are in general made from polymers like thermoset resins [39, 40].

3.4. Other Techniques. While the three typologies described above are the most common, some authors have started to investigate alternative techniques that could be useful in some cases. The most important class are the passive AVS. In [10, 41], a "palm-sized autonomous glider" (Figure 14) with a 10 cm wingspan weighing only 2 g is described. Since this class of vehicles does not have generation of thrust, meaning they are passive, they need to be hand launched or dropped, for example, from aircrafts.

Another example of an alternative topology is a blimp or airship. Although an unmanned airship is presented in [42],

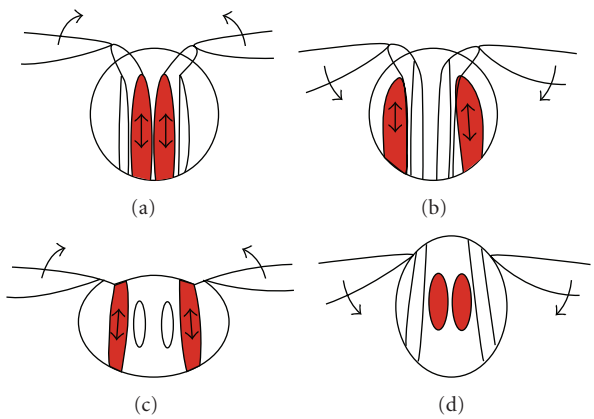

Figure 12: Insect wings beat generation: direct muscles (a, b) and indirect muscles (c, d) [35].

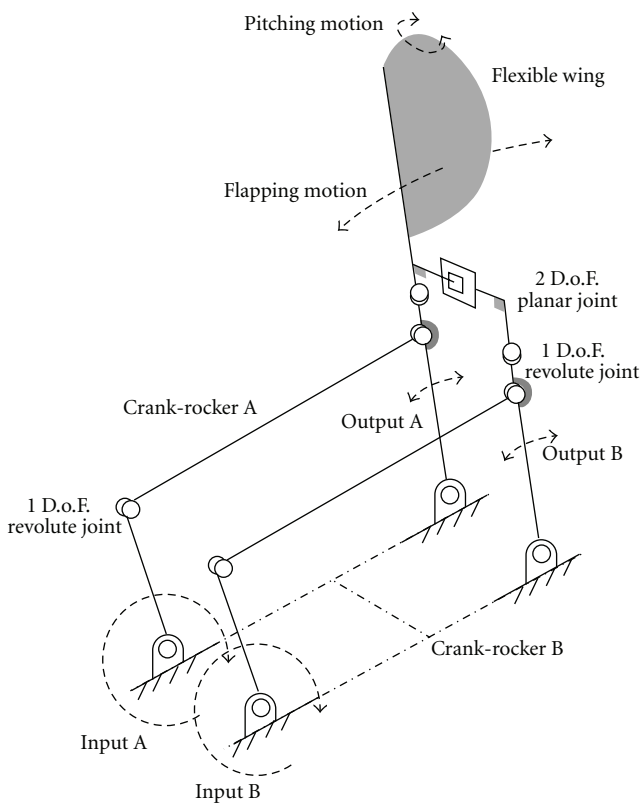

Figure 13: Rigid-body representation of the parallel crank-rocker mechanism. Full revolutions at inputs A and B produce reciprocating outputs A and B, which cause the wing to flap. Introducing a phase lag between the two linkages (and hence outputs) introduces a pitching motion to the wing [35].

the dimensions are out range of the specification of NAV and MAV.

4. AVS Typologies Comparison

Among the different typologies presented, it is important to choose one that offers the greatest advantages in terms

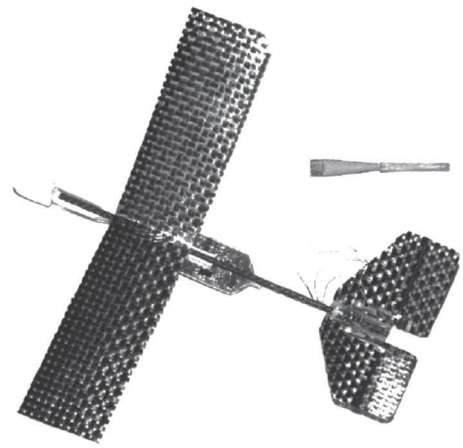

Figure 14: Palm-size micro glider [41].

of reliability, efficiency, and suitability for the application areas presented in Section 2. Unfortunately, none of these typologies have advantages only, and thus compromises must be made. Since fixed-wing vehicles are able to fly with much less thrust with respect to their real weight, they are perfect for relative large area control and high autonomy missions. Unfortunately, as we reported in Figure 3, the L/D ratio sharply decreases as soon as the Reynolds number decreases below 500000, and, thus, the main advantages of this typology (low consumption) become less pronounced compared to larger aircrafts. Since the Reynolds number decreases rapidly with miniaturization, the obvious advantages of the fixed-wing topology compared to other typologies such as helicopters, becomes less pronounced.

Also, since fixed wing topologies are incapable of hovering, they are less suitable for finding and overseeing targets. In [43], an algorithm that allows fixed-wing vehicles to lock on to the target while flying is investigated. The results are still unsatisfactory and too complex. In addition, their lack of hovering capabilities also renders them less suitable for indoor missions. For many customers, such as military and tactical squads, this limitation is not acceptable.

For users that require hovering capability, rotary-wing typology appears to be a good solution. In addition to hovering, they offer good maneuverability and medium complexity.

This is also the only configuration capable to "*combine high and low speed characteristics* [1].

The main disadvantage of rotary wings is the relative high power consumption. To overcome this problem, many researchers have investigated flapping wings. The basic idea is that if insects have this kind of propulsion, and they are able to generate high lift, they are probably very energy efficient. Unfortunately, this is challenging, since nature and engineering are based on different evolution processes. Nowadays, it is still not fully documented whether this method provides better efficiency than the much simpler rotary wing principle [13]. Some authors [38, 44] claim that they provide better performances, others [11] claim the contrary. However, these studies are not very comprehensive and should be considered

Table 3: Flying principle comparison focused on ability to miniaturization [14] (1: bad, 2: medium, 3: good).

	Fixed	Rotary	Bird	Blimp
Power cost	2	1	1	3
Control cost	2	1	1	3
Payload	3	2	2	1
Maneuverability	2	3	3	1
DOF	1	3	3	1
Stationary fly	1	3	2	3
Low-speed fly	1	3	2	3
Vulnerability	2	2	3	2
VTOL	1	3	2	3
Endurance	2	1	2	3
Miniaturization	2	3	3	2
Indoor usage	1	3	2	2
Total	*20*	*28*	*26*	*26*

with caution. In [21], a comparison between a flapping-wing system and a rotary-wing system is done. It is reported that the hover efficiencies only differ with less than 5% and thus are almost negligible. Therefore, it can be assumed that both principles have comparable efficiency in the ultralow Reynolds number regime. However, rotary-wing systems are simpler and can, therefore, more easily be miniaturized. In addition, "*they are also the only controllably hovering flying objects at the moment*" [1].

For this reason, rotary wings are acknowledged as the most suitable topology for NAV [11, 13, 21]. Table 3 shows one comparison table reproduced from [14].

5. Rotary Wings: Main Part Analysis

In this section, conventional helicopter NAVs are reported and analyzed. Many of the discussions made in this section can be easily extended to the other typologies, since technologies such as energy storage, propulsion, and communications, are independent of the typology.

5.1. Airframe. It is well known in aerodynamics that the shape that provides the best aerodynamic performance in subsonic speed is the drop-based shape [45].

The design begins typically with finding placements for large components such as motors and battery. During this step, the center of gravity of the system and its location should also be considered. This space optimization is not an easy problem. In [46], an example of design optimization and positioning of the center of mass for a nano-helicopter is presented. In particular, a generic-based algorithm is used for "*organizing a given set of components and payloads such that the resulting flight vehicle has the most compact overall size and still fulfills the given physical and control constraints*" [46]. Once all the parts of the system have been allocated, it is possible to start to design the enclosures of the vehicle as a double drop-shaped hull (Figure 15).

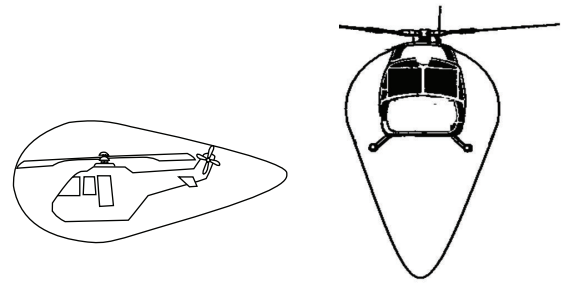

Figure 15: Double drop section: lateral view (left) and vertical section (right).

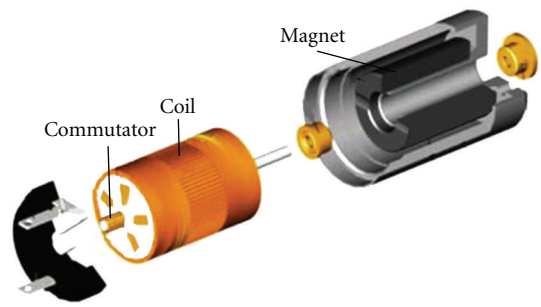

Figure 16: Coreless motor structure, from [74].

The horizontal drop shape (Figure 15(left)) is needed to reduce the aerodynamic drag during forward flight. Since the main rotor pushes down the air, it will create an airflow that pushes the helicopter body towards the ground, increasing the power consumption. Once more, a drop-shape body cross-section (Figure 15(right)) will reduce the drag forces, reducing the power consumption further. Airframe design can truly be considered much more than an aesthetic endeavor. Due to the lack of useful simulators in the ultralow Reynolds number regime, many companies base their development more on workmanship experience than on simulations.

Carbon fiber composites are the main materials used for AVS airframes, because they have high strength-versus-weight ratio and are easily accessible.

5.2. Propulsion. All the three active AVS typologies presented above need to generate motion. There are several ways to make an air vehicle fly. The most common and easiest way is to use electric motors. Almost all the existing prototypes use electric motors due to their high efficiencies, reliability, and ease of control.

Since coreless motors are lighter and smaller than, for example, direct current (DC) iron-core motors, they are considered more suitable. As their name indicates, there is no iron core inside their motor structure. The magnet is positioned directly inside the coil, and then the rotor coil is wrapped around the magnets without using any iron material as illustrated in Figure 16.

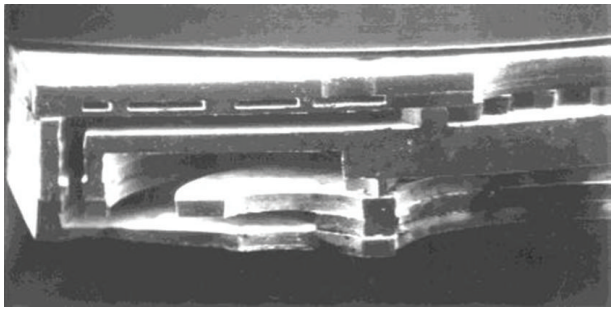

Figure 17: Micro gas turbine, SEM image [49].

In addition to the small dimensions and the low weight, another advantage of coreless motors is the lack of iron losses that are reflected in a higher efficiency. Furthermore, since the rotor is very light, it has a small inertia that allows extremely fast accelerations and decelerations.

However, the lack of iron in the center reduces the motor heat dissipation. To avoid overheating and thermal problems, they are only used for small and low-power motors.

Although an electric motor is the most suitable for AVS applications, it can be seen in Figure 8 that more than the half of the electric energy present in the AVS is used to generate lift. It could, therefore, be advantageous to replace electric motors with other systems, such as gas turbine or internal combustion engines (ICE). Two AVS examples using ICE are presented in [47], in which a motor provided by Cox Company were used. However, as the engine of this vehicle was quite large, it will be difficult to integrate into future NAVs. Most recent studies on miniaturized ICE [48] show that, with the current technology, it is possible to build a miniaturized combustion motor of 0.3-0.4 cc.

Even though ICE motors are interesting for AVS applications; they suffer of one big disadvantage compared to electric motors: they are very noisy. This limits the application in NAVs that have to be used for tactical missions, where it is required to have high stealth skills.

Micro-gas turbines could be another alternative. In [49], an example of the fabrication of an extremely small turbine with dimensions around 2 cm × 2 cm × 0.4 cm with a combustion chamber of 0.195 cubic cm is given. It has been built using six silicon wafers and configured for hydrogen fuel (Figure 17).

ONERA Company announced in 2008 that they had demonstrated a micro gas turbine suitable for AVS. Their turbine can supply from 50 to 100 W with dimensions around 2-3 cm for the diameter and the height [50]. The combustible in this case could be either hydrogen or propane (Figure 18).

Despite significant efforts by numerous groups [49, 51], no known commercialization of MEMS gas turbine generators are currently known.

Finally, the possibility to include a hybrid system, such as electric motors and combustion engines should be mentioned. Although this technique has been already used with good results in larger air vehicles [52], it is not suitable for smaller systems such as NAV in which both weight and size represent very strict constraints.

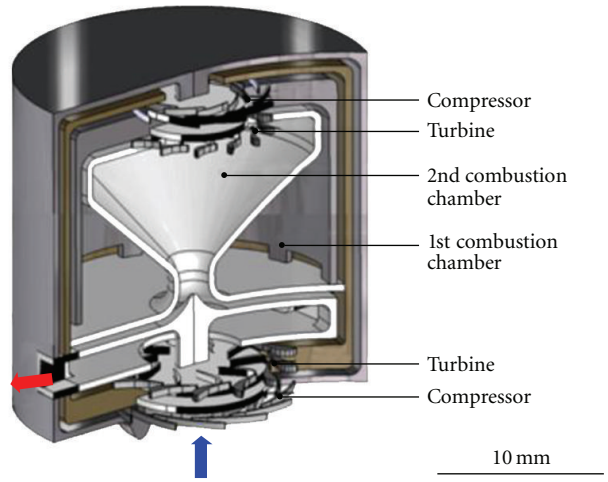

Figure 18: Architecture of the ONERA Micro gas turbine, reproduced from [50] ONERA, the French Aerospace Lab.

5.3. Energy Storage. All the active AVS typologies need electric energy on board to feed the electronic circuits, sensors, actuators, and the communication devices. Furthermore, if electric motors are used, a large part of the electric energy will be used for the propulsion supply motors. Since energy stored in batteries does not require any conversion to be useful for both the electronics and propulsion, batteries seem to be the most appropriate for electric MAV. Furthermore, the energy density of the batteries has steadily increased during the last years, mainly thanks to the effort of the companies producing smart phones, notebooks, and other consumer electronics. In 2006, the battery market reached 50 billion dollars and is expected to expand to more than 70 billion in 2011 [53]. As a result, many companies continue to invest large amounts of money on battery research, mainly focusing on reducing dimensions and increasing the energy density.

Ni-Cd batteries have now almost completely been replaced by more energy dense lithium-based batteries that also are less toxic [53]. Furthermore, the most advanced batteries (intelligent batteries) include circuitry that optimizes the cells' discharge curves with respect to the loads. They "*exploit various battery-related characteristics such as charge recovery effect, to enhance battery lifetime and ensure safe operation*" [54].

Unfortunately, despite these improvements, the most advanced batteries also provide much lower energy densities than sources, such as gasoline or methanol, as shown in Figure 19.

Methanol could be used in a gas turbine as presented in the previous section, providing much more power compared to battery based systems.

Another alternative is fuel cells. A fuel cell system is conceptually a sort of battery in which the fuel is transformed into electric current trough an electrochemical process. There are several kinds of fuel cells which mainly differ with respect to the principle of energy conversion. Currently, the most promising fuel cells for AVS are proton exchange membrane (PEM) fuel cell and direct methanol fuel cell

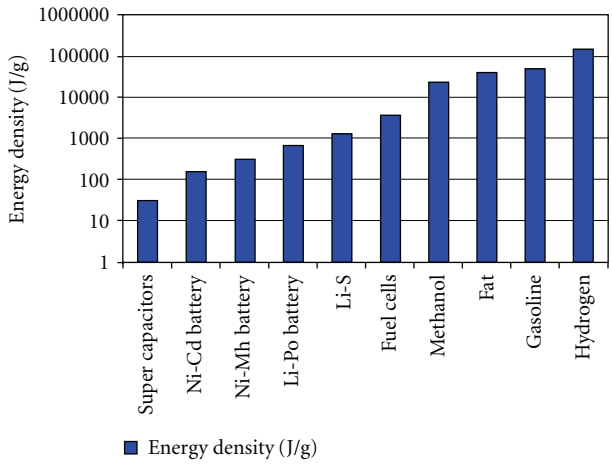

Figure 19: Energy densities of various energy storage systems, graph adapted from [33, 53, 75–77].

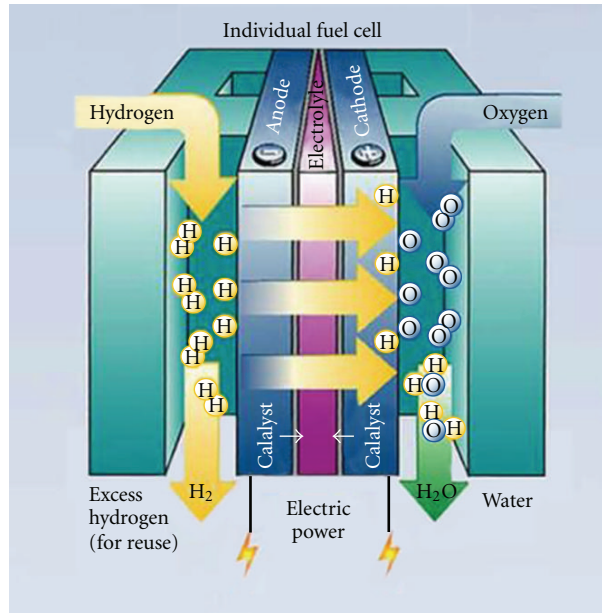

Figure 20: PEM fuel cell principle [78].

(DMFC) which could be considered as a subcategory of the PEM.

The schematic of a PEM fuel cell is reported in Figure 20 [51]. It basically consists of an anode catalyst and a cathode catalyst separated by a membrane that can be crossed only by protons. In the classical configuration, PEM uses hydrogen on the anode side and oxygen on the cathode side.

The hydrogen atoms that reach the anode catalyst dissociate into protons and electrons. The protons can cross through the membrane and reach the cathode. Here they will react with oxygen to form water. The electrons left behind the membrane are forced to "travel" inside the electric circuit, generating an electric current. It is clear that, in this case, the only residual waste is water, and thus this is very environmental friendly. Unfortunately, hydrogen does not occur naturally and thus has to be produced by chemical processes, wasting energy. Furthermore, hydrogen has a high mass energy density (143000 J/g) but a very low volumetric energy density (10790 J/L), which makes it difficult to store. In fact, it has to be transformed to liquid form, compressed at high pressure, or transformed to other forms with high volumetric densities, such as metal hydride.

To overcome this problem, several new kinds of cells have been developed. Among these, one of the most interesting is the DMFC. It uses pure methanol as fuel, which simplifies the fuel storage.

The working principle is similar to PEM, but the chemical reactions are a little bit more complicated. DMFC residual wastes are water and carbon dioxide, and the overall cell efficiency is lower compared to a PEM cell.

These fuel cells are already available in the market [55], with quite small dimensions (several cm) and low weight (few hundred grams). An example of an MAV powered by a fuel cell is "The Hornet", developed in 2003 by DARPA, it "*uses absolutely no batteries, capacitors, or other sources of energy*" (except fuel cells) [56]. The Hornet has a wingspan of 38 cm and a total weight of the vehicle around 170 g, including fuel.

Since the weight budget of NAVs is very limited, further development is required before fuel cells become a viable alternative energy source.

Besides fuel cells, ultracapacitors have become interesting the last few years. The latest improvements have made this power storage principle attractive also for AVS applications, and they have already been used in some prototypes [12]. Since they are an evolution of normal capacitors, their main features are fast charging, high peak current, and virtually unlimited charge-discharge cycles [57]. The main drawback consists of the output voltage that strongly depends on the charge status of the capacitor. *By the time an ultracapacitor reaches a 25-percent state of charge, its voltage has dropped by half* [57]. Besides this, when compared with other energy sources, they have a relative low energy density. Recently, in [58], a new electrostatic nanocapacitor (shown in Figure 21) which "*dramatically increases energy storage density of such devices—by a factor of 10 over that of commercially available devices—without sacrificing the high power they traditionally characteristically offer*" was announced.

Ultracapacitors are, therefore, candidates to play an important role for future energy storage systems in AVS. Solar cells should also be mentioned as a potential useful energy source. Even though photovoltaic systems are interesting for AVS, the small dimensions of NAVs, the weight budget constraints, and the mainly indoor application area (low light) limit the efficiency and the available energy.

5.4. Transmissions. Basically, for AVS, two different kinds of signals have to be transmitted: control signals and data signals. The control signals are needed for take-off, landing and for piloting the vehicle in general while the data signals are basically the data collected by onboard sensors of AVS, such

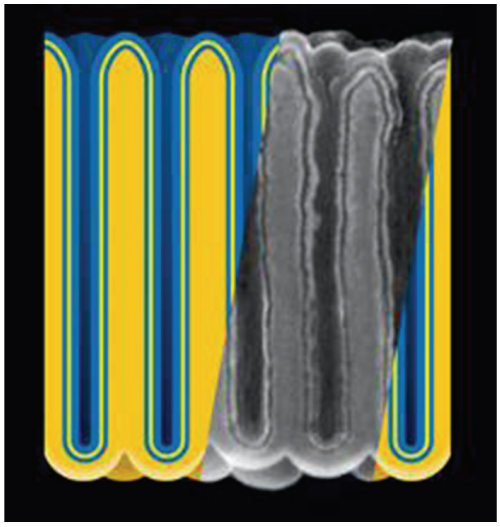

Figure 21: Electrostatic nanocapacitor. Developed by Maryland NanoCenter [58].

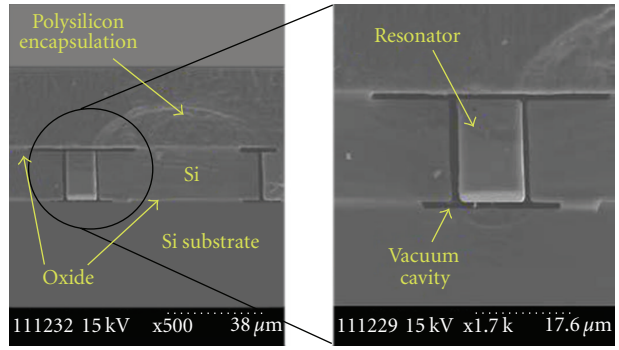

Figure 22: Example of an MEMS resonator [59].

as camera, microphones, gas sensors, and so forth, which for many applications need to be transmitted to a base station.

Control signals are mainly transmitted from the ground station to the vehicle while the data is sent from the vehicle to the user. An example of control communication systems on board is given in [16], where they developed a home-made RF transmitter for use onboard an MAV. With a weight of 8 g, it could transmit at 56 mW. The transmitter operated at a frequency range between 1.18 and 1.45 GHz. Furthermore, a microdemodulator operating at 50 MHz and weighing 5.4 g was used at the receiver end [16].

Another example is found in [25], where only a receiver was used onboard. In particular, the receiver, including a phase locked loop (PLL), weighed around 12 g, and it consisted of a 7-channel pulse code modulation system. Since no data was to be sent back to the base station no transmitter was required on board that vehicle.

When reducing the AVS dimensions, the major challenges for the communications parts are represented by the weight and size of the antennas, filters, and resonators. Antenna shape strongly depends on the operating frequencies and, thus, will depend on external factors, such as application (military frequencies are different from civilian frequencies), distances, bit rate, and so forth. This requires the antenna design to be application specific.

The size, weight, and performance of resonators depend on the operating frequency. Several examples of micromechanical resonators for various frequency ranges can be found in the literature. In Figure 22 is shown one example of it reproduced from [59]. Since quartz resonators suffer from high power consumption and relative bulky size [59], developing MEMS resonators could help overcome these drawback, and, thus, this is the most interesting candidate for substituting the quartz resonators [60].

Other examples of filters and resonators can be found in [61, 62], where systems for 22 GHz and 140 MHz bands were described.

Such devices can help to not only decrease the overall power consumption of the communications systems, but their small size and weight relative to the quartz systems they replace also help reduce the size, weight and power consumption of the overall system.

5.5. Sensor and Actuators. Sensors can roughly be divided into two categories. The first one contains the sensors that are necessary for flight control, the second is sensors that are a part of the payload and provide mission-specific information.

Theoretically, AVS should be able to fly only with a 3-D accelerometer and a 3-D gyroscope. Ideally, if we know the initial position, we will be able to calculate all the later positions only by integrating the resulting vector acceleration two times to find the position, while 3-D gyroscope signal is used to maintain flight stability. However, since all gyroscopes and accelerometers suffer from offsets and drifts, for instance with time and temperature, the accuracy of the calculated position will decrease over time. Additional sensors can be used to compensate somewhat for drifts and offsets. For example, in [63], it is stated that "*accelerometers and gyros can only be used for the pitch and the roll, while for yaw measurements, magnetometers have to be used*" [63]. In fact, if the roll rate is integrated with respect to time to find the roll angle, it "*will lead to drifting errors*" [63]. Another interesting solution is presented by the "Paparazzi project" described in [64], in which "*a free and open-source hardware and software project intended to create an exceptionally powerful and versatile autopilot system*" is described. The proposed solution uses two infrared (IR) sensors positioned on the side walls of the AVS.

The basic concept is that if the vehicle is perfect parallel to the earth surface, then both the sensors will detect the same temperature and thus get the same signal. On the other hand, if there is any misalignment (Figure 23), one sensor will reveal the earth temperature (warmer) while the other one will reveal the sky temperature (colder). Based on this principle, it is possible to correct for the tilt angle. Furthermore, it is also feasible to use more than one pair, for calculating not only the roll angle but also the pitch angle. However, even though this method is very useful for larger AVS, it has poor functionality for NAVs, especially

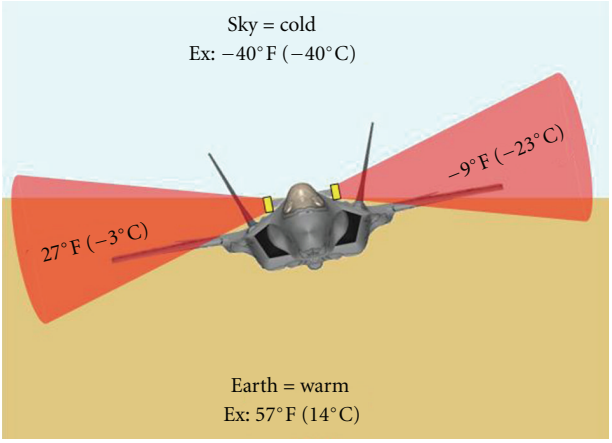

Figure 23: Example of angle compensation using two IR sensors reproduced from [64] under GNU FDL 1.2.

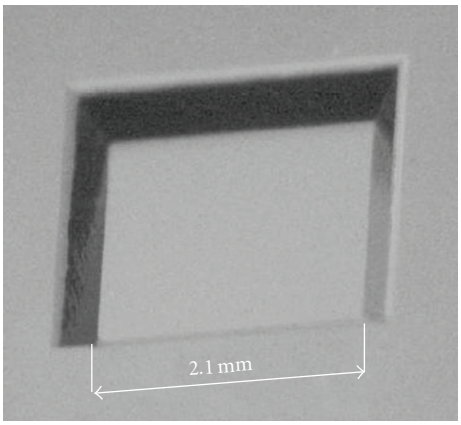

Figure 24: Example of ultrasmall microphone, diaphragm [66].

during indoor missions where this kind of IR tracking works poorly because the IR radiation signals are more or less unpredictable.

For NAV applications, in which each extra sensor means additive space, power, and weight, the system should be kept as simple as possible, using for example very low drift gyroscopes or accelerometers or using some compensation circuitry.

The other class of sensors is the data-collecting sensors that provide useful information for the users. Examples are cameras, microphones, gas sensors, biological sensors, radiation sensors, and so forth. Depending on the applications, most AVS will include one or more of these data sensors.

Cameras and microphones are two of the most useful data sensors for AVS. A camera is required to help the user pilot the vehicles when there is no direct vision between them (e.g., in indoor missions). Similarly as for batteries, smart phones and other consumer electronics have driven the development. The smallest available cameras nowadays are based on CMOS sensors which offer "*advantages in on-chip functionality, system power reduction, low cost and miniaturization*" [65] when compared with the earlier used CCD image sensors.

Figure 25: Graphic representation of the GCS from Prox Dynamics, containing three NAVs in the bottom side while the controls and the LED screen are placed on the upper side [17].

Microphones are useful in spying, rescue operations, and similar applications. Today, micro- and nanotechnologies allow building very small microphones, such as those in [66] with diaphragm dimension of $2.1 \times 2.1\,\text{mm}^2$ (Figure 24) using a "*single-crystalline wafer as the substrate for the microphone capsule*" [66].

Micro- and nanotechnologies also provide great improvements for gas sensors, since "*the sensitivity of chemical gas sensors is strongly affected by the specific surface of sensing*" [67]. Using nanotechnologies, it is possible to build nano structures with a larger sensing area and either keeping the sensitivity constant while reducing the size or increasing the sensitivity while keeping the size constant. Many different materials can be used for building gas sensors. Some examples can be found in [68] where metal oxide is used, or in [69] that presents gas sensors based on conducting polymers. Depending on the application, a range of other sensors can also be used. In this case, important selection criteria for the choice of sensor are small dimensions, low weight, and low power consumption.

Actuators are needed for different applications on board AVS. They are used for flight control, for instance, making the vehicle turn, for moving the sensors, for example, movable cameras or for building useful tools, such as micropliers for picking up samples. Similarly as for flapping-wing systems, linear actuators are theoretically the most suitable solution for this application. Although there are a lot of studies of new materials and new concepts for linear actuators, all the existing prototypes have limited maximum elongation and/or long response time that limit the applicability on board AVS. The suboptimal solution is using microservo actuators that are rotary actuators. They consist of a small electric motor, with some cogwheels that form a microgear. In 2002, a microharmonic drive was realized as one of the smallest microbacklash-free servo actuator in the world [70] with a size of 6 mm in diameter (another version is available with 8 mm diameter size) and

Table 4: Quality comparison of actuators: adapted from [35, 79].

Actuators	Advantages	Disadvantages
Linear actuators		
Piezoelectric Ceramic	(i) Excellent performances except strain output (ii) Strain output can be magnified using bender arrangements	(i) Require high activation voltage
Shape memory alloy	(i) Excellent performance except frequency range	(i) Poor fatigue life
Magnetostrictor	(i) Excellent performances except strain output	(i) Require high activation voltage
Solenoid	(i) High strain	(i) Low energy density
Electroactive Polymers (EAP)	(i) Dielectric elastomers outperform muscle in both stress and strain output.	(i) Only ionic EAPs operate on low voltage (ii) Novel technology not widely available
Rotary actuators		
Electric motors	(i) Efficiency (ii) Reliability (iii) Versatility	(i) Weight (ii) Dimensions

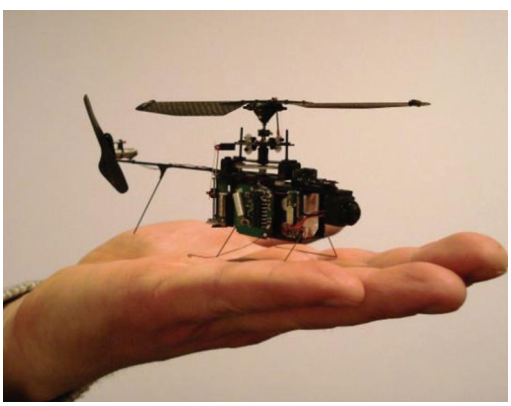

Figure 26: The Hornet 2-b (Prox Dynamics), complete with camera and video transmitter [17].

with only 1 mm axial length. It is made with nickel-iron, and it has an output torque of 50 mNm (for the 8 mm diameter gear). Other rotary actuator technologies, such as piezoelectric motors [71] or shape alloy motors [72], are still under development, and they are yet not mature enough for AVS applications. Table 4 shows a quality comparison of some linear and rotary actuators.

6. Future Trends

Considering the short-term future (1–3 years from mid-2010), rotary-wing NAV will be the most important commercial type, since it has the best performing technology at present and the near future. Prox Dynamics [17] has prototypes that will be available on the market in 2011. They present a system consisting of two parts: the NAV and the ground control station (GCS). The GCS (shown in Figure 25) has three different uses: (1) tt will protect the vehicles during the transport, (2) it will be used as remote control system for the NAV in flight. (3) As a station for recharging the AVS batteries. The whole system (NAV + GCS) will have a total weight less than 1 kg, and dimensions of 15 cm × 15 cm × 5 cm [2] (Figure 26).

These systems will be customizable by the clients and equipped with different sensors depending on mission needs.

Specifications for those AVS state that will be able to fly for up to 30 minutes with a 10 m/s maximum speed. It has a video camera and transmitter for the video signal to the GCS.

However, in the future, flapping-wing solutions are viable and will improve maneuverability and efficiency relative to rotary NAVs. Several technologies can potentially replace batteries as power supplies in future NAV. Recent advances make ultracapacitors a good candidate. However, depending on future developments, fuel cells are also promising, in particular direct methanol fuel cells, where the fuel storage is less complicated than for hydrogen-based fuel cells.

Further size and weight reductions of communication systems are important issues for the future. Micro- and nanoelectromechanical systems (MNEMS) technologies can be used to provide devices, such as lighter, smaller, and less power consuming resonators and filters than the current state of-the-art devices. However, reducing antenna dimensions while keeping acceptable performance is challenging since antenna performance is related to size governed by the laws of electromagnetic radiation. Furthermore, the transmission power cannot be reduced under a certain threshold without degrading the quality of the communication. MNEMS actuators will also replace the relative heavy rotary actuators (based on small electric motors), with lighter and more energy efficient linear actuators based on new materials, such as electroactive polymers. However, the improvements will be relatively small, since the avionics on board of an NAV are already ultraminiaturized (a few grams).

Future NAVs will most likely be equipped with GPS and radar systems. Infrared and/or high-definition cameras could be included. Mission-specific sensors and actuators could be removed and replaced depending on the application. A quick-connection method can help to, for example, rapidly replace a gas sensor with a radiation sensor in a few seconds. Nanotechnology could play an important role also

in aerodynamic improvements. For instance, a combination of different thin deposited layers of functional materials could allow the realization of morphable wings. These wings will be able to change their shape in accordance with the flying regime in order to maximize, in realtime, the efficiency of the vehicle. The shape changing can for example be on the attach angle or on the wing surface roughness.

Future trends could also include the development of sophisticated software that will enable operating future ultrasmall NAVs in coordinated swarms. Furthermore, with the future improvements of artificial intelligence, some of them will have decision-making capabilities, opening the way to completely new mission profiles.

7. Conclusions

In this article, the main typologies of air vehicle systems used for micro- and nano-air vehicles have been presented. The typologies are fixed-wing, rotary-wing, flapping-wing and passive AVS. For each type, the main features are described, with a particular focus on their advantages and disadvantages. Several examples of existing prototypes have been described, and a final comparison between fixed-wing, rotary-wing, flapping-wing, and passive AVS have been presented. The rotary-wing principle is at present, and in the near future, in most NAV applications, the best option since they are capable to hover and have good maneuverability in NAV range dimensions. Military surveillance and reconnaissance are the most promising applications for such vehicles. Flapping-wing typology adapted from nature, first of all entomopters adapted from insects, is a promising future option, but more long-term research is needed to make this typology practical for AVS in general and for NAVs.

Power requirements and power sources for NAVS are major challenges for present and future NAVs, resulting in limited flight times around or less than 30 minutes and payload capabilities around 10 grams or less. Rechargeable batteries, mostly rechargeable lithium ion batteries will in the near future, remain the main power source in NAVs, with most of the power used by the electric motors. Fuel cells and ultracapacitors show promising potentials to be used in the future, but more research and development are needed to make them practical and with high enough power density for use in NAVs. In addition, the development of a new class of gas turbines, which have already been proven promising, can surprise us in the near future. Sensors will play an increasingly important role, as they will be more and more used for improving flight control and collecting various information data from the environment during missions. For special missions and requirements, new sensor classes have to be developed; they will be focused on having low weight and low power consumption. Communications will remain a challenge as the power consumption scales poorly with size reduction of the NAVs. Micro- and nanotechnologies are enabling technologies for NAVs that will evolutionarily contribute to further size and weight reductions, improved sensors and actuators for better flight control and data collection during missions, and improved energy sources with higher power densities.

Acknowledgments

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