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► To cite this version:

Sébastien Grondel, Mathieu Colin, Marie Zwingelstein, Sofiane Ghenna, Caroline Soyer, et al..
Towards the use of flapping wing nano aerial vehicles. Modern Technologies Enabling Safe
and Secure UAV Operation in Urban Airspace, IOS Press, pp.52-63, 2021, 9781643681887.
10.3233/NICSP210006 . hal-03541944

HAL Id: hal-03541944

<https://hal.science/hal-03541944v1>

Submitted on 9 Oct 2024

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Towards the use of Flapping Wing Nano Aerial Vehicles

Sébastien Grondel^{a,*}, Mathieu Colin^b, Marie Zwingelstein-Colin^a, Sofiane Ghenna^a,
Caroline Soyer^a, Eric Cattan^a and Olivier Thomas^b,

^a*Univ. Polytechnique Hauts-de-France, INSA Hauts-de-France, CNRS, Univ. Lille, Yncrea, Centrale Lille, UMR 8520 IEMN, DOAE, F-59313, Valenciennes, France*

^b*Arts et Métiers, LISPEN EA 7515, 8 Boulevard Louis XIV, 59046 Lille, France*

Abstract. In the last decade, the potential of Micro Aerial Vehicles (MAVs) has generated an enormous interest in this technology and numerous applications have therefore been proposed in military and civilian fields. More recently, researchers have begun to work on a new and miniaturized generation called Flapping Wing Nano Aerial Vehicles (FWNAVs) who could be particularly promising for the indoor inspection. Before to be able to use efficiently these FWNAVs, there are however significant scientific and technical challenges to solve due to the scaling down. These include aerodynamics of low Reynolds number flow, small-scale power generation and power storage, navigation and communication, propulsion and control as well as manufacturability. This paper sets out the potential applications of such FWNAVs and reviews some of the challenges related to aerodynamics, stability, and design trends.

Keywords. Flapping wing, Nano Aerial Vehicle, aero elasticity, control, energy source.

1. Introduction

There is currently an increase of demands on Micro aerial vehicles (MAVs), as they extend the range of UAV's applications in military and civil fields. Major efforts have been made to develop miniaturized structures for propulsion and navigation systems, flight controllers, on-board electronics and payloads, etc. which explains why these MAVs now benefit from the latest technologies and have great maneuverability, portability and propulsion efficiency. This situation is the reflection of abundant scientific research, which is crystallized in particular in dedicated international scientific congresses as for example the International Micro Air Vehicles conferences and competitions (IMAV), during which an international MAV's competition is systematically held each year [1].

A lesser known, but equally important fact is that the researchers are seeking to push back the technical limits to offer more smaller and more lighter aerial vehicles. This new generation is called Nano Aerial vehicles (NAVs) and the challenge is to maintain the aerodynamics and navigation performances when scaling down. Although it appears possible to miniaturize MAVs to design and fabricate NAVs, there are however, some limitations imposed by the nature and classical micro-fixed wing or rotating wing

* Corresponding Author, E-mail: sebastien.grondel@uphf.fr.

vehicles appear useless when the size tends to the centimeter. A potential solution is to draw inspiration from nature and in particular from the small birds and flying insect species to design Flapping Wing Nano Aerial Vehicles (FWNAVs).

The aims of this work is to present a survey of the last advances of FWNAVs. The outline is the following. First, we propose in section 2 to describe the classification of the small aerial vehicles, i.e. to recall the main difference between the MAVs and NAVs. Then, section 3 is dedicated to the completely spectral of civilian and military application areas for these small aerial vehicles with a special attention being given to those emerging with the FWNAVs. Finally, section 4 deals with the last scientific and technological challenges to solve in order that the FWNAVs operation becomes a success story.

2. Classification of small aerial vehicles

The development of unmanned air vehicle was initially for military use, which explains that the generally adopted definitions for MAVs and NAVs originate from the United States Defense Advanced Research Projects Agency (DARPA).

2.1. MAV's definition

Using the DARPA definition proposed in 1997 [2], a MAV is 15 cm or less in largest linear dimension, includes payload less than 100 g, has a range of 10 km, peak velocities over 13 m/s, and operates for more than 20 minutes. There exists currently three main types of MAV meeting these requirements: the fixed, rotary and flapping wings MAV.

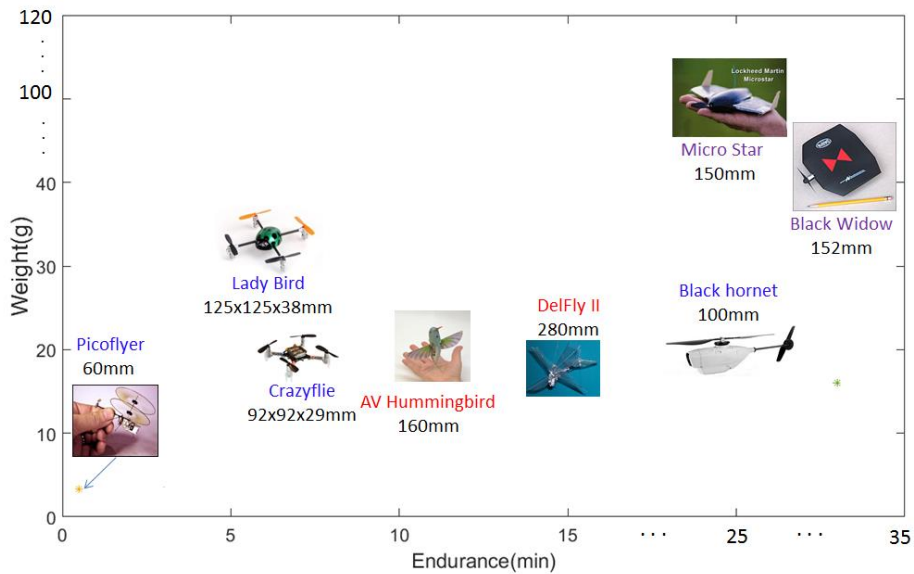


Figure 1. Some examples of existing MAVs with illustration of their main characteristics.

To illustrate some examples, Figure 1 represents the flying time of several existing MAVs against their weight. Violet, blue, and red colors allow symbolizing fixed, rotary,

and flapping-wing vehicles respectively. From this figure, it is clear that the endurance of fixed-wing MAVs such as the Micro Star [3] and Black Widow [4] is longer than the other wing types. However, the inability to hover and the higher mass make them less interesting for indoor inspection. Rotary-wing MAVs such as Crazyflie [5] and Lady Bird [6] can hover as well as take off and land vertically. Moreover, they are maneuverable and suitable for indoor applications. Nevertheless, their endurance is short and drastically decreases when they reach centimeter dimensions, as in the case of the Picoflyer [7]. Small-scale flapping wings offer better endurance performances than fixed and rotary-wing vehicles. The Delfly II [8] can fly 8 minutes longer than the Crazyflie, which is nearly the same weight, and almost 9 minutes longer than the Lady Bird, which is double its weight. However, it is not always true that any small flapping-wing vehicle outperforms small rotorcrafts. The Black Hornet [9], for example, is an exception because its hovering efficiency, i.e the ratio between the weight of the aerial vehicle and the power to keep it aloft is equivalent to that of the AV Hummingbird [10]. This confirms the results obtained in [11] which demonstrate that flapping trajectories are better than revolving wings only for Reynolds number lower than 100.

2.2. NAV's definition

In 2005, the DARPA again pushed the limits of aerial robotics by announcing the 'Nano Air Vehicle' program, which had the requirements of 10 g or less vehicles with 7.5 cm maximum dimension, able to fly 1 km or more (see Table 1). Such kind of new aerial vehicle must also be able to enter buildings, penetrate narrow entrances and transmit data without being detected. Whether in terms of stealth, portability or multiplicity, millimeter-scale systems considerably broaden the scope of applications for more traditional unmanned aerial vehicles, and hovering appears ideal for operating in confined environments. It therefore seems well suited for indoor reconnaissance missions with both military and civilian requirements.

Table 1. Design requirement for NAVs [12]

Specification	Requirements	Detail
Size	$\leq 7.5\text{cm}$ (3inch)	Maximum dimension,
Weight	$\leq 10\text{g}$	Objective Gross Takeoff Weight
Payload	2g	Mission dependent
Speed (Fast)	5.7	High speed flight for $>1000\text{m}$
Speed (Slow)	5.7	Low speed flight for $>60\text{s}$
Hovering ability	Yes	Hovering for $>60\text{s}$
Cruising ability	Upper three items	Total of the upper three items
Range	1 km	Operational range
Endurance	$> 20\text{ min}$	Total mission duration
Navigation	MSRE $<0.5\text{m}$	Mean squared residual error

3. Applications

3.1. Civilian applications

Previously confined to the role of toys in the hands of children and keen-model maker, the small unmanned aerial vehicles have conquered the civilian markets and their applications are already numerous.

In the area of agriculture [13], the use of MAVs is largely developed and can be classified into two main categories: treatment (spraying in general), and diagnosis (collection of geo-referenced data on the state of crops). For treatment, the vehicle must be capable of hovering, with a larger payload, while avoiding obstacles close to the ground, which is the case of MAVs with rotating wings (of the "multi-rotor" type). For diagnosis, the vehicle carries the right sensor (visible or infrared) at a high enough altitude to avoid all obstacles and can cover large areas quickly, which is the case with fixed-wing MAVs. The image obtained with a MAVs does not differ structurally from a satellite image, but the accuracy obtained is close to the centimeter scale and is higher because of the lower flight altitude. Above all, the small unmanned aerial vehicles allow us to avoid being hindered by clouds. The most advanced MAV manufacturers in the agricultural sector offer dedicated sensors advanced camera systems, infrared, multispectral or reflectance sensors, or thermal reflectance sensors or even thermal cameras. The choice of on-board sensor depends on the biomass, chlorophyll content, leaf density, water stress or simple imaging (estimation of pest damage) measurement.

Another application of MAVs is the inspection in Railway surveillance and Maintenance. The National Society of French Railway (SNCF) for example is taking advantage of the agility of MAVs to improve its network monitoring methods and associated performance [14]. MAVs that allow information to be taken without affecting traffic open up prospects in a number of areas:

- monitoring and control of vegetation on the edge of the tracks;
- prevention and detection of all kinds of intrusions into railway premises, particularly to combat metal theft;
- inspection of engineering structures (bridges, viaducts), stations (roofs, canopies), workshops or trains (roofs), and rock walls;
- inspection of electrical installations to detect, for example, defective components (hot spots);
- rapid detection of obstacles or damage to the track in the event of bad weather or malicious acts;
- site monitoring.

Some societies have already chosen to use MAVs for the inspection of their warehouses. Hence, Hardis Group [15] is proposing a system mounted on a MAV designed to automate inventory and stock control operations in warehouses, in order to identify and correct storage errors. The innovation consists of several components: first, a device allows the MAV to move autonomously thanks to an integrated cartography of the warehouse and a predetermined flight plan. Second, this device is coupled with a processing system capable of identifying and capturing, thanks to an on-board camera, the information to carry out the inventory. Specifically, the algorithm developed allows associating the image with its position in the warehouse and automatically translating it in 3D into a storage location.

More recently, Scientists at the University of Bristol [16] have successfully mapped radiation levels around a Japanese nuclear power plant using a MAV. They say it is the safest way to monitor levels. Helicopters and other monitors do similar tests, but none are able to get close enough to give a comprehensible profile. In addition, Drone Adventures [17] is conducting post-disaster mapping missions in places like Haiti, where updated maps can be critical to facilitate distribution (in the short term) and management of infrastructure and its repair (in the long term). They collaborated with the Center for

Spatial Information Science at the University of Tokyo to explore how the area devastated by the Fukushima disaster is changing. Drone Adventures made a detailed mapping of three different cities around Fukushima.

When all sectors are considered, the civilian drone market offers long-term prospects valued at several billion dollars, attracting European avionics manufacturers such as Dassault, Thales and EADS who benefit from their experience in the military sector.

In the civilian field, the major advantage of the NAVs sought is their small size, which would allow them to be used in confined environments and inside buildings, which is impossible for the decimeter-sized MAVs. The applications targeted would mainly be the surveillance and exploration of sensitive industrial environments (chemical, nuclear, etc.) or the search for people in hostile environments (rubble following natural disasters, etc.). Many others applications can be envisaged, such as for example the pollination of flowers by a swarm of drones or the monitoring of elderly people isolated in their homes.

3.2. Military applications



Figure 2. US Army roadmap for UAS 2026-2035 [18].

Traditional unmanned aerial vehicles have changed the way we think about armed conflict and play a very important role in intelligence and targeted attacks. It is therefore quite natural that the armed forces are now interested in MAVs. In fact, dedicated MAVs for military applications already exist. In 2013, British troops used a rotary wing MAV with a wingspan of 10 cm and a weight of 16 g on the frontline in Afghanistan to send vital information to the ground. They were the first to use these brand new Norwegian-made micro-helicopters, which reliably transmitted video and images to a handheld device on the battlefield. This aerial vehicle is believed to be the smallest surveillance drone for military use ever built. It is worth noting that the UK Ministry of Defense recently purchased 160 Mav's from Prox Dynamics for a £20 million contract [19].

The DARPA is not to be outdone: as shown in Figure 2, it can be noted that their roadmap (2026-2035) for the US army's drones proposes the effective use of NAVs by 2028.

Due to their dimensions, the NAVs may have their own specificities in the military field:

- Among the possible missions envisaged for NAVs, those that predominate in the first place are most certainly intelligence, surveillance and reconnaissance missions. The small size of these devices combined with their flight capacity gives them new fields of application and should allow their use for urban operations in confined spaces such as buildings (homes, hotels, industrial environments, etc.) or tunnels [20]. In addition, the combination of multi-spectral, small size and precision sensors should provide operators with information on areas that usually endanger combatants. The realizations envisaged for these NAVs would be based on the manufacture of artificial flying insects or very small birds capable of flying inside buildings or tunnels in a very discreet manner, while transmitting information on its immediate environment.
- Nanotechnology is also currently a source of innovation in terms of extremely small and accurate nuclear, biological and chemical sensors. Currently, miniature chemical sensors designed to detect specific molecules such as contaminants are already in development. Deployed in swarms, NAVs equipped with such molecular sensors could quickly identify the type of contaminant and disperse to determine the extent of the contaminated area and report back [21]. Each NAV may have a different marker.
- In swarm form, the NAVs could also be used to support ground units either in urban areas or in open terrain. These devices could continuously scan the area around a ground force and when an enemy is identified, ground units could then quickly attack and neutralize the targets. Direct attacks appear more difficult. However, by employing NAVs equipped with a lethal agent [22], attacks on individuals can be envisaged.
- From a strategic perspective, another potential mission of NAVs would be to strike directly at the enemy's nerve center. In a conflict, strategic targets are usually well defended and usually far behind the enemy's front lines. Thus, a long-range platform is usually needed to reach them. Current technology limits the range of NAVs to very short distances due to problems of energy storage and propulsion efficiency. Until these limitations are overcome, NAVs will require other modes of transportation, such as dropping from a larger aerial vehicle, in order to reach their intended targets. Soldiers on the ground or even from large drones or aircraft could launch these types of vehicles to the area of interest. Deployed in large numbers, they would then provide wide coverage of confined spaces at low cost due to their low overall acquisition cost [23].
- These devices could also remain dormant until their sensors detect movement or chemical traces of potential targets.

4. Challenges for the FWNAVs

When surveying the state of the art of FWNAV's, prototypes below 7.5 cm are rare and only three of them, the "RoboBee"[24], the "Flapping wing Robot"[25] and the "Robotfly" [26] (Figure 3) are currently capable of flying while powered by an external source (see Figure 3). These FWNAV's have been fabricated from carbon fiber and thin film laminates. They have a wingspan around 3 cm and weigh under 200 mg. They rely on an articulated drive mechanism and a piezoelectric actuator or an electromagnetic actuator to enable wing flapping. Given state of art commercial microbatteries [27], their flight time would be 5 to 10 minutes if it was possible to lift the battery, which is unfortunately not the case now.

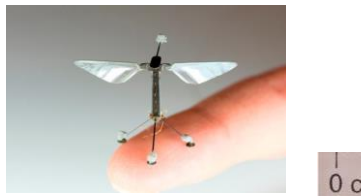


Figure 3. RoboBee (60mg, tethered), Flapping wing Robot (80mg, tethered), RobotFly (190mg, wireless powered by a remote laser source) [24-26].

A first conclusion that follows naturally from the literature is that as we tend to decrease the size and weight of unmanned aerial vehicles to meet the NAV DARPA definition, we quickly reach the limits of what the rotary and fixed wings can offer. Since at the millimeter scale only insects are capable of flying, it appears logical to turn to biomimicry. Therefore, there is a clear need to find new manufacturing methods, design strategies, and actuation and control concepts to overcome the preceding limitations. We propose to summarize below the main challenges and advances made in recent years in this field at international and national level.

4.1. The choice of manufacturing technologies

At the micrometer scale, microsystems manufacturing technologies seem to offer a very attractive solution since they allow the reliable and precise realization of microstructures compatible with the characteristics of insects while minimizing their weight. Major advances include the work of H.Y. Chan *et al* [28] who proposed the realization of a structure built using Microelectromechanical Systems (MEMS) technologies and validated this concept by building 1mm long thermal actuators with Parylene wings that could be actuated up to 200Hz. In the same vein, T. Nick Pornsin-Siriak *et al* [29] proposed the construction of wings using microsystems technologies, using a titanium alloy for the ribs and Parylene for the wing membrane. On this NAV, the wings were mounted on a transmission mechanism manufactured using conventional mechanical techniques. Three PhD students, funded by the Air Force Institute of Technology, were also involved in using PolyMUMPs [30,31,32] to make NAVs driven by electrostatic combs.

Although capable of setting wings in motion, all these devices are far from being able to reproduce the kinematics of insect wings. To our knowledge, IEMN and ENSAM are the only team to propose a structure entirely fabricated using MEMS technologies, called OVMI for "Object Volant Mimicking Insect" with characteristics very similar to

those of insects. Moreover, the proposed prototype in Figure 4 is at the same time capable of producing large flapping and twisting movements [33] and a lift greater than the weight [34], which demonstrates the interest of the used approach.

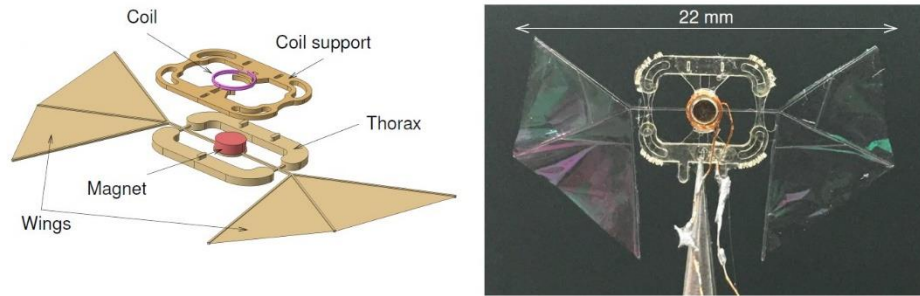


Figure 4. OVMI (25mg, 22mm span) [35].

4.2. Understanding of aero elastic phenomena at this scale

Although traditional lift-generating mechanisms generally lose effectiveness as unmanned aerial vehicle size decreases, millimeter-scale FWNAs should potentially take advantage of a number of unique aero elastic phenomena observed in insects. Thus, a FWNAs with insect-like dimensions and flight principles could outperform most of aerial prototypes presented in this paper.



Figure 5. a) wing trajectory by looking at a section of the wing drawn in red with the point representing the leading edge, b) tracking of this section during up and down translational movements and slope inversion during pronation and suspension interpreted as rotation, c) evolution of flapping and rotation in phase quadrature [36,37].

So far, considerable progress has been made in understanding insect flight, and it is well known that lift generation results from both a wide range of unconventional

aerodynamic mechanisms [38] as well as from specific kinematics induced by the flexible characteristics of wings [39]. Initial findings indicate that the wings are flexible both due to weight constraints and probably to achieve better aerodynamic performance. More specifically, and as illustrated in Figure 5, the movement of the wing relies on the combination of four basic movements: downward movement, supination, upward movement and pronation [40].

In the case of flexible wings, the up and down motions involve a flapping motion while supination and pronation result in a twisting motion in a phase shift that is in quadrature with the previous motion. It is this quadrature phase shift, i.e. the attainment of a maximum amplitude for one movement when the other is zero, which produces aerodynamic forces leading to lift. This is this particular features which guided the design and optimization of the OVMI family of FWNAV, based on the combination of two basic flapping and twisting vibration modes [41]. It was also shown that the aerodynamic effects on the vibration of the wings can be viewed in a structural model as an amplitude dependent damping [42], which simplifies an early stage design procedure. As mentioned earlier, a key element of insect flight is the flexibility of the wing structure, which often changes shape dynamically during flight [43] but its exact role on aerodynamic performance remains highly controversial.

4.3. *Flight control and stabilization*

The flight control of flapping wing NAV's is currently widely studied. Most of the work presented in the literature refers to the famous six-degree-of-freedom aircraft equations found in many flight dynamics textbooks, such as Etkin and Reid [44]. In this sense, Doman *et al* [45,46] propose the modelling and control of a NAV based on the RoboBee. The aerodynamic model used in the simulations is developed in [47] and is based directly on the work of Sane and Dickinson [48,49]. The use of the standard equations of motion for a FWNAV can be justified here by assuming that the acceleration or gyroscopic effects at the wings are negligible compared to the effects of the body, or that these effects calculated over one flapping cycle are identically equal to zero. Some authors [50,51] nevertheless claim that the mass/inertia effects of the wings should be included to allow for better flight control, which requires proposing a mechanical model of a multi-body system. The simulation results of this work show significant differences in the position and orientation of the NAV compared to the predictions made by the standard flight dynamics model. However, control algorithms now need to be tested on a real prototype to definitively validate these findings.

Another approach to flight control is to rely on methods that mix experimentation and analysis. As an example, Perez *et al* [52] propose in their work a two-step methodology to solve the problem: in the first step substantial a priori information about the system is collected by identification methods. In the second step, the information directly collected by static flapping experiments is used to design the controller used in vertical flight. The design of the proposed controller is based on the idea of treating the excitation signal as a sub-system of the NAV.

4.4. *Embedded electronic and energy sources*

To ensure flight control of the FWNAV, it is also essential to be able to embed the suitable electronics. Among the indispensable elements that theoretically make contactless flight possible are the microcontroller, the sensory orientation sensors, the

power supplies, and the communication system. To date, there are however, no electronic components embedded in a NAV of the size of an insect. Such an issue requires checking the feasibility of producing application-specific integrated circuits (ASICs), in order to propose adapted solutions at this scale. Moreover, although some solutions are explored for the energy sources like the use of micro fuel cells [53] or small micro batteries [54], significant research on the topic needs to be conducted.

5. Conclusions

This paper has presented a summary of the future challenges that need to be solved to create an autonomous FWNAV of millimeter size. To design and fabricate such a vehicle, it was pointed out that it is essential (1) to understand the effects of low Reynolds numbers in insect flight; (2) to propose an innovative structure using micro-fabrication technologies dedicated to micro-systems and to miniaturize the components, in particular the electronics; (3) to develop low-level control of micro-actuators and specific sensors. In addition, collective production using micro-fabrication technologies could lead to very low production costs. The success of such a research is key to many applications in both the civil and military fields.

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