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Original Research Article

Nature Inspired Flying Vehicles and Future Challenges in Aerospace

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Abstract

The challenges of modern urban warfare require high agility flying machines capable of flight in confined dirty, dull and dangerous (D^3) environments. Recent technological advancements in the field of aerospace and materials have enabled the exploration of flight regimes and designs similar to those of birds and insects. Flying robots with a size limit of 6 inches in all dimensions are called Micro Air Vehicles (MAVs) [1] and smaller ones with the size constraint of 1 inch are termed Nano Air Vehicles (NAVs). Fixed wing aerial vehicles are generally preferred in this flight regime due to simplistic design but these lack the hovering capability. Rotary wing designs are also being pursued with added hovering capability, but these cannot move faster through the air and their endurance is limited by the size and capacity of on-board batteries. In order to mimic the maneuverability of birds and insects, flapping wing designs are required which could produce lift and thrust efficiently using the same wing planform. Future, advancements in materials, manufacturing technology and miniaturization of electronics will enable design and development of flapping wing robots similar to natural birds and insects with very demanding mission profiles. This paper aims at highlighting the future requirements of urban warfare along with the challenges being faced to pursue flapping wing designs mimicking insects and birds flight.

Keywords: Micro Air Vehicle, Nano Air Vehicle, Low Reynolds Number, Aerial Robotics

1. Introduction

Richard Feynman a famous Physicist said in his keynote speech at Caltech back in 1959 that there is plenty of space at the bottom. This hypothesis laid the foundation for the modern science of Nanotechnology. In 1960s, a simple computer was as big as a room and now there are quad core processors working in smart phones. The size keeps shrinking with continuous improvements in performance and this pursuit is never likely to end. The advancement in aviation has also followed the same analogy. The challenging requirements of modern urban warfare require autonomous small flying robots inspired by insects and birds capable of maneuvering flights in confined spaces along with carrying mission specific payloads. The basic inspiration and motivation for flying has always come from millions of birds and insects species, but aerospace designers have not been able to produce designs which could mimic efficient flapping kinematics of these natural flyers. Birds and insects efficiently generate lift and thrust using the same wing planform but fixed wing airplanes utilize wings for lift generation only and require separate propulsive devices to produce thrust. Despite progress in aviation from first flight of Wright Brothers' primitive flyer in 1904 to modern supersonic Jets with flight speeds in excess of Mach 3.0, all fixed wing flyers require engines or motors for

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propulsion. Rotary wing designs have also been developed and flown successfully with their additional hovering capability but these cannot fly faster and possess limited range and endurance. Flapping wing designs have not been pursued until recently with the development of propulsive devices to support flapping kinematics and availability of wing planforms with efficient lift and thrust generating airfoils suitable for the flapping flight regime [2].

The need for design and development of small scale aerial robots is driven by the recent paradigm shift in military warfare including counter insurgency operations and guerrilla warfare in urban terrains. There is a specific need for over the hill or other side of the building missions where these small aerial robots can be launched and with on-board video link can communicate the location (exact coordinates) of offenders along with activity on the other (hostile) side [3]. The other utilizations include access and direct information from dirty, dull and dangerous (D^3) environments in case of major fire breakouts, natural calamities, chemical or biological attacks, radiation hazards and terrorist operations involving hostages etc. Other than their military utilizations, these small aerial robots have numerous applications like road traffic monitor- ing, hazardous material sensing, power lines & gas pipelines inspections, real estate aerial photography, wildlife surveys and media reporting etc [4]. Octacopter Aerial Drones have been utilized in the recent Sochi Winter Olympics 2014 to film the snowboarders [5].

Defense Advanced Research Projects Agency (DARPA) in USA provided the geometric definition and minimum performance requirements for Micro Air Vehicle (MAV) in 1998 limiting the geometric size to less than 6 inches in all dimensions [1]. Many successful MAVs have been designed and developed worldwide and are being effectively utilized in military operations and civil applications alike. Similarly, the aerial vehicles with size constraint of 1 inch are termed Nano Air Vehicles (NAVs). NAVs have opened new dimensions in the modern urban warfare operations and are being aggressively pursued by academia and industry. There has been a continuous reduction in size of designed aerial vehicles [6] with the time as shown in Figure 1.

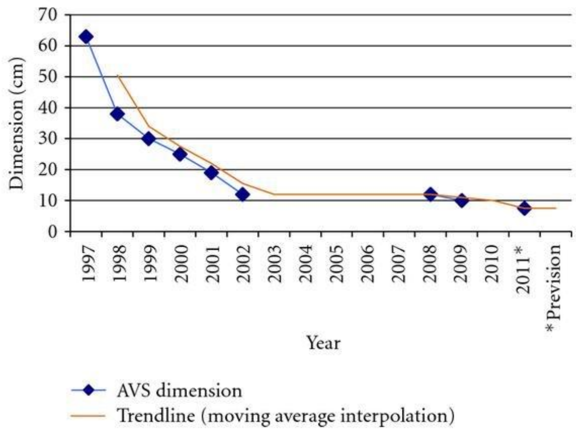

Figure 1. Reduction in Size with Time [6]

2. Future Missions

Modern urban warfare scenarios require highly agile autonomous platforms which can move inside confined spaces for real time surveillance and reconnaissance roles. Similarly, these are required to explore and survey D^3 environments involving chemical, biological and radiation hazards. That is not all, there could be specific missions for example to collect DNA and blood samples from targets without being getting noticed just like a mosquito or an even smaller insect [7]. The payloads could be incapacitating agents, poisonous or flammable chemicals. There will be minimal to no collateral damage and all of these robots will have targeted delivery missions. These flying machines could be utilized for disaster assessment after an attack or a natural calamity. A swarm of these micro flyers may also be deployed at a certain point in space by larger UAV platform (mother-ship) and could remain dormant in power saving mode before getting active when target appears in the scene. The mission could be targeting or tagging of sensitive targets. The power may be extracted from existing environmental sources like power lines and vibrating platforms for longer endurance. The list goes on and on and will populate further with the advancements in technology.

3. Natural Flyers

Many scientists continue to study how various species have mastered various challenges of flight and what are the flying capabilities of birds, bats and insects? The basic requirement to stay in air is to produce sufficient amount of lift to support the body weight and at the same time produce forward thrust to overcome the air resistance. The size obviously matters and since flapping of wings produces lift and thrust together, smaller animals have to flap their wings faster to stay in air and overcome air resistance. Birds flight mechanics is significantly different from those of the insects primarily due to difference in Reynolds Number (Re) as shown in Figure 2 [6].

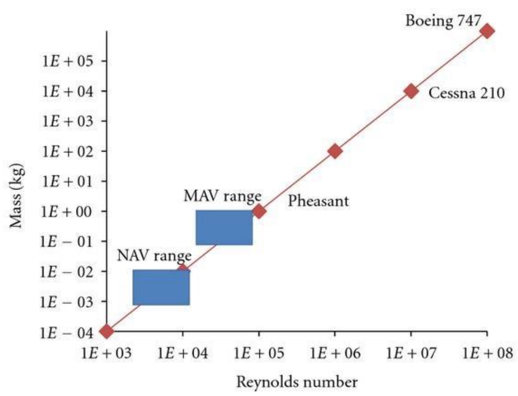

Figure 2. Reynolds Number Regimes [6]

$Re = (\rho V C)/\mu$

where

ρ =Air Density

V =Velocity

C =Chord Length

μ =Dynamic Viscosity Coefficient

In case of birds, the flying surface of wings is not just skin but feathers which provide aerodynamic advantage by reducing and optimizing the local turbulences coming from flapping of wings thus resulting in increased lift, lesser drag and hence reduced energy consumption of birds [8]. Bats are another sub category between birds and insects because bats have fundamentally different wings from birds. Although birds have better range and endurance, the bats outperform birds in aerobatic ability. The bats use their fingers to change the shape of their wings to perform precise acrobatic maneuvers to catch insects in air. Hummingbird is at the edge of birds category. It has the unique ability to hover as well as has feathered wings. It also has the highest flapping frequency among the birds [9] as can be seen in Figure 3. Researchers propose that the hovering hummingbird produces two trails of vortices, one under each wing per stroke that help generate the aerodynamic forces required for the bird to power and control its flight [8]. The optimal generation of these vortices is the key for unique flight capabilities of hummingbirds.

Figure 3. Flapping Frequency vs Weight [9]

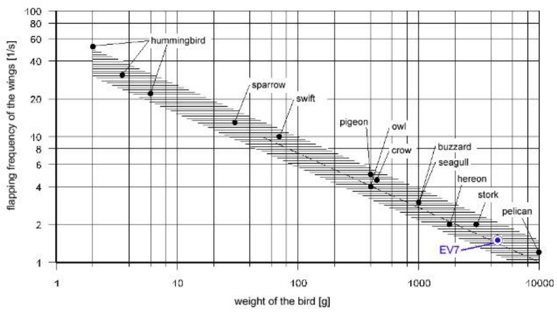

Figure 3. Flapping Frequency vs Weight [9]

Insects can not only hover but can perform aerodynamic feats like flying backwards. Insects not only produce pressure gradients for favorable lift and thrust by flapping but also exploit local and transient pressure changes in the air to increase uplift [10]. The physics of insect flying is way more complex and different from birds flight. The Reynolds number of flight is significantly lower than the birds flight. The aerodynamic efficiency of optimized wing planform along with added contributions from multiple wings and legs enable insects to fly using their whole bodies. However, in case of birds only wings are the main lift and thrust contributors. At the scale of insects, the effects of viscosity of air are different from those felt by relatively bigger birds species. The wings are required to flap at very high frequencies to sustain flying, hence endurance is reduced. For smallest flying insects not visible with naked eye, the flapping frequencies as high as 350 cycles per second have been recorded with high speed cameras [11].

For a bird or insect in flight, key similarity parameter is called the Strouhal number (St).

$St = (fA)/U$

where

f = Flapping Frequency

A = Flapping Amplitude

U = Forward Speed through the Air

Birds, bats, and insects flying at cruising speed seem to be constrained to a Strouhal number range of 0.2 to 0.4 as can be seen in Figure 4. It would be interesting to know that even dolphins, sharks and bony fish follow the same trend [12].

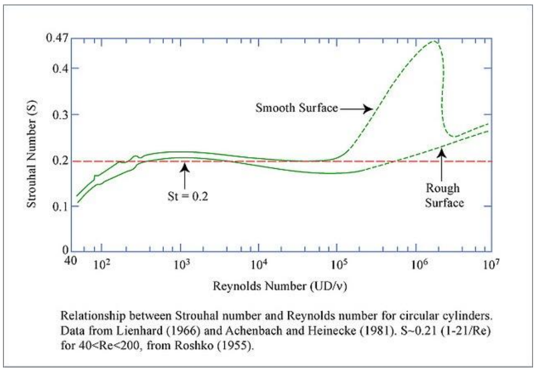

Figure 4. Strouhal Numbers for Different Species [12]

4. Current State of the Art

4.1. Micro Air Vehicles

DARPA proposed fixed wing MAV designs with 6 inch size constraint are already in action. Even slightly bigger size miniature UAVs with better payload capabilities are already being deployed for real time surveillance applications. Black Widow MAV developed by AeroVironment Inc, is shown in Figure 5 [13]. In order to add the hovering capability, rotorcraft based MAVs as shown in Figure 6 are being pursued [14] and current research focuses on increasing endurance of these designs by using high density batteries and ultra-capacitors [15]. These designs are being utilized for military surveillance and reconnaissance purposes and may prove to be a game changer in future clashes. Most of these are hand launched with few being bungee launched. Many of these American products like Black widow, Raven, Dragon Eye, Puma, Wasp and plenty of quadcopters, hexacopters and octacopters designs are already being used by US Army and marines. The roles and functional specifications vary for these products with endurances as high as many hours for Stalker to few minutes for black widow and wasp. Similarly operational ceilings vary from altitudes of 100 ft to more than 2000 m [16]. Design and Performance parameters of representative MAVs are given in Table 1 [16]. Almost all the developed nations are using these platforms for battlefield and urban surveillance. Indians are also using these miniature UAVs for surveillance [17]. Other missions include traffic monitoring, aerial photography, coverage of sporting events, political gatherings, social events and many more applications.

Figure 5. Black WidowFixed Wing MAV [13]

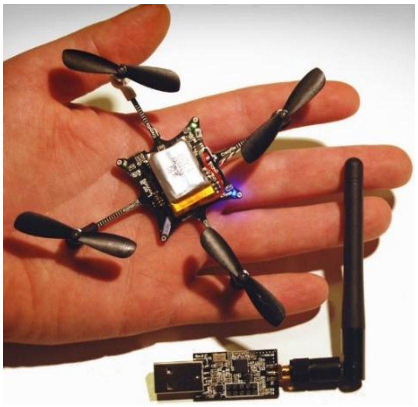

Figure 6. Crazyflie Nano Quadcopter [14]

Table 1. Design and Performance Parameters of few representative MAVs [16]

Vehicle Properties	Unit	Black Widows (Aerovironment)	Hoverfly (Aerovironment)	LUMAV (Auburn Univ.)	MicroStar (Lockheed Martin)	Microbat (CalTech Univ)	MICOR (UMD)
GTOW	grams	80	180	440	110	10.5	103
Cruise Speed	m/s	13.4	15-20	5	13.4-15.6	5	2
Wing Loading	N/m²	40.3	-	-	70.9	40	-
Disk Loading	N/m²	-	70	185	-	-	25
Wing Span or Rotor Diameter	cm	15.24	18	15.24	22.86	15.24	15.24
Max L/D	-	6	N/A	N/A	6	N/A	5
Endurance	minutes	30	13.2	20	25	2'16"	3
Hover Endurance	-	N/A	7.3	N/A	N/A	N/A	3
Power Source	-	Lithium-ion Battery	Lithium-ion Battery	2 Stroke IC Engine	Lithium-ion Battery	NiCad N-50 Cells	Lithium-ion Battery
Energy Density	W-h/kg	140	140	5500 methanol	150	100	150
Hover Power	-	N/A	24.5	70	N/A	N/A	11
Hover FM	-	N/A	0.39	0.41	N/A	N/A	0.55

4.2. Unconventional Designs

Some very unconventional designs include Entomopter [18], the flapping wing insect designed for exploration of Mars [19]. It had tandem x wings configuration with on board fuel servicing at NASAs Mars rover as shown in Figure 7. The proposed design has on-board sensors for surface video footage and sub surface scans in the hilly terrain of Mars [18]. Researchers at Caltech have made Microbat Ornithopter that flies freely and fits in the palm of ones hand is shown in the Figure 8 [23, 24]. Vanderbilt University has also produced a similar insect [25]. Similarly, development of Cyborg beetle is being pursued by DARPA with research funding of more than 200 million dollars [20].

Figure 7. Entomopter for Mars Exploration Mission [18]

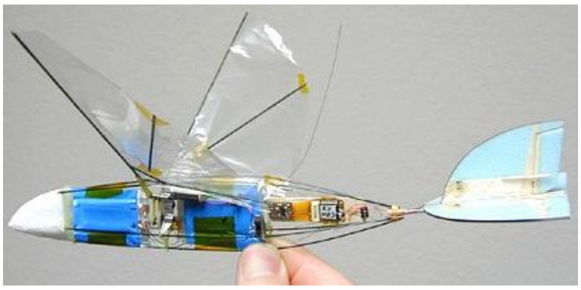

Figure 8. Microbat Ornithoper Designed at Caltech [23]

4.3. Nano Scale Flapping NAVs

NAVs mimicking the insects flights are still a challenge for the current state of the art. There are numerous demonstrations of NAVs by various academic institutions like robofly, dragon fly and ornithopter. Even the formation flight in terms of swarms of these NAVs have been successfully demonstrated.

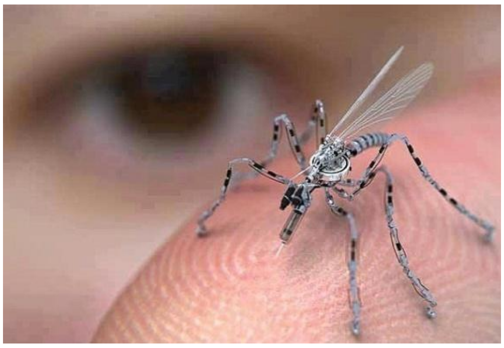

Figure 9. NAVs in DNA Sample Collection Mission [7].

The flapping NAVs are being designed and configurations as light as less than 2 grams in weight are being actively pursued [21]. Due to limited availability of hardware to support such innovative designs, hardly any product has on-board camera for live video [22]. Most of the products are classified and media reports have been there for long with pictures like Figure 9 showing nano robots in DNA and blood sample collection missions [7]. Although, no credible evidence exists for such small spying bugs, it was reported in Washington post that small bugs like dragon flies were discovered spying an antiwar rally in Missouri, US back in 2007 [7].

4.4. Aerial Robotics Competitions

In order to promote innovation and creativity, there are many design, build fly contests worldwide for autonomous and radio controlled flyers with very challenging payloads and flight requirements. The International Aerial Robotics Competition (IARC) [26] is held simultaneously at US and China with very challenging mission requirements. Every IARC mission required autonomous flying robots to interact with their environment and the competition has been going on for the past 23 years. The last mission (6^{th}) required the robots to locate an opening in a building, enter when a surveillance camera was not looking, navigate crowded hallways, avoid or disable security systems, interpret signage in Arabic, and finally reach a particular room without bumping any walls or landing. From there, the robot had to locate a particular paper inbox containing a flash drive. It had to then retrieve that flash drive, replace it with an identical blank flash drive, and exit the building within a short time span. This challenging mission was accomplished last year by a team from Tsinghua University, Beijing, China repeatedly demonstrating the entirety of the mission.

5. Future Challenges

Although the current state of the art is very promising and progress is being made at a very faster pace, the autonomous agile flight at the scale of insects is still a distant vision. The design and development of these insect scale flying robots is hindered by numerous challenges [2]. It is a common misconception that since humans have seen birds and insects fly for so long, and with the availability of high speed imaging tools and techniques, all that is required to be done is to mimic what these natural flyers perform at best and copy how they interact with their environment. In fact biologists have been trying to analyze the flying creatures and aerospace engineers have tried to match their analytical models to predict the same performance. The designer’s job is significantly different from analysis, he is trying to develop a new flying robot and its ability to achieve the requirements is no given fact. A design oriented approach is needed for such a design which is generally not offered from animal flight studies.

5.1. Aerodynamic Challenges

There are numerous challenges faced by such designs like the non-availability of appropriate aerodynamic design methods and tools along with the need for flow control techniques to match the aerodynamic efficiencies achieved by birds and insects.

1) Analytical Methods and Tools: Most of the theoretical and analytical tools available for conceptual design including flow field modeling and prediction of pressure and shear are only applicable to high Reynolds number flight [27]. The potential flow solvers generally employed for analysis of bigger scale problems does not account for the skin friction drag and boundary layer effects. Similarly, the methods available to account for skin friction drag like flat plate boundary layer approximations are not applicable to low Reynolds number problems involving MAVs and NAVs due to unsteady nature of flow [28]. So the first problem in design is inapplicability of available analytical methods to these designs. Hence, the challenge is to devise analytical methods and tools for accurate prediction of aerodynamic characteristics of these micro flying robots operating at very low Reynolds numbers.

2) Airfoils Optimized for Low Reynolds Number: The airfoil shapes utilized at high

Reynolds numbers for bigger airplanes perform poorly at low Reynolds numbers. Moreover, optimized airfoils [28], [29] proposed in the research literature for such design applications are very few; leaving designers with a very limited choice. So either the designer has to live with the very few proposed airfoils, or has to optimize an airfoil within the design problem, which requires tremendous additional computational time and cost.

3) Computationally Intensive Flow Solutions: The inapplicability of available analytical methods to MAVs and NAVs operating at low Reynolds numbers confine the space of design methods to CFD alone. Application of steady state Euler solutions and quasi steady solutions is only limited to few fixed wing designs and cannot be preferred due to the unsteady nature of flow [27] involved in flapping wing applications [30]. The only credible numerical tool available for flow field modeling at these low Reynolds numbers is Navier Stokes CFD simulation. The Unsteady RANS and eddy viscosity turbulence models are suitable for fixed wing MAVs with wing spans of more than 6 inches [30], but the error increases for smaller size MAVs and NAVs that too involving the flapping with multiple wing surfaces. Large Eddy simulations (LES) and direct numerical solution (DNS) are the preferred prediction methods for this flow domain, which are computationally intensive and cannot be used as a conceptual design tool. That too coupled with airfoil optimization [29] is a way bigger problem even for the state of art computational frameworks of today.

4) Efficient Flapping Kinematics: Flapping kinematics involve three synchronized movements; plunging which is pure flapping, pitching which is change of incidence angle that translates into change in angle of attack and sweeping which is forward and backward motion in upstroke and downstroke. The flapping kinematics is shown in Figure 10 [21]. The presence of bound and leading edge vortices during the strokes and optimal shed vorticity at the end of strokes results in very

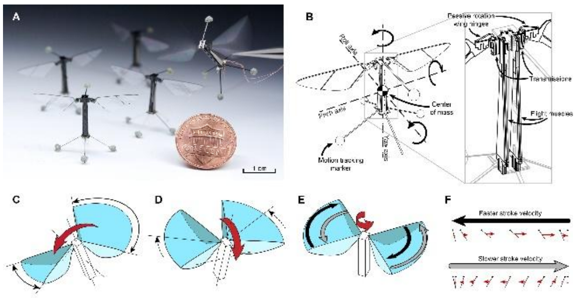

Figure 10. Kinematics of Flapping Wing Flight [21]

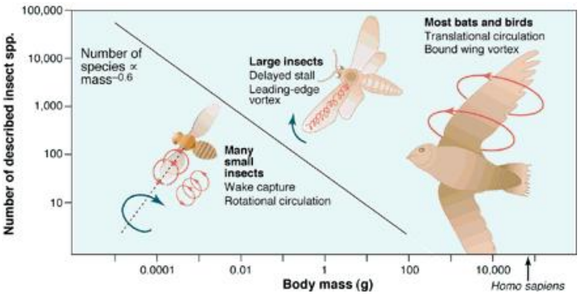

Figure 11. Different Vortices Produced by Birds & Insects Flapping Wings [31]

high values of lift coefficient that enable vertical take off and high maneuverability to these natural flyers. Insects even go one further step and exploit the ambient turbulences and wake left in the flow to their advantage as shown in Figure 11 [31]. This is further supported by flexible wings which adapt the optimal contours required during the different stages of flapping strokes. Unfortunately, aerospace designers do not have the tools, materials and control mechanisms available to perform the same feats. Hence, the same aerodynamic efficiencies have to be achieved by using unconventional flow control techniques. One of the prospective candidates for high lift generation is circulation control technique using Coanda effect. The same technique has proven successful in Super STOL aircraft and maximum lift coefficients in excess of 5.0 have been achieved using circulation control on rounded trailing edge airfoils of fixed wing aircraft [32]. Entomopter for Mars exploration mission was designed to have lift augmentation using Coanda effect [19]. So one of the future challenge for such flapping wing micro flyers is to bring in unconventional lift augmentation techniques to achieve aerodynamic efficiencies required at that scale.

5.2. Propulsion Challenges

Flapping kinematics require propulsive mechanisms which could enable simultaneous plunging, pitching and sweeping motion. These complex movements at such smaller scales involve high variation in incidence angles coupled with higher flapping frequencies and amplitudes. Propulsive mechanisms should not only be able to achieve desired kinematics but must also be driven by high density fuels to sustain mission capable flights with minimal weights. Reciprocating chemical muscle (RCM) is one such devise which has already been tested and achieves the equivalent effect of flapping kinematics by utilizing circulation control rather than actual plunging and pitching movements. Frequencies in excess of 70 Hz have been demonstrated by reciprocating actuators [33] utilizing the waste gas from RCM, but would require tremendous improvements and miniaturization for utilization in future flying robots at the scale of insects. RCM is shown in Figure 12.

Figure 12. Reciprocating Chemical Muscle for Flapping Wing Propulsion [33]

Core-less motor is another prospective candidate which is lighter than conventional iron core motor, but has the disadvantage of reduced heat dissipation [34]. Similarly, miniaturized internal combustion engines are being built with combustion motors of 0.3 to 0.4cc. Even though internal combustion engines seem appropriate for these applications; they suffer one big disadvantage of being noisy as compared to electric motors [35]. This limits their application in NAVs to be used for tactical missions, where it is required to have high stealth features.

Micro-gas turbines could be another alternative. An extremely small turbine with dimensions around 2 cm x 2 cm x 0.4 cm is shown in Figure 13. ONERA Company announced in 2008 that they had demonstrated a micro gas turbine suitable for micro air vehicles [36]. The turbine can supply from 50 to 100W with dimensions around 2 to 3 cm for the diameter and the height. The combustible in this case could be either hydrogen or propane. Despite significant efforts by numerous groups no commercial MEMS gas turbine generator is currently known for MAVs and NAVs. Even micro sized fuel cells in research might be a viable option for future NAVs [37, 38].

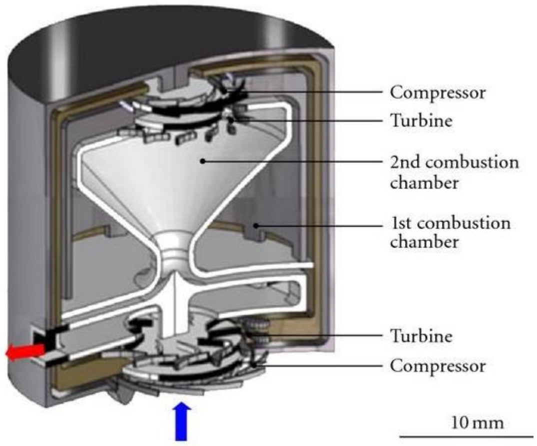

Figure 13. Micro Gas Turbines for MAVs [36]

5.3. Material and Manufacturing Limitations

Birds use feathered wings to their advantage by optimizing shed vorticity resulting from flapping. Similarly, insects use flexible morphing wing surfaces to optimize contours during the different stages of flapping cycle in addition to exploiting local turbulences in environment for increased uplift. Unfortunately, materials and manufacturing limitations of current state of the art do not allow design and fabrication of feathered and morphing wings. If the efficient flapping kinematics of birds and insects would have to be replicated, new materials and manufacturing processes are required to facilitate morphing surfaces for insect scale vehicles and feathered wings for bird scale vehicles.

At the scale of these futuristic vehicles, each milligram of weight saving is important. Nanotechnology could play an important role in aerodynamic improvements by weight savings along with performance enhancement. For instance, a combination of different thin deposited layers of functional active materials could allow the realization of morphable wings [39]. These wings will be able to change their shape in accordance with the flight regime in order to maximize, in real time, the efficiency of the vehicle. The shape changing can for example be on the attached angle or on the wing surface rough- ness. Recently with the advent of mesoscopic manufacturing methods, the first demonstration of a 60 milligram flapping-wing device which can produce thrust greater than its body weight has proven the feasibility of creating insect-scale flying robots using these techniques [40].

5.4. Electrical and Electronic Challenges

1) Size & Weight of Components: The size and weight of electrical and electronic components including communication systems for the future NAVs is another constraint. Micro and nano electromechanical systems (MNEMS) technologies can be used to provide devices, such as lighter, smaller, and less power consuming resonators & filters than the current state of-the-art devices [41], [42]. 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 relatively heavier rotary actuators, with lighter and more energy efficient linear actuators based on new materials, such as electro-active polymers [43, 44].

MAVs and NAVs utilize different sensors to interact with the surrounding environment in accomplishment of their designated missions. These sensors include cameras, microphones, biological/chemical and radiation sensors etc. All these sensors are required to meet the stringent payload constraints along with ultra-low power requirements set for future ultralight MAVs and NAVs. The current state of the art definition for a sensor requires weight to be less than 2 grams and power consumption of less than 100 mW [6]. Future NAVs will be equipped with navigation and radar systems along with on-board infrared high-definition cameras. Ultra miniaturized components for all systems will be required to bring this vision to reality as shown in Figure 14 [42].

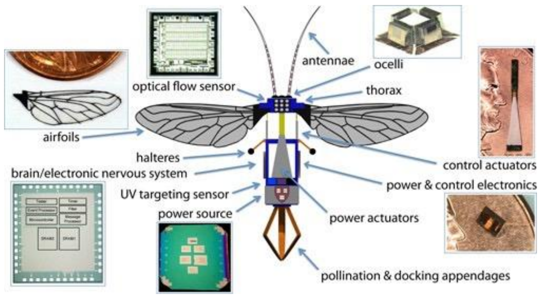

Figure 14. Electrical and Electronic Systems of Future NAVs [42]

2) Optical Vision Challenges: Surveillance missions may require high-resolution sensors with the ability to operate in the complete range of outdoor light levels, thus requiring a high dynamic range for the sensors. These imaging sensors (either optical or IR) need to have sufficient sensitivity and resolution to meet the miniaturized requirements of MAVs and NAVs. A minimum resolution of 1000 x 1000 pixels is deemed essential for recognition of human figures at the mission altitude of 100 m [6]. Prospective candidates for the current visible imager based on CCD and CMOS devices are given in Table 2 [45].

Table 2. Candidates Device Architectures for MAVs [45]

Parameter	CCD-1 : Full Frame no Shutter	CCD-1 : Full Frame with Shutter	CCD-3 : Interline Transfer with Frame Store	CMOS Actual Pixel
Resolution	1000x1000	1000x1000	1000x1000	1000x1000
Pixel Size	5x5 μm	5x5 μm	5x5 μm	<20 μm x <20 μm
Quantum Efficiency	> 85%	> 85%	20 % + Lenslet array	20-25 %
Read Noise	< 10 e^- at 1 MHz	< 10 e^- at 1 MHz	< 10 e^- at 1 MHz	< 14 e^- at 0.1 MHz
Packet Size	40,000 e^-	30,000 e^-	15,000 e^-	64,000 e^-
Dark Current	100 pA/cm^2	300 pA/cm^2	50 pA/cm^2	500 pA/cm^2
Shutter	move to frame store	Electronic	Electronic	Electronic
Frame Store	Yes	Yes	Yes	No
Noiseless Binning	Yes	Yes	Yes	No
Voltage Level	11 V	21 V	5 V	5 V
Signal Output	Analogue to Digital or Charnge to Digital Convertor	Analogue to Digital or Charnge to Digital Convertor	Analogue to Digital or Charnge to Digital Convertor	Analogue to Digital Convertor

3) Guidance, Navigation and Control Issues: Autonomous flight of futuristic MAVs and NAVs involves various challenges related to Artificial Intelligence and Cognition. These challenges include State Estimation and Adaptive or Iterative Learning. These micro flyers are required to be able to localize the position, sense obstacles, possess enough on-board computational power to generate trajectories to navigate around the obstacles and be able to track those trajectories with reasonable accuracy. State Estimation is dependent on the installed on-board sensors and relevant data processing capabilities. The complex indoor environment includes obstacles, tight corridors and induced winds due to walls. However, outdoor environment has it's own challenges like winds, direct sunlight, sun shadowing etc. These factors can further com- plicate the consistency and accuracy of estimation algorithms. Configuration design, mobility and payload considerations are added constraints on the available computational power and limited sensor resources. Iterative learning and adaption will significantly improve with artificial intelligence applications like Neural Networks and Fuzzy Logic. Apprenticeship and variants of reinforcement learning algorithms, coupled with an expert human operator are likely to improve results [46].

GPS based navigation inside confined spaces is not effective for these micro flyers. Optical flow based navigation using a single camera based vision sensor which generates velocity vector field for all the objects moving around has proven successful for obstacle avoidance and navigation [47]. But unfortunately to build the hardware including sensors, controllers, and on-board processors at that scale of milligrams is still a daunting challenge. Future trends might also include the development of sophisticated software that will enable operating future ultra-small NAVs in coordinated swarms. There is a consolidated effort to develop a Robotic Operating System (ROS) that will be broad-base upon which new developers and code writers can make new software solutions for MAVs and NAVs control applications [48]. Proprietary and dedicated on board operating systems might be required to improve efficiency of computational power in future.

5.5. Optimization Algorithms and Frameworks

In case of these futuristic micro flyers, if one discipline needs an extra milligram of weight from those predicted earlier, then some other discipline has to compensate for that extra one milligram. Multidisciplinary design optimization would have to be carried out by using frameworks like collaborative optimization, and system sensitivity analysis to optimize the overall objective function along with satisfying all the system constraints [49]. These frameworks and algorithms work best with legacy codes and simple analytical tools for each discipline. In case of these unconventional designs, analysis tools even for conceptual design are Navier stokes CFD coupled with aeroelastic structural analysis. This kind of process is computationally very intensive and is a challenge for current state of the art parallel computing clusters. In future customized computing platforms might be needed for such design applications.

5.6. Human Rights & Privacy Concerns

The successful pursuit of these micro flyers in future urban warfare roles and other applications will require dedicated efforts and positive contributions from all quadrants. But once this fiction gets to reality, serious privacy concerns [50] will be there for common man along with the fear that if these products get to the anti state agents, these could prove lethal. It has already been demonstrated at numerous occasions that even university students have been able to hack into US drone aircraft and overtook the sophisticated sensors by utilizing equipment as inexpensive as 1000 dollars [51]. These future products would have to be safeguarded from hacking and privacy laws would have to be enforced to protect human rights and privacy.

6. Conclusion

The future of aerospace industry is nature inspired flapping wing vehicles mimicking birds and insects flight. The future wars will not be fought with conventional fighters and planes. The future war machines of urban warfare will be these MAVs, NAVs and smaller vehicles. With the advancements in design and development of these micro flying robots, the design configurations will approach closer and closer to natural flyers. The size will keep shrinking and fiction movies of today might seem to be a reality in future. But it is certain that natural flyers will always be ahead of human technology and will continue to be a source of inspiration and motivation.

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