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FLOW SIMULATION AROUND A MICRO AIR VEHICLE IN A PLUME CHARACTERIZATION SCENARIO

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ABSTRACT

Numerical simulation of flow around a recently developed micro air vehicle (MAV) at the University of Colorado is presented. The vehicle design is so a network of such vehicles could be used for plume characterization in urban areas. The MAV network will map out the concentration of a plume and calculation of concentration gradient will guide the network toward the source of the contamination. Computational results of the aerodynamic characteristics of the Colorado fixed wing MAV are presented. A morphing wing concept based on biomimetic of bat's flight is proposed. The adaptive wing suggested in this study changes shape according to the flight modes and conditions - extending fully while loitering or in light winds and becoming more sweptback and flexed to cruise between locations or in stronger winds. This means that the wing is more adaptable and overall energy consumption of the vehicle will be reduced.

1 INTRODUCTION

Micro air vehicles (MAVs) have attracted significant attention since mid-1990's for both civilian and military applications. In 1992, when the smallest airplanes in use were the Uninhibited Aerial Vehicles (UAVs) with a wingspan on the order of one meter, Hundley and Gritton suggested that it would take only 10 years for one to develop a 1 cm wingspan vehicle that can carry a 1 gram payload [1]. It is clear that this goal has not been achieved yet, mostly because of lack of knowledge of MAV aerodynamics. MAVs are by definition small aircrafts which fly at relatively low speeds. Such flight characteristics will result in flow regimes with Reynolds numbers below 200,000. Another aerodynamic signature of MAVs is wings with small aspect ratio; in most cases the chord is roughly equal to the wingspan. This combination of low Reynolds number flight and low aspect ratio wings results in a flow regime totally alien to conventional aircraft. Although small birds and insects have been flying under these conditions for quite some time, this is a new flight environment for man-made aircraft.

In order for required MAV capabilities to be realized, several areas will need more focused attention. The absence of sophisticated computational analysis methods, lack of commercially available microelectro-mechanical sensors, and the difficulties associated with accurate experimental work at this scale have all restricted research. From a system and manufacturing standpoint, technological advances in microfabrication techniques and in the miniaturization of electronics in the last decade made mechanical MAVs feasible. Research challenges include

- Aerodynamic at low Reynolds numbers
- Low aspect ratio wings
- Stability and control issues associated with low weight, small moments of inertia, wind gust, and lack of dynamic models.
- Miniaturization
- Cooperative control
- Autonomy
- Micro sensors

One of the most interesting and least understood aspects of MAV flight is the aerodynamics [2; 3; 4; 5; 6]. Small birds and insects works at a similar flow regime. Unsteady aerodynamics play a significant role in MAV flight and stability. Furthermore, small mass of MAVs make them susceptible

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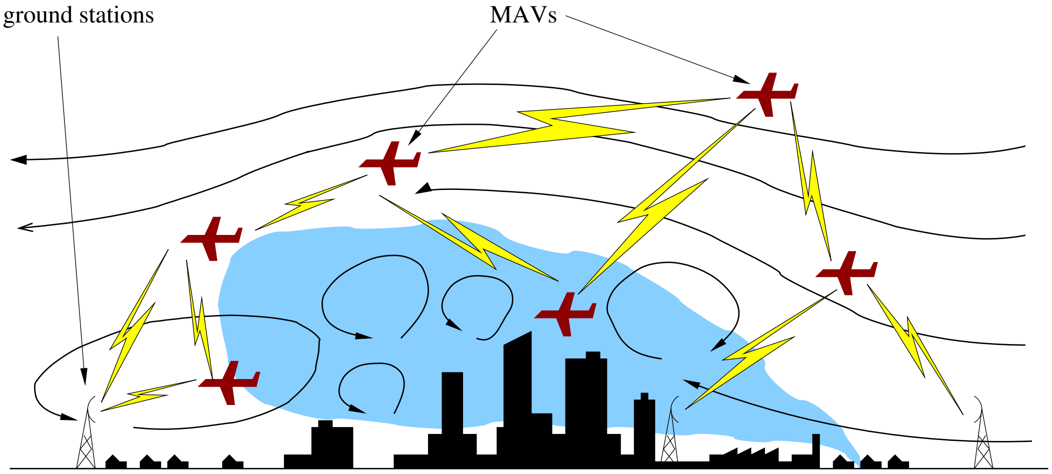


Figure 1: . The sensor network of MAVs provides high-quality volumetric sensing for accurate plume dispersion prediction.

to atmospheric turbulence and gusty wind conditions. In order to generate enough lift, flight stability and performance, MAV designs require novel aerodynamic concepts. This manuscript reports on recent progress in design, fabrication, and simulation of a fixed-wing MAV (CMAV) at the University of Colorado.

Motivating Scenario

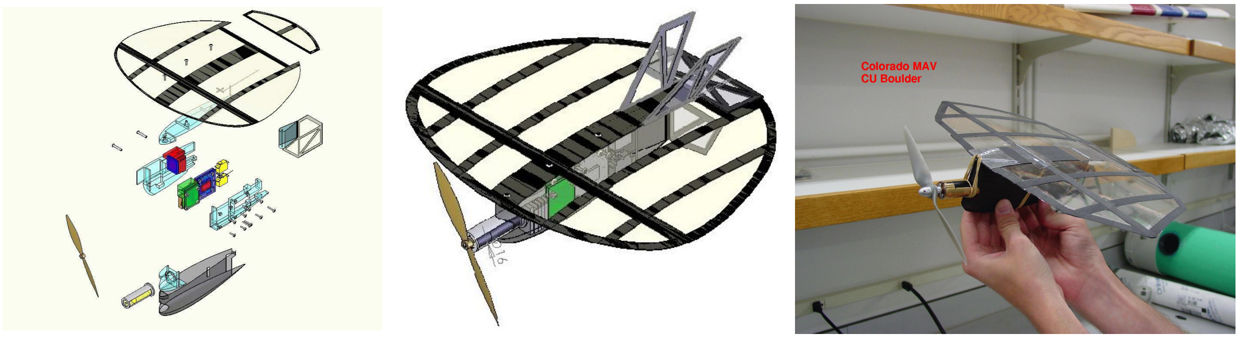
Hazardous contaminants can be released in urban areas and atmosphere. They can be transported over large distances, remaining in the air for long periods of time, or deposited at varying distances away from the source region. Such releases may result during transport of hazardous materials as in tanker truck or railroad spills, they may stem from on-site accidents as in the case of industrial chemical release, or they may be intentionally released as in a chemical/biological/nuclear terrorist attack. Under the Clean Air Act, 188 hazardous air pollutants are currently regulated [7] that have been associated with a wide variety of adverse health effects, including cancer and other neurological, reproductive, and developmental diseases. In such cases, it is crucial to provide decision makers with accurate information about the exact location of the contamination source and its subsequent dispersion in the environment as soon as possible.

Required toxin concentration information is difficult to obtain. In order to accurately estimate the location of the contamination source or to predict the dispersion of contaminants it is necessary to obtain volumetric concentration data. Fixed sensors at ground level (or rooftop, top of the traffic lights) will not provide required information for such calculations. Consequently, sensors in the air above the areas of concern are required. Figure 1 illustrate the general idea in such scenarios. MAVs are located at various points in the area of interest, *e.g.,* top of buildings or traffic lights. A Sensor network of many airborne sensors gathers volumetric data, communicating it to a base station for combination with a dispersion model to predict plume evolution or to find the source of contamination.

We suggest a network of MAVs that can be easily located at various locations (such as top of traffic lights and top of tall buildings). They will have rechargeable batteries, connected to the city power network, and equipped with suitable sensors. Such small MAVs can be easily self-lunched by a catapult mechanism. The moment the sensors are activated (by detecting a toxic agent) the MAVs can be lunched to follow the concentration gradient of the toxic plume to its source. Furthermore they will provide initial data to predict long term dispersion of toxins.

Colorado MAV Design

Recently a flexible wing MAV was designed and built (see Figure 2) at the University of Colorado. Four view CAD model of Colorado MAV are shown in Figure 3. While the current vehicle does not have morphing capability its membrane wing will provide a platform for further investigation. Although it is



(a) (b) (c)

Figure 2: Colorado MAV, a flexible wing micro air vehicle designed, fabricated, and tested at the University of Colorado. (a) CAD model assembly, (b) CAD model, (c) CMAV prototype.

desirable for small UAVs to be able to fly when large wind gusts are present, there are limited studies to address this issue. Because MAVs are essentially small flying wings, there is a need to develop efficient low Reynolds number, low aspect ratio wings that are not overly sensitive to wind shear, and gusts.

The MAV is designed to serve as a platform for characterizing the flight performance of different low Reynolds number wing designs by measuring the in-flight accelerations due to control inputs and gusts. The platform houses an onboard flight computer and communications system that can process sensor information, transmit data to a ground station, and control the aircraft via pilot input from the ground station. Three-axis accelerations can be measured using an on-board Inertia Measurement Unit (IMU). In addition, the MAV has proven to be an excellent educational tool. A great deal of insight into the subtleties of MAV design has been gained through the process of engineering a working MAV, and the current platform serves as a strong base for continuing development.

The MAV airframe consists of a low aspect ratio elliptical membrane wing with an integrated elevator at the trailing edge, two angled vertical stabilizers attached ahead of the elevator, a fuselage below the wing that houses the electronics and propulsion system, and a rudder attached to the trailing edge of the fuselage. The wing is a cambered-plate design with a root chord of 11 inches and a span of 13 inches. The camber profile is taken from a reduced-thickness Eppler 387 airfoil, and the wing is unswept, has no dihedral and no geometric twist. The wing is constructed from narrow strips of pre-impregnated carbon fiber that form structural ribs. This design was inspired by the successful design used on the MAVs constructed by the University of Florida [8]. The wing structure is covered by a single layer of Saran film, which has proven to be very light-weight, strong and easy to repair. The fuselage is also made from pre-impregnated carbon fiber, and machined high-density foam pieces inside the fuselage hold the electronics and motor in place.

The core of the electronics package is the flight computer, to which is connected a 64 kbps communications module, a 3-axis rate-gyro and accelerometer IMU module, a motor speed controller, and two servos for the rudder and elevator. Vehicle accelerations are computed from the IMU data in flight, and can be both stored on-board the flight computer and transmitted to the ground. The flight computer also receives control inputs from a pilot through the ground station and converts them to the appropriate signals for the speed controller and servos to control the throttle and control surfaces. The electronic systems are powered by four Lithium-Polymer cells, which also provides power to the small DC brushless motor.

The design of the MAV is highly modular, and thus allows flexibility in the configuration of the vehicle. At the core of the vehicle is the flight computer, communications system, and IMU. This package can determine and record in-flight responses, and can be used to control servos and motor controllers. This package can be used in any number of different configurations, even those than have no other component in common with the current MAV.

The fuselage and all of the internal components form a platform that facilitates testing of different aerodynamic configurations. The wings, control

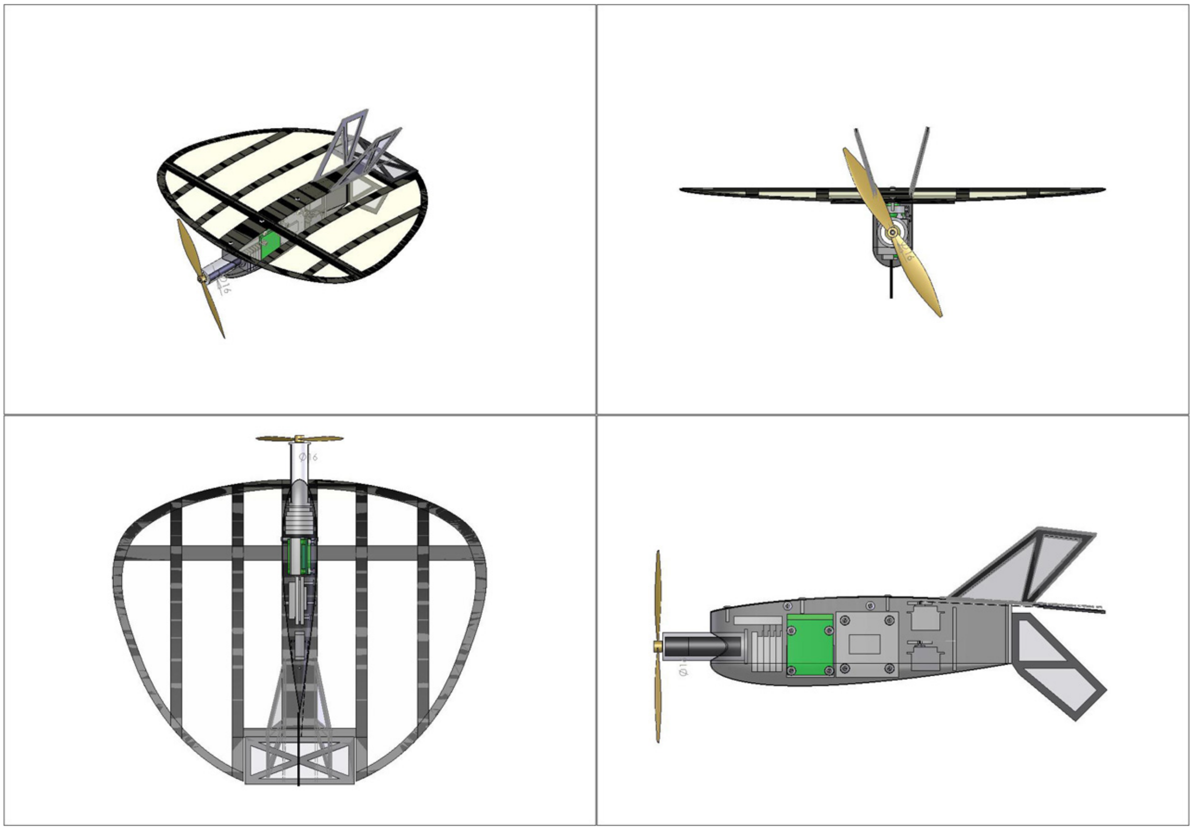


Figure 3: Four view CAD model of Colorado MAV.

surfaces and propulsion system can be easily interchanged, and the manufacturing techniques used on the wings, control surfaces and the fuselage itself make it possible to fabricate new parts in a matter of hours. This makes it possible to rapidly iterate designs and test and analyze the responses of multiple wing configurations in a single session.

Computational Approach

The CFD solver used in this study was originally developed at CENAERO. This solver is a domain decomposition based parallel three-dimensional compressible Euler and Navier-Stokes solver which combines finite volume and finite element discretizations on unstructured tetrahedral meshes. It features an upwind scheme using a piecewise linear reconstruction of the flow variables in each control volume for the convective term, and a P1 finite element Galerkin approximation for the diffusive term [9; 10]. Both convective and diffusive terms are evaluated with edge-based formula. The solver uses the AOMD (Algorithm Oriented Mesh Database) library [11] for the management of the topological mesh entities across the processors. Pseudo time-integration is performed for steady state flows with the backward Euler scheme. Since this scheme is implicit, the flow solver must solve at each time-step a system of nonlinear equations. For this purpose, it relies on an inexact Newton method using a finite difference GMRES solver preconditioned by a restricted additive Schwarz algorithm [12; 13].

Starting from the CAD model shown in Figures 2(b) and 3, an anisotropic grid was generated with 459,000 points and 2.1 million tetrahedra. About 10 layers of stretched elements are located close to the MAV in order to capture accurately the boundary layers. The average thickness of these stretched elements is equal to 10 mm. Figure 4 displays several views of the surface mesh as well as a cut along the symmetry plane of the MAV. The refinement on the leading and trailing edges of the wing as well as on the engine can be observed in these figures.

The flow is assumed to be viscous and the

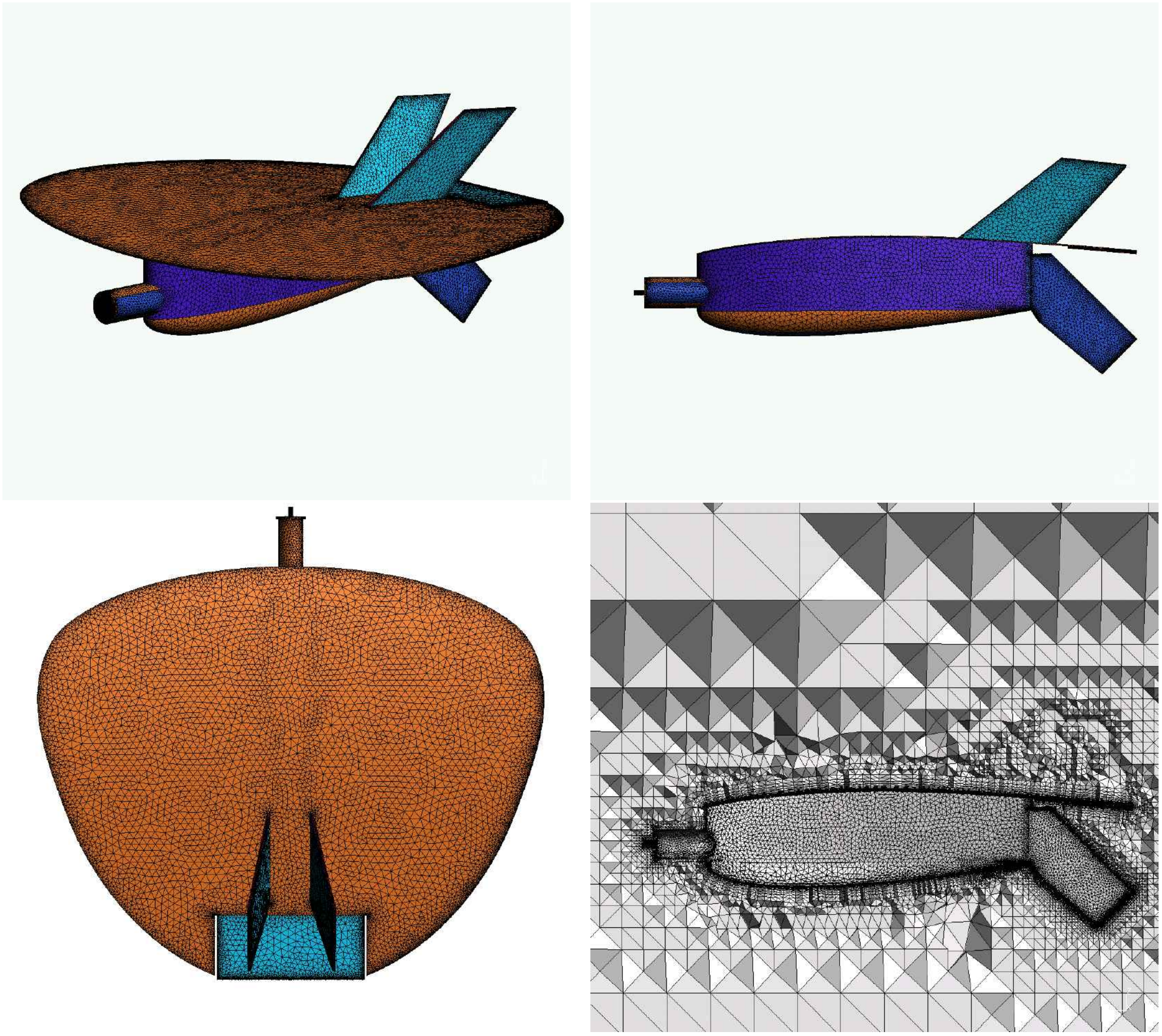


Figure 4: Computational grid around the CMAV.

freestream velocity and the angle of attack are first set respectively to 14 m/s and 15 deg. Figure 5 shows the streamlines obtained for these conditions.

The freestream velocity and the angle of attack are then varied. Figure 6 shows the aerodynamic efficiency curve, where a maximum glide ratio of 3.8 is observed. Similar glide ratio was measured by Waszak *et al.* [14] for a flexible wing MAV. Increase in flight Reynolds number would increase the lift to drag ratio. For a solid wing MAV (the Black Widow) Grasmeyer and Keennon [15] reported a much higher lift to drag value of 6. This is a much smaller number than that for a high aspect ratio airplane. For optimal endurance, the airplane should fly with an incidence of 7 degrees at high air speed. Similar angle was reported by Waszak *et al.* [14]. This does not take into account the power consumption of the electrical engine. In the low incidence range, i.e. under 5 degrees, a low aerodynamic efficiency is obtained, and this should therefore be avoided during the flight. The ratio remains roughly constant when the angle of attack increases so that the MAV should fly in the range of 5 to 12 degrees of angle of attack to maintain a good endurance.

The current solver is a compressible CFD code. It is well-known that low-speed compressible flows are stiff due to small ratio of the convective speed to the speed of sound [16]. The Mach number of

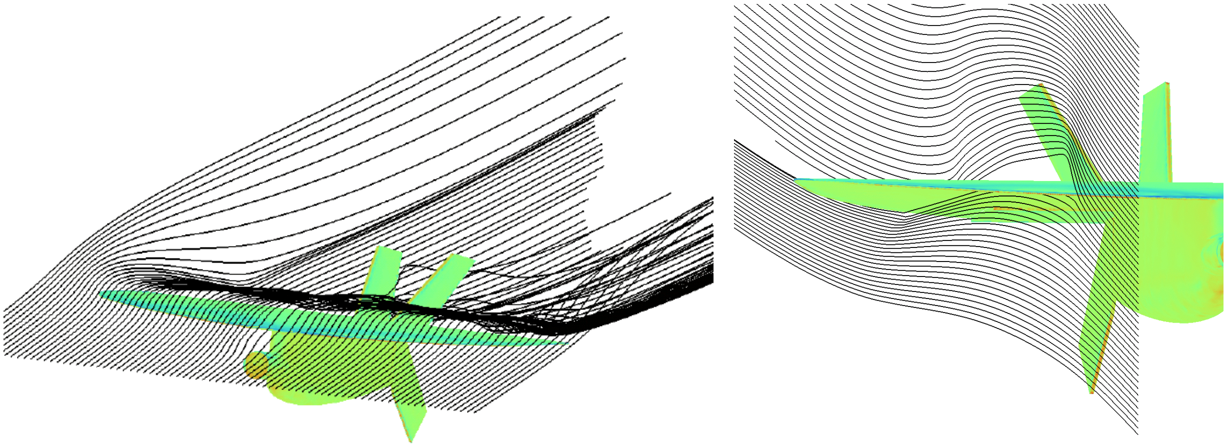


Figure 5: Streamlines around the CMAV at 15° AoA.

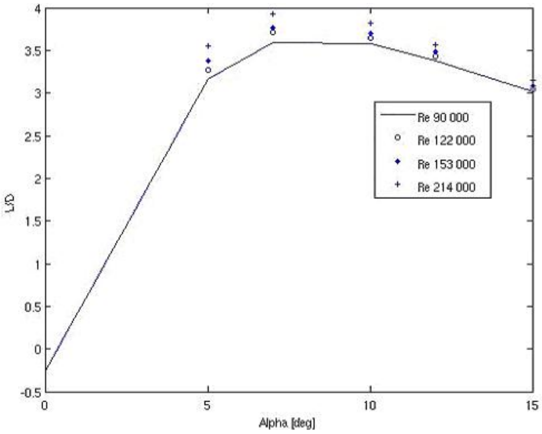


Figure 6: C_L/C_D for various Reynolds numbers.

flows considered in this study are ranged between 0.025 and 0.05. These are marginal values for such flow regimes, which could affect the accuracy of the calculations. We are in the process of implementing an incompressible solver for MAV simulation. Furthermore, implementation of a dynamic Lagrangian averaged Navier-Stokes-α equations for turbulence modeling is under investigation [17; 18].

Biological Inspiration for an Adaptive Flexible Wing MAV

An effective MAV network must also be able to perform their missions in all weather conditions (*i.e.,* precipitation, wind shear, and gusts). Therefore, new vehicle designs are required to meet these challenges. To this end, a close look at biological flight mechanisms could be beneficial. Not all the insects of the comparable size appear to use the same aerodynamic and configurational solutions to achieve flight. A review of bird and insect flight reveals that they use two specific mechanisms to overcome the small-scale aerodynamic limitations of their wings: flexibility and flapping. In this study we will not consider flapping flight as man-made flapping flight involves complicated mechanical joint designs and requires muscle energy densities that are not available with the existing technology. Consequently, we will focus on flexibility and morphing capabilities of bat and small insects flight.

Birds and insects exploit the coupling between wing flexibility and aerodynamics. By changing their wing shape and effective size, birds and insects effectively increase the Reynolds number seen by the wings without increasing their forward flight speed, and increase their flight stability in various flight and atmospheric conditions. Despite some advantages of flapping flight (see *e.g.,* [19]), the additional complexity of such aircraft do not currently make them competitive with fixed wing designs. Consequently in this manuscript we will not consider flapping flight.

No single fixed wing shape may be suitable for the actual flight conditions where changes in the wind speed are of the same magnitude as the flying speed. A wing with some ability to adapt to the instantaneous flight conditions may be the only workable solution. Jenkins *et al.* [20] and Ifju *et al.* [8] observed that wings with flexible coverings increase flight stability and performance of MAVs. Ifju *et al.* [8] also considered the extension of the membrane and twisting of the framework (resulting in angle of attack changes as well as decambering along the wing length) to generate adoptive washout in response to air speed and overall angle of attack.

Bats are the only mammals in the world capable of true flight (see Figure 7a). The physics of lift are similar for bats and birds, but the wing design and manner of bat flight are very different. A bat's entire body is a flying sail. Its leathery wings are formed of a membrane stretched across its outstretched fingers and arms, and fastened to its sides, heels and tail. A Bat's wing is the result of evolution of a hand with fingers. Consequently, a bat can support a membrane wing with zero cross section, while a bird's wing has feathers and a relatively thick cross section. The membrane is very thin and consists of two layers of skin with small muscles between them. The intrinsic muscles and elastic fibers help to keep the membrane taut during changes of wing geometry. A bat can reduce its wing span by up to 20% while keeping the membrane taut. This flexibility results in superior energy conservation and flight stability and great maneuverability of bat flight. Bats roll from side to side by changing the angle of their wings. The tail, with its attached flight membrane, acts as a stabilizer and as a rudder for sudden turns. These observations support the use of a flexible membrane for our MAV design.

The proposed adaptive wing has an adaptable spar that has three segments and a flexible joint system, as depicted in Figure 7. It can be extended or folded into a zigzag, altering the shape of the wing to get maximum benefit from changing winds. This design provides a range of wing shapes that are efficient across a greater range of wind strengths. The elastic wing is held taut by the extended spar and fingers. In lighter winds the wing is fully extended, while in stronger winds the wing becomes more flexed and streamlined in shape. To adapt to changes in spar shape, the wing-cloth must be elastic. It is important that the wing maintains a taut and efficient foil shape without becoming baggy or wrinkled in different configurations. We expect that this could prove to be the most complex aspect of this design. Our wings will be fabricated with a carbon fiber skeleton and expendable latex rubber skin and they give the MAV the ability to adapt to the flow to provide smoother flight. A similar design was implemented by R. Dryden in sails for windsurfing and sailing. He reports that the shape and size of the sail can be easily changed by the force applied to the boom by the surfer or the sailor. In our design a servo will be used to change the wing shape. See Figures 7 and 8.

The adaptive wing (see Figures 7 and 8) suggested in this study changes shape according to the flight mode and conditions - extending fully while loitering or in light winds and becoming more sweptback and flexed to cruise between locations or in stronger winds. This means that the wing is more adaptable and overall energy consumption of the vehicle will be reduced and can be used over a wider wind range. The combination of a flexible membrane wing and an adaptive wing shape will certainly capture some of the characteristics of bat flight. Note that, in contrast to bat flight that uses flapping to generate thrust, in this study we use a propeller to produce thrust. Flapping will bring new challenges that are not matched by the current microfabrication and energy storage technologies.

The benefits of the flexible membrane wing appear to be substantial but not well understood. In addition, the nature of the micro air vehicles and the flexible wing concept make analysis of the vehicle quite challenging. In fact the vehicle provides an excellent basis upon which to develop and apply ongoing research in aerodynamics, and dynamics and control, aeroservoelasticity, multifunctional structures, microelectronics, measurement systems, and many others.

Conclusions

Micro Air Vehicle (MAV) designs in a toxic plume characterization scenario are investigated. Design and fabrication of a flexible fixed wing MAV at the University of Colorado are reported. Numerical simulation of flow around the Colorado MAV is considered and preliminary results are presented. An adaptive wing concept based on biomimetic of bat's flight is proposed. The proposed adaptive wing has an adaptable spar that has three segments and a flexible joint system. It can be extended or folded into a zigzag, altering the shape of the wing to get maximum benefit from changing winds.

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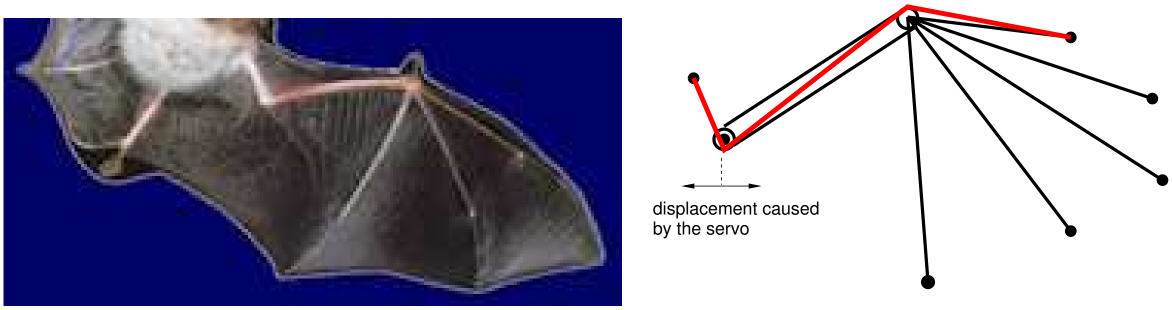

(a) (b)

Figure 7: (a) Bat's wing: The elastic wing membrane (patagium) is supported by the outstretched limbs, body, and tail. The membrane is very thin and consists of two layers of skin with small muscles between them. (b) Adaptive spar mechanism: The adaptive spar has three main segments connected by joints. The two elements forming the middle segment ensure that the movements of extension and flexion are co-ordinated. A side-to-side rotation of the middle elements provides the correct change in airfoil when changing wing shape. With the tensioner released, the spar can be folded for compact packaging of the MAV.

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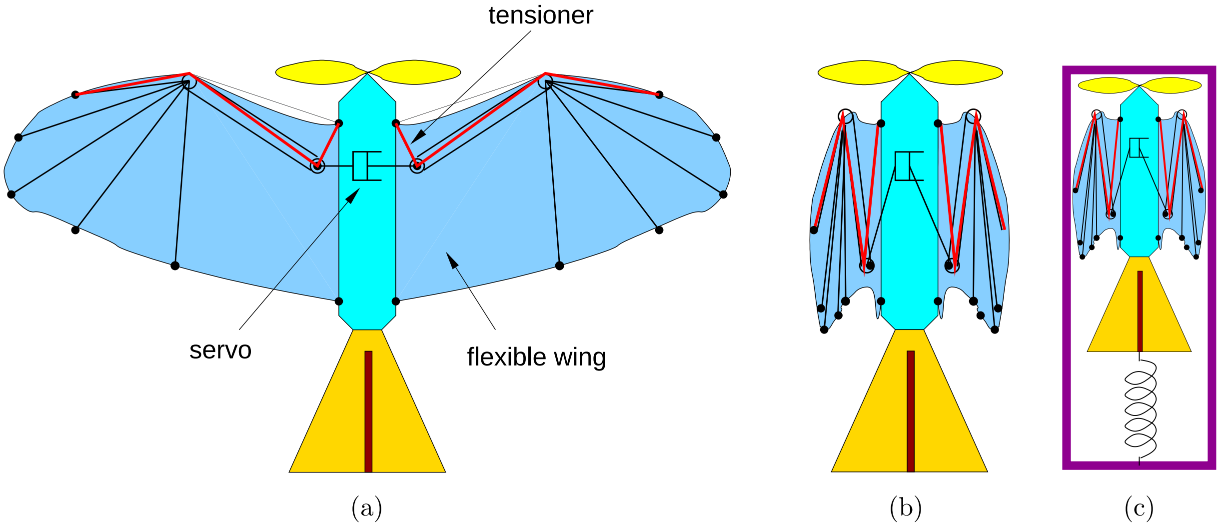

Figure 8: Schematic of the Colorado Morphing Wing MAV. (a) In fully expanded wing form (b) In folded wing form. (c) Encapsulated in a lunching tube for mobile suitcase sensor station. The tail is added to provide pitch and directional stability

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