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Engineering Notes

Sensor Emplacement on Vertical Surfaces with Biologically Inspired Morphing from Bats

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I. Introduction

SITUATIONAL awareness is a criticality for decision-making that affects operations in urban environments. Accordingly, information about the system must be available through real-time measurements. Sensors can often be placed throughout a region using a mix of static mounts and moving vehicles; however, the ability to dynamically mount a sensor at any location in response to an event is difficult.

A mission of particular interest is sensor emplacement onto vertical surfaces. Valuable information may be obtained from measurements, such as acoustic signatures or thermal images, from vantages that observe or overlook windows and buildings along with areas of high traffic. Some obvious applications of surveillance include homeland security, fire monitoring, search and rescue, and analysis of structural integrity. In each situation, sensors must be strategically placed to provide the type of information from a specific aspect to maximize the situational awareness.

A bat provides an obvious source of inspiration for this mission of sensor emplacement onto vertical surfaces within an urban environment. Its size and agility are ideal for maneuvering in small spaces. Most important, a bat is able to fly toward a wall or grating and attach itself to that surface. The bat undergoes a series of physical alterations as it transitions from flapping flight to gliding flight while approaching the wall. These alterations are mainly changes to the shape and configuration of the wings relative to the body.

This concept of morphing to alter the physical configuration in flight is being incorporated into aircraft [1]. Incorporating actuators and other mechanisms can enable vehicles to vary parameters, such as sweep [2,3] and dihedral [4,5], during flight. The resulting range of configurations will have an associated range of flight dynamics and, consequently, maneuvering.

A micro air vehicle (MAV) is ideally suited for consideration of this mission and especially appropriate for consideration of a biologically inspired design given the similarity in size and airspeed to bats. Optimal design of such vehicles is generally difficult given the uncertainties associated with low Reynolds numbers [6,7]; however, adopting shapes from biological systems has generated some effective designs. Obviously, aerodynamics are an important feature of many biological systems [8], as demonstrated by testing in wind tunnels [9]. The concepts from avian systems have been studied for flight by considering pitching [10], expandable span [11], two-joint sweep [12], and even high-frequency flapping [13]. In each case, the study showed the efficiency and performance of the biological concept but were unable to realize the concept through an actual flight vehicle.

This Note considers the design of a micro air vehicle using a bat for inspiration on morphing. The design does not consider the entire flight regime of a bat; rather, the design limits attention to the specific maneuver of sensor emplacement on a vertical surface. The effect of morphing the wings in a manner similar to bats is investigated and shown to be highly effective in achieving the maneuver. In particular, the aerodynamics are shown to alter by increasing agility in pitch and roll but remaining stable in yaw as a result of the morphing.

II. Maneuver

The maneuver of specific interest is sensor emplacement onto a vertical surface. The basic concept, as shown in Fig. 1, assumes that the entire vehicle will adhere to the surface. The specifics associated with adherence and sensor orientation are important but beyond the scope of this Note; instead, the flight dynamics associated with the maneuver are the consideration.

The investigation will restrict attention to the final phase of the maneuver. The initial approach is standard flight in which the bat uses flapping for propulsion and control. When nearing the surface, the flapping ceases and the vehicle transitions to gliding flight. The vehicle then pitches sharply to contact, and eventually adhere to, the surface. This final phase of gliding and pitching are the elements uniquely associated with sensor emplacement and thus central to this study.

Also, some amount of roll is typically introduced during the final phase of the maneuver. The vehicle will pitch up sharply then roll such that one wing is rotated closer to the surface. This wing effectively grabs onto the surface by adhering. The maneuver is finally completed by simply rotating back around this contacted wing so that the entire body adheres to the surface.

III. Biological Inspiration

A. Bats

Bats are the only mammals capable of sustained self-powered flight as a result of several unique flight mechanisms. The bone structure of their wing is analogous to the human arm and hand, although several of the joints are fused in a bat. This structure affords many degrees of freedom, enabling the bat to vary camber, wing sweep, dihedral angle, and wing twist, as well as to curl and fold the wing. A thin elastic skin membrane covers the bone structure and fuses down the side of the bats body. Muscles allow the bat to tighten and relax the membrane, affording yet another mechanism to control wing geometry. These adaptations provide bats with the mechanisms required for extreme maneuverability.

Biologically inspired flight control of aircraft is often based upon the flight of birds. Although this approach is logical for many MAV applications, birds evolved separately from bats and have developed a different skill set. Birds certainly alter their geometry through actuating joints and feathers; however, birds do not have precise shape control from musculature as bats. This limited ability to control geometer and the higher wing loading as compared with bats results in birds having a higher stall speed and less maneuverability at low flight speeds. Also, birds do not regularly perch vertically inverted, whereas this behavior is well developed in bats.

The flight dynamics of bats have been extensively studied; however, the maneuver of landing for perching or roosting has

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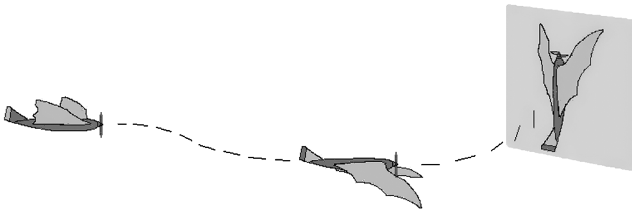

Fig. 1 Representative maneuver.

received relatively less attention than other behaviors. In general, studies have analyzed issues related to the primary modes of flapping flight or nonflapping flight. The flapping mode includes various maneuvers such as forward flight [14], rising hovering [15], stationary hovering [16,17], rolling [18], and turning [19]. The nonflapping mode includes both soaring [20] and gliding [21].

Also, the nature of stability for this maneuver differs from the traditional considerations. Numerous studies note that biological systems, such as birds and bats, do not have a vertical tail to provide directional stability and so shape control is used [22–24], along with a stabilizing contribution from flapping [25]. Analysis even indicates how bats sweep their wings back to maintain stability at lower airspeeds [26]. In this case, the maneuver seeks a dramatic pitch and roll, and so stabilizing influences that seek to keep the wings straight and level must be reduced [27], along with configurations that increase the moment of inertia in the pitch axis [28].

The objective of this study is to design aircraft that are inspired by bats; consequently, the analysis will restrict attention to bat features that are salient to the maneuver and which may be reproducible on an aircraft. The muscular control of the membrane and flapping behavior during approach will thus be ignored. The aspects of wing structure and wing configuration will be the primary focus as enabling technologies for the specific maneuver of sensor emplacement on a vertical surface.

B. Wing Model

Pteropus pumilus is chosen as a biological system from which to investigate sensor emplacement. This bat, commonly known as the little golden-mantled flying fox, is selected for its size and roosting behavior. *Pteropus pumilus* has a wingspan of 30 in. and a weight of approximately 7 oz. Most important, it is capable of performing a flipping maneuver to perch on ceilings or landing on vertical surfaces, as shown in Fig. 2.

IV. Aircraft Model

A baseline planform is chosen for the representation of a MAV inspired by bats. The general shape of this planform, as depicted in Fig. 3, has wings similar to the bat wing. A vertical tail is included to simplify the aerodynamics because bats and birds control their shape to provide directional stability [22,23]; however, this Note will only consider open-loop flight dynamics and thus use a tail to provide a commensurate level of stabilization.

Fig. 2 *Pteropus pumilus*.

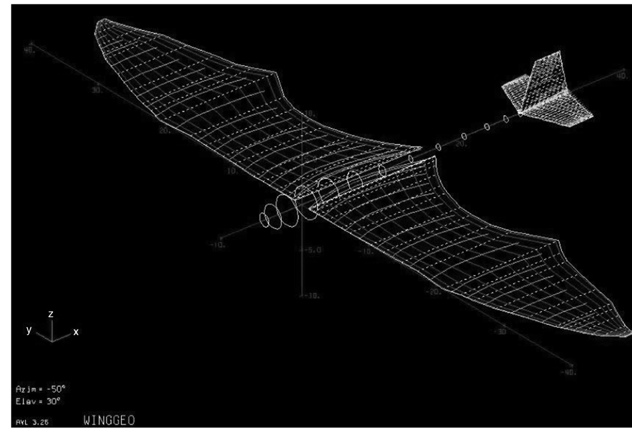

Fig. 3 Computational model of vehicle.

A series of configurations will be analyzed by morphing this baseline configuration. Specifically, the angles of wing sweep and dihedral will vary. These angles are each allowed to range independently between 0 and −30 deg, where a negative angle of sweep corresponds to outboard closer to the nose and a negative angle of dihedral corresponds to tips lower than the root. A representative set of configurations with maximum morphing is presented in Fig. 4. The morphing of individual angles is straightforward with traditional definitions of sweep and dihedral, and the combination of both results from morphing the sweep about the original reference of span direction and then morphing the dihedral about the fuselage reference.

Also, the flight dynamics are analyzed at an airspeed of 7 m/s to fall within the range of observed speeds at which bats approach surfaces before landing [29]. The aerodynamics of vehicles, or bats, at these speeds and Reynolds numbers are difficult to compute; however, reasonable approximations have been found using a steady inviscid panel method [30] for which trends between flight data and computed estimates match [31].

V. Aerodynamics

A. Pitch Moment

The ability to rapidly pitch the aircraft is obviously critical to performance of the maneuver. As such, the pitch moment generated by the wings is computed for each configuration. The nondimensional coefficient C_m indicates the magnitude of pitch moment scaled by the dynamic pressure and chord length. This coefficient of pitch moment is shown in Fig. 5, in which a positive value corresponds to a nose-up moment.

The coefficient of pitching moment shows considerable variation for the various configurations. The baseline case that has no angle of sweep or dihedral has a negative moment; however, the introduction of morphing creates a positive moment. The moment is continuously increasing almost linearly as the sweep increased, and the moment increases sharply as the dihedral increases then remains relatively constant as the angle increases beyond 10 deg. Conversely, the combination of both sweep and dihedral induces the largest moment until angles of 10 deg and then decreases in magnitude until the angles reach 22 deg.

B. Lateral-Directional Static Stability

Successful completion of the maneuver has disparate requirements for maintaining attitude. Some amount of roll is desired to provide some rotation of one wing closer to the surface; conversely, any yaw should probably be avoided because it introduces a rotational moment that may hinder adhering the wing to the surface.

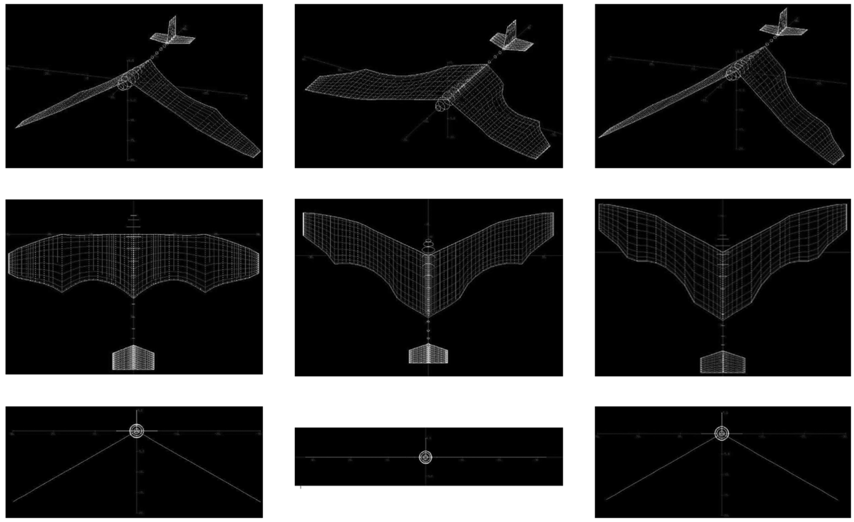

Fig. 4 Model with −30 deg of dihedral and 0 deg of sweep (left), 0 deg of dihedral and −30 deg of sweep (middle) and −30 deg of dihedral and −30 deg of sweep (right) from different viewpoints.

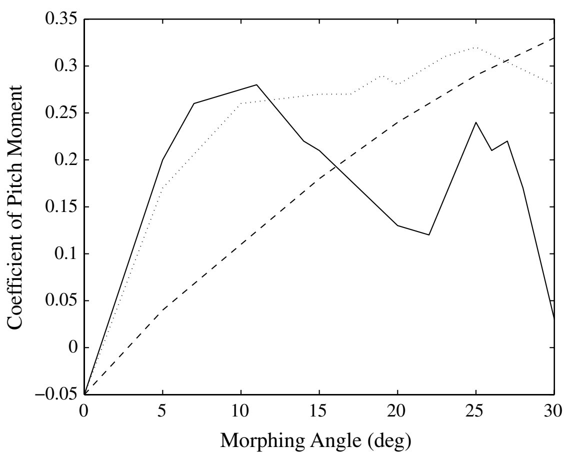

Fig. 5 Coefficient of pitch moment for morphing only sweep angle (dashed line), morphing only dihedral angle (dotted line), and morphing both sweep angle and dihedral angle (solid line).

Configurations are thus desired that have static stability in yaw but not roll. A pair of metrics indicate this static stability by noting whether a perturbation to angle of sideslip will be counteracted by the resulting aerodynamics.

The effect of wing configuration on lateral stability is demonstrated in Fig. 6 using C_{l_β} as the rate of change of roll moment with angle of sideslip. A negative value of this term indicates that the vehicle will roll away from the direction of sideslip and thus be stable. In this case, the morphing adds a positive and destabilizing contribution to the stability. Morphing of only the sweep angle increases the value but it remains negative and stable. Introducing variations to dihedral, either alone or in combination with sweep, quickly contributes a large value that makes C_{l_β} positive and destabilizes the aircraft.

The directional stability is indicated using the rate of change of yaw moment with angle of sideslip C_{n_β}, as shown in Fig. 7. A positive value of this parameter indicates that the vehicle will turn into a sideslip and thus remain stable. Morphing individually either the sweep or dihedral reduces the value of C_{n_β} but does not actually destabilize the vehicle. Conversely, the combination of morphing both sweep and dihedral reduces C_{n_β} until the vehicle is actually unstable for angles greater than 15 deg.

C. Static Margin

The static margin is related to longitudinal stability and indicates whether the vehicle will reject a perturbation to angle of attack. This parameter is actually computed as a measure of distance between the center of gravity and a location denoted as the neutral point. The

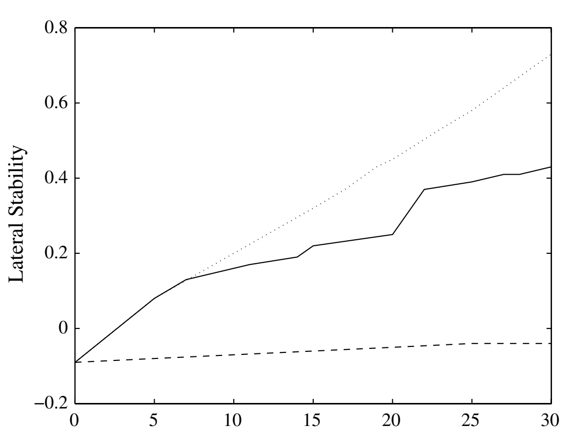

Fig. 6 Variation of rolling moment coefficient due to sideslip for morphing only sweep angle (dashed line), morphing only dihedral angle (dotted line), and morphing both sweep angle and dihedral angle (solid line).

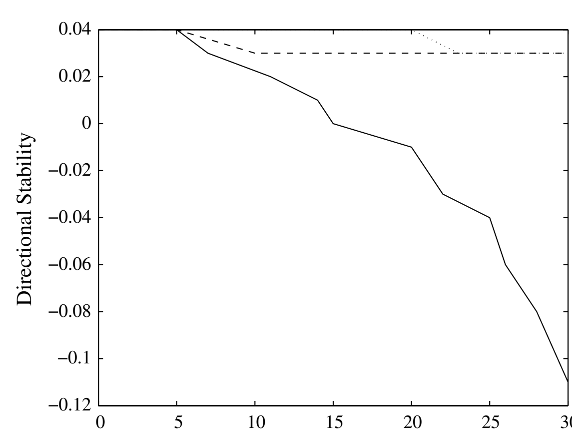

Fig. 7 Variation of yawing moment coefficient due to sideslip for morphing only sweep angle (dashed line), morphing only dihedral angle (dotted line), and morphing both sweep angle and dihedral angle (solid line).

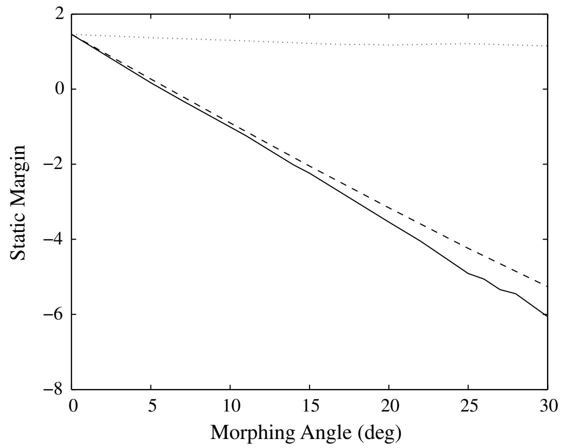

Fig. 8 Static Margin for Morphing only sweep angle (dashed line), morphing only dihedral angle (dotted line), and morphing both sweep angle and dihedral angle (solid line).

magnitude of the static margin relates the magnitude of this distance measure and thus relates the magnitude of the restoring moment.

The static margin, as shown in Fig. 8, reflects a significant dependency on the type of morphing. Specifically, the static margin remains positive when only the dihedral angle is varied, whereas any variation greater than 5 deg to the sweep will cause instability.

VI. Conclusions

Morphing both the wing sweep and wing dihedral is an effective technique to enable the mission of sensor emplacement on a vertical surface. The maneuver requires a large pitch moment (as shown in Fig. 5) so that the nose goes up, a loss of lateral stability (as shown in Fig. 6) so that one wing rotates toward the surface, maintaining directional stability (as shown in Fig. 7) so that the wing is not rotated around the surface, and loss of static margin (as shown in Fig. 8) so that the vehicle does not counteract the induced angle of attack when pitching. Morphing only wing sweep does not reduce the lateral stability, whereas morphing only wing dihedral does not reduce the static margin. As such, only the simultaneous morphing of sweep and dihedral achieves all the objectives.

Also, the bat appears to have evolved a maneuver that maximizes these benefits. The pitching moment is greatest for angles between 5 and 10 deg, the lateral stability is lost only for angles greater than 5 deg, the directional stability is maintained only for angles less than 15 deg, and the static margin is lost for angles greater than 5 deg. As such, the optimal angles for morphing appear to be between 5 and 10 deg, which coincides with observed morphing of bats from video sequences.

The actuation required for such morphing is actually achievable using off-the-shelf servos. Existing vehicles have shown sweep changes of 30 deg in less than 1 s using these servos, which are easily available from the hobby community [32].

Acknowledgments

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