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Morphing and growing micro unmanned air vehicle: Sizing process and stability

M. Hassanalian, A. Quintana, A. Abdelkefi *

Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM 88003, USA

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ABSTRACT

An optimized and comprehensive method is proposed in order to design an efficient micro unmanned air vehicle with morphing and growing capabilities. In the sizing process, to select the optimum wing shape, three different shapes are compared based on an aerodynamic analysis, and a tapered wing is selected for the compressed mode. Then, since the wingspan, wing area, wing loading, and other parameters are changing as function of time, a transition analysis is carried-out during the sizing process. By using the calculated surface area and considered aspect ratio for compression and expansion modes, the wingspan is determined as function of time. Considering the estimated weight, the required lift coefficient is calculated and then two types of airfoils are selected. Finally, after completing the optimal geometric design, aerodynamic analyses are carried out to investigate the performance of the growing drone. The proposed strategy for designing efficient micro unmanned air vehicles for a well-defined mission can be utilized and extended to design other growing micro unmanned systems depending on the mission.

1. Introduction

As technologies advance, the need for drones with a magnitude of capabilities including unmanned, micro, and nano air vehicles has increased for both civilian and military applications [1–5]. This introduces a new era in which autonomous unmanned air vehicles (UAVs) are capable of perceiving and generating solutions in complex environments [5]. Due to their several potential applications and functions, the popularity of these devices has greatly risen, leading to a variety of unique drones with different sizes, shapes, and weights [6]. The development in micro-electro-mechanical systems (MEMS), sensors, fabrication and navigation methods, and power systems have made possible the design and manufacturing of a wide range of drones [7]. In other words, drones often vary widely in their configurations depending on the platform and mission. Therefore, there are various classifications for them based on different parameters. Considerable advantages of the drones have led to the conduction of a myriad of studies aiming at optimizing and enhancing the ability of this group of planes [8]. Avian flight can be considered as very efficient flying machines; thus bio-inspired designs offer potential benefits for drones [1–3,9].

One of the interesting aspects of avian flight dynamics is how natural flyers, such as birds can deform their shape to optimize their flight in different flight modes. For most of the birds, these changes take place through morphing of the wings. Therefore, the concept of a morphing drone originated from the observation of birds as they flew [10]. Birds have a unique ability to change several aspects of their wings and body mid-flight in order to alter velocity, altitude, and maneuverability or to save energy. Some examples of these mid-flight morphing abilities include spanning and sweeping which can occur during the flight modes, such as diving, flapping, gliding, soaring, turning, and landing. All of which create a beneficial outcome depending on the birds' mission. Furthermore, birds are also capable of modifying their winglets, either expanding them causing decreased velocity and altitude or compressing them creating the opposite effect [11]. Inspired from natural flyers, the evolution of unmanned aerial vehicles has advanced drastically over the past few years and due to the birds morphing capabilities; they are an ideal study subject to base the design of morphing drones upon. In drones, several designs have helped to improve upon their speed, endurance, efficiency, and maneuverability. As the efficiencies of UAV flight enhanced with basic static designs, the notion of dynamic configurations became utilized. A morphing drone can be defined as an air vehicle that changes its configuration during the flight to maximize its aerodynamic performance at different flight conditions [12–15].

Based upon the research witnessed in birds and their morphing, engineers have worked on developing similar capabilities in UAV's in order to improve their endurance, altitude, velocity, maneuverability, compressibility, stealth, and/or payload. There can be multi-

* Corresponding author.
E-mail address: abdu@nmsu.edu (A. Abdelkefi).

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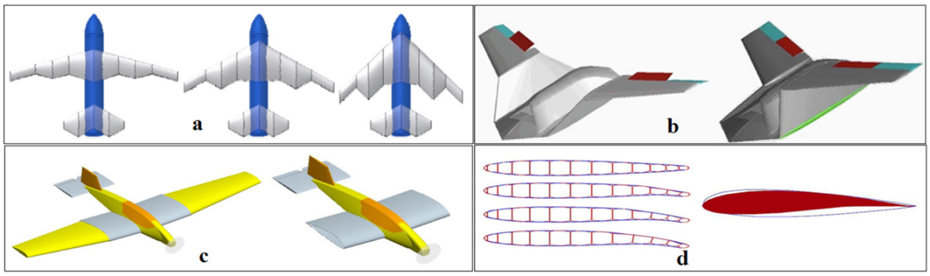

Fig. 1. Different types of morphing for unmanned air vehicles, (a) sweeping [17], (b) spanning (2D) [17], (c) spanning (3D) [18], and (d) camber variation [17].

ple forms of wing morphing either 2-dimensional or 3-dimensional [16]. All morphing types are used in a specific environment, but efficiency is always an underlying priority with any type of drone. In addition, each type of morphing winged 2D design has unique benefits, which makes them an ideal choice when used for a specific mission. The first example of a morphing winged UAV is based on varying the sweep angle mid-flight. Similar to the way birds achieve a dive, decreasing the sweep angle produces an increase in the velocity, decreases the ceiling height, and produces a compressed device that is more difficult to detect [17]. The next type of morphing is a wing with variable airfoil thickness and angle of incidence [18]. By altering the angle of incidence of the airfoil, drones can decelerate/accelerate, create quicker turns, or produce analogous types of beneficial outcomes. Similarly, varying the thickness of the airfoil may allow an increase in the lift [17]. In Fig. 1, different types of morphing methods in drones are depicted.

Nowadays, there are many organizations that are developing the morphing technology, such as DARPA, Lockheed Martin, NASA, and others [19]. For example, DARPA developed a UAV with the capacity of changing the shape of the planform during the flight with variable wingspan and sweep angle (Fig. 1(a)) [17]. Lockheed Martin designed a drone with wing folding ability (Fig. 1(b)) [17]. NextGen Aeronautics Company developed a UAV which is able to change its root chord length and sweep angle [20]. Researchers from the University of Kentucky and Dover University also designed some drones with the capability of inflating its wings during flight. In their design, the wings are inflated and deflated according to their missions [21]. One of the most efficient types of morphing shapes is wing spanning, in which the wingspan is changed. Different concepts were tested in this field. Scarborough [22] and Cadogan et al. [23] developed the inflatable wings, Blondeau and Pines [24] designed the pneumatic telescopic wings, and the telescopic wing servo-/pulley-actuated was presented by Vale et al. [25].

As described above, various types of projects were carried out on morphing drones in which their goal is performance enhancement and energy efficiency. One of the issues that all of the morphing types are struggling with, is the stability problem caused by asymmetric span variations during the transition. To handle these types of problems and increase the performance of drones, a new morphing concept is proposed for drones that can change their total dimensions, such as wing and the tail arm.

2. Concept of growing micro unmanned air vehicle

In this study, a growing micro unmanned air vehicle is designed. The main purpose of the offered concept is to design an optimum drone that can change its dimensions according to the defined missions. As discussed above, the stability in transition mode of morphing drones is one of the challenging steps for design and flight assessments. Consequently, a new concept that changes the dimensions of the wings and fuselage is proposed. This methodology can result in an improvement in the drones' performance, expansion in its flight range, enhancement of its stealth capability, reduction in drag, increase in its endurance, altitude, and payload, and reduction in vibrational instability. What makes this design unique is that instead of only relying on two possible modes, the use of a controlled mechanism allows for a wide range of designs. In other words, the advantages of this design do not only come from the final expanded form, but also from the transitional phase. During the expansion of the wing, the center of gravity is independent of the increased spanning, especially in the case of an almost rectangular wing shape, which is not significantly altering the CG position along the longitudinal axis. Furthermore, in order to keep the same vertical tail volume coefficient during the transition mode, there is an elongation in the length of the fuselage arm instead of changing the horizontal tail surface. Even though, this elongation is moving back the CG, due to the lower weight of the tails and arm compared to the weight of the wing and fuselage, our design still will be stable throughout transition mode. In Fig. 2, a schematic view of the application of this morphing concept in different flight altitudes and missions is shown.

3. Design process of growing micro unmanned air vehicle

It is indicated that the design process of a growing UAV involves (1) sizing process which includes the specification of the mission and aviation plan, determination of the aspect ratio, constraint analysis, and weight estimation; (2) determining the wing dimensions and airfoil shape; (3) designing the fuselage and booms; (4) determining the horizontal and vertical tails properties, (5) designing the spanning actuators; (6) specifying the center of gravity (CG) of the drone which can be carried out after calculating the position of the aerodynamic center (AC) and simulating the equilibrium and stability equations; (7) selecting the electrical components of the UAV; (8) and finally after optimizing the efficiency of the designed UAV, the control system is selected and then the fabrication process takes place [4,8,26]. One of the challenging parts of design is the sizing process which should be satisfied in the transition mode. At every moment of growing in this mode, the UAV should be stabilized in all axes. In Fig. 3, an overall view of the design process is presented.

3.1. Sizing process of growing micro unmanned air vehicle

Based on the defined missions, the drone should be able to change its size. For instance, if it is supposed to fly in a low altitude, dense location, such as a forest, a small sized micro UAV is required. But, if in some parts of the defined mission high altitude and endurance are planned, a larger drone is needed. Hence, the growing drone should adjust its dimensions according to the defined mission. Based on this mission, selected planform, and range of aspect ratios, a constraint analysis is carried out for the growing drone that results in the determination of the wing loading and thrust loading ranges [4]. For growing drones, the estimated weight is constant in different mode phases. Furthermore,

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