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Investigation of a robust tendon-sheath mechanism for flexible membrane wing application in mini-UAV

Shian Lee [a], Tegoeh Tjahjowidodo [a,*], Hsuchew Lee [b], Benedict Lai [a]

[a] *School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, North Spine (N3), Singapore 639798, Singapore*
[b] *Dept. of Mechanical and Manufacturing Engineering, University of Calgary, 2500 University Drive N.W., Calgary, Canada T2N 1N4*

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ABSTRACT

Two inherent issues manifest themselves in flying mini-unmanned aerial vehicles (mini-UAV) in the dense area at tropical climate regions, namely disturbances from gusty winds and limited space for deployment tasks. Flexible membrane wing (FMW) UAVs are seen to be potentials to mitigate these problems. FMWs are adaptable to gusty airflow as the wings are able to flex according to the gust load to reduce the effective angle-of-attack, thus, reducing the aerodynamic loads on the wing. On the other hand, the flexible structure is allowing the UAV to fold in a compact package, and later on, the mini-UAV can be deployed instantly from the storage tube, e.g. through a catapult mechanism. This paper discusses the development of an FMW UAV actuated by a tendon-sheath mechanism (TSM). This approach allows the wing to morph to generate a rolling moment, while still allowing the wing to fold. Dynamic characteristics of the mechanism that exhibits the strong nonlinear phenomenon of friction on TSM are modeled and compensated for. A feed-forward controller was implemented based on the identified nonlinear behavior to control the warping position of the wing. The proposed strategy is validated experimentally in a wind tunnel facility by creating a gusty environment that is imitating a realistic gusty condition based upon the results of computational fluid dynamics (CFD) simulation. The results demonstrate a stable and robust wing-warping actuation, even in gusty conditions. Accurate wing-warping can be achieved via the TSM, while also allowing the wings to fold.

1. Introduction

Mini-unmanned aerial vehicles (UAV), also known as drones, can be deployed for various purposes, for example, surveillance missions or payload delivery, therefore sparking an increasing amount of research interest. The mini-UAVs can be separated into two main categories, which are the fixed wings and the rotary wings. The difference in performance between these two is significant [1]. Fixed wings are more suitable for example for border patrol missions as the aircraft will be able to handle longer flight time and carry more payload. The mini-UAV discussed in this paper will solely be a fixed wing.

Mini-UAVs are extremely stealthy, and are usually defined as a UAV light and small enough to be carried and operated by a single human operator. However, due to the small weight and moment of inertia, they are also very susceptible to gusts

* Corresponding author.
E-mail address: ttegoeh@ntu.edu.sg (T. Tjahjowidodo).

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and thus becomes a challenging vehicle to pilot. Gusty environments, especially in tropical climates with frequent thunderstorms [2] pose a huge challenge to these aircraft. Huge control surfaces and fins and an onboard autopilot are the conventional methods to help increase the control authority and stability of the mini-UAVS. Quick deployment and easy storage of the mini-UAV are also critical for a surveillance mission. Usual fixed wing mini-UAVs may take up a lot of space as the wingspan can reach up to more than 1 m. In typical operations, the operator will have to disassemble the mini-UAV for transportation and then assemble it again for deployment. This will expose the operator to dangerous elements, as well as cause a delay which might allow the surveillance target to exit the surveillance area before the mini-UAV is ready. For the purpose of quick deployment and easier storage, the foldable wing is one of the solutions.

Research on flexible wings for fighter aircraft already exists [3], but recently there is an increasing number of works being done specifically for mini-UAVs. FMW by [4] has paved a way for the work in this paper. Being able to deploy immediately without any installation or assembly is one of the advantages of the FMW mini-UAV. By folding the wings around the fuselage for storage and transportation, the mini-UAV can also be launched directly from the storage tube, which has been shown by Prioria Robotics Maveric UAV from Florida. Adaptive washout, a phenomenon which occurs in the FMW, allows the FMW mini-UAV to handle higher angle of attack, delay stall response and dampen gust disturbances as well [4]. The ease of repair of the FMW is also a very valuable feature. A damaged wing can be repaired fairly quickly and easily by applying some adhesive on the damaged area.

Developed by the University of Florida, the FMW is fabricated by curing layers of prepreg carbon fiber [4]. It is impossible to install a servo and actuate a conventional aileron on the wing as the wing is very thin and flexible, thereby rendering the very little amount of roll control. This is a major drawback of the FMW. In [5], the FMW is warped to increase the roll control authority. Various wing-warping methods have been tried, but most are not suitable as the wing is constrained span-wise and becomes unfoldable.

In this research, the application of a tendon-sheath mechanism (TSM)to actuate the FMW is investigated. The inspiration for this research originated from the mechanism of a flexible endoscopic system that uses tendon-sheath as the mechanism for actuation [6,7]. The actuation is delivered by attaching one end of the tendon-sheath to the trailing edge of the FMW, while the other end is connected to a servomotor secured inside the fuselage that will generate the motion. Tension forces can be transmitted via the tendon-sheath to the FMW when the servomotor is activated. This approach still allows the FMW to fold as the tendon-sheath can be routed along the wing while taking only minimal space. Sufficient warping for roll control can be achieved using the TSM and is shown in experiments [8]. However, it is observed that there are some nonlinear behaviors of the TSM, which will deteriorate the wing-warping accuracy without an appropriate control strategy.

Flight control systems are required to provide aerodynamic assistance in any aircraft systems. Most of the commercial autopilots implement the PID control algorithm [9]. There are a few works involving adaptive control techniques, such as fuzzy logic controllers [10], adaptive neural network controllers [11], or robust controllers such as LQG/LTR and H_∞ controllers [12] as well. Boundary layer control is another effective method of controlling the mini-UAV, especially during low Reynold's number or high angle of attack [13,14].

This paper presents the characterization of a TSM applied for FMW wing-warping application. Nonlinear dynamic behavior that is apparent in the TSM will be identified and modeled as well, which later on is utilized to implement a model based controller to regulate the wing-warping. Subsequently, the performance of the system is validated experimentally in a wind tunnel under a specific gusty environment scenario simulated by a CFD model. The experiments and results of the nonlinear behavior identification of the TSM wing-warping are shown in Section 3. A nonlinear model based on General Bouc–Wen model for hysteresis is introduced for the TSM wing-warping in Section 4. Section 5 presents the controller design and testing for the wing-warping, and also a CFD simulation to design the testing environment. Finally, the conclusion of this paper is drawn in Section 6.

2. Flexible membrane wing characteristics

Being foldable is the main characteristic of the FMW. The FMW is specifically designed to fold around the fuselage of the UAV for storage, as illustrated in Fig. 1a. In order to fold downwards around the fuselage while be able to withstand the aerodynamic loads when unfolded, the airfoil is designed to be very thin and also curved in the chord-wise direction, measuring only 1.2 mm in thickness.

The FMW is curved along the chord-wise direction at the leading edge, allowing the wing to only fold downwards span-wise while being rigid against the forces from below the wing. This allows the FMW to bear the aerodynamic loads without buckling easily. Fig. 1 shows the FMW at the folded and unfolded stage. Reinforced ribs which start from the mid to the trailing edge support the nylon fabric, which carries most of the aerodynamic loads. Weighing at only 160 g and spanning 1 m with an area of 0.19 square meters, the FMW is very light for its size. During wind tunnel tests, the FMW can generate up to 20 N of lift force without buckling.

In addition to the ability to fold, the FMW also has a passive mechanism known as the adaptive washout, which allows the wing to flex and adapt to the gusty airflow [4]. As the wing is also flexible in the chord-wise direction, the wing will flex according to the direction of the gusts, changing the effective angle-of-attack on the wing in favor of the flight response. For example, if the gust perturbs from below, the wing will then flex upwards in the chord-wise direction, decreasing the effective angle-of-attack and also reducing the aerodynamic loads on the wing. The FMW will also flex with the changes in