Actuation and control of wing warping via tendon-sheath mechanism for flexible membrane wing mini-UAV

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Actuation and Control of Wing Warping via Tendon-sheath Mechanism for Flexible Membrane Wing Mini-UAV

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Abstract

Unmanned Aerial Vehicles, also known as drones are very suitable and efficient for border patrol and surveillance missions. No human pilot is being put at risk, but they are usually not fully utilized due to the costs and operational difficulties. The introduction of the mini-UAV, which is much less expensive and also easier to operate, can minimize losses even if the aircraft perishes during the mission. However, given the frequent gusty conditions in lower altitudes, the mini-UAV can be difficult to maneuver. The flexible membrane wing (FMW) developed in this thesis helps to mitigate the effects of the gusts with the adaptive washout effect. Additionally, the FMW provides the convenience of quick deployment and storage by being foldable along the fuselage. This thesis details the research to achieve more roll control authority while preserving the adaptive washout and also foldable feature. A novel method of wing warping was discovered, which relies on the tendon-sheath mechanism. The nonlinearities of the tendon-sheath mechanism (TSM) actuated wing warping were identified and then modeled using a modified General Bouc-Wen (GBW) model for hysteresis. The parameters for the modified GBW model was found by utilizing optimization methods. A TSM wing warping controller, which is the main contribution of this thesis, was designed with a feed-forward and feedback control. The comparison between open loop and closed loop wing warping is shown. A significant improvement in warping accuracy was achieved in the closed loop system and is documented in the thesis. Further verifications such as computational fluid dynamic simulations, wind tunnel tests and flight tests were conducted to show the robustness and real world usability of the TSM wing warping controller on the FMW mini-UAV. This thesis has demonstrated the feasibility of the TSM wing warping roll control on the FMW mini-UAV while keeping the adaptive washout mechanism and the foldability of the FMW for storage purposes.

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Nomenclature

α	angle of attack
AR_{HT}	horizontal tail aspect ratio
AR_W	wing aspect ratio
b_{HT}	horizontal tailspan
b_W	wingspan
c	chord length
C'_W	mean aerodynamic center
C_D	drag coefficient
C_{HT}	horizontal tail volume ratio
C_L	lift coefficient
C_M	pitching moment coefficient
C_n	yawing moment coefficient
C_r	rolling moment coefficient
C_Y	side force coefficient
CG	center of gravity
d	rotating cylinder diameter
e	gap between RSC and trailing edge of airfoil

g	gravitational acceleration
K_D	derivative gain
K_I	integral gain
K_P	proportional gain
L	length of the supporting strings for the bifalar pendulum
l_{HT}	horizontal tail moment arm
m	mass of aircraft
S_{HT}	horizontal tail area
T	rotational oscillation period of the bifalar pendulum
AFW	Active Flexible Wing
APM	Ardupilot Mega
FMW	Flexible Membrane Wing
GBW	General Bouc-Wen
HIL	Hardware In Loop
MAV	Mini Aerial Vehicle
MFC	Macro Fiber Composite
PID	Proportional-Integral-Derivative
SMA	Shape Memory Alloy
TSM	Tendon-Sheath Mechanism
UAV	Unmanned Aerial Vehicle

Chapter 1

Introduction

1.1 Background

In recent years, there has been an increasing amount of interests in using mini-unmanned aerial vehicles (UAV) for surveillance missions. They are relatively cheap to fly, highly agile, stealthy, and most importantly do not endanger the human operator as they fly into hazardous areas.

Loosely defined as a UAV light and small enough to be carried and operated by one human operator, the mini-UAVs are extremely stealthy. However, they are also very susceptible to wind gusts, and is, therefore, difficult to pilot. Ways to help to pilot the mini-UAVs include having huge control surfaces and fins and an onboard autopilot, thus increasing the available control authority of the mini-UAVs. Conventional fixed-wing mini-UAVs take up a lot of space as the wingspan can be up to 1 meter or more. The operator will have to disassemble the mini-UAV for transportation and then assemble it again to deploy. This inconvenience can be costly for the operator, especially when the surveillance target might move away from the surveillance area before the mini-UAV is ready.

The flexible membrane wing (FMW) mini-UAV can be deployed instantly without any assembly required. This is achieved by folding the wings around the fuselage for storage and transportation, and the operator can launch the mini-UAV directly from the storage tube. This feature has been shown by the Prioria Robotics Maveric UAV. The flexibility from the wing also provides some aerodynamic advantage. Adaptive washout [1] allows

the flexible wing membrane mini-UAV to handle higher angle of attacks. Disturbances such as gusts can be dampened as well. The other advantage of the flexible membrane wing is the ease of repair at the field. If the wing is damaged it can be repaired 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 [1]. As the wing is very thin and flexible, it is very difficult, or almost impossible to install a servo and actuate a conventional aileron. This leads to the very little amount of control authority and is a drawback of the FMW.

1.2 Theory of Flight

An aircraft, no matter rotary or fixed wing, achieves flight by creating lift. Figure 1.1 shows the forces acting on an aircraft during stable cruising flight. Four main forces acting on the body are *Lift*, *Drag*, *Thrust* and *Weight*. When the lift is greater than weight, the aircraft climbs. Similarly, when thrust is greater than drag, the aircraft accelerates. Lift and drag is created when the air flows over the wings. The lift equation is written as

$$L = C_L(\frac{1}{2}\rho V^2 S) \quad (1.2.1)$$

and the drag equation is written as

$$D = C_D(\frac{1}{2}\rho V^2 S) \quad (1.2.2)$$

where

ρ = density of air

V = velocity

S = surface area

From the lift and drag equations, it is desirable to maximize C_L while minimizing C_D , which is the bulk of the design and engineering work of the aerospace engineer. C_L and C_D

Figure 1.1: Equations of motion of an aircraft in stable flight.

are values that can be obtained by running wind tunnel experiments or computational fluid dynamics simulations. In this thesis, the FMW is tested using both methods to obtain the data.

The attitude of the aircraft can be controlled in the air by deflecting the control surfaces on the wings, horizontal tail and vertical tail. Figure 1.2 shows the three axis which the aircraft can rotate on. In a typical aircraft, the control surface on the wings, which are known as ailerons, control the roll. The elevators, which are control surfaces on the horizontal tail controls the pitch, and rudders on the vertical tail control the yaw. As the control surfaces deflect, a moment is created. Thus, the aircraft will rotate with respect to the axis of the created moment. For example, when the ailerons are deflected asymmetrically, with the right aileron down and the left aileron up, the right wing will exert an extra force upwards while the left wing exerts an extra force downwards. In this scenario, a left rolling moment is created and thus causing the aircraft to roll left. This thesis will be discussing mainly on the roll rotation of the FMW mini-UAV, as the wing warping of the FMW acts as the ailerons, causing a roll in the mini-UAV.

1.3 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

Figure 1.2: Equations of motion of an aircraft in stable flight.

between these two is significant [2]. Fixed wings are more suitable for border patrol missions as the aircraft will be able to achieve higher endurance, therefore covering more area.

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 and thus becomes a challenging vehicle to pilot. Gusty environments, especially in tropical climates with frequent thunderstorms [3] 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 meter. 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 the 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, a foldable wing is one of the solutions.

There exists some research on flexible wings for fighter aircraft [4], but recently there are an increasing number of works being done specifically for mini-UAVs. FMW by [1] has paved a way for the work in this thesis. 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 attacks [1]. This allows the FMW to handle a higher angle-of-attack, delays stall response and dampens gust disturbances as well. 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 [1]. 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.

1.4 Available Flexible Wing UAVs

Carbon fiber membrane flexible wings are already available in the market. There are a few UAVs that employ this technology and they will be compared in this section. There are also some UAVs which used cloth or parachute as wings, or some which employ flapping mechanisms, and those are not included in this list. Some of the UAVs compared in this subsection are Nighthawk MAV, Maveric UAV, Skyseer UAV, and the MAV from the University of Florida. These UAV have a lot in common, which are the flexibility of the wings and the material used in the wings. All of the UAVs listed above have both spanwise and chordwise flexibility except for Nighthawk.

Nighthawk (Figure 1.3) is an MAV developed by Applied Research Associates, Inc.[6]. The purpose of this aircraft is to conduct surveillance and reconnaissance missions, with minimal operator training. The entire aircraft, including wings, are constructed of carbon fiber. The wings are span-wise flexible, allowing them to be rolled and wrapped around the fuselage for storage in a 6-inch diameter tubes. Nighthawk weighs about 0.73 kg, has a 66 cm wingspan, and can fly for more than 60 minutes with a range up to 10 km. The cruise speed is about 9.3 m/s to 15.4 m/s, with a service ceiling of about 3.4 km. The payload carried are an electro-optical camera and thermal imagery. It can be launched

fairly easily by hand tossed.

Figure 1.3: Nighthawk UAV[6].

Maveric UAV (Figure 1.4) is developed by Prioria Robotics Inc.[7]. Similar to the Nighthawk, the Maveric is equipped with foldable wings which can be rolled up and the whole aircraft can be stored and launched in a 6-inch tube. Besides span-wise flexibility, the Maveric includes chordwise flexibility as well, which helps in gust alleviation. According to the company, it can and operate in wind up to 20 knots sustained, and 30 knots gusting. It has 45-75 minutes of endurance, a ceiling of 4.8 km, and a stall speed of 9 m/s.

Figure 1.4: Maveric UAV[7].

Another flexible wing UAV is the Skyseer UAV (Figure 1.5), developed by Octatron. It is developed for surveillance purposes as well, and the Los Angeles County Sheriff's

Department is currently experimenting with this UAV as a means of crime prevention technology. It weighs about 1.42 kg, has an endurance of 45 to 60 minutes, and a cruise speed of 10.2 m/s. The wings have a span-wise flexibility[8].

Figure 1.5: Skyseer UAV[8].

A new MAV has been developed by Ifju et al.[1] as well, which is shown in 2.1. Their MAV is very small in size, weighing only 80 grams and a wingspan of about 15 cm. The wings of this MAV constructed using latex with carbon fiber reinforcement strips. This MAV has a good gust alleviation mechanism, as a result of the adaptive washout of the wings. This MAV can fly up to 11 m/s, and it is quite easy to fly given the very small size.

All of the flexible wing UAVs listed above possess a critical flaw; they do not have ailerons, a critical control surface for roll control. The research in this thesis can help improve roll control by installing a mechanism on the flexible wing UAV in place of the aileron, and also can help to alleviate gust to overcome the weather uncertainties.

1.5 Motivation

Border patrol and surveillance missions are always risky and full of unknowns. At the land or seas where border security needs to be carefully maintained, a lot of manpower is required. Currently, the border patrol is relying more on surface vehicles such as boats and off-road vehicles. In recent years, there is a growing need for better surveillance and security. By relying on land or sea vehicles alone is not efficient nor quick enough to

gather information or react to emergencies at the surveillance area. In this situation, air surveillance is a good option as it can cover a lot of area in a short amount of time. While the aircraft has this advantage, the main disadvantage is it is costly and also requires a lot of maintenance to operate. A good solution towards this problem is to introduce a mini-Unmanned Aerial Vehicle (UAV) to the mission. A mini-UAV is small and also does not require any pilot on board to operate, therefore minimizing the risks of the mission. This new technology is the key to better border security and control. They can be controlled remotely by a human pilot or flown autonomously with the onboard autopilot. UAVs are suitable for missions that are too dangerous or dull for the human pilot. There are two main categories of UAVs. The fixed wings, with a lower trust-to-weight ratio (usually smaller than one), and the rotary wings with the trust-to-weight ratio being larger than one. The lift from fixed wing aircraft is generated by the wings, and the headwind is required for the wings to acquire lift. On the other hand, the rotary wings can hover because the lift is generated by the rotating wings.

For border surveillance purposes, the fixed wing UAV is preferred. The fixed wing aircraft can cover more area; is more fuel efficient; and also has a much higher endurance compared to the rotary wings. Moreover, there are no hovering requirements during the missions. These advantages allow the UAV to travel much further, therefore ensuring the safety of the human pilots. However, there is a multitude of disadvantages as well. As the fixed wing mini-UAVs operate in low altitude, they are more susceptible to weather conditions. The size, weight and moment of inertia of the mini-UAV are quite low, which leads to a high sensitivity to gusts. Besides, the mini-UAVs also operate in the low Reynold's number region due to the low operating airspeed and small wing chord size, and that also contributes to the gust sensitivity of the mini-UAV. Some other drawbacks are that the fixed wing UAV takes up more space than a rotary wing, and usually requires a longer time to set up and deploy.

FMW mini-UAV, on the other hand, has the ability to mitigate the disadvantages mentioned above. Designed to fold along the fuselage, the FMW is able to shorten deployment time and also saves storage space as it can be folded and stored in a tube. The adaptive washout mechanism unique to the FMW is able to dampen the gusts by passively changing the AOA according to the gust angles to reduce or increase lift[1]. These

effects are highly desirable, as the FMW mini-UAV can now fly at low altitudes without being affected as much by bad weather conditions, and also the operator can safely deploy the FMW mini-UAV from inside a ground vehicle without exposing himself to the dangerous or harmful environment. Again, these new abilities are not without trade-offs. The FMW, being too thin to house a servo, and the trailing edge unable to be trimmed off for an aileron, is unable to provide roll control for the UAV. The rolling moment has to be induced from rudders or elevons.

The drawback of the FMW has piqued the interest of the author, and this problem proves to be challenging. How does one increase the roll control of an FMW, without sacrificing the desired attributes? First of all, there is a lack of space for servos on the wing, unlike conventional foam based wings. Second, the trailing edge of the FMW cannot be trimmed, as the FMW will just flutter in the airflow instead of providing extra lift as an aileron. Third, installing bulky mechanisms such as servos or push rods and the like will hinder the ability of the FMW to fold. There are some efforts by others to increase the roll control of the FMW, but the foldability is sacrificed. A better method is required in order to preserve the desired qualities of the FMW while providing ample lateral control. Once this can be achieved, the usefulness of the FMW mini-UAV will be vastly improved. These challenges provide plenty of incentives and are therefore an excellent research topic.

1.6 Objective, Scope and Contributions

1.6.1 Objective

The objective of this research work is to develop a FMW mini-UAV which has a new method of wing actuation mechanism for lateral control, while maintaining the capability of being foldable around the fuselage for storage and quick launching purposes, as well as maintain the adaptive washout mechanism. Currently there exists some methods of warping the FMW for lateral control, but all of them hindered the foldability of the FMW along the fuselage.

1.6.2 Scope

Part of the scope of this study is to sought out a method of wing warping actuation which can produce produce a sufficient amount of rolling moment and thus increasing the lateral controllability of the FMW mini-UAV, while maintaining the constraints.

With a new method of wing warping for the FMW, there will be a need of a new controller to control the warping outputs of the FMW. The scope of this thesis therefore also contains the work of identifying the nonlinearities of the new warping mechanism, modeling the mechanism, and finally, to develop a new type of controller based on the model of the new warping mechanism.

In order to proof that the newly developed controller, along with the novel wing warping actuation method performs well, a flight test will be required. The flight test is yet another part of the scope of work in this thesis.

1.6.3 Contributions

The contributions of this thesis includes a newly developed method of wing warping actuation for FMW which can fulfill the requirements of foldability along the fuselage as well as maintaining the adaptive washout mechanism, the identification and modeling of the wing warping actuation, and a new controller design for the FMW mini-UAV. Testing and validation of the controlled wing warping actuation in various conditions, as well as a flight test was done to proof the worthiness of the novel wing warping actuation for the FMW.

1.7 Thesis Outline

This thesis is divided into two main parts, with a bulk of the work being done on the TSM, and another part being done on the FMW mini-UAV. By combining the work from both sides, the resulted TSM actuated FMW mini-UAV is then constructed and flight tested. Figure 1.6 shows the connection between the chapters and provides a clearer flow of the thesis structure.

This thesis is organized into the following chapters:

- Chapter 2 shows a brief and concise review of the literature related to the dynamics,

Figure 1.6: Structure of the chapters.

actuation, and control of the flexible wing, and also some related works on the flexible wing UAV. Different methods of actuation for the FMW, as well as experiments to determine the feasibility of the actuation methods are shown in this chapter as well.

- Chapter 3 provides a review of the identification and modeling of the TSM wing warping. The identification experiments and also the optimization of the parameters of the model is shown in this chapter.
- Chapter 4 reviews the control design, simulation, and verification of the TSM wing warping control.
- Chapter 5 shows the FMW mini-UAV design and fabrication process. The aerodynamics, geometry and mass properties of the FMW mini-UAV, as well as the identification and modeling of the whole aircraft, are also presented in this chapter.
- Chapter 6 shows the test flight procedures and flight data.
- Chapter 7 concludes the thesis with a discussion of the achievement of this research, and also provides a few possible future work suggestions.

Chapter 2

Literature Survey & Theoretical Basis

2.1 Overview

This chapter gives a brief but concise review on the literature related to this research. Topics related to flexible wing dynamics, actuation and control are discussed. FMW for mini-UAV is a relatively new concept, so there exists very little available literature on this topic. There are, however, more literature on the flexibility and aeroelasticity of the wings for manned aircraft. Some literature on smart materials for aerospace applications is also discussed because of the similarities in flexibility of the mechanical properties. A brief review of various control techniques for UAVs is discussed as well. Finally, an intensive study of the FMW is described, along with some experiments to determine the best actuator for the FMW.

2.2 Flexible Wing Studies

A study on flexible wing is done to further understand the nature and the characteristics. The flexibility of the wing leads to many desirable and also undesirable effects, directly impacting the performance of the FMW mini-UAV in this thesis.

Flexible wing research used to be done mainly for fighter aircraft. The Active Flexible Wing (AFW) by NASA and Rockwell was a new concept at that time. In a typical air-

craft, wing flexing is an undesirable effect, as it will cause control issues, such as aileron reversal. However, for the AFW, they exploited wing flexibility to provide weight savings and improve aerodynamics by operating with a flexible wing and without a horizontal tail. In order to counter the aileron reversal problem, the AFW operates by using multiple leading and trailing edge wing control surfaces to provide roll. A computer controlled, active roll control system (ARC) is designed to select the best control surface to actuated to roll the vehicle, according to the flight conditions. In [4], it was estimated that a 15% of weight savings is possible, by eliminating the structures required for flutter suppression, gust loads and maneuver loads.

Recently, more research work on flexible wing aircraft were done by [1]. The flexible wings can reduce the effects of gusts and unsteady aerodynamics while increasing the desirable flight stability and structural durability [1]. As the mini-UAV operates in a low Reynolds number range, the wind speed difference may change the Reynolds number up to 30%, causing considerable changes in the aerodynamics of the mini-UAV. The unique shape of the FMW is able to adapt to different flight conditions and turbulences via the passive mechanism of adaptive washout [1], as shown in Figure 2.1. As the wing is also flexible in the chord-wise direction, the wing will flex away from the direction of the gusts, changing the effective angle-of-attack on the wing in favor of the flight response. More explanation on the adaptive washout mechanism is discussed in detail at Section 2.3.1. The FMW is made of a very thin sheet of membrane, in [1] its made of Icarex and pre-preg carbon fiber supports. For this thesis, the FMW is fabricated using pre-preg carbon as well as Nylon cloth. Another feature of the FMW used in this thesis is that it is able to fold along the fuselage for easy storage and portability. More details about the characteristics of the FMW can be found in Section 2.3.

In [9], it is deduced that a flexible wing can increase lift and reduce drag by analyzing the flexible wing using computational fluid dynamics (CFD) code. The aeroelasticity and control of a highly flexible, high aspect ratio human powered aircraft have been investigated by Schoor et al.[10]. The dynamics of aircraft will change according to flight conditions due to the flexibility of the structure, therefore, the aeroelastic effects are not to be ignored. Finite element method (FEM) beam elements are used to analyze the wings, with the air mass of the wings taken into account. At low altitudes, the first wing bending

Figure 2.1: The wings of this MAV by Ifju et al. flex under load [1], displaying the adaptive washout capability.

mode changes from oscillatory to critically damped with the increase of flight speed. It is therefore very crucial to carry out aeroelastic analyses for fatigue prediction. Results showed that simplification by separating the rigid body modes and flexible modes are not justified, as many flexible modes are required to yield a reliable aeroelastic model. In [11], similar opinions were had about the stability of high altitude long endurance (HALE) aircraft with large wing deflections. The inverted U-shape caused unstable yaw and roll attitudes. Changes of wing shape will cause many unwanted changes, for example, pitch inertia, the location of the center of gravity, aerodynamic center and aerodynamic forces and moments. It was also found out that the aerodynamic formulation interacts with the structural wing deflection and they are strongly coupled. In [12], the possibility of using elastic wing twist and camber to achieve roll at all dynamic pressures was examined. Assessment has been made between twist control and conventional aileron control for both subsonic and supersonic flights. The strain energy required for the twist to roll has been determined. Data such as strain energy required for a certain roll rate is recorded in detail. Active wing warping control via existing piezoelectric material for induced strain has been investigated [13]. It is proposed to use anisotropic piezo-composite actuators (APA) as an integral load bearing component of the wing structure. In that particular experiment, both conventional aileron aircraft and APA induced wing warping aircraft satisfies the experiment constraints.

In [14], the flexibility of the wing as a mean of roll control is investigated. Aileron is effective for rigid wings in low dynamic pressures, but for high dynamic pressures, the

wing deformation can be significant, therefore reducing roll moment or even inducing roll reversal. Wing deformation is used to induce roll, instead of regarded as an unwanted disadvantage. LQR is used as the control in the simulation for real size plane. Two Mach numbers were tested, and results showed the first four flexible modes to be unstable in open loop, while the closed loop is stable. The work done by the actuators were calculated for different Mach numbers and control weighting parameters. Increase in dynamic pressure or Mach number will decrease the strain energy required, and an increase in control weight will increase the time required to stabilize roll rate and will also decrease the maximum actuator forces required. An analysis of the flight dynamics of a highly flexible flying wing aircraft configuration was presented [15]. Nonlinear analysis is used as the deformation of the aircraft is very large. It was found that the deformation of the wing can be used to positively affect the stability and control of the aircraft. The flexible wings are modeled structurally as a beam. Results showed that large wing deformation leads to less lift, and thus requires a higher angle-of-attack. An increase in payload also leads to an unstable phugoid mode. In [16], the performance and stability of a flexible wing tailless MAV was discussed, which the wings twists and dihedral angles of the wings can be changed symmetrically or asymmetrically to control the flight speed independent of angle-of-attack and flight path angle as well (Figure 2.2). Wing dihedral angles can be used for longitudinal and yaw control without a vertical tail. This configuration allows the MAV to perform rapid turns and also regulate side slips.

2.3 FMW Properties & Characteristics

Being able to fold 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 2.3a. Figure 2.3b shows the FMW mini-UAV when in the deployed state. 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, as illustrated in Figure 2.4.

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

Figure 2.2: The use of wing dihedral for longitudinal and yaw control.[16]

(a) Flexible membrane wing in the folded state. (b) Flexible membrane wing unfolded.

Figure 2.3: The FMW being able to fold around the fuselage for storage.

the wing. This allows the FMW to bear the aerodynamic loads without buckling easily. Figure 2.3 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 grams and spanning 1 meter 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 35 N of lift force without buckling. Below is a table of the specification of the FMW.

Figure 2.4: Flexible membrane wing thin airfoil.

Wingspan	1 m
Chord length	0.25 m
Mean aerodynamic chord	0.22 m
Area	0.19 m ²
Aspect ratio	5.158
Weight	160 g
Average Thickness	1.2 mm

2.3.1 Advantages of FMW

There are three main advantages of the FMW. FMW can be folded when in storage, and also launched from a tube. Besides, they also offer a greater stall resistance and a smoother flight. Finally, they provide an increase in roll stability.

The idea of launching a mini-UAV from a tube has been explored and designed in [17]. The FMW UAV is a suitable candidate for such applications. The FMW also has a passive mechanism known as the adaptive washout, which allows the wing to flex and adapt to the gusty airflow [1]. As the wing is also flexible in the chord-wise direction, the wing will flex away from 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 chord-wise, decreasing the effective angle-of-attack and also reducing the aerodynamic loads on the wing. The FMW will also flex with the changes in the headwind velocity, increasing or decreasing the lift forces generated and providing a smoother flight and better stall resistance. The FMW will recover to the original airfoil shape, restoring the lift forces when there are no disturbances. This adaptive washout

phenomenon helps to provide a smoother flight and allowing an easier flight control.

The increase in roll stability is achieved with the FMW providing a slight dihedral angle. An aircraft with dihedral wings experiencing a roll disturbance will have an increase in effective angle-of-attack for the lowered wing, resulting in greater lift on the lowered wing which will passively roll the aircraft back towards the steady level [18]. The FMW tend to be bent upwards during flight due to the lift forces on the wings. Besides, the high wing location on the fuselage also helps with the roll stability [19].

2.3.2 Span-wise Flexibility

Span-wise flexibility is important in the wing folding procedure. Figures 2.5 and 2.6 show the numerical simulations for lift force (L) and lift and drag ratio (L/D) among three different wings; rigid, stiff, and flexible wings vs angle-of-attack[20].

Figure 2.5: Numerical simulation at 8.9m/s or 20 mph[20].

Figure 2.6: Numerical simulation at 17.9m/s or 30 mph[20].

It can be observed that the maximum lift coefficient and induced drag are increased

with span-wise flexibility. Therefore, at lower angle-of-attacks, the CL/CD performance of the flexible wing is lower but increases with higher angle-of-attack. It can be concluded that the span-wise flexibility provides more static stability by examining the Nighthawk MAV.

2.3.3 Chordwise Flexibility

Chord-wise flexibility is directly related to the alleviation of gusts. The chordwise flexibility is dependent on the different design variables such as the wing materials, wing spar, etc. The lift over drag performance, and also the gust response of chordwise flexibility at low Reynold's number (70,000) has been provided by [21]. Hyperelastic material e.g latex has been used for the flexibility. The different wing configurations of the experiment can be seen in figure 2.7.

Figure 2.7: Design of wing configurations for chord-wise flexibility [21].

Figure 2.8: Lift coefficients and lift to drag ratios of various designs[21].

The results in Figure 2.8 showed that chordwise flexibility allows the stall to be delayed at higher angle-of-attacks, resulting in a higher lift/drag ratio compared to rigid wings[22]. It is suspected that due to the excessive fluttering for wing configuration FM01, which was the most flexible wing in the experiment, it has a lower lift and higher drag coefficients at lower angle-of-attacks. FM03 is determined as the optimum wing configuration, which was the configuration chosen for the FMW design in this thesis.

2.4 Wing Warping Studies

Wing warping is studied in order to better understand the requirements and also the results, to prepare for the experiments and results comparison in this thesis. The experiments in Chapters 5 and 6 are about measuring the wing warping effectiveness, therefore this Section about wing warping study is critical to the thesis.

Wing warping, or morphing in other technical writings, are essentially the intentional change of shape of the wing or the airfoil. Wing warping has been practiced since the invention of the airplane by the Wright brothers [23]. In their case, the wings were twisted via cable and pulleys to achieve roll control. Similarly, the FMW mini-UAV can achieve more roll control authority by wing warping.

Wing warping was applied to FMW mini-UAVs to provide roll control, and it provides great roll control [5]. The UAVs are difficult to fly without warping, as steering and gust rejection are accomplished using coupled roll and yaw motion from Dutch roll dynamics. The use of torque rods and Kevlar threads for warping mechanism has also been tried [5]

(Figure 2.9). By comparing the use of only rudder or wing warping vs. roll rate and yaw rate of the MAV, results has shown that wing warping is better. The performance of wing warping is almost perfect, it induces an almost pure roll with minimum yaw motion [5].

In another similar work, wing warping was applied on their flexible wing UAV platform to eliminate control surface hinges, shown in Figure 2.10 [24]. Torque rods and Kevlar threads are used to actuate the flexible wings. There are two methods of wing warping used, namely wing curling and wing twisting. Both methods provide sufficient roll control in their experiments, although wing twisting provides a higher level of roll control compared to wing curling. Multi-point wing shaping was also tested, by using multiple torque rods and connecting them to different sections of the flexible wing.

Figure 2.9: Wing warping methods using Kevlar threads (left) and torque rods (right)[5]

Figure 2.10: Warping in action showing undeflected wing (left) and warped wing (right)[24]

Wing warping optimization work for the FMW mini-UAV has been researched by

[25]. The wing warping was done using torque rod, and very little power was needed. A numerical model of the flexible wing has been obtained to optimize the torque rod configuration. The leading edge and center of the wing are fabricated with 3 layers of bi-directional plain weave carbon fiber, with the inner layer in a 90° orientation, while the outer layers oriented in 45° . The battens are constructed with 2 layers of uni-directional carbon fiber oriented in 90° . Icarex was used for the skin of the wing, and it is not cured together with the carbon fiber but glued on later. In the finite element analysis, membrane elements, beam elements, and plate elements were used. For the aerodynamic model a vortex lattice code Athena Vortex Lattice (AVL) was used, where the inputs are vehicle geometry, inertial properties, and flight conditions, and the code outputs various aerodynamics. From the results (Figures 2.11 & 2.12), it was found that there are tradeoffs between the roll rates and the Lift/Drag ratio. Actuation near the wing tip will increase the roll will but decreases the Lift/Drag ratio. Multiple torque rods approaches were also tried, which can warp a greater area of the flexible wing. After optimization, both roll rates, and Lift/Drag ratio has been significantly improved [25].

Figure 2.11: Roll rates of a MAV with different torque rod placements. Data gathered at 15m/s and 3° angle of attack[25].

Micro aerial vehicles (MAV) are the ideal platform for wing warping, as they require a relatively low energy to warp [26]. The power requirement for the smart material may be higher than available on board, therefore posing a challenge for smart materials actuation. Linear model was able to represent the warping aircraft, which means control design should be straightforward. In the experiment, it was also found that thin under-cambered airfoil has delayed stall response, which is an advantage [26]. **Wing warping**

Figure 2.12: Lift/Drag ratio of a MAV with different torque rod placements.
Data gathered at 15m/s and 3° angle of attack[25].

allows the decoupling of lateral and longitudinal flight dynamics, as wing warping induces an almost pure roll with minimum yaw motion [5], making the MAV easier to pilot. Besides, wing warping also provides impressive stall and spin characteristics can be used for high agility maneuvering.

The location for warping is critical as it will affect the roll rate and also the lift over drag of the aircraft. High roll rates can be achieved if the wing is warped near the tip, but if done excessively near the wing tip, the wing will experience tip stall, and therefore inducing an adverse roll moment [25]. The degree of warping should, therefore, be limited, and also be done slightly further from the wing tip. In [25], an optimized location of warping was identified by comparing the roll rate and lift over drag of the aircraft. In this paper, a similar location was chosen for this FMW for optimal performance.

The concepts of wing warping is explained in [27] with great detail. Global warping means changes along the wing span. This warping changes the overall wing load distribution and aerodynamic characteristics. Local warping, on the other hand, means changes of the cross sections of the wing airfoil. Local warping will induce changes in the aerodynamic characteristics of the airfoil and lift coefficient (refer to Figure 2.13). To allow for wing warping, the most critical part is the wing skin. It has to be flexible enough to permit large deformations, yet stiff enough to transmit aero loading. If the wing skin is chosen to be stiff for the loading requirement, then a lot of energy will be needed for deformation, and it will also be more prone to failure. On the flipside, flexible skin allows large deformations to be done easily, but it is unable to carry the aerodynamic loads and

maintain its shape. There are a few generic warping modes explained, and they are Intra rib warping - warping in between two end ribs and Inter rib warping - warping in between the end ribs. The former induces wing shearing (changes in wing sweep (Figure 2.14c)) and wing twisting or wash out (Figure 2.14b), and also wing extension (Figure 2.14d). The latter induces relative rotation, such as wing folding (Figure 2.14a).

Figure 2.13: Global and Local warping[27].

The wing warping mechanisms described in [28, 29] are more applicable to a cambered wing. However, the ideas presented are still valid to this thesis. A new concept was found in [28] for controlling wing twist by separating the wing skin at the trailing edge. The discontinuity of the wing skin allows the required actuation energy to be decreased. The wing warping is induced a few sliding houses, a thread house, and a threaded rod. The upper skin will be connected with the thread house, and the lower skin will be connected with the sliding house. The rotation of the thread house will induce a linear motion of the thread house, thus warping the wing. A novel seamless aeroelastic wing is shown in Figure 2.15, which has a hingeless flexible trailing edge control surface is able to warp as well [29]. The wing is warped using a curved beam and disc actuation mechanism called the eccentuator. The advantages of their method are weight saving, improved aerodynamic efficiency, increased operational flexibility, and less concentrated hinge load on the wings.

(a) Folding wing warping.

(b) Twisting wing warping.

(c) Shearing wing warping.

(d) Extension wing warping.

Figure 2.14: Different wing warping modes[27].

Figure 2.15: (a) Seamless aeroelastic wing skin, (b) spars, motor, and curved beam, (c) deflected wing model[29].

2.5 Wing Warping Actuation Methods

Actuation methods for wing warping are very diverse. It is a critical piece of information in this thesis, as it will determine the method implemented on the FMW. The main

contribution of this thesis will be developing a novel actuation system and a controller for the carbon fiber membrane flexible wing. Traditional actuation methods are not suitable for the flexible wing, as the flexible wing lacks the structure to house an aileron, and also due to the flexibility of the wings, they are prone to control reversal problems. In this section, the various actuation methods that are applicable to flexible wings are discussed. The following sections describe the different actuation methods available, the smart material options, the robust control theory and the proposed actuation methods and control for future investigation and development. There are several actuation systems that are suitable for flexible wing UAVs. The requirement for this actuation system is quite stringent - it needs to have a large bandwidth for a very fast response, and also it needs to be light as well as energy saving, as there is a limited power available in UAVs. The various actuation systems for flexible wing control are presented in the following subsections.

2.5.1 Piezoelectric Actuators

Piezoelectric actuators show promising aspects for use in UAV in the direction of active boundary layer control, high bandwidth noise suppression and aeroservoelastic tailoring. Piezoelectric materials produce a voltage when applied stress, and also vice versa. Therefore, the piezoelectric material is also suitable both as actuator and sensor. They can be designed such that they extend, contract or bend when a voltage is applied. Piezoelectric materials have a relatively high bandwidth as well[30].

One of the drawbacks of conventional piezoelectric is that they are able to operate only in a limited range. However, there are two high-displacement piezoelectric actuators, namely RAINBOW (Reduced And Internally-Biased Oxide Wafer) [31] and THUNDER (THin layer composite UNimorph ferroelectric DrivER and sensor) [32] which have been developed to overcome this limit on displacement performance. These devices consist of a piezoelectric ceramic layer bonded to one or more non-piezoelectric secondary layers. Internal stresses created during elevated temperatures processing helps to enhance displacement. Another disadvantage of piezoelectric material is it requires a very high voltage - sometimes more than a few kilovolts to generate only a few mm of displacement. Therefore, an additional electric device is needed on board the UAV to provide the high

voltage required.

The MFC (Figure 2.17a) was invented by NASA in 1996 and is now commercialized by Smart Material as the licensed manufacturer and distributor of the patented invention. MFC has the adaptability and flexibility to be customized to fit the customer's specific needs and to meet the requirements for new applications. According to the manufacturer Smart Material, the MFC is constructed by sandwiching rectangular piezoceramic rods between layers of adhesive, electrodes and polyimide film[30]. The MFC is given an initial interest because it can be bonded to various types of structures or embedded in a composite structure. Hence, it can be cured together with the carbon fiber layup during the wing fabrication. When a voltage is applied it will bend or twist according to the modes, counteract vibrations or generate vibrations as shown in Figure 2.16. It can also function as a sensitive strain gauge, sense deformations, noise, and vibrations if no voltage is applied[30].

In short, the MFC has a list of advantages which are very applicable to the FMW. It is flexible, has a bending mode, and also most importantly it is embeddable to the FMW. It is, therefore, possible to have the MFC cured together with the carbon fiber wings at the lower and upper side of the wings to increase bending torque, similar to what [33] has done. The limitation to this configuration and also other piezoelectric materials is that they require a very high voltage in order to generate displacement, and therefore needing a high voltage amplifier. If the amplifier is heavy, the UAV may not be able to carry the amplifier on board.

One of the solutions to the aforementioned problem is to use the high voltage amplifier provided by Smart Material Corp. The AMD2012-CE3A & B Dual Output Variable Controlled HV Power Supply shown in Figure 2.17b is specifically designed for battery operation to supply high voltage to the MFC. The AMD2012-CE3 weighs only approximately 14 grams, and therefore is light enough for the UAV to carry on board. It requires an input voltage of 10 to 15 volts DC and gives a variable voltage supply from 0 volts to 2000 volts[30].

Piezoceramic actuators for UAV flight control were utilized and results showed that the actuators were effective in both wind tunnel and flight tests [33]. The material used for actuation is macro fiber composite (MFC). Some advantages of MFC is that MFC

Figure 2.16: Different modes of the MFC.

Figure 2.17: The MFC and its compatible transformer.

actuation does not require drag inducing linkages and any moving parts. The relationship between the voltage input and displacement output of the MFC were discussed, given the nonlinearities like hysteresis, aerodynamic loading effects, and creep. It was found that the dynamic pressures loads and hysteresis contributed most of the nonlinearities. However, these nonlinearities can be modeled and corrected. Results from the open loop control show more problems related to hysteresis. The authors applied a method called Biwarp, which is essentially MFCs embedded on both top and bottom, with one contracting and the other extends, therefore inducing actuation. It is also possible to implement a sensor and closed loop control for the MFC actuation system.

2.5.2 Nylon String Attachment

Warping of inflatable wings is similar to the problem in this thesis, where conventional roll control methods are not applicable. Smart materials and mechanical actuators was examined for the inflatable wings in [34]. Nitinol wires and a pulley system with nylon

lines and servos were used to warp the wings. The wing actuation was to only pull down the trailing edge of one side of the wing, with the other side of the wing stays in neutral position. The roll rate was satisfactory with about $170^\circ/\text{s}$. Flight control tests were performed in [35] for their inflatable wing UAV. In that experiment, the inflatable wings were actuated using nylon lines and Nitinol. The predictions of roll control effectiveness and correlations of forces required to warp the wings were determined. Soft foam (Figure 2.18) were used to imitate inflatable wings for flight tests to determine the wing warping performance. It was found that the performance of the inflatable wing warping was comparable to the conventional aileron [36]. A modeling process was developed in [37] to predict the aileron effectiveness derived from the equations of motions of the aircraft as a parameter for roll control. The inflatable wing UAV was flight tested autonomously using Ardupilot and it performed doublets in flight. The doublets were then analyzed and the actual aileron effectiveness was found to be within 8 percent of the predicted aileron effectiveness. As for the FMW, this method works but it is not elegant, as the Nylon string tends to get tangled when the FMW is folded. Besides, it is also not robust as the Nylon string will break easily. For an unfoldable foam wing, the Nylon string method is feasible.

Figure 2.18: Wings fabricated from soft foam[36].

2.5.3 Air Flow Control

This technology allows the UAV to be controlled by just pumping air directly at the trailing edge of the wing into the boundary layer. Lift is increased when air enters the upper surface of the flow, therefore allowing pitch and roll control without flaps. FLAVIIR

Flapless UAV in Figure 2.19 uses fluidic thrust vectoring and circulation control, enable flapless control of the pitch and roll by using a secondary air flow.

Figure 2.19: FLAVIIR Flapless UAV.

2.5.4 Shape Memory Alloy

Shape Memory Alloy (SMA) is an alloy that returns to its original programmed shape when heated. This attribute is desirable as the SMA can be programmed into any shape during the cold forge stage, and it will return to the programmed shape when heat is applied, no matter how deformed it becomes.

Typically in roll control, the trailing edge of a wing are actuated by the mechanical links connected by the push-pull SMA wires. The wires will be heated anytime when desired, and the trailing edge of the wing will return to its original shape. A major drawback of this actuation method is there is only at most two different shapes stored in the SMA's memory. This can be done through training, by cooling the SMA to a specific temperature and then deform it while heating it to a specific temperature. In this way, the SMA can “learn” both the low temperature and high-temperature shape.

2.6 Experiments to Determine FMW Warping Actuator

In order to facilitate the actuator selection process, some experiments were conducted to test the feasibility of Shape Memory Alloy (SMA), Piezoelectric Actuators and Dielectric Elastomer Actuator. The following subsection will describe the experiments done and the conclusion of the experiments. It must be brought to attention that the main requirement of allowing the FMW to fold must be fulfilled, therefore methods such as torque rods and Nylon strings are not considered in this experiment.

2.6.1 Shape Memory Alloy

A simple test was conducted to find out the feasibility of the SMA as the flexible wing aileron actuator. The SMA tested in this experiment is the conventional Nickel Titanium, also known as NiTi or Nitinol. When in ambient temperatures, the SMA is fully malleable,

(a) SMA at ambient temperature.

(b) SMA at high temperature.

Figure 2.20: Shape memory alloy at different temperatures will morph into its memorized shape.

easily bent to any desired shape. Figure 2.20a shows the Nitinol intentionally twisted into this shape to show that it is malleable. In default, the Nitinol is programmed to go back to a straight line when the temperature of the wire is increased. Figure 2.20b shows that after increasing the temperature of the wire, the wire sprung back to a straight line almost immediately.

The Nitinol wire was reprogrammed by holding it static while treating it with high

heat. This will cause the Nitinol wire to memorize the new configuration, hence the name shape memory. While the new configuration is programmed, it still does not help very much because there is only one configuration available for every piece of wire.

As there is only one configuration per wire, an idea to perform the aileron actuation will be to have at least two Nitinol wires acting in opposite directions, much like an artificial muscle pulling the flexible wing. However, this idea is not feasible. First of all, aileron actuators require a large degree of movement and also different degrees of deflection. Although the SMA can provide a large amount of deflection displacement, it does not fulfill the second condition, where it is constricted by only one configuration per piece of wire. Even if we try to use the artificial muscle approach, the aileron will still be able to move only two-way, without any control in between the different positions. The lack of control of position is what discourages the usage of SMA in this research.

Another downside of the SMA is the temperature control required for the Nitinol wire, as it is actuated by varying the temperature of the wires. Temperature is one of the harder parameters to control accurately. It can be influenced and affected by the ambient conditions easily. Therefore, it is not a very reliable technique to control the aileron actuation. According to Tan et al.[38], the austenite state of the SMA starts at 52.540°C and austenite finish at 60.900°C, while martensite state starts at 44.780°C and martensite finish at 32.840°C. Therefore, the temperatures between the austenite and martensite states are very close, resulting in a difficult control of the smart material. Achieving the martensite state is also very challenging, as the only control input is to increase heat. In order to achieve the martensite state is to cool down the SMA via the airflow, which is a variable parameter during flight.

In conclusion, SMA is not very helpful when it comes to actuating ailerons, which requires accurate position control, and more than just one configuration. A more suitable application for SMA may be wing sweeping or the change of airfoil shapes for different stages of flight.

2.6.2 Piezoelectric Actuator

An experiment was conducted by utilizing a piece of Macro Fiber Composite (MFC) to determine the feasibility of MFC for the purpose of actuating the FMW. The MFC used

for the experiment is a P1 type, d_{33} effect actuator, with the fibers oriented in 0° . The model the MFC tested is M-2814-P1, and it has an active length and width of 28 mm and 14 mm, an overall length 38 mm, an overall width 20 mm, capacitance of 0.61 nF, free strain of 1550 ppm, and a blocking force 195N, according to the user manual. The amplifier used in this experiment is the PDX150b. According to the user manual, the PDX150b can reach a voltage of -30 V to 150 V, and can produce a peak current of 2A. However, the voltage required for MFC is in the thousands, therefore, very little displacement is expected in this experiment.

(a) MFC connected to amplifier.

(b) Oscilloscope showing the voltage of 4.4V.

Figure 2.21: Experiments performed on the MFC.

The setup of the experiment is shown in Figure 2.21a. The MFC is connected to the output of the amplifier, which is the red box in the middle, and the amplifier is connected to an oscilloscope at the right. The box at the left is the signal generator, where the gain and frequency of the input signal can be controlled. A sinusoidal signal was given as an input with 4000 Hz. The red LED light flashed at the amplifier, signaling an overload. Figure 2.21b shows the output voltage of the amplifier when it was overloaded, which is about 88 V. The gain of the amplifier is 20V/V, therefore, $Voltage = 4.4V \times 20V/V = 88V$.

During the excitation of the MFC, no movement was detected but a buzzing sound can be heard, and the pitch of the buzzing sound can be controlled by changing the frequency of the actuation. This result was expected, given the strain is only 1500 ppm, which translates to 0.0372 mm, and is not visible to the naked eye. The displacement is concluded as too small for FMW warping actuation.

2.6.3 Dielectric Elastomer Actuator

Dielectric materials have been investigated as well. 3M VHB 4910 was chosen as the dielectric elastomer actuator (DEA). The DEA was secured to the flexible membrane wing and was able to warp the wing as well. However, the whole setup was very bulky and the DEA was covering all of the areas of actuation, as illustrated in Figure 2.22. This will disrupt the airflow and therefore will possibly disturb the aerodynamics of the flexible wing. Besides, it was very difficult to mount to the wing and will break easily. By having the DEA installed makes the wing difficult to fold, which defeats the purpose in the first place. The DEA also require an immense amount of voltage to actuate, reaching up to 5 - 10 kilovolts. A heavy step up transformer will be required to actuate the DEA. DEA is therefore concluded as unsuitable.

Figure 2.22: Dielectric Elastomer Actuator (DEA) fixed on the FMW.

2.7 Tendon-sheath Mechanism

After a detailed survey about the TSM, it is decided as the actuation method in this thesis. The tendon-sheath mechanism implies a piece of tendon, which is actually a Teflon-coated Kevlar thread, moving inside the sheath, which is a round-wire coil, as presented in Figure

2.23a. The force transmission and also the characteristics of a TSM is presented in [39]. Simple friction models are discussed and also the simulation of the TSM was shown (Figure 2.23b). Different lengths, as well as the different bending angles of the tendon-sheath, will significantly affect the characteristics of the TSM tension transmission.

(a) Schematic of a tendon-sheath [40]. (b) Simulation results of the TSM tension input output characteristics.[39].

Figure 2.23: Tendon-sheath and its hysteresis characteristics.

An extensive investigation was done on the friction-based tendon sheath model for control purposes in [41]. Four main phases of the TSM characteristics is categorized. Some important assumptions on the TSM were also mentioned in order to develop the model, which are negligible axial deflections of the tendon, only axial motions are taken into consideration while neglecting the transversal motions, the TSM is kept at a constant curvature, and also always maintained by a force to ensure that slack is kept to a minimum. Different models like the symmetric Bouc-Wen model and the asymmetric Bouc-Wen mode were compared. The nonlinearities of the TSM was identified, and also a controller was designed to achieve better performance on the TSM position control in [40].

The analysis, modeling, and identification of nonlinear systems with hysteresis is discussed in [42]. As it is very difficult to model the hysteresis behaviors using the laws of physics, the hysteresis models are created artificially by choosing a set of parameters particular to the system being modeled. The Bouc-Wen model is one of such models that requires an optimization process to obtain suitable parameters for the nonlinear hysteresis system. The Generalized Bouc-Wen model [43] can be used to describe highly asymmet-

ric hysteresis loops. A system with a high degree of asymmetry cannot be described by conventional Bouc-Wen class models. This model is particularly useful to TSM actuation of mechanical systems, for example in this thesis a warping wing, which contains an asymmetric hysteresis. More details and analysis are documented in Chapter [3.4.2](#).

2.8 Friction in a Nutshell

As the nonlinearities of the TSM stem mainly from the friction, this section is devoted to a study of friction in mechanical systems to better understand the cause of the hysteresis in TSM.

Friction forces exists in all interaction between one body over or along another. Energy is always lost in the form of heat when friction is present. Sometimes it can be a nuisance, reducing the efficiency of a mechanical system, but sometimes it can be a desirable property, such as providing braking or damping to a mechanical system. Therefore, it is critical that the characterization of the friction forces be understood to ensure the mechanical systems be subjected to the correct amount of friction forces. It is difficult to characterize friction as the behavior is highly nonlinear, depending on the displacement, velocity and time of the system.

Perhaps the most well known friction model is the Coulomb friction model, which is also referred as the classical friction model, is an adequate approximation for many physical systems. However, the Coulomb friction model only approximates the friction forces in the sliding regime, where there is a non-zero relative velocity between the bodies. When the relative velocity is zero, the model simply defines the friction force as below the static friction value. This model is very difficult to simulate, as its very difficult to determine when the velocity will cross zero. Besides, in the practical world, motion do not start and stop abruptly and micro sliding displacements will be observed [\[44\]](#). Therefore, in order to properly characterize the friction forces interacting in a mechanical system, better models are required. There are two main regimes in friction, namely the pre-sliding and the sliding regime.

2.8.1 Pre-sliding Friction

When the velocity of the contacting body is decreased and the motion is reversed, the system is in a pre-sliding friction regime. In the pre-sliding regime, the friction forces are a function of velocity as well as displacement, and the friction-displacement relation involves a non-local memory hysteresis [45]. Pre-sliding regime involves only a small displacement. The corresponding hysteresis depends on the current as well as the past history of the input and output displacement.

The non-local memory hysteresis behavior can be modeled by using a parallel connection of N Maxwell-slip elements, which can be represented by two state equations. When the elementary model sticks, the elementary friction force F_i can be modeled like a linear spring, and is written mathematically as:

$$\frac{dF_i}{dt} = k_i v \quad (2.8.1)$$

where k_i is the stiffness of each elementary model and v is the velocity. When the friction force is higher than the maximum value of the force that it can sustain, W_i , the elementary model will slip. W_i , the maximum elementary friction force, can be obtained by solving:

$$\frac{dF_i}{dt} = 0 \quad (2.8.2)$$

A set of equivalent dynamic parameters were formulated by [46] for systems subjected to pre-sliding friction. The system is assumed to be hysteretic springs. The equivalent dynamic parameters are shown as:

$$k_e = -\frac{4}{A\pi} \int_0^\pi \left(y \frac{A}{2} (1 - \cos(\theta)) \right) \cos(\theta) d\theta \quad (2.8.3)$$

$$c_e \omega = -\frac{8}{\pi A^2} \int_0^A \left(y(q) - \frac{y(A)}{2} \right) dq \quad (2.8.4)$$

where $q = A\cos(\theta)$ is the excitation of the hysteretic spring, k_e is the equivalent stiffness, c_e is the equivalent damping, ω is the frequency of excitation, A is the amplitude, and $q = A\cos(\theta)$ is the excitation of the hysteretic spring. With these equivalent dynamic parameters, the displacement equation of a system subjected to a pre-sliding friction and a periodic force can be written as:

$$m\ddot{x} + c_e\dot{x} + k_ex = F_0\sin(\omega t) \quad (2.8.5)$$

where k_e and c_e depend on the amplitude of the motion.

2.8.2 Sliding Friction

Sliding regime occurs when the contacting body is moving away from a pre-sliding limit, and the friction is determined by the function of velocity. Usually, as motion starts to accelerate, the velocity will increase beyond the pre-sliding regime. The friction force of the sliding regime becomes a function of the sliding velocity, often described by the Stribeck curve, more commonly described as a static friction at zero velocity, and Coulomb force at high velocity [44]. At the sliding friction regime, the friction force usually has a maximum value, also known as static force, and then decreases with the increase of sliding velocity. This phenomenon is called the Stribeck effect. In the sliding regime, the model in equation 2.8.2 is no longer valid.

In numerous friction models, the friction regimes in both pre-sliding and sliding are merged in order to provide a smooth transition, such as [47] and [48]. For [48], Dahl proposes a constant Coulomb friction in the sliding regime, and then approximates a first order function of the position for the pre-sliding regime, which is dependent on the velocity direction. In [49], the behavior of microscopic contact points are captured, and is assumed as a bond between flexible bristles. The model is named as Reset Integrator model. As the surfaces rub against each other, the strain of the bond increases and the bristles act as springs until the maximum force is met and the bristle then snaps and proceeds to form a new one. These models however, do not include the steady-state friction characteristics of the Stribeck function [44].

2.8.3 Friction Models

Friction models can be classified into three types, with the different amount of prior knowledge of the physics of the systems. White-box models, as the name suggested, requires a significant prior knowledge and physical insight. Black-box models can be obtained without any priori physical knowledge. Grey-box models is created when some knowledge of the physical system can be obtained, but some parameters have to be estimated from the data. The following subsections will discuss the LuGre, Leuven and the Generalized Maxwell-Slip (GMS) models, which are categorized as grey-box models.

2.8.3.1 LuGre Model

The LuGre model [50] is the first model to describe friction which transitions smoothly between the pre-sliding and sliding regime, without the application of switching functions. The model also takes into account the breakaway forces and its dynamics. A state variable z is introduced to represent the deflection of the elastic bristles, together with a state equation. The average deflection is given as:

$$\frac{dz}{dt} = v - \sigma_0 \frac{|v|}{s(v)} z \quad (2.8.6)$$

$$F_f = \sigma_0 z + \sigma_1 \frac{dz}{dt} + \sigma_2 v \quad (2.8.7)$$

where F_r is the friction force, σ_0 is the viscous friction coefficient, σ_1 is the micro-viscous friction coefficient, and σ_2 is the damping coefficient. The Stribeck effect $s(v)$ is then expressed as:

$$s(v) = F_c + (F_s + F_c) e^{-|\frac{v}{V_s}|^\delta} \quad (2.8.8)$$

where F_c is the Coulomb friction force, F_s is the static force, V_s and δ is the shaping factor of the Stribeck function. The LuGre model is able to capture the hysteresis in the pre-sliding regime, however it is unable to model the non-local memory effect.

2.8.3.2 Leuven Model

In [51], a more complete friction model which includes the non-local memory behavior in the pre-sliding regime was introduced as the Leuven model. The friction force equation and nonlinear state equation are expressed as:

$$F_f = F_h(z) + \sigma_1 \frac{dz}{dt} + \sigma_2 v \quad (2.8.9)$$

$$\frac{dz}{dt} = v(1 - \text{sgn}(\frac{F_d(z)}{s(v) - F_b})|\frac{F_d(z)}{s(v) - F_b}|^{\delta_1}) \quad (2.8.10)$$

where $F_h(z)$ is the hysteresis force and δ is the shape determining factor during transition from pre-sliding to sliding. F_b represents the value of F_h at the beginning of a transition curve, while $F_d(z)$ is the transition curve at a certain time, commonly a point-symmetrical increasing function of z . The following rules are observed when the model is implemented, where during motion reversal, *S_min* or *S_max*, and the value of $F_h(z)$ has to be memorized in stack and replaces the value of F_b , while the state variable z and $F_d(z)$ are reset. If the loop is closed, the last values on the stack of memory associated with this loop are removed, and the value of F_b is the last value in the stack of remaining memory[44].

Two disadvantages of the Leuven model were described in [52]. There is a discontinuity problem when a loop is closed, where the model has to reset the value of z and $F_d(z)$ to zero to keep $F_h(z) = F_b + F_d(z)$ constant. The same goes for F_b and $F_d(z)$ as well in the turn of $\frac{dz}{dt}$. The new model, with $\frac{dz}{dt}$ and F_f being continuous functions, is presented as:

$$\frac{dz}{dt} = v(1 - \text{sgn}(\frac{F_h(z)}{s(v)})|\frac{F_h(z)}{s(v)}|^{\delta_1}) \quad (2.8.11)$$

The second disadvantage will be the memory stack algorithm. Stack overflow problems may occur if many unclosed loops are initiated. This problem can be solved by modeling the hysteresis with non-local memory using a parallel connection of Maxwell-slip element. Each element (from Eq 2.8.14 and 2.8.2) has one common input z , one output F_i , and k_i and W_i are the parameters for each element. The sum of the hysteresis forces F_i will be the total hysteresis force for the system:

$$F_h(z) = \sum_{i=1}^N F_i \quad (2.8.12)$$

2.8.3.3 Generalized Maxwell-Slip (GMS)

The GMS model formulated in [53] is derived based on a generic friction model, to incorporate the maximum friction characteristics with the minimum parameters. The GMS model is similar to the original Maxwell-slip model, with slight modifications at the function when the model slips. The GMS is given as:

$$\frac{dF_i}{dt} = k_i v \quad (2.8.13)$$

when the model is sticking, and:

$$\frac{dF_i}{dt} = \text{sgn}(v)C(\alpha_i + \frac{F_i}{s(v)}) \quad (2.8.14)$$

when the model is slipping.

In this model, α_i is the normalized maximum friction force of each element, C is a constant which represents the rate of friction force that follows the Stribeck effect. When the elementary friction force is equal to the maximum $W_i = \alpha_i s(v)$, the asperity will slip. Once the model is slipping, it will remain in that state until the movement direction is reversed, or the velocity approaches zero.

2.9 UAV Control Strategies

Control strategies of UAVs were studied for preparation of Chapter 5. The FMW mini-UAV will require a certain amount of autopilot to effectively test the wing warping performance of the TSM wing warping controller. It is also in the interest of this thesis to be able to configure a better autopilot to perform in various flight regimes.

UAVs are highly dynamical and nonlinear systems, therefore it is hard to get an accurate and complete nonlinear model of the system. UAV autopilot is a closed loop

Figure 2.24: Structure of UAV Autopilot system[54].

Figure 2.25: UAV flight control system[54].

control system with several parts like a state observer, state estimator and flight controller (Figure 2.24)[54].

The autopilot consists of sensors like inertial measurement unit (IMU) and GPS for tracking (Figure 2.25). Some autopilots also include an infrared sensor as an altitude estimator, as the earth emits more infrared waves than the sky. There are three different control layers in an autopilot, which are the inner loop on roll and pitch control for attitude tracking, the outer loop on heading and altitude control for trajectory or waypoints tracking, and the waypoint navigation. Many commercial autopilot systems

use PID controllers as they are simple and easy to design and understand, higher level control strategies can be built on top it, and it requires little memory and processing resources. There are disadvantages as well. PID controllers need to be re-tuned if the model changes. **Autopilot with PID controllers may also be unstable** with disturbances such as gusts, and they can also be difficult to tune, requiring advance skill and experience. It is also mentioned that future autopilot systems will require more robustness.

To address the robust control issue, Robust inventory control strategy (RICS) is developed in [55]. The robust inventory control strategy applies the sliding mode controller, which is more effective than conventional PID controller and model-based predictive controllers (MPC). RICS is also considerably easier to tune than PID or MPC controllers, as MPC even requires tuning for nominal stability. There are some assumptions when applying the RICS, which the uncertain parameters and disturbances are assumed to be bounded. A robust nonlinear controller was designed for a complete UAV mission [56]. This robust controller applies both dynamic inversion and H_∞ control, with an inner/outer loop control structure for a full envelope nonlinear controller. The inner loop employs a time scale separation approach to linearize the nonlinear model. The outer loop is an H_∞ control for robustness and performance goals. In [56] it was stated that to control uncertain systems, it is required to design a fixed controller which is uncertainty independent, which the design requirement is guaranteed in the presence of significant uncertainties in which are bounded. They used a nonlinear aircraft dynamic model, but used linear aerodynamic and propulsion system model for their design, as shown in Figure 2.26.

Figure 2.26: Schematic of the Robust Nonlinear control system[56].

In [57], an L_1 adaptive controller for mini-UAV autopilot has been designed and vali-

dated. UAVs operate under very uncertain conditions, therefore, the adaptive controller is suitable for the UAVs. The inner loop of their autopilot is regulated by an adaptive L_1 controller, while the outer loop is still regulated by a PID controller. This technique can be implemented for both linear and nonlinear systems without parameter adjustment or tuning procedure, and the controller is robust to unmodeled dynamics and model uncertainties. PID controller autopilot lacks adaptability, therefore always needed to be tuned in the presence of gust disturbances or change of payload or any other kinds of disturbances. They also found that PID control performs better at pitch tracking, while the L_1 is better for velocity and roll tracking.

In [58] the robust linear control is examined, along with model reduction methods for gust rejection on large, very flexible aircraft using only trailing edge control surfaces. The aircraft simulated has a rigid fuselage and very flexible wings, hence similar to the high-altitude long-endurance (HALE) aircraft. It was found that the H_∞ controller works well for a large linearized system, and can still perform adequately for nonlinear systems in response for short gusts, but the performance decreases with the increase of gust length. The reason is that long gusts approach the low natural frequency of the 1st bending mode of the wing. It is also shown that model reduction on the linear system only has very little effect on the behavior of the aeroelastic system, but the benefit in terms of computation power is very significant.

In [59], a nonlinear flight control system named Enhanced Stall And Recovery Control System (ESARCS) is presented, and that allows a UAV to operate under control through stall regimes. The complete nonlinear aerodynamic database of the vehicles is used and a nonlinear time-varying and state dependent control gains are developed. Linear control is insufficient because linearization assumption neglects the nonlinearities like wing and fin stall. It is stated that designing a linear flight control that uses large gain tables is iterative, time-consuming, costly, and moreover does not work well in stall regimes. ESARCS is able to detect when the state has reached or pass stall conditions, and can recover the aircraft by driving the control surfaces away from a stall, or even permitting post stall operations. ESARCS provides a number of advantages, which are: improving threat evasion by allowing tighter turns, the capability of short take-off and landing, allowing larger payload capability, enhancing formation flight patterns, and reducing production

cost.

There is also some research done in the neural network and fuzzy logic control for the gust alleviation problem. In [60] an online control system is designed based on the neuro-fuzzy theory for gust alleviation purposes. According to [60], their online control system is very robust. There is one host control system and one online control system which can adjust the parameters according to the different flight situations. However, the online control system will not work when there are gust disturbances, it will only collect signals and make adjustments and only resume working and reconstruct the new control system when the gust is over. In [61] the performance of Baseline trajectory following controller is investigated for a nonlinear fighter aircraft and it is found to be insufficient under severe winds and single or multiple control surfaces failure. It was enhanced by applying two neural networks called Minimum Resource Allocating Networks (MRAN) and the performance is increased as the new controller is able to handle multiple control surfaces failure under severe winds. In [62] a method to model the actuation lines of the smart materials actuator in a warping wing system using adaptive neuro-fuzzy inference systems is presented. Four independent neuro-fuzzy controllers were created using a hybrid method, which consists of back propagation and Least Mean Square methods to train the fuzzy inference systems. The forces and electrical currents applied are correlated to the actuator's elongation.

2.10 Gust Alleviation

One of the advantages of the FMW mini-UAV is gust alleviation. Therefore, works on gust alleviation have also been reviewed as the FMW mini-UAV is designed to be able to dampen gusts.

A methodology for calculating flight dynamics and gust response of a highly flexible aircraft is presented by [63]. Nonlinear beam model was used for the wings, and the gust response was calculated based on different gust models. Results showed that spanwise nonuniform gust model predicted a much higher response than the uniform gust model. In [64], the feasibility and controllability of an Autonomous Gust Insensitive Aircraft (AGIA) are investigated. The specialized aircraft can be tuned to be passively unperturbed by

gust by making some aerodynamic derivatives zero. By making some of these adjustments, the aircraft will be passively unstable, but it can be stabilized using a stability augmentation system (SAS). AGIA contains an unstable spiral mode which can be stabilized via SAS. Conventional UAV with a stable trim will need more actuation and control during gusts, thus pushing the limits of the autopilot and the linkages as well. AGIA, on the other hand, does not need as much control in the gust, but will need some stabilization during normal flight conditions. In [65], an analysis of a gust alleviation system for an unconventional flexible three surfaces aircraft, which consist of a canard, main wing and horizontal plane at the tail named XDIA is presented. Both discrete and stochastic gust has been simulated, and a complete aeroservoelastic simulator has been realized, which is capable of including gust effects and free flight motion of the aircraft. The control system showed acceptable stability and robustness.

2.11 Summary

An extensive overview on the literature related to flexible wings, wing warping, UAV control strategies, gust alleviation techniques, and tendon-sheath mechanism is presented in this chapter. An extensive overview of the different attributes and advantages of the FMW is discussed. It is also shown in this chapter about the investigation of different actuation methods for the FMW, and most the available actuation methods do not allow for the flexible wing to fold downwards, or just unsuitable for the flexible wing. The main actuation method investigated in this thesis, the tendon-sheath mechanism (TSM) will be introduced in the next chapter. This thesis will focus mainly on the TSM actuated roll control of the carbon fiber FMW mini-UAV, with the wing foldability as the main constraint.

Chapter 3

Identification and Modeling of Wing Warping via Tendon-Sheath Mechanism

3.1 Overview

In this chapter, wing warping actuation via TSM is explained in detail as a way of inducing rolling moment for the FMW. There are numerous advantages that outweigh the disadvantages of TSM on the FWM. In this experiment, a tendon-sheath mechanism (TSM) is used to warp the flexible wing. Experiments have been performed to show that the TSM is able to provide sufficient warping for roll control. The characteristics of the TSM and important conditions for proper identification is presented. Nonlinear behaviors, namely the hysteresis and backlash of the wing warping via TSM has also been identified. Some background of the TSM is shown in Section 3.2. The experiments and results of the nonlinear behavior identification of the TSM wing warping are shown in Section 3.3. A nonlinear model based on Generalized Bouc-Wen model for hysteresis is introduced for the TSM wing warping in Section 3.4. The TSM wing warping nonlinear model forms the backbone of this thesis, paving a way to design a nonlinear controller for the TSM wing warping mechanism in the following chapter.

3.2 Background

The application of a tendon-sheath mechanism (TSM) to actuate the FMW is investigated. The inspiration of this research originated from the mechanism of a flexible endoscopic system that uses tendon-sheath as the mechanism for actuation. The tendon-sheath mechanism implies a piece of tendon, which is actually a Teflon-coated Kevlar thread, moving inside the sheath, which is a round-wire coil. 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 [78].

Only tensile forces can be transmitted via the TSM. When tension is given at the input side of the TSM, the tendon becomes tighter and therefore starts to slide along the sheath, creating a pulling force at the output side of the TSM. The relationship between the tension input and the output is not linear, therefore, modeling of the input and output characteristics, as well as a controller is needed when accurate positioning control is required [79]. Typically, a high pretension is given to the tendon, in order to increase the efficiency and a quicker response. TSM is useful for FMW warping because the tendon-sheath is flexible and it is able to be mounted without requiring much space. The trailing edge of the wing is connected to the output side of the TSM (Figure 3.1), and the servomotor is connected to the input side of the TSM. Therefore, tensile forces can be transmitted from the servomotor placed inside the fuselage to the trailing edge of the FMW in order to control the wing warping. The flexibility of the TSM allows the FMW to fold downwards for storage purposes, which is the primary objective of the FMW in the first place.

To summarize, the advantages of TSM actuation greatly outweighs the disadvantages. One of the requirements of this thesis is to produce a controllable, warping flexible wing which can fold around the fuselage. It is found that TSM actuation can fulfill this requirement and the other methods such as torque rods or smart materials cannot. The TSM actuation can allow a force strong enough to warp the flexible wing, and while being

Figure 3.1: The trailing edge of the FMW is fitted with the tendon.

a flexible piece of string when it is not under tension, the TSM can be folded along with the FMW for storage. The TSM is also relatively cheap, and easy to install on the FMW, which can be billed as another bonus advantage. Finally, the TSM wing warping can also allow adaptive washout on the FMW.

The disadvantage of the TSM is the nonlinearities which arise from the hysteresis, which makes wing warping control more complex. This Chapter sets out to identify the degree of hysteresis, and then to model it accordingly to design a controller, enabling a high performance wing warping FMW.

3.2.1 Tendon-Sheath Characteristics

Figure 3.2: Relation between position input and position output [78].

The tendon-sheath actuated wing warping mechanism is characterized by a relationship between the input and output position. It is known that there are four distinct phases during the transmission, namely releasing phase to pulling phase (Phase 1), pulling phase (Phase 2), pulling to releasing phase (Phase 3), releasing phase (Phase 4) [41]. Figure 3.2 illustrates the four phases of the tendon-sheath mechanism. During Phase 1, the servo rotates and pulls the tendon, the input tension increases and therefore increasing the friction force. At this stage, the output position P_{out} will not change until the friction force has been overcome. In Phase 2, the static friction has been overcome, and P_{out} changes with the input position P_{in} . In Phase 3 the servo starts to rotate in the opposite direction, reducing the input tension. However, P_{out} does not immediately reduce, as the friction force delays the reduction of force from the input to output. The tension of the tendon is reduced, and it will take some time for the flexible wing to overcome the friction and start springing back into its original position. Phase 4 shows unloading phase where P_{out} is moving together with P_{in} . This unique characteristic of the tendon-sheath is due to the friction force occurring between the tendon and the sheath [41]. This unique characteristic is attributed to the non-local memory hysteresis effect that is apparent in friction phenomenon [80, 81]. Similar behavior is also observed in many electromechanical systems, such as in a pneumatic artificial muscle (PAM) [82, 83] or piezoelectric driven mechanisms [84].

To achieve the same characteristic every time the tendon-sheath mechanism is activated, extra precaution has to be taken to ensure the tendon is in the pre-tensioned state. If the tendon is loose and not pre-tensioned, there will be less, or no transmission of force from the input to the output. Also, there are a few assumptions made when characterizing the tendon-sheath mechanism:

- Negligible change in the axial deflection of the tendon.
- The tendon is moving along the sheath only, without any vibrations.
- The total curvature of the tendon-sheath is constant.

One of the more critical issue to be aware of is the total curvature of the tendon-sheath. [40] found that as long as the total curvature is kept constant, the characteristics will stay constant. In this thesis, the total curvature of the tendon-sheath is 270° to imitate the

total curvature in the designed mini-UAV, as shown in Figure 3.4. It has been found that the same amount of force is needed to actuate the tendon-sheath mechanism for a sharp bend or a gradual bend of the tendon. In the mini-UAV, the tendon-sheath will be required to bend in a sharp 90° in order to take up as little space as possible.

3.3 Identification Experiment

Figure 3.3: Experimental setup of the wing warping via tendon-sheath mechanism.

Figure 3.3 shows the proposed dynamic test experiment setup. The tendon-sheath used in this setup is from Asahi Intecc Co. The size of the tendon is $WR7 \times 7OD0.27$ mm, while the round wire coil sheath has an inner diameter of 0.36 mm and an outer diameter of 0.8 mm. The servomotor used in this setup is Faulhaber 2342S024CR with a gearhead with a ratio of 66:1. The encoder attached to this servomotor is Faulhaber HEDS-5540. A separate encoder, OMRON E6A2-CWZ3E is mounted to the top of the gearhead, together with the servomotor shaft adapter, in order to accurately track the

movement of the tendon without the gear backlash. A customized servomotor shaft adapter was designed and 3D printed. The tendon is then secured onto the shaft adapter via bolt and nuts. The position of the input tendon can be calculated as the diameter of the servomotor shaft adapter is known. The diameter of the shaft adapter is 1 cm, therefore one full turn of the shaft adapter will generate a pull of π cm. The driver connected to the servomotor is ADVANCED MOTION CONTROLS 25A8PWM servo drive. A 24 volts power supply is used to supply power the servomotor.

(a) Total tendon curvature is 270° in the experiment setup.

(b) A schematic of the total tendon curvature at the FMW.

Figure 3.4: The tendon is routed along the FMW with a total of 270° .

The tendon-sheath is then bent and routed along the span of the wing as illustrated in Figure 3.4b. The total curvature angle has to be kept at a constant 270° , as this is

the design for the UAV, as shown in Figure 3.4a. The yellow circles denote the 90° bends, while the green lines are to highlight the tendon-sheath routes. There are three 90° bends for the tendon-sheath to finally reach the output side. The output tendon is secured to the trailing edge of the wing by a bolt and a nut. When the servomotor pulls the tendon, the trailing edge of the wing will be pulled towards the leading edge, causing the warp.

Figure 3.5: Flexsensor is mounted on top of the wing.

It has been regarded that measuring the deflection of wing warping is difficult [5]. For this experiment, however, an unconventional method is used to measure the angle of warping at the flexible membrane wing. An analog 4.5" flexsensor by Spectra Symbol is taped securely on to the flexible membrane wing, as illustrated in Figure 3.5. The position chosen for the flexsensor is at the main warping area, which is the rib of the flexible membrane wing. The unique property of the flexsensor allows accurate reading of the warping angles of the wing. As the flexsensor is bent, the resistance will increase. Before installing it to the wing, the flexsensor is tabulated with various angles of bending to find out the relationship of bending angle and resistance. With the flexsensor, it is now possible to read the actual warping deflection of the wing, which was very difficult previously.

The whole setup is mounted on a customized test rig, fabricated by laser cutting and joining together the acrylic templates. All the electronics are connected to a dSPACE 1104 controller board via BNC connectors. The system is controlled by a PID controller designed in MATLAB Simulink, which can be loaded into the dSPACE controller board. During the experiment, a sinusoidal input is given to the servomotor, and the wing warping angle is then measured to acquire the nonlinear behavior of the tendon-sheath. Different

input amplitude and frequencies can be given to the wing, but are limited to 20° and 3 Hz only, as it is the sweep rate specified for many existing military aircraft with hinged control surfaces [85]. For a mini-UAV, this performance is more than sufficient.

Figure 3.6: Hysteresis behavior of the wing warping via TSM.

In order to characterize the dynamic property of the system, the wing was actuated for 10 seconds with various constant frequencies and amplitudes. The resulting output motion is captured through the flexsensor reading. The experiment was carried out with different frequencies and amplitudes, ranging from 0.5 Hz to 3 Hz, and from 5° to 20° , referring to maximum aileron sweep rate specified for many existing aircraft with hinged control surfaces [85]. The general shape of the dynamic behavior of the wing warping with TSM agrees with the theory shown in Figure 3.2, with the four distinct phases, easily observed. Figure 3.6 shows the relation between wing warping and tendon-sheath input at a frequency of 3 Hz. It is also found that the change in frequency did not affect the general shape and bias of plots significantly. In addition, a non-local memory hysteresis is observed when multiple loops are prescribed to the system, as shown in Figure 3.13a (details about non-local memory hysteresis is in [80]). However, when Figure 3.6 and the ideal TSM property in Figure 3.2 is compared in detail, we can observe some slight discrepancy at the transition between Phase 1 & 2 and also the transition between Phase 3 & 4, where there is a gradual change in gradient instead of a sharp edge, much like a “hardening” effect. Figure 3.7 shows a typical symmetric hysteresis behavior, which is very much different from the hysteresis behavior of the TSM actuated FMW.

Figure 3.7: Symmetric hysteresis behavior [42].

“Hardening” phenomenon

Initially, it was suspected that the FMW in the chord-wise direction possesses nonlinear properties, as the FMW is made of composite materials, therefore contributing to the “hardening” effect. The geometry of the FMW may also be a cause of the “hardening” effect as well. Therefore, a Finite Element Analysis (FEA) was carried out to investigate the exact cause of the “hardening” effect. The software used for the FEA is ANSYS Workbench. In the analysis, as shown in Figures 3.8a to 3.8d, the wing trailing edge is pulled at the same direction as the tendon pulling it in the experiment. From the FEA result, as illustrated in Figure 3.9, the wing was shown to warp with a slightly decreasing rate as the tendon input is increased (“softening”). Even though it does not agree with the experimental results, but it can be shown to be mathematically correct.

The minor arc model can be used to explain the results from FEA. P_{in} (refer to Figure 3.2), which is the displacement of the tendon-sheath, is essentially the change of the distance between the two end points of the arc. P_{out} , the wing warping is the central angle of the arc, and will change with P_{in} if the minor arc length $r\theta$, which is the wing is kept constant. Referring to Figure 3.10 and the law of sine, the relationship between P_{in} and P_{out} in Phase 2 and Phase 4 can be modeled by:

$$\frac{l}{\sin \theta} = \frac{r}{\sin \frac{\pi - \theta}{2}} \quad (3.3.1)$$

(a) Finite element analysis of the wing, viewed from the side.

(b) FMW is simulated with a deflection at the trailing edge.

(c) Another angle of the FMW during FEA, viewed from the back.

(d) Another angle of the FMW during FEA, with a deflection at the trailing edge.

Figure 3.8: Finite element analysis of the wing warping.

$$l + dl = \frac{\sin \theta}{\sin \frac{\pi - \theta}{2}} r, \theta < \pi \quad (3.3.2)$$

Figure 3.9: Warping angles vs trailing edge deflection in the FEA.

where l is the arc length (FMW camber, equivalent to the initial tendon length), r is the radius of the arc, and dl is the change of displacement of the tendon-sheath input. The relationship between the warping angle θ and dl is nonlinear, as rate of θ increases with dl .

Figure 3.10: Illustration of the arc model.

As the FEA and minor arc model (Figure 3.10) showed that the geometry of the FMW cannot be the cause of the “hardening” phenomenon, another experiment is performed to investigate the cause of the nonlinear curves. A simple direct actuation of the FMW

was carried out, which consists of the tendon without the sheath being constricted to the trailing edge of the FMW, and the other end secured to the servo motor. This experiment allows a thorough investigation of this phenomenon by eliminating all the hysteresis caused by the friction on TSM and focus only on the wing warping itself.

Figure 3.11: Direct actuation experiment setup of the FMW.

(a) Hysteresis of the FMW for different pre-tensions in the tendon. (b) Hysteresis behavior of the FMW with tendon-sheath at low (left) and very high pre-tensions (right).

Figure 3.12: Hysteresis behaviors of the flexsensor and wing.

Figure 3.11 shows the setup of the experiment. The tendon was given different pre-tensions, or more precisely the wing was given different initial warping angles. For both the low and high initial warping angles cases, consistent results are observed. Figure 3.12a shows the wing warping output vs the direct tendon input for the low pre-tension (with

0° initial warping) and high pre-tension case (20° initial warping) . For both cases, the relationship of the output vs input of the wing warping appears to be quite linear. From the results of this experiment, it is obvious that the “hardening” nonlinearity is not due to the geometry or material properties of the FMW.

As suggested by [41], the pre-tension of the tendon-sheath will affect the general hysteresis behavior, especially in the transition from Phase 1 to 2 and Phase 3 to 4. Subsequently, the TSM is installed back to check for the effects of pre-tension. Two different pre-tension levels are prescribed to actuate the FMW, and the hysteresis behavior was recorded. The difference between low pre-tension and high pre-tension is observable in Figure 3.12b. In the low pre-tension tendon-sheath, the hysteresis behavior exhibits the arched (nonlinear) line in Phases 2 & 4. There are no definite, sharp corners during the transition from Phase 1 to 2 (and from 3 to 4). When the tendon-sheath is given very high amounts of pre-tension, the nonlinear “hardening” effect (arched curve degree) lessens. This indicates that the phenomenon in Phases 2 & 4 is, indeed, caused by insufficient pre-tension. Although a linear relationship in Phase 2 & Phase 4 is desirable for the ease in the modeling and control tasks, it is not achievable in this FMW warping case. As the pre-tension is increased, the FMW will start to warp, affecting the airfoil shape and aerodynamic properties. Therefore, the pre-tension in the tendon-sheath for FMW warping must be kept low enough such that the FMW does not have any initial warping angles.

3.4 Results & Analysis

3.4.1 Results

The experimental data is filtered with the `filtfilt` command in Matlab, which performs zero-phase change filtering. The experiment was conducted with various frequencies and amplitudes, ranging from 0.5 Hz to 3 Hz, and from 5° to 20°. Figures 3.13b and 3.13c presents the data obtained from the experiment. The behavior of the wing warping with tendon-sheath is found to be very similar to the well known nonlinear behavior of the tendon-sheath mechanism as shown in Figure 3.2. Figure 3.15a in red shows the relation between wing warping and tendon-sheath input with a frequency of 3 Hz. The four distinct

phases are very pronounced. It was also found that the change in frequency did not affect the general shape and bias of plots significantly, as the plots overlap on each other for different frequency inputs. The phases are still observable for higher amplitudes, although phase 1 where the tendon is shifting from releasing to pulling is not as obvious compared to the lower amplitudes. The tendon-sheath actuated wing warping also exhibits a non-local memory hysteresis, as shown in Figure 3.13a.

(a) Experiment results showing the re- (b) Experiment results for different input
lation between wing warping and frequencies and amplitude of 5 °.
tendon-sheath input with two fre-
quency inputs of 1 Hz & 2 Hz.

(c) Experiment results for different input
frequencies and amplitude of 20 °.

Figure 3.13: Results from the identification experiments.

3.4.2 Analysis

3.4.2.1 Wing Warping Equations of Motion

Figure 3.14: Illustration of a tendon element equilibrium [39].

For actuating linear springs, the static model of a tendon-sheath mechanism (Figure 3.14) is given as [39, 86, 79]:

$$F_f = \mu N \text{sign}(\dot{\epsilon}) \quad (3.4.1)$$

$$\Delta T = -F_f \quad (3.4.2)$$

$$\delta = \frac{1}{EA} T = \rho T \quad (3.4.3)$$

where F_f is the friction force and N is the normal force between the tendon and the sheath, $\dot{\epsilon}$ is the tendon velocity, T is the tension, δ is the elongation of the tendon, E is the Young modulus, A is the cross-sectional area of the tendon, and

$$\mu = \begin{cases} \mu_s, & \text{if } \dot{\epsilon} = 1 \\ \mu_d, & \text{if } \dot{\epsilon} \neq 1 \end{cases} \quad (3.4.4)$$

is the Coulomb friction coefficient. Neglecting the effect of stiction and assuming that $\dot{\epsilon}$ has the same sign throughout the whole length of the tendon, the infinitesimal tendon element can be modeled as:

$$N = Td\gamma = T\frac{dx}{R} \quad (3.4.5)$$

$$dT = -F_f = -\mu T\frac{dx}{R} \text{sign}(\dot{\epsilon}) \quad (3.4.6)$$

When the input tension is transmitted to the other end, the relation between T_{in} and T_{out} will be [39, 86, 79]:

$$T_{out} = T_{in} \exp[-v \text{sign}(\dot{\epsilon})] \quad (3.4.7)$$

where $v = \frac{\mu}{R}L$, therefore v will always be positive. In this case, the ratio of T_{in} and T_{out} is:

$$\frac{dT_{in}}{dT_{out}} = e^{-v} \text{if } \dot{\epsilon} > 0 \quad (3.4.8)$$

$$\frac{dT_{in}}{dT_{out}} = e^v \text{if } \dot{\epsilon} < 0 \quad (3.4.9)$$

This model was chosen as the relationship between position and tension is linear for a linear spring. Therefore, the same model which is derived from the tension can be applied to this experiment where the input and output are positions. From the model above, the ratio between T_{in} and T_{out} is a constant, therefore the gradient of Phase 2 and Phase 4 should be a straight line. However, this was not observed in the data obtained from this experiment.

This can be explained when the wing is viewed as an arc. P_{in} , which is the displacement of the tendon-sheath, is essentially the change of radius of the arc. P_{out} , the wing warping is the central angle of the arc, which will change with the radius if the arc length is kept constant. Therefore, the relationship between P_{in} and P_{out} in Phase 2 and Phase 4 can be modeled by:

$$\theta = \frac{L}{R-x}, L > (R-x), R > x \quad (3.4.10)$$

where L is the arc length (flexible wing camber), R is the radius of the arc, and x is the change of displacement of the tendon-sheath input. The relationship between the warping angle θ and x is nonlinear, as the rate of θ increases with x .

3.4.2.2 Modified Generalized Bouc-Wen Model

The wing warping with asymmetric backlash hysteresis was modeled using a Generalized Bouc-Wen model by Song et al. [43]. The Generalized Bouc-Wen model was chosen because it provides enough flexibility in shape control to describe highly asymmetric loops.

The Generalized Bouc-Wen model is expressed as:

$$f_s(x, \dot{x}, z) = \alpha k_0 x + (1 - \alpha) k_0 z \quad (3.4.11)$$

where x denotes the displacement; $\dot{x}$ denotes the velocity; α = post to pre-yield stiffness ratio; k_0 = initial stiffness; and z = auxiliary variable that represents inelastic behavior.

The evolution of z is determined by an auxiliary ordinary differential equation:

$$\dot{z} = \dot{x} [A - |z|^n \Psi(x, \dot{x}, z)] \quad (3.4.12)$$

where $\dot{z}$ = derivative of z with respect to time; A and n = parameters that control the scale and sharpness of the hysteresis loops, respectively; and $\Psi(x, \dot{x}, z)$ = nonlinear function of $x, \dot{x}, z$ that controls other shape features of the hysteresis loop.

The Ψ function of the Generalized Bouc-Wen model is:

$$\Psi(x, \dot{x}, z) = \beta \phi^T \quad (3.4.13)$$

where β and ϕ are **vectors** given as:

$$\beta = [\beta_1 \ \beta_2 \ \beta_3 \ \beta_4 \ \beta_5 \ \beta_6] \quad (3.4.14)$$

$$\phi = [\text{sgn}(\dot{x}z) \ \text{sgn}(x\dot{x}) \ \text{sgn}(xz) \ \text{sgn}(\dot{x}) \ \text{sgn}(z) \ \text{sgn}(x)] \quad (3.4.15)$$

and β is the parameter that controls the shape [43].

In this thesis, some modifications are necessary in order to better capture the nonlinear curves of Phase 2 and Phase 4. The modified Generalized Bouc-Wen model is expressed as:

$$\theta(x)(t) = \lambda_1 x^2 + \lambda_2 x + \lambda_3 + \lambda_z z \quad (3.4.16)$$

$$\dot{z} = \dot{x}[A - |z|^n \Psi(x, \dot{x}, z)] \quad (3.4.17)$$

$$\Psi(x, \dot{x}, z) = \beta \phi^T \quad (3.4.18)$$

where β and ϕ are **vectors** given as:

$$\beta = [\beta_1 \ \beta_2 \ \beta_3 \ \beta_4 \ \beta_5 \ \beta_6] \quad (3.4.19)$$

$$\phi = [\text{sgn}(\dot{x}z) \ \text{sgn}(x\dot{x}) \ \text{sgn}(xz) \ \text{sgn}(\dot{x}) \ \text{sgn}(z) \ \text{sgn}(x)] \quad (3.4.20)$$

By introducing a quadratic expression $\lambda_1 x^2 + \lambda_2 x + \lambda_3$, the “hardening” effect of the wing warping hysteresis is better captured. In the modified Generalized Bouc-Wen model, λ_1 and λ_3 is the new parameters added into the model, while λ_2 is equivalent to αk_0 and λ_z is equivalent to $(1 - \alpha)k_0$ from the Generalized Bouc-Wen (GBW) model.

3.4.2.3 Method of Identification of Parameters

The GBW model is then validated with the experimental data, by curve fitting the model to the data. To get a good curve fit, a total of 12 parameters of the GBW has to be optimized. They are $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, A, n, \lambda_1, \lambda_2, \lambda_3$ and λ_z . The 12 parameters were first estimated using the Genetic Algorithm (GA), where the results are subsequently used as initial values to optimize the parameters further by using Nelder-Mead simplex algorithm.

In the optimization process, the experiment data was first filtered to reduce the measurement noise. The experiment was recorded in a 7500 Hz sampling rate, which translates to 7500 data points a second. During the experiment, the TSM was actuated from 0.5 Hz to 3 Hz, in pure sinusoidal form, and also in a random inputs with a cutoff frequency of 2 Hz, and the wing warping output was captured 7500 times a second. The method of filter used in this analysis is a Matlab function *filtfilt*, which performs zero-phase change filtering, with a cutoff frequency of 20 Hz. After the measurement noise is accounted for,

the Genetic Algorithm (GA) is used to perform the first round of optimization. The value to optimize in the GA is the RMS error between the model and the data. Once a set of parameters which perform well enough to hit the RMS tolerance set in the GA script is found, the set of parameters is then optimized using Nelder-Mead algorithm to find the local minimum. For both GA and Nelder-Mead, the default options are used, and the value being optimized is the RMS error between the model and the data. Below is a summary of the experiment data and optimization details.

Excitation form	Sinusoidal and Random (2 Hz cutoff)
Sampling Rate	7500 Hz
Length	10 seconds
Noise filter	Matlab <i>filtfilt</i> cutoff frequency 20 Hz
Optimized variable	RMS error between model and data

As an example, the data set from Figure 3.6 is used for the optimization, and the final optimized parameters are given as

$$\begin{aligned}
\beta &= \begin{bmatrix} 1.39342 & 0.56559 & -1.26507 & -1.2851 & 0.56462 & 0.38963 \end{bmatrix} \\
A &= 1.3708 \\
n &= 1.77414 \\
\lambda &= \begin{bmatrix} 0.24846 & 2.09571 & -1.95466 \end{bmatrix} \\
\lambda_z &= -2.04379
\end{aligned} \tag{3.4.21}$$

In this model (as shown in blue in Figure 3.15a), a quadratic function was added to better capture the nonlinear, increasing rate curve (“hardening”) for Phase 2 and Phase 4. This quadratic function actually captures enough “hardening” effect of the hysteresis loop, therefore, is suitable for the preliminary modeling.

The identification results are repeatable. With the same set of parameters, this model is applied to another data records, i.e. the 10° warping, and the results are satisfying. Figure 3.15 shows the comparison of different data records. Figure 3.15a shows a wing warping of a bigger amplitude (15°) and Figure 3.15b illustrates the smaller wing warping amplitude (10°). For both plots, the red line represents the data while the blue line

represents the model. It can be observed that the identical model matches different data records with a satisfactory performance.

(a) Modeling of the wing warping with TSM (15°), with Parameters 3.4.21. (b) Modeling of wing warping with TSM for another dataset (10°) with Parameters 3.4.21.

Figure 3.15: Illustration of the differences when the same model is applied to different data set.

3.4.2.4 Random Inputs Parameters Optimization

The experiment was further extended with a random input filtered with a cutoff frequency of 2 Hz, in order to obtain a better hysteresis model for the feed-forward controller design. Similarly, the random wing warping angle output was captured by the flex sensor attached securely to the rib of the flexible membrane wing.

The hysteresis model is required for the simulation and its inverse is required in order to design a feed-forward control. Inverse hysteresis model simply means the model of wing warping angle as input vs. tendon-sheath deflection as output of the TSM wing-warping mechanism. Various Bouc-Wen model available are described in [42], and the Generalized Bouc-Wen (GBW) model is suitable for asymmetric hysteresis behaviors. From the experimental data, it can be observed that the hysteresis is indeed asymmetric. Therefore, Generalized Bouc-Wen model by Song et al. [43] was chosen for both the normal and inverse hysteresis case. The inversion of the GBW model does not require an approach [40, 87, 88, 89]. The modification that is proposed in the application for TSM

in FMW is attributed to the inclusion of the slack of the tendon-sheath that exhibits geometric nonlinearity. As geometric nonlinearity is easily invertible, the proposed model can be concluded to be invertible as well.

Even with a random control input, the “hardening” effect is still observed in the experiment. This is caused by the insufficient pre-tension in the tendon-sheath [41, 40]. It is unreasonable to give maximum pre-tension for this experiment as the flexible membrane wing will start warping as the pre-tension increases. Therefore, the polynomial function $\lambda_1 x^2 + \lambda_2 x + \lambda_3$ is crucial to obtain a more accurate model.

From the experiment, a random tendon-sheath control input was given and the wing warping angle was captured. The hysteresis plot was curve fitted with the Generalized Bouc-Wen model and then the initial parameters were found by utilizing the Genetic Algorithm optimization method. Another round of optimization with the Nelder-Mead simplex algorithm was done to obtain a set of more accurate parameters. The parameters of the model are:

$$\begin{aligned}
\beta &= \begin{bmatrix} 1.22538 & 0.10635 & -1.53121 & 0.79072 & 0.44963 & -1.27259 \end{bmatrix} \\
A &= -1.0780 \\
n &= 2.9647 \\
\lambda &= \begin{bmatrix} 0.18804 & 0.65872 & 0.041577 \end{bmatrix} \\
\lambda_z &= 2.1259
\end{aligned} \tag{3.4.22}$$

Figure 3.16 shows the experimental data and the simulated model. The experimental data is shown by a red solid line, while the modified General Bouc-Wen model is in a blue dashed line.

3.4.2.5 Inverse Model Parameters Optimization

The similar optimization process was then repeated to obtain the parameters for the inverse hysteresis model, which has the wing warping as inputs and the tendon-sheath distance as outputs. This inverse model will be used as a model for the feed-forward block in the wing-warping controller. The parameters of the inverse model are:

Figure 3.16: Modeling of wing warping output vs tendon-sheath input with Parameters 3.4.22. Red is the experimental data, blue dashed line is the simulated model.

$$\begin{aligned}
 \beta &= \begin{bmatrix} 19.8351 & -8.6135 & 0.8325 & -3.1266 & 10.6984 & -18.5 \end{bmatrix} \\
 A &= 3.9953 \\
 n &= 3.1179 \\
 \lambda &= \begin{bmatrix} -0.0205 & 0.7120 & 0.7958 \end{bmatrix} \\
 \lambda_z &= 0.5369
 \end{aligned} \tag{3.4.23}$$

For this inverse model as shown in Figure 3.17, the red solid line is the experimental data while the blue dashed line is the simulated model. It can be observed that inverse model fits better than the normal model (with the RMS error being 0.26°) when Figure 3.16 and Figure 3.17 is compared. The plot in Figure 3.18 shows the accuracy of the model when tracking the wing warping output, in the usual tendon-sheath inputs at the x-axis and wing warping at the y-axis. The output tracking of the model can be observed in more detail from Figure 3.19.

Figure 3.17: Modeling of tendon-sheath deflection as outputs vs. wing warping angle as inputs, with Parameters 3.4.23. Red is the experimental data, blue dashed line is the simulated model.

Figure 3.18: Figure 3.17 plotted in reverse.

(a) Wing warping input position.

(b) Tendon-sheath output position.

Figure 3.19: The outputs from the experiment are in blue, and the outputs from the model are in red.

3.5 Summary

This chapter has demonstrated that the tendon-sheath is a suitable mechanism for wing warping to achieve roll control, while still allowing the flexible wing to fold towards the fuselage for storage. The tendon-sheath has numerous advantages over other means of actuation, in particular, it does not take up much space and is relatively robust. Nonlinear hysteresis and backlash behaviors of the wing warping with tendon-sheath mechanism have been identified, and the next chapter will describe the design and testing of a robust controller to adequately control the position of the wing warping angle.

Chapter 4

Simulation and Control of Wing Warping via Tendon-Sheath Mechanism

4.1 Overview

In Chapter 3 the nonlinearities of the TSM induced wing warping have been identified, and this chapter will show that the wing warping angle is controllable in simulation, as well as in experiments. A feed-forward model is generated, and a PI feedback control is added into the loop for further robustness. The results of both the simulations and experiments will be discussed in this chapter.

Section 4.2 shows the controller design and simulation of the wing warping via TSM with and without disturbances. Section 4.3 presents the controller testing for the wing warping, and also a CFD simulation to design the testing environment. Finally, the summary of this chapter is drawn in Section 4.4. This chapter displays the results of the nonlinear controller, which is designed base upon the nonlinear model from the previous chapter, essentially proving the validity of this thesis.

4.2 Controller Design & Simulation

A feed-forward control was constructed utilizing the inverse of the identified model obtained from the optimization process as shown in 3.4.23, where the control strategy is presented in Figure 4.1. A feed-forward control is added into the whole control structure because the TSM wing-warping hysteresis has been identified, and it is possible to predict inputs required by injecting the inverse of the hysteresis model at the feed-forward block. This Figure shows the feedback, which is represented by the PID block and the loop going back, as well the feed-forward, represented by the loop going through the feed-forward block. The plant, which is the FMW, is represented in the final block with the control inputs in TSM deflections (mm) and wing warping outputs in degrees. In order to demonstrate the effectiveness of the proposed control strategy, the system is simulated with three different control schemes, i.e. open loop, PID feedback only and feed-forward/feedback. To test the robustness of the system, some disturbances were introduced to the warping output and the similar cases were simulated again. The gains for the PID controller were tuned appropriately for the control strategies, The method of selecting the gains are done empirically, and are described as below:

1. Introduce disturbance into the system.
2. Set all gains as 0.
3. Gradually increase Kp until system is oscillating.
4. Reduce the Kp by half.
5. Gradually increase Ki until system is oscillating.
6. Reduce Kp gradually until system is not oscillating.
7. Repeat steps 5 and 6 until a satisfactory performance is achieved.

The final results of the gain tuning came with $Kp = 7$, $Ki = 1$ and $Kd = 0$, which is essentially a PI controller. Kd is not required because the system is already performing quite well with just Kp and Ki .

For all the simulation results, the blue dashed line represents the open loop system, red dots represent the feed-forward-only system, and the black solid line represents the

feed-forward plus feedback system. All the systems were simulated with a sinusoidal input ranging from 0.5 Hz to 3 Hz and also with a random input with a cutoff frequency of 2 Hz.

Figure 4.1: Block diagram of the system with feed-forward and feedback.

4.2.1 Results and Discussion of the Simulation

The simulation results are presented in Figures 4.2a to 4.5d, where the system was simulated by prescribing a constant frequency as well as a filtered random input signals with 1 Hz cutoff frequency to the input side of the TSM. As observed from the figure, the PI feedback only controller is not as accurate as the combined feed-forward/feedback controller. When some disturbance is present on the system, the combined feed-forward/feedback controller still outperforms. The last simulation was taken by introducing a white noise signal on the TSM model to imitate disturbance on the system. In particular, Figure 4.3a and Figure 4.5a illustrate the effectiveness of the model-based controller that manage to linearize the system.

4.2.1.1 Simulation Without Disturbance

With an accurate model, the feed-forward control performs very well. As the tendon-sheath actuated wing warping was characterized and modeled with the General Bouc-Wen model and with a good accuracy, it leads to a satisfactory feed-forward controller. The feed-forward control system is simulated and compared with the open loop system. A simple PI feedback is added into the feed-forward system and simulated as well. Each system (feed-forward-only and feed-forward + feedback) was simulated with sinusoidal inputs of varying frequencies from 0.5 Hz to 3 Hz and also with random frequency input.

As the simulated responses from 0.5 Hz to 3 Hz are very similar, only the plots for 1 Hz input and random input are shown in this Chapter.

Figure 4.2d shows the hysteresis behavior of the system when the input is 1 Hz. It can be observed that the feed-forward system actually works quite well. Due to the imperfect modeling of the system, the feed-forward system (in red) did not totally eliminate the nonlinearity of the open loop system. By introducing a PI feedback into the feed-forward system, it can be observed that the hysteresis is almost eliminated. For random inputs, Figure 4.3d shows the same qualities for the feed-forward and feed-forward plus feedback systems. The output comparison with the reference signal, the tracking error and the input signals are shown from Figures 4.2a to 4.3c. It can be observed that the feed-forward plus feedback system is performing much better than just the feed-forward-only system.

4.2.1.2 Simulation With Disturbance

The simulation was repeated with a disturbance input, given as a random signal filtered with a cutoff frequency of 2 Hz. The random signal is introduced at the output of the system, which simulates the wind gusts at the wing, creating disturbances to the flex sensor readings. In [90], the aircraft L-1011 has the highest wing torsion when the gust is at between 2 - 3 Hz. In [63], very low gust frequencies (in the 0.001 to 0.2 rad/s) was affecting the flexible wing aircraft. The gust response for different aircraft is greatly affected by the geometry and material of the wing. For this simulation, 2 Hz was chosen as a cutoff frequency for the disturbance input. Further investigations will be needed to find out the frequency which corresponds to the highest power spectral density of the flexible membrane wing bending moment and torsion.

Figures 4.4a to 4.5d shows the simulation results of the wing warping system with disturbance. From the simulation results, it is observed that the disturbance affects the lower sinusoidal input frequencies much more than the higher sinusoidal input frequencies. The disturbance does not affect the random inputs simulation significantly. As expected, the feed-forward plus PI feedback system is the best performing, as the feedback loop helps to eliminate the disturbances. Feed-forward alone is not enough as it will not anticipate any disturbances. Figure 4.4c shows the greater feed-forward plus feed-forward control

inputs to eliminate the disturbances.

4.2.2 Conclusions from the Simulation

The simulation (Figures 4.2 to 4.5) shows that the performance of the feed-forward system is satisfactory if the model is accurate enough and if there are no disturbances. However in real applications, there are bound to be disturbances and modeling inaccuracies, therefore adding a PI feedback into the control loop can be very beneficial by making the system more robust against those elements. The nonlinearity of the tendon-sheath mechanism is quite severe, but they are controllable in the simulation. The simulation results are promising, and the next step will be to perform closed loop wing warping with tendon-sheath experiments.

4.3 Controlled Wing Warping via TSM Experiments

This section presents the model-based controller to regulate the wing warping. Subsequently, the performance of the system is validated experimentally on a wind tunnel owing to a specific gusty environment scenario simulated by a CFD model.

In order to capture the asymmetric hysteresis on the wing warping actuation, a generalized Bouc-Wen model by Song et al. [43] is referred. Some modifications are introduced to better capture the nonlinearity of Phases 2 & 4 as presented by Do et al [40, 41, 91]. The model for the controller is expressed as:

$$\theta(x)(t) = \lambda_1 x^2 + \lambda_2 x + \lambda_3 + \lambda_z z \quad (4.3.1)$$

$$\dot{z} = \dot{x}[A - |z|^n \Psi(x, \dot{x}, z)] \quad (4.3.2)$$

$$\Psi(x, \dot{x}, z) = \beta \phi^T \quad (4.3.3)$$

where β and ϕ are matrices given as:

$$\beta = [\beta_1 \ \beta_2 \ \beta_3 \ \beta_4 \ \beta_5 \ \beta_6] \quad (4.3.4)$$

$$\phi = [sgn(\dot{x}z) \ sgn(x\dot{x}) \ sgn(xz) \ sgn(\dot{x}) \ sgn(z) \ sgn(x)] \quad (4.3.5)$$

(a) Comparison between output and 1 Hz reference input. (b) Tracking error for 1 Hz input.

(c) Control input for 1 Hz. (d) Hysteresis for 1 Hz input.

Figure 4.2: Simulation of the TSM wing warping at 1 Hz.

With a severe nonlinear behavior as shown in the experiments, a controller is required for precise wing warping position control. Without accurate wing warping control, the mini-UAV will have unreliable roll control, therefore jeopardizing the safety and flight qualities. By utilizing the parameters identified from the experiments, a modified General Bouc-Wen model (from Section 3.4.2.2) has been used for the feed-forward/feedback controller design.

(a) Comparison between output and random reference input. (b) Tracking error for random input.

(c) Control input for random reference input. (d) Hysteresis for random inputs.

Figure 4.3: Simulation of the TSM wing warping at random frequencies.

4.3.1 Controller implementation

The controller is subsequently tested in a lab bench, by nesting the Simulink model into the dSPACE 1104 controller board. The nesting process is simply to load the Simulink model in Figure 4.6a on to the PC which is connected to the dSPACE 1104, and then run the Simulink on the target hardware. The model in Figure 4.6a will be loaded to the dSPACE 1104, and the input outputs of the experiment will be recorded as a Matlab file in the PC. Figure 4.6b shows the feed-forward block in the model.

(a) Comparison between output and 1 Hz reference input with disturbance. (b) Tracking error for 1 Hz input with disturbance.

(c) Control input for 1 Hz with disturbance. (d) Output vs. input for 1 Hz input frequency with disturbance.

Figure 4.4: Simulation of the TSM wing warping at 1 Hz with disturbance.

The FMW was actuated by a filtered random signal with 1 Hz cutoff frequency and amplitude of 4° on two different cases, i.e with and without disturbance. Controller performances of the wing warping via tendon-sheath actuation when given random inputs without disturbance are illustrated in Figure 4.7. For the output comparison, the setpoint is in dashed blue, while the output is in red. For others the open loop is dashed blue, PI feedback only is green, feed-forward plus feedback is in black. The combined feed-forward/feedback controller exhibits superior performance with quantitative performances

(a) Comparison between output and 1 Hz reference input with disturbance with disturbance.
(b) Tracking error for random input with disturbance.

(c) Control input for random reference input with disturbance.
(d) Hysteresis for random input frequency with disturbance.

Figure 4.5: Simulation of the TSM wing warping at random frequencies with disturbance.

of 2.04° root-mean-square (RMS) error in a case of PI only system compared to 0.285° RMS error in the feed-forward/feedback controller. The difference in performance between the PI only system and the open loop system is insignificant, as the RMS error of the open loop system is 1.727° . In this experiment, the gains for the PI were $K_p = 7$ and $K_i = 1$. Again, the gain tuning was done empirically. It was found that very high gains in the

(a) Simulink model containing the feed-forward/feedback controller.

(b) Feed-forward controller model in Simulink.

Figure 4.6: The feed-forward block.

PI controller will cause instability in the system, causing the TSM to snap and fail. The feed-forward/feed-back controlled TSM wing-warping is asymptotically stable, provided that the gains of the PI controller do not push the response towards the unstable region.

Figure 4.7: Experimental results (no disturbances).

4.3.2 Robustness against gusty environment

As the atmospheric conditions in tropical areas tend to be gusty, the controller is required to be robust against gust disturbances. Therefore, the robustness of the system in a gusty environment has to be validated. The FMW mini-UAV is designed to dampen high-frequency gusts to fly in windy conditions, such as over the tropical oceans for surveillance missions. The winds in a tropical climate can be quite gusty, with gust factors reaching up to 2.27 in non-thunderstorm weather and up to 2.78 in thunderstorms [3]. The turbulence intensities are recorded to be around 34% to 38% in thunderstorms [92]. However, the turbulence intensities and gust factors measured over a day are not fully representative as the flight duration of mini-UAVs is quite short. In very strong and sudden winds, the mini-UAVs might even be blown away without a chance of following

the desired flight path. Therefore, for realistic situations, the FMW mini-UAV is designed to dampen high-frequency gusts over a short period of flight time. In order to operate in such conditions, the wing warping of the mini-UAV is required to be controllable and the adaptive washout mechanism should still function to dampen the high-frequency gusts.

In the first place, in order to validate the robustness of the controller, an artificial gusty environment has to be designed respecting the atmospheric scenario. To create an artificial gusty environment which can create high frequency gust, the fastest and cheapest method is to place a bluff body within the airflow and induce the vortex shedding with a certain frequency, which is a function of the dimension of the bluff body as well as the velocity of the flow. The location of the turbulence, where the shedding occurs has to be determined. This is the sweet spot for the FMW to be placed to be hit by the strongest gusts in the wind tunnel. Again, the fastest and cheapest method to achieve this is via CFD simulation. Before proceeding with the simulation, there are a few constraints that must be clarified.

1. The wind tunnel that was planned for this experiment has a test section of 780 x 720 x 2000 mm.
2. With a limited test section space, it is impossible to insert a massive bluff body to generate gust. A feasible sized bluff body has to be defined.
3. The cruising speed of the FMW mini-UAV is determined to be 7 m/s, by referring to empirical data.

In this study, commercial code Ansys FLUENT [93] was adopted to solve the Unsteady RANS equations for momentum conservation and continuity equations. The URANS equations are as following:

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (4.3.6)$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_j U_i}{\partial x_j} = g_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{(-\bar{u}_i \bar{u}_j)}{\partial x_j} + \nu \frac{\partial^2 U_i}{\partial x_j^2} \quad (4.3.7)$$

Where x_i is the spatial coordinate, t is the time, U_i is the averaged velocity, u_i is the fluctuating velocity, p is the averaged pressure, and ρ is the fluid density. Due to

the ensemble averaging process done to the Navier Stokes equations, additional equations are required to close the momentum equations. In this study, we employed the standard $k - \epsilon$ model [94] which introduces additional transport equations for the turbulent kinetic energy (k) and its dissipation rate (ϵ) due to its popularity and also its simplicity. The transport equations for k and ϵ are given as:

$$\frac{\partial k}{\partial t} + \frac{\partial k U_i}{\partial x_j} = -\bar{u}_i \bar{u}_j \frac{\partial U_i}{\partial x_j} - \epsilon + \frac{\partial}{\partial x_j} \left\{ \left(\frac{\nu_t}{\sigma_k} + \nu \right) \frac{\partial k}{\partial x_j} \right\} \quad (4.3.8)$$

$$\frac{\partial \epsilon}{\partial t} + \frac{\partial \epsilon U_j}{\partial x_j} = -C_{\epsilon 1} \frac{\epsilon}{k} \bar{u}_i \bar{u}_j \frac{\partial U_i}{\partial x_j} - C_{\epsilon 2} \frac{\epsilon^2}{k} + \frac{\partial}{\partial x_j} \left\{ \left(\frac{\nu_t}{\sigma_\epsilon} + \nu \right) \frac{\partial \epsilon}{\partial x_j} \right\} \quad (4.3.9)$$

Where ω_t is the eddy viscosity and is computed by combining k and ϵ as

$$\omega_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (4.3.10)$$

ω is the molecular kinematic viscosity and the model constants: $C_{\epsilon 1}, C_{\epsilon 2}, C_\mu, \sigma_k$, and σ_ϵ have the following values determined experimentally with air and water for fundamental turbulent shear flows [2-3]: $C_{\epsilon 1} = 1.44$, $C_{\epsilon 2} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\epsilon = 1.3$.

Second order upwind scheme was selected for the transport equations to minimize numerical diffusion except for pressure, where Standard interpolation was employed instead. Second order upwind was used for momentum, k , and ϵ to increase the accuracy and reduce numerical diffusion, while coupled scheme was used for the pressure-velocity coupling. The transient terms were approximated by fully implicit, second-order accurate finite differences and the pressure was interpolated using the pressure staggering option. Further details of the modeling techniques can be found in the FLUENT user manual [95].

Figures 4.8 shows the computational domain with air entering the domain with a constant velocity and leaves domain from a pressure outlet boundary. The symmetry boundary condition was used for the lateral sides of the domain and no-slip boundary condition was applied along the rectangular cylinder and ground surfaces. Approximately, three million grid points were used in our computations with the minimum and maximum spatial resolutions specified to be 0.005 mm and 100 mm, respectively. Specifically, the maximum y^+ was kept below 1 to ensure that the boundary layer can be fairly well

resolved. The final meshing of the bluff body can be seen in Figure 4.9. We believe that the mesh size used in this study is sufficient to produce reliable quantitative results as the predicted mean velocity at the recirculation zone agrees well with the measured mean velocity, as evidenced in Table 4.1. A time step of 1×10^{-4} s was chosen to advance the solution in time.

Figure 4.8: Computational domain of the study.

Figure 4.9: Meshing of the bluff body.

Based on the CFD simulation, when a solid cube with the dimension of 60 x 200 x 100 mm was placed in a test section with a dimension of 780 x 720 x 2000 mm and the inlet flow velocity was set to be 7 m/s, a velocity profile as shown in Figure 4.10a will

be obtained. It is shown that at 600 mm away from the solid cube and 390 mm from the ground as indicated by the white colored sphere is the best location for mounting the FMW, as the wing is within the turbulence area generated by the vortex shedding. Figures 4.10b shows the velocity vector and profiles in three dimensions.

(a) Two dimensional velocity profile of the solid obstacle.

(b) Velocity vectors of the wind around the obstacle.

Figure 4.10: CFD simulation configuration and results.

Figure 4.12 shows the instantaneous vortex cores generated by the bluff body placed in the vicinity of ground. The second frame shows how the vortex is detached and shed downstream, introducing perturbation at a frequency of approximately 11 Hz to the flow. With the simulation turbulence values being higher than the values found in a standard

atmospheric condition, the artificial gusty environment is comparable, or even more severe than the real environment. The blue sphere in the figure indicates the desired location for the FMW during the wind tunnel tests. Figure 4.11 show the velocity of the airflow in the time domain, and from this figure it can be calculated that the frequency of the shedding is approximately 11 Hz. The Strouhal number of the oscillating flow is given as:

$$St = \frac{fL}{U} \quad (4.3.11)$$

where f is the frequency of shedding, L is the characteristic length and U is the flow velocity. This gives a St number of 0.157, comparable to the results published at [96] for various Reynolds number. The Reynolds number of this particular flow situation is given as:

$$Re = \frac{uL}{\nu} \quad (4.3.12)$$

where u is the velocity of the flow, L is the characteristic length, and ν is the kinematic viscosity of the fluid. The Reynolds number is found to be 38674 in this flow situation. At very high Reynolds numbers, turbulent flow tends to occur, and will produce vortex shedding. Therefore, when compared to the literature about bluff bodies placed in a high velocity air flow, the results of the CFD is acceptable when compared to [96]. With U determined at 7 m/s, the bluff body is therefore generating vortex shedding at 11 Hz, which is very close to what the mini-UAV will be facing in realistic flight conditions. This strong vortex shedding will generate powerful gusts to disturb the FMW during the wind tunnel experiment, which is desirable as the final objective of this experiment is to validate the robustness of the TSM wing-warping controller.

Upon the completion of the testing design, in order to test the robustness of the system against gusty conditions, the whole experimental setup was placed inside a designed closed loop wind tunnel. The wind tunnel test section has 780 mm in width, 720 mm in height and 2000 mm in length (due to the space constraint and the symmetrical structure of the mini-UAV, only half of the structure was tested in the wind tunnel, where the flex sensor and tendon-sheath is installed at the tested wing only).

Figure 4.13 shows the FMW setup secured inside the closed loop wind tunnel test section. Both the gusty and steady flow experiments based on the simulation results were performed for comparison. Prior to the experiment, the velocity profile of the gusty

Figure 4.11: Velocity of the airflow in the time domain.

environment inside the wind tunnel was investigated to ensure its agreement to the CFD simulation result. The profile was recorded by taking the average of velocity components measured using Sentry ST732 hot-wire anemometer (capable of 0-40 m/s velocity measurement range with 0.01 m/s resolution) at 18 different points indicated by black dots in Figure 4.10a. The averaged measured velocity profile and the mean velocity from CFD simulation at the respective 18 points are listed in Table 4.1 for comparison, with the bracketed values generated from the CFD simulation. From the table, we can see that the generated gusty profile at the wind tunnel exhibits good agreement with that obtained from simulation. The gusts generated were quite severe and, as a result from FMW testing, the whole FMW was oscillating vigorously. To satisfy our curiosity, besides the 7 m/s flow velocity, a 12 m/s flow velocity was also prescribed. Since both demonstrate similar results, only the results for 7 m/s are shown in this Chapter.

Figure 4.14 shows the results of the robustness testing. The wing warping with tendon-sheath actuation was performed under gusty environments, with a wind speed of 7 m/s. For the output comparison, the setpoint is in dashed blue, while the output is in red. For others the open loop is dashed blue, feed-forward plus feedback is in black. The results suggest similar conclusion compared to the results from the previous ones when no gusty disturbance is involved. The combined feed-forward/feedback controller demonstrates

Figure 4.12: Vortex structure identified using Q-criterion ($Q = 10,000$). The Q-criterion is colored with velocity magnitude.

better performance that is attributed to the nonlinear TSM model.

Table 4.1: Mean velocity at different locations in the experimental test setup. Bracketed values are from CFD.

		Velocity (m/s)						
y (mm)	300	8.4 (8.31)	7.1 (7.27)	8.8 (8.31)	9.1 (9.0)	9.0 (7.62)	7.1 (6.92)	
	200	0.9 (1.04)	1.3 (1.38)	1.5 (1.38)	2.2 (2.58)	5.1 (4.85)	6.6 (6.23)	
	100	1.3 (1.38)	1.5 (1.63)	1.8 (2.08)	3.7 (3.46)	4.3 (4.15)	5.1 (4.85)	
		0	100	200	300	400	500	600
		x (mm)

Figure 4.13: Flexible membrane wing in wind tunnel for controller robustness testing.

(a) Output comparison.

(b) Tracking error.

(c) Input comparison.

(d) Hysteresis comparison.

Figure 4.14: Experimental results (with disturbances).

4.4 Summary

By making use of the modified Bouc-Wen model for the TSM hysteresis, a robust feed-forward plus feedback control has been designed to control the wing warping position of the FMW. Simulations of the feed-forward/feedback controller has shown to be working effectively, with and without disturbances. Following the success of the simulation, the controller is then implemented onto the FMW hardware, and then experiments were performed to measure the effectiveness of the FMW warping vs the warping inputs. It has been shown in Section 4.3 that the controller is performing well, with and without gust disturbances, proving the robustness of the controller for the TSM actuated wing warping. In order to generate a controlled and familiar gust disturbances from the wind tunnel, CFD has been done to find out the size and position of the bluff body in the wind tunnel test section. Following the results from the CFD, a bluff body was placed in a wind tunnel and the experiment was done with the gust disturbances as designed in the CFD.

It can be concluded that the feed-forward/feedback controller has helped reduced the hysteresis behavior significantly, even with severe disturbances acting on the system. The feed-forward/feedback controller remains stable as long as the PI gains are not tuned to a very high value. However, there are a number of difficulties in this experiment. It has been observed that initializing the pre-tension of the tendon-sheath is challenging as it is difficult to obtain the same pretension at every experiment. If the pre-tension is significantly varying, the model will change extensively and thus rendering the feed-forward control not as effective. To investigate this issue, an adaptive backstepping controller has been implemented to the TSM actuated wing warping system in [97]. In that study, it was found that the adaptive backstepping controller performs well and is more robust than the feed-forward controller. However, the feed-forward/feedback controller is also as robust, or and can be done in a simpler method as presented in this thesis. A conclusion can be drawn upon that as long as the model change is minimal, the feedback control will be able to compensate, and therefore a small change in pre-tension will not render the whole control system ineffective. A future work suggestion will be to design an adaptive controller which is robust to model changes, such as gain scheduling, Linear parameter-varying or fuzzy control systems. The wing warping control has been shown

to work in gusty environments, as shown in the wind tunnel experiments, further proving the robustness. The TSM also enables the adaptive washout to still be effective. The proposed model based controller is offered as a platform to develop the flight control structure for the FMW mini-UAV based on TSM actuation.

Chapter 5

Flexible Membrane Wing mini-UAV Design, Build, and Characterization

5.1 Overview

This chapter highlights the design, build, and test of the FMW mini-UAV prototype. The prototype is the first of its kind, being actuated by a TSM for wing-warping to control the roll rate. A detailed discussion about the design choices and also the procedure of fabrication is shown in this chapter, as well as the various empirical testing of the FMW mini-UAV prototype. Section 5.2 presents the FMW mini-UAV design and build process, as well as the failure of the manufacturing process used in this prototype. In Section 5.3, the natural frequency of the aircraft as well as the determination of the moment of inertia is determined via empirical methods. Section 5.4 displays the aerodynamic properties of the FMW mini-UAV prototype, as well as the validation of the adaptive washout mechanism. The summary of this chapter is finally drawn in Section 5.5. This chapter supports the thesis by providing a real world implementation of the novel TSM wing warping design into a real UAV. Flight tests are also conducted and will be shown in the next chapter.

5.2 Flexible Membrane Wing Mini-UAV Design and Build

A mini-UAV was designed and built in order to validate the TSM actuated FMW warping. Also, the fuselage design can be used in the wind tunnel tests for the aerodynamic characterization. The design process of the UAV was done by identifying the high-level requirements, e.g., payload weight and size, flight endurance, cruising speed, top speed and etc.; and then following the steps in [98, 19] to guide the aircraft sizing and geometry decisions.

5.2.1 Flexible Membrane Wing Fabrication

The FMW is the most critical part of the process. The fabrication of the carbon fiber membrane wing is a complicated and tedious process, involving a lot of steps and also different materials, equipment, and handling techniques. The fabrication process will be described in detail below.

First of all, a 3D mold is designed and the design sent to a professional aluminum fabrication machinist. The 3D mold is made of aluminum (Figure 5.1) as it can withstand the pressure and also the heat of the curing process, which an autoclave will be used in the later steps for curing. The aluminum sheet is then hammered into a 3D mold according to the design. As the mold is hammered by hand, slight imperfections and bumps will exist, which is why the aluminum mold will then be paste with clay and then sanded to so the bumps on the surface of the aluminum will be smoothed out.

After fabricating the mold, a drawing of the wing planform is made on a piece of board (Figure 5.2). The board is to be used as a template to draw the wing planform on the carbon fiber pre-preg. Once the wing planform is drawn, the carbon fiber pre-preg will be cut according to the wing planform design.

After three copies of carbon fiber wing planform are cut out, they will be placed on top of each other, which will form the leading edge and of the wings. Unidirectional carbon fiber strips are cut and then placed on the main carbon fiber wing planform. A total of 6 layers of carbon fiber reinforcement strips is used in this fabrication process to provide a higher stiffness. The Nylon skin is placed together with the carbon fiber to form a

Figure 5.1: 3D aluminum mold

Figure 5.2: Drawing the wing planform on the carbon fiber pre-preg

winged shape material. This is where all the human errors were made. Misalignment of the carbon fibers, untidy cuts, inaccurate measurements and the like usually happens at this step, causing an unstable and unpredictable quality of the wing.

After all the layers have been placed properly on top of each other, the pre-preg carbon fiber layup will be placed on top of a layer of peel-ply, which is in turn placed on top of a non-porous Teflon release film. The carbon fiber wing is then covered by the same

material with the same layup. The whole assembly will be placed on top of the aluminum mold, and then taped on to be kept in place. A vacuum bag will be placed around the assembly and then bag sealant tape is used to secure the vacuum bag with the aluminum mold. Extra care must be used to ensure that the vacuum is air tight.

The carbon fiber layup is cured under high temperature and pressure in the autoclave (Figure 5.3), using the built in program “Autoclave 10743”. After the curing cycle is complete, the carbon fiber wing will be separated from the mold and the vacuum bag. At this point, the wing will be checked for irregularities and imperfections. Extra bits of the wing are then trimmed off, and the wing fabrication is then complete (Figure 5.4).

Figure 5.3: Autoclave

Due to the complicated and high number of steps involved in the fabrication of the flexible wing, it is difficult to manufacture the exact same quality every time. The fabrication process is designed to be repeatable, however, there will always be some deviation of the quality of the wings produced.

5.2.2 Fuselage Design

As the wing is required to fold around the fuselage for storage, the FMW is installed at the top of the fuselage, with a top wing configuration. The payload of the mini-UAV is a visual camera to record the flight. Various electronics, e.g., servos, autopilot

(a) Top view of the flexible wing

(b) Bottom view of the flexible wing

Figure 5.4: Top and bottom view of the FMW.

microcontroller board, electronic speed controller, are also required, not to mention the source of energy which will be a Lithium-Polymer battery. The location of the electronics and battery are critical as they will affect the center of gravity of the aircraft, and has to be determined carefully. The total weight of the aircraft is limited to less than 1.2 kg in order to fulfill the stall speed, take off speed and cruising speed requirements.

The preliminary sizing of the aircraft was done to house all the electronics and payload inside the fuselage. After designing the fuselage, the tail design was done by limiting the horizontal tailspan to 0.3 meters, for the tube launch capability in the future. The horizontal tail aspect ratio AR_{HT} was recommended to be $\frac{2}{3}$ of the wing aspect ratio [99], therefore:

$$AR_{HT} = \frac{2}{3}AR_W \quad (5.2.1)$$

$$S_{HT} = \frac{b_{HT}^2}{AR_{HT}} \quad (5.2.2)$$

$$= 0.0262m^2 \quad (5.2.3)$$

where AR_{HT} is the horizontal tail aspect ratio, AR_W is the wing aspect ratio, b_{HT} is the horizontal tail span and S_{HT} is the horizontal tail area. The tail volume ratio C_{HT} was chosen to be 0.5, as most of the mini-UAVs have similar tail volume ratios. Therefore, the horizontal tail moment arm, l_{HT} can be found with the tail volume ratio equation:

$$C_{HT} = \frac{l_{HT}S_{HT}}{C'_WS_W} \quad (5.2.4)$$

$$l_{HT} = 0.806 \quad (5.2.5)$$

where C'_W is the mean aerodynamic chord and S_W is the wing surface area. The fuselage nose is then designed using a CAD software. A pre-determined CG location has been designed, and all the internal components as well as the payloads were placed inside of the fuselage, and shifted for the weight balance to achieve the desired CG location. Figure 5.5 shows the internal components and payloads location of the mini-UAV, which has the CG at the desired location.

Figure 5.5: CAD drawing of the FMW mini-UAV.

5.2.3 Fuselage Fabrication

For a rapid prototype, 3D printing was chosen as the method of fabrication, with the ABS plastic as the main material of the structure. ABS was chosen because of the high stiffness and low density, therefore giving a high strength over weight ratio for the mini-UAV. Besides, the melting point for ABS is considerably higher than other plastics, proving to be a better material for the mini-UAV. The fuselage was designed with a modular concept in mind, with interchangeable parts for different missions. For example, in surveillance missions, the mini-UAV will be equipped with a high-resolution camera module, whereas in search and rescue missions the fuselage can be swapped with a payload dropping module for distributing rescue packs to a disaster zone. Besides, a damaged part will be easily replaceable, without the need to re-fabricate the whole fuselage structure all over again. A carbon fiber square rod was chosen for the construction of the tail boom, as it is both light and stiff. Figure 5.6 shows the assembled FMW mini-UAV.

After assembly, an initial flight test was carried out, and it has been found that the 3D printed fuselage could not withstand the landing impact. As illustrated in Figure 5.7,

Figure 5.6: 3D printed FMW mini-UAV. Carbon fiber rod is used for the tail boom.

the ABS plastic was unable to withstand the landing impact. Most of the cracks occur at the joined areas, as these are the weakest points of the structure. The fuselage nose was

Figure 5.7: 3D printed fuselage cannot withstand the landing impact.

broken from the body due to the fragile joined parts of the 3D printed fuselage. Currently, ABS can only be printed via the fused deposition method (FDM). The requirement of the fuselage is such that the skin thickness to be only 1 mm due to the weight constraint. The FDM printer was unable to fabricate a structure with a tall height and thin skin, as the ABS plastic will droop. Therefore, the only method is to partition the fuselage into

several sections in the longitudinal direction, and then fabricate the parts to be bonded later. This method proved to be unsuccessful, as the joined areas are weaker, creating weak links around the fuselage.

After realizing that the 3D printing was not a viable technique, the corrugated board was used as a quick substitute as they are easily available in the market, light and strong. Moreover, the corrugated board is able to handle shocks and impacts. The fabrication methods of the corrugated board fuselage is relatively simple, by joining together the boards and aligning strips of the corrugated board with different orientations at areas that needed more reinforcement. The finished corrugated board FMW mini-UAV is shown in Figure 5.8.

Figure 5.8: FMW mini-UAV fuselage built from corrugated board.

5.3 Flexible Membrane Wing mini-UAV Characterization

A few characteristics of the FMW mini-UAV are difficult to obtain mathematically, therefore, empirical tests are performed to obtain them. The aerodynamic data, natural frequencies and moment of inertia of the FMW mini-UAV are obtained experimentally. Wind tunnel tests (shown in Section 5.4) provided the necessary aerodynamic data. Modal testing was performed to study the natural frequencies of the FMW, and finally, the moment of inertia of the mini-UAV was found using the bifilar pendulum method.

5.3.1 Flexible Membrane Wing Natural Frequency Test

The fundamental frequency of the FMW is particularly important as the flexibility of the wing will induce fluttering if the gust frequency happens to be the natural frequency of the FMW. For the FMW, the fundamental frequency was determined experimentally via impact hammer modal testing [100]. In particular, the first mode, or the fundamental frequency is the most critical to the FMW, as the deflection will be the greatest. From Figure 5.9a, it can be observed that the first mode of the FMW occurs at near to 7 Hz.

(a) Frequency response of the FMW obtained from modal testing. (b) Coherence of the frequency response.

Figure 5.9: The results from the modal testing of the FMW.

The coherence diagram (Figure 5.9b) shows a peak at 7 Hz, signifying a high confidence of accuracy of the natural frequency. A slow motion video was captured on the vibration of the FMW, and the vibration frequency of the FMW from the video was shown to be 7 Hz as well.

5.3.2 Determination of Moment of Inertia

A bifilar vertical-axis torsional pendulum test (Figure 5.10) was to find out the for moment of inertia of the mini-UAV in the longitudinal direction. Strings were attached to the center of gravity of the UAV, and then the UAV was hung from the ceiling as a bifilar pendulum. The moment of inertia is of interest because the roll rate of the mini-UAV given a rolling moment can be found if the moment of inertia is known. The following

equation shows the moment of inertia of the mini-UAV:

$$I = \frac{mgT^2l_p^2}{16\pi^2L} \quad (5.3.1)$$

$$= 0.016975kgm^2 \quad (5.3.2)$$

where m is the mass of the mini-UAV, g is the gravitational acceleration, T is the rotational oscillation period of the bifilar pendulum, l_p is the length of the bifilar pendulum, and L is the length of the supporting strings for the bifilar pendulum.

Figure 5.10: Measuring the moment of inertia in the roll axis experimentally.

5.4 Wind Tunnel Tests

Two separate wind tunnel tests were performed to investigate the aerodynamic characteristics of the FMW mini-UAV. Steady uniform airflow was used to identify the aerodynamic properties of the FMW, while controlled gusty airflow was used to study the adaptive washout mechanism of the FMW and to validate the gust response dampening ability of the FMW mini-UAV.

5.4.1 Aerodynamic Forces Characterization

The IIUM wind tunnel used for this experiment is designed for a maximum wind speed of 50 m/s, with a test section 2.3 m wide, 1.5 m high and 6 m long. The six component force balance equipped in this wind tunnel is able to handle:

Lift Force	± 2350 N
Drag Force	± 800 N
Pitching Moment	± 900 Nm
Side Force	± 2000 N
Yawing Moment	± 250 Nm
Rolling Moment	± 1200 Nm

A large test section (Figure 5.11) was required in order to negate the wall effects of the wind tunnel, which will affect the results of the wind tunnel tests. The FMW mini-UAV was tested in two different wind speeds, which are 12 m/s and 15 m/s. The cruising speed of 9 m/s was not tested because the wind tunnel was unable to generate a steady uniform flow at such low speeds, and was producing a lot of noises from the turbine. Initially, the FMW mini-UAV was tested at a negative α of -4° and the whole wing fluttered aggressively. Figures 5.12a and 5.12b illustrates the severe degree of fluttering. A similar incident occurred at 0° α , which results in the decision of testing the FMW at an α of 2° onwards. The fluttering occurred because the FMW is rigid against forces from below the wing, but weak against the forces from above the wing. This property is desired, as it can allow the wing to provide lift while still being able to fold downwards around the fuselage. Even though the FMW was oscillating very aggressively, the TSM stayed intact and was able to still perform wing warping, proving its robustness in very harsh conditions.

Figure 5.11: Wind tunnel used for the aerodynamic forces characterization.

(a) First frame from the fluttering video capture.

(b) Second frame from the fluttering video capture.

Figure 5.12: The FMW fluttering aggressively inside the wind tunnel when the α is at negative.

The wind tunnel testing results are shown from Figures 5.13a to 5.17b. All the experimental results were taken three times at the same α and then averaged. The wind tunnel may be unable to generate a steady uniform flow during the 12 m/s experiment, as the results looked considerably scattered when compared to the results from a typical wind tunnel test. Therefore, the wind tunnel results from the 12 m/s are regressed to show the regression function in red. The results from both 12 m/s and 15 m/s are shown below for comparison. The β sweeps are done in an α of 2° .

The maximum C_L of the FMW reached to almost 1.5 when tested in 12 m/s wind speed. The drag coefficient readings from the wind tunnel for 12 m/s wind speed are quite scattered, as it can be observed in Figure 5.13b that the values are not increasing steadily with the α . However, the regressed trend line shows a reasonable drag coefficient curve, with an increasing drag with the α . Figures 5.13c & 5.13d shows the lift over drag and the drag polar with the regressed function in red. The moment coefficient diagram in Figure 5.13e shows the FMW mini-UAV being stable in flight, as the values are negative and decreases with α , following the standard trend of a stable aircraft. The 12 m/s wind tunnel experiment results are noisy, with the suspected primary reason being the wind tunnel unable to generate a steady uniform flow at 12 m/s as well. However, the regressed function line shows a reasonably familiar lift and drag performances for an aircraft, and can be used as a basis for further analysis.

(a) Lift coefficient C_L vs. α (deg) in 12 m/s. (b) Drag coefficient C_D vs. α (deg) in 12 m/s.

(c) C_L over C_D vs. α (deg) in 12 m/s. (d) C_L vs. C_D in 12 m/s.

(e) Pitching moment coefficient C_M vs. α (deg) in 12 m/s.

Figure 5.13: Aerodynamic coefficients of the FMW mini-UAV with varying α in 12 m/s wind speed (regressed).

One would expect the β (yawing angle) to not significantly affect the C_L , C_D and C_M as they are components of the longitudinal stability derivatives. During the beta sweep tests it can be observed that is true. The yawing moment coefficient C_n , rolling moment C_r and side force coefficient C_Y should increase with β , as shown in the Figures [5.14d](#), [5.14e](#) & [5.14f](#). Once again, the plots are regressed to better show the trend line, as the measurements are very scattered due to the wind tunnel unable to generate a steady uniform 12 m/s flow.

(a) Lift coefficient C_L vs. β (deg) in 12 m/s.

(b) Drag coefficient C_D vs. β (deg) in 12 m/s.

(c) Pitching moment coefficient C_M vs. β (deg) in 12 m/s.

(d) Yawing moment coefficient C_n vs. β in 12 m/s.

(e) Rolling moment coefficient C_r vs. β (deg) in 12 m/s.

(f) Side force coefficient C_Y vs. β (deg) in 12 m/s.

Figure 5.14: Aerodynamic coefficients of the FMW mini-UAV with varying β in 12 m/s wind speed (regressed).

(a) Lift coefficient C_L vs. α (deg) in 15 m/s. (b) Drag coefficient C_D vs. α (deg) in 15 m/s.

(c) C_L over C_D vs. α (deg) in 15 m/s. (d) C_L vs. C_D in 15 m/s.

(e) Pitching moment coefficient C_M vs. α (deg) in 15 m/s.

Figure 5.15: Aerodynamic coefficients of the FMW mini-UAV with varying α in 15 m/s wind speed.

When the FMW is placed in a 15 m/s wind speed, the wind tunnel data during the α sweep looks smoother and also more similar to the expected aerodynamic performance of a thin wing. From this wind tunnel test it was found that the FMW is able to generate a very high lift at C_L close to 1.5, and did not buckle at even very high wing loading, reaching up to 150 g/dm^2 . It can be determined clearly from the Figure 5.15c that the cruising alpha should be at 8, as the C_L is 1.25, which provides a lift force of 10.86 N (1.1 kg, which is the MTOW of the UAV) during the design cruising speed of 9 m/s, according to the lift equation (Eq 1.2.1). Coincidentally, the highest lift to drag ratio can also be found at that α . Therefore the UAV incidence angle should be designed to be 8 degrees. Figure 5.15a shows that the FMW stalled at $\alpha = 14$.

One would expect the β (yawing angle) to not significantly affect the C_L , C_D and C_M as they are components of the longitudinal stability derivatives. During the beta sweep tests it can be observed that is true. The deviation of the C_L is only within 0.05 and C_D within 0.03 (with an outlier at $-12^\circ \beta$ which leads to around 0.09 deviation). C_M is shown to be increasing with β , producing an asymmetry on the pitching moment for the FMW mini-UAV. The asymmetry of the C_M may be caused by the imperfect fabrication of the FMW, as the FMW is constructed by hand and may be slightly unbalanced. The FMW, being flexible, may be flexing in different degrees and producing different pitching moment on the mini-UAV when it is yawing at very high degrees.

The yawing moment coefficient C_n , rolling moment C_r and side force coefficient C_Y should increase with β , which is shown in the wind tunnel tests as expected. The data shows a significant amount of measurement noise, with quite some deviation from the regression function (in red). However, the regressed trend line shows a positive linear slope for all three lateral coefficients. The R^2 between the linear regression and data for all the lateral coefficients are:

$$R^2 C_Y = 0.94811$$

$$R^2 C_n = 0.41351$$

$$R^2 C_r = 0.73461$$

The measurement noises are mostly due to the low sensitivity of the force balance. The force balance is designed to handle up to $\pm 2000 \text{ N}$ side force, $\pm 250 \text{ Nm}$ yawing moment and $\pm 1200 \text{ Nm}$ rolling moment. In this experiment, the side forces exerted on the force

balance are only within a mere ± 2 N, the yawing moment within only ± 2 Nm and the rolling moment within only ± 3 N. However, the trend line can still be obtained from the measurements, and it is matching the expected behavior. The regressed wind tunnel data from the 12 m/s wind speed is also matches the data from the 15 m/s wind tunnel data.

It can also be observed from the wind tunnel experiment that the rigid wing has a much lower stall α when compared to the FMW. In Figure 5.17a, the rigid wing stalls when α is at 10° , while for the FMW the stall angle is at around 14° when the wind speed is 15 m/s, and the FMW seems to not stall even in 18° when the wind speed is 12 m/s.

The rolling moment vs. the warping angle is critical for the identification of the FMW roll rate and is obtained in this wind tunnel experiment. When running this test, the FMW was held steady in an α of 2° . Figure 5.17b shows the rolling moment increasing linearly with the warping angle, until when warping angle reaches 14° , where the rolling moment starts to decrease. This phenomenon is quite well known as adverse rolling. For conventional wings, adverse rolling will happen when the ailerons are exerting too much force such that the wings itself are twisting into the opposite direction, creating the opposite rolling direction as intended from the pilot. In [12], the relationship between dynamic pressure and roll rate were investigated for rigid and flexible wings, and it was found that as dynamic pressure increases after a certain point, flexible wings will lose the roll rate. For the FMW, the rolling moment starts decreasing when the warping angle is beyond 14° in 15 m/s. Therefore, in wind speeds larger than 15 m/s, it is undesirable to warp the FMW more than 14° . Further investigations are required to map the relationship between the roll rate, warping angle and also the dynamic pressure for the FMW.

5.4.2 Adaptive Washout Validation

One of the capabilities of the FMW is to dampen the longitudinal gust response via the adaptive washout mechanism. When a longitudinal direction gust hits the FMW from below, it will create an extra lift force but the lift force will be dampened as the FMW will flex chordwise passively, changing the airfoil shape and also the effective α [1]. Thus, the gust response of the FMW is much lower compared to a conventional rigid wing. As a foreign object, which is the TSM is installed to the FMW, a validation of the adaptive washout is required. A gusty flow wind tunnel test is performed to obtain data about the

gust response of both the FMW mini-UAV and the conventional rigid wing mini-UAV to validate the adaptive washout mechanism of the FMW when it is installed with the TSM.

The experimental setup was referred to the video in [101]. The mini-UAV test model was suspended inside the wind tunnel, with freedom of rotational movement in the pitch and roll axis, as well as freedom of translational movement in all the three axes. Nylon strings were used to suspend the model, and with rubber bands tied to the end of the Nylon strings to help increase the deflection and rotational angles of the model. The Nylon strings were attached to the nose and the tail of the model, as well as at the aerodynamic center of the model to support the weight of the model. The static margin of the model was set to 5% for a more sensitive response to gusts. The model was fitted with all the payload, with an all up weight suspended in the wind tunnel to obtain a close approximate of the moment of inertias, and also to better simulate a real flight situation. Figure 5.18a illustrates the model being suspended in the test section of the wind tunnel.

To generate longitudinal gusts, a rotating slotted cylinder (RSC) device was used. The RSC is a very simple mechanism; only one rotating cylinder is required to generate gusts. The frequency of the gust will be two times the rotation of the cylinder. The RSC used in this experiment was designed by following [102, 103]. The chord length of the airfoil c in the gust generator is 0.2 m, and the diameter of the RSC is $d = 0.25c$. The thickness of the RSC is $t = 0.0313c$ and the gap between the airfoil trailing edge and the RSC is $e = 0.08c$. NACA 0012 was used as the airfoil for the gust generator. The RSC gust generator is shown in Figure 5.19. The frequency of the gust is set at 7 Hz as this is the fundamental frequency of the FMW, as it will induce the highest amplitude of the FMW. Therefore, the RSC rotates at 3.5 revolutions per second.

The model was fitted with accelerometers and gyroscopes at the center of gravity to detect the movements of the model, and the oscillation data is then streamed and recorded to a data acquisition computer. Figures 5.20a to 5.20f shows the gust response of the rigid wing and FMW model. From the plots, it can be observed that the adaptive washout mechanism of the FMW helped to alleviate the gust response, especially in the z-axis, as the FMW model has fewer movements in the gusty airflow compared to the rigid conventional wing model. The standard deviation of the rigid wing movements is generally larger compared to the FMW, with the most significant difference in the z-

axis acceleration at 214.82 for the rigid wing and 94.17 for the FMW. TSM does not inhibit the adaptive washout mechanism to help dampen the gust response for the FMW. The confirmation of the Adaptive Washout Mechanism capability at the fundamental frequency demonstrates its effectiveness at the critical condition. It can be expected that the FMW mini-UAV will perform well at any other disturbance frequencies.

(a) Lift coefficient C_L vs. β (deg) in 15 m/s.

(b) Drag coefficient C_D vs. β (deg) in 15 m/s.

(c) Pitching moment coefficient C_M vs. β (deg) in 15 m/s.

(d) Yawing moment coefficient C_n vs. β in 15 m/s.

(e) Rolling moment coefficient C_r vs. β (deg) in 15 m/s.

(f) Side force coefficient C_Y vs. β (deg) in 15 m/s.

Figure 5.16: Aerodynamic coefficients of the FMW mini-UAV with varying β in 15 m/s wind speed.

(a) C_L vs. α (deg) in 12 m/s for the rigid wing. (b) Rolling moment (Nm) vs. Warping angle (deg).

Figure 5.17: Aerodynamic properties of the rigid wing in 5.17a, and the rolling moment of the FMW in 5.17b.

(a) Conventional rigid wing model.

(b) FMW mini-UAV model.

Figure 5.18: The rigid wing and FMW model being suspended in the middle of the test section of the wind tunnel.

Figure 5.19: Gust generator with a rotating slotted cylinder.

(a) Roll angle vs time for the rigid wing model.

(b) Roll angle vs time for the FMW model.

(c) Pitch angle vs time for the rigid wing model.

(d) Pitch angle vs time for the FMW model.

(e) Z axis acceleration vs time for the rigid wing model.

(f) Z axis acceleration vs time for the FMW model.

Figure 5.20: The roll, pitch, and z-axis acceleration of the rigid wing and FMW model in 7 Hz gusts.

5.5 Summary

The FMW was designed to dampen gusts while in flight, and also to fold around the fuselage for storage. However, the FMW lacks a suitable actuation method to be able to provide ample rolling moment. The TSM is proven to be a suitable candidate to provide the needed actuation without sacrificing the desired attributes of the FMW.

Furthermore, a mini-UAV was designed and various tests were performed to identify the characteristics of the mini-UAV. From the wind tunnel tests, the FMW installed with TSM still displays the adaptive washout, being able to dampen the longitudinal gusts quite well when compared to a rigid, conventional wing. It is also shown that the rudder only input does not induce as much rolling moment as the wing warping in the wind tunnel tests. Flight tests were conducted, and the wing warping was proven to be a better method to induce rolling moment when compared to rudder input only. The TSM actuated FMW with a feed-forward & feedback control strategy is proven to work well on a real flight.

One of the findings from the wind tunnel experiments was roll reversal of the FMW. Due to the flexibility of the wing in the chordwise direction, roll reversal will exist when the dynamic pressure is very high. Careful saturation of the FMW warping is necessary for the safety of the aircraft. The future work may be to characterize the occurrence of roll reversal in different situations and to have a better control strategy to prevent it.

Chapter 6

Flight Tests

6.1 Overview

The flight tests were conducted in order to examine the flight qualities of the FMW prototype. A few crucial data, namely the comparison of the rudder induced roll rate and both the open loop & closed loop wing warping induced roll rate are captured during the flight test. This chapter will cover the setup of the flight test, the outcomes and the conclusion of the flight test. This chapter will show the importance and superiority of the TSM wing warping controller developed in this thesis.

6.2 Location & Time

The NTU Sports & Recreation Center football field was chosen as the flight test site, as it is a huge open space with no obstacles around, and more importantly, there are no people or pedestrians around so it is safe to conduct flight tests around that area. The flight tests are held in the late afternoons when there are fewer people exercising at the field.

6.3 Test Setup

The flight test setup consists of many components, with a new FMW mini-UAV prototype linked to the ground control station via a wireless data link telemetry, the microcontroller

PCB with loaded with the TSM controller, and also an autopilot on board the UAV. The equipment and setup of the flight test will be discussed in the following subsections.

6.3.1 UAV

Due to manufacturing defects, the designed mini-UAV was not successfully flown. A fuselage made of a corrugated board was used instead for the flight test. Similarly, the TSM actuated FMW was mounted to the top of the fuselage, giving the mini-UAV a top wing configuration. The tail volume ratio for the corrugated board UAV is identical to the designed values, therefore the stability performance of this plane should be very near to the designed aspects. The APM 2.5 is fitted to the CG of the FMW mini-UAV to track the flight data, as well as to provide autopilot control to the aircraft. The specifications of the UAV is listed in the table below.

Wingspan	1 m
CG location	0.25 m behind leading edge
Weight	1060 g
Wing loading	53 g/dm^3
Powerplant	Electric motor & 9"x6" propellers
Estimated flight time	8 minutes

6.3.2 Microcontroller PCB

A STM32F4 microcontroller PCB (Figure 6.1) with the feed-forward and feedback control strategy for the TSM wing warping is fabricated and then fitted to the FMW mini-UAV. All the sensors and actuators related to the wing warping are connected to this PCB.

6.3.3 Autopilot Board

The APM 2.5 as shown in Figure 6.2 was used for the flight test. It is the same as the APM 2 but slightly upgraded as it now comes with a casing. The main control strategy used for the autopilot is PID feedback for all the flight dynamics.

Fortunately, as the relationship between the rolling moment and the warping position can be modeled as a linear curve from wind tunnel tests, a PID feedback control will suffice. For the FMW mini-UAV, a PD feedback control is implemented to control the

Figure 6.1: Microcontroller PCB.

Figure 6.2: APM 2.5.

roll rate, with a default PD gains of $K_P = 0.16$ & $K_D = 0.02$, while the feed-forward & feedback controller is the inner loop, controlling the wing warping position. The default PD gains from the autopilot firmware was not changed, because it was found to work with most fixed wing aircraft configurations. The firmware is illustrated in Figure 6.3. From the wind tunnel tests, roll reversal of the FMW has been found at warping angles of 14° in 15 m/s wind speed. In this flight test, the wing warping has been saturated at 14° in order to avoid adverse rolling of the mini-UAV. In the future, further investigation will

be needed to examine the relationship between rolling moment and dynamic pressure of the FMW.

Figure 6.3: Autopilot default gains.

6.3.4 Wireless Datalink

The wireless datalink telemetry used for the flight test is the 3DR Radio Telemetry as shown in Figure 6.4. It was chosen as it is compatible with the APM 2.5 and very easily setup to run. The telemetry is a crucial part of the flight test as it can be used to transmit the flight data directly to the ground control computer for further analysis.

6.3.5 Ground Control

The APM Planner program was used, and it was installed in a Linux machine. A full battery charge was ensured before the experiment so the data can be logged without failure.

Figure 6.4: 3DR Radio Telemetry set.

6.3.6 UAV Setup

The procedures for the mini-UAV flight setup is as follows. First, the transmitter is switched on, with the throttle and minimum and located at a safe distance away from the mini-UAV and working people. The mini-UAV is then positioned on the ground and leveled before the battery is connected. After connecting the battery, the APM 2.5 will automatically calibrate itself. The calibration will be done when the lights stopped flashing on the APM 2.5. The directions of the servos of the UAV are then checked with the transmitter to ensure they are correct. After the servo checks, the UAV will be ready for taking off. Figure 6.5a shows the separated FMW and fuselage while Figure 6.5b illustrates the mini-UAV fully assembled.

The ground control station will be switched on and connected to the mini-UAV. The flight modes, battery percentage, and GPS locking are then checked prior to the flight missions. The mini-UAV is then switched to stabilize mode to check if the servo directions are correctly calibrated with the APM 2.5. After ensuring the servos direction stored inside the APM 2.5 are correct, the mini-UAV is switched back to manual mode.

(a) The FMW and the corrugated board fuselage of the UAV.

(b) The fully assembled UAV.

Figure 6.5: The FMW mini-UAV.

6.4 Results

Flying the FMW mini-UAV requires a good piloting skill as the aircraft is very fast and responsive. Figure 6.6 shows the mini-UAV cruising in the sky. There is more roll control authority with the wing warping mechanism, compared to the rudder input. According

to the pilot, the mini-UAV is very difficult to control with the rudders only, as this mini-UAV is a fast aircraft. Rudders are able to provide yaw and banking control only at low speeds, i.e. during gliding. During all the flight tests the weather was gusty, however, the mini-UAV was able to fly steadily under control with the closed loop wing-warping mechanism. The worst performing case is the open loop wing warping, the aircraft was barely under control at all.

Figure 6.6: Flight test of the FMW mini-UAV.

6.4.1 Open Loop Wing Warping Induced Roll Rate

The aircraft was configured with the open loop TSM wing warping mode to test for open loop TSM wing warping induced roll rate. Figures 6.7 displays the results of the open loop wing warping roll response. A wing warping doublet input was given, and the aircraft was unresponsive. The open loop wing warping control did not provide a sufficient control of the rolling moment of the mini-UAV, as experienced during flights and also shown in the flight data, with a correlation coefficient of only **0.0945**.

6.4.2 Rudder Induced Roll Rate

Rudder input can also induce rolling, however, it is not as effective as the wing warping. From Figure 6.8, it is shown that the roll rates of the aircraft is slightly more responsive. The correlation coefficient between the rudder inputs and the roll rates is **0.1347**, which is slightly more, but still insignificant.

(a) Wing warping inputs (open loop). (b) Roll rate of the FMW mini-UAV.

Figure 6.7: Roll rate of the FMW when given a wing warping doublet (open loop).

(a) Rudder inputs from pilot. (b) Roll rates of the FMW mini-UAV.

Figure 6.8: Roll rate of the FMW when given rudder doublets.

6.4.3 Closed Loop Wing Warping Induced Roll Rate

Subsequently, the closed loop wing warping was tested. Figure 6.9 shows the results of the closed loop wing warping induced roll rate. From the data, it can be observed that the closed loop TSM wing warping has the best performance, and the aircraft was responsive to the desired pilot controls. The cross correlation in Figure 6.10 shows that the wing-warping input and the roll rate output (feed-forward/feedback controller) has a lag of 0.3 seconds. With the feed-forward/feedback controller, the mini-UAV was able to achieve

a **0.7625** correlation coefficient between the wing warping input and the roll rate, much more significant compared to the open loop and rudder induced roll. Below is a summary of all the correlation coefficients recorded from the flight tests.

$$R_{\text{open loop}} = 0.0945$$

$$R_{\text{rudder}} = 0.1347$$

$$R_{\text{closed loop}} = 0.7625$$

(a) Wing warping inputs (closed loop). (b) Roll rates of the FMW mini-UAV.

Figure 6.9: Roll rate of the FMW when given wing warping doublets (with feed-forward/feedback controller).

Figure 6.10: Cross correlation between the wing-warping input and roll rate output of the FMW mini-UAV with feed-forward/feedback control.

6.5 Summary

The flight test presented in this chapter has shown that the TSM actuated wing warping FMW is able to fly in a well-controlled manner, provided that the wing warping is controlled by the feed-forward/feedback controller designed in the previous chapters. The rolling moment is much greater when the FMW is warped, compared to the rudder only input, therefore generating a higher roll rate. In order to have a better control of the FMW mini-UAV, it is crucial that the TSM actuation with feed-forward/feedback control is installed to the FMW mini-UAV. One of the difficulties faced during the flight tests is the launching of the FMW mini-UAV. It has to be thrown by hand, and a minimum take-off speed of 7 m/s to 8 m/s has to be achieved in order to get into the sky. Future work will be to fabricate a tube launcher since the FMW can be folded around the fuselage.

Chapter 7

Conclusions & Future Work

7.1 Conclusions

There are a number of conclusions that can be drawn based upon the research done from the previous chapters. Novel knowledge contributed in this thesis will be highlighted in **bold**.

7.1.1 Conclusions related to Flexible Membrane Wing

The FMW has a few unique characteristics when compared to a traditional rigid wing i.e. it is much thinner, lighter and most importantly it is able to fold downwards spanwise. This attribute allows the FMW to be stored while folded inside a small space, hence the FMW mini-UAV can be deployed within seconds without any installation procedures at the field. Adaptive washout is a passive mechanism that helps to dampen the gusty airflow and has been explained in detail. The fabrication process of the FMW has been shown and the challenges remain to be human errors and very dependent on carbon fiber handling skills. Other available actuation methods are experimented and validated before the **TSM method is found to be the most suitable**. The reason for selecting TSM actuation is that it allows the FMW to be foldable, exerts enough force to warp the wing, and also allows the adaptive washout mechanism to be active.

7.1.2 Conclusions related to Identification of the Wing Warping via Tendon-Sheath Mechanism

Through the experiment, **nonlinear behaviors of the TSM actuated wing warping have been identified, and they produced an asymmetry hysteresis which can be modeled with a General Bouc-Wen hysteresis model.** During the experiment, a **“hardening” phenomenon of the wing warping was discovered,** and various analysis including FEM and mathematical modeling of the wing warping was performed to figure out the exact reason, and it was found that the **lack of pretension contributes to the “hardening” effect of the wing warping.** The identification of the nonlinear behaviors is critical for the controlling the wing warping in the subsequent chapters. The knowledge of pretensioning the TSM is critical as it will change the hysteresis model of the TSM wing warping.

7.1.3 Conclusions related to Modeling of the Wing Warping via Tendon-Sheath Mechanism

A **General Bouc-Wen model for hysteresis was selected** as the basis of the modeling of the TSM wing warping. **Modification of the General Bouc-Wen model** was done to take into account of the “hardening” phenomenon. The modification is critical as it **creates a much better model for capturing the hysteresis of the TSM wing warping.** The new model has a total of 12 parameters to be optimized, and the optimization process was done utilizing the Genetic Algorithm and also the Nelder-Mead algorithm. Genetic Algorithm optimization was performed initially and then followed by the Nelder-Mead algorithm to get more precise results. With this optimization process, the **RMS error of the model is only 0.26° .**

7.1.4 Conclusions related to Simulation of the Wing Warping via Tendon-Sheath Mechanism

The nonlinearity of the FMW warping is quite severe and therefore the **feedback PI controller alone is found to be insufficient** to accurately control the wing warping. A feed-forward control block is constructed based on the inverse of the mod-

ified General Bouc-Wen model. Simulations of the wing warping showed promising results, with the feed-forward plus feedback controller performing very well. It was found that the **feed-forward-only controller is sufficient to control the FMW warping when there is no disturbance.** When the disturbance is introduced, the feedback controller was required to reduce the errors. The **combined feed-forward and feedback controller was designed** for the FMW warping via TSM.

7.1.5 Conclusions related to the Experiments on Control of the Wing Warping via Tendon-Sheath Mechanism

It was shown in the experiment that **feedback control by itself was not enough** for the highly nonlinear system, therefore **requiring a feed-forward controller.** For the feedback PI control, high gains will not function well and will make the system unstable with unwanted oscillations. The RMS errors found from the experiment were **0.285° for the feed-forward plus feedback control, 2.04° for feedback only, and 1.727° for open loop.** CFD analysis was done to design an extreme gusty condition in the closed loop wind tunnel for the FMW warping control robustness validation. The experimental data from the gusty environment showed the wing warping with the **feedback/feed-forward controller can perform well under disturbance.**

7.1.6 Conclusions related to Design, Build and Characterization of the Flexible Membrane Wing UAV

A mini-UAV is designed via standard textbook methods and was initially fabricated via 3D printing to save time in the manufacturing process. In the initial flight test, the 3D printed mini-UAV failed during impact, as the ABS plastic was very brittle due to fabrication process and wall thickness being too small. Another attempt was made using another material, the corrugated board to build the UAV, with the same geometry as designed. The natural frequency of the FMW was found from the modal testing, and the first mode is found to exist at around 7 Hz. The bifilar vertical-axis torsional pendulum test was done to obtain the moment of inertia of the aircraft. Wind tunnel testing for the aerodynamic data, as well as the validation of the adaptive washout mechanism, were

done. It was found that **rolling moment increases linearly with wing warping, and adverse roll will occur beyond 14 ° warping at 15 m/s.**

7.1.7 Conclusions related to the Flight Tests of the Flexible Membrane Wing Mini-UAV

The mini-UAV is stable and flies at a very high speed, requiring ample space or good piloting skills to operate it. From the flight data, the aircraft shows very little oscillations during flight. **The closed loop wing warping induced roll rate is much higher than the open loop wing warping or rudder induced roll rate.** This proves that the TSM wing warping is a suitable method of actuating the FMW. The flight qualities of the FMW mini-UAV have been greatly increased with the introduction of the TSM wing warping method.

7.2 Future work

A list of suggestions of future work related to the extension of this research is presented below.

- The initial pretension of the TSM is difficult to verify and also be kept constant. More work can be done in this area to get either a more constant pretension or an adaptive controller can be designed to take into account the changes of the pretension.
- The FMW mini-UAV is currently being launched by hand. A suitable launching system can be designed in the future for easier storage and launching purposes.
- The fabrication process of the FMW is a huge variable and it is difficult to keep the same quality each time the FMW is produced. A more constant method or an automated system of wing fabrication can be looked into.
- Landing the FMW mini-UAV is very similar to a controlled crash towards the ground. More work can be done in terms of the landing sequence to improve the landing process. Perching, or vertical take off and landing can be one of the methods.
- The FMW is currently built for a mini-UAV sized aircraft. It will be a significant research effort to discover the scalability of the FMW if it is possible to be scaled to a bigger sized aircraft.

Bibliography

- [1] Ifju, P., Jenkins, D., Ettinger, S., Lian, Y., Shyy, W., and Waszak, M., *Flexible-wing-based micro air vehicles*, Aerospace Sciences Meetings, American Institute of Aeronautics and Astronautics, 2002, doi:10.2514/6.2002-705.
- [2] Filippone, A., *Flight performance of fixed and rotary wing aircraft*, Elsevier, 2006.
- [3] Choi, E. C., “Extreme wind characteristics over Singapore—an area in the equatorial belt,” *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 83, No. 1, 1999, pp. 61–69.
- [4] Boyd, P. I., Cole, S., and Miller, G., *A summary of the Active Flexible Wing Program*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 1992, doi:10.2514/6.1992-2080.
- [5] Garcia, H., Abdulrahim, M., and Lind, R., *Roll Control for a Micro Air Vehicle Using Active Wing Morphing*, Guidance, Navigation, and Control and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2003, doi:10.2514/6.2003-5347.
- [6] ARARoboticSystems, “Nighthawk Micro Air Vehicle (MAV),” 2013.
- [7] Prioria, “Maveric UAS,” 2013.
- [8] Octatron, “Skyseer UAV,” 2013.
- [9] Chinnasamy, P. and Chen, Y., “Application of Computational Fluid Dynamics on Smart Wing Design,” *43rd AIAA Aerospace Sciences Meeting and Exhibit, 10-13 Jan 2005, Reno, Nevada, USA*, 2005.

- [10] Schoor, M. v., Zerweckh, S., and Flotow, A. v., *Aeroelastic stability and control of a highly flexible aircraft*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 1989.
- [11] Chang, C. S., Hodges, D. H., and Patil, M. J., “Flight Dynamics of Highly Flexible Aircraft,” *Journal of Aircraft*, Vol. 45, No. 2, 2008, pp. 538–545.
- [12] Khot, N. S., Eastep, F. E., and Kolonay, R. M., *Wing Twist and Camber for the Rolling Maneuver of a Flexible Wing without Aileron*, American Institute of Aeronautics and Astronautics, 1997.
- [13] Cesnik, C. and Brown, E., *Active Warping Control of a Joined Wing/Tail Airplane Configuration*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2003, doi:10.2514/6.2003-1715.
- [14] Khot, N. S., Zweber, J. V., Velez, D. E., Oz, H., and Eastep, F. E., “Flexible Composite Wing with Internal Actuation for Roll Maneuver,” *Journal of Aircraft*, Vol. 39, No. 4, 2002, pp. 521–527.
- [15] Patil, M. J. and Hodges, D. H., “Flight Dynamics of Highly Flexible Flying Wings,” *Journal of Aircraft*, Vol. 43, No. 6, 2006, pp. 1790–1799.
- [16] Paranjape, A. A., Chung, S.-J., Hilton, H. H., and Chakravarthy, A., “Dynamics and Performance of Tailless Micro Aerial Vehicle with Flexible Articulated Wings,” *AIAA Journal*, Vol. 50, No. 5, 2012, pp. 1177–1188.
- [17] Ott, J. and Biezad, D., “Design of a Tube-launched UAV,” *3rd AIAA Unmanned Unlimited Technical Conference, Workshop and Exhibit, AIAA Paper*, Vol. 6493, 2004.
- [18] Ferguson, L. A., *A Computational Model for Flexible Wing Based Micro Air Vehicles*, Ph.D. thesis, Texas Tech University, 2006.
- [19] Roskam, J., *Airplane Design: Determination of stability, control and performance characteristics: far and military requirements*, DARcorporation, 2002.

- [20] Pitcher, N. A. and Maple, R. C., *A Static Aeroelastic Analysis of a Flexible Wing Mini Unmanned Aerial Vehicle*, Ph.D. thesis, Air Force Institute of Technology, 2008.
- [21] Hu, H., Tamai, M., and Murphy, J. T., “Flexible-membrane Airfoils at Low Reynolds Numbers,” *Journal of Aircraft*, Vol. 45, No. 5, 2008, pp. 1767–1778.
- [22] Weisshaar, T., Nam, C., and Batista-Rodriguez, A., “Aeroelastic Tailoring for Improved UAV Performance,” *AIAA Structures, Structural Dynamics, and Materials Conference*, 1998, pp. 20–23.
- [23] C. Culick F. E., “The Wright Brothers: First Aeronautical Engineers and Test Pilots,” *AIAA Journal*, Vol. 41, No. 6, 2003, pp. 985–1006, doi: 10.2514/2.2046.
- [24] Abdulrahim, M., Garcia, H., and Lind, R., *Flight Testing a Micro Air Vehicle Using Morphing for Aeroservoelastic Control*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2004, doi:10.2514/6.2004-1674.
- [25] Stanford, B., Abdulrahim, M., Lind, R., and Ifju, P., *Design and Optimization of Morphing Mechanisms for Highly Flexible Micro Air Vehicles*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2006, doi:10.2514/6.2006-2162.
- [26] Abdulrahim, M., Garcia, H., and Lind, R., “Flight Characteristics of Shaping the Membrane Wing of a Micro Air Vehicle,” *Journal of Aircraft*, Vol. 42, No. 1, 2005, pp. 131–137.
- [27] Breuker, R. D., Abdalla, M. M., and Gürdal, Z., “A Generic Morphing Wing Analysis and Design Framework,” *Journal of Intelligent Material Systems and Structures*, Vol. 22, No. 10, 2011, pp. 1025–1039.
- [28] Vos, R., Gurdal, Z., and Abdalla, M., *A Novel Mechanism for Active Wing Warping*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2008, doi:10.2514/6.2008-1879.

- [29] Guo, S. and Perera, M., “Optimal design of an aeroelastic wing structure with seamless control surfaces,” *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 223, pp. 1141–1151.
- [30] SmartMaterial, “Macro Fiber Composite,” 2013.
- [31] Shen, X., Han, J.-H., and Lee, I., “Study of a reduced and internally biased oxide wafer PZT actuator and its integration with shape memory alloy,” *Smart materials and structures*, Vol. 15, No. 4, 2006, pp. N89.
- [32] Helbaum, R. F., Bryant, R. G., Fox, R. L., Jalink Jr, A., Rohrbach, W. W., and Simpson, J. O., “Thin layer composite unimorph ferroelectric driver and sensor,” *National Aeronautics and Space Administration Report*, Vol. 1, 1995.
- [33] Probst, T. A. and Kochersberger, K., “Smart Material Actuators as a Means of UAV Flight Control,” 2012.
- [34] Simpson, A. and Jacob, J., *Aerodynamic Control of an Inflatable Wing Using Wing Warping*, Fluid Dynamics and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2005, doi:10.2514/6.2005-5133.
- [35] Simpson, A., Jacob, J., and Smith, S., *Flight Control of a UAV with Inflatable Wings with Wing Warping*, Fluid Dynamics and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2006, doi:10.2514/6.2006-2831.
- [36] Smith, S. W., Doepke, E., Ashcraft, S. W., and Thamann, M. A., *Design of a Rapid Prototype Wing Warping Test Aircraft*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2013, doi:10.2514/6.2013-1925.
- [37] Thamann, M. A. and Smith, S. W., *Modeling and Flight Testing of Wing Shaping for Autonomous Flight Control*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2013, doi:10.2514/6.2013-1926.

- [38] Choon, T. W., Salleh, A. S., Jamian, S., and Ghazali, M. I., “Phase transformation temperatures for shape memory alloy wire,” *ENFORMATIKA*, Vol. 19, 2007, pp. 304–307.
- [39] Palli, G. and Melchiorri, C., “Model and control of tendon-sheath transmission systems,” *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*.
- [40] Do, T., Tjahjowidodo, T., Lau, M., Yamamoto, T., and Phee, S., “Hysteresis modeling and position control of tendon-sheath mechanism in flexible endoscopic systems,” *Mechatronics*, Vol. 24, No. 1, 2014, pp. 12–22.
- [41] Do, T., Tjahjowidodo, T., Lau, M. W. S., and Phee, S. J., “An investigation of friction-based tendon sheath model appropriate for control purposes,” *Mechanical Systems and Signal Processing*, Vol. 42, No. 1, 2014, pp. 97–114.
- [42] Ismail, M., Ikhoulane, F., and Rodellar, J., “The hysteresis Bouc-Wen model, a survey,” *Archives of Computational Methods in Engineering*, Vol. 16, No. 2, 2009, pp. 161–188.
- [43] Song, J. and Der Kiureghian, A., “Generalized Bouc–Wen model for highly asymmetric hysteresis,” *Journal of engineering mechanics*, Vol. 132, No. 6, 2006, pp. 610–618.
- [44] Tjahjowidodo, T., *Characterization, modelling and control of mechanical systems comprising material and geometrical nonlinearities*, Ph.D. thesis, Katholieke Universiteit Leuven, 2006.
- [45] Al-Bender, F., Lampaert, V., and Swevers, J., “Modeling of dry sliding friction dynamics: From heuristic models to physically motivated models and back,” *Chaos: An Interdisciplinary Journal of Nonlinear Science*, Vol. 14, No. 2, 2004, pp. 446–460.
- [46] Al-Bender, F., Symens, W., Swevers, J., and Van Brussel, H., “Theoretical analysis of the dynamic behavior of hysteresis elements in mechanical systems,” *International journal of non-linear mechanics*, Vol. 39, No. 10, 2004, pp. 1721–1735.

- [47] Lampaert, V., *Modelling and control of dry sliding friction in mechanical systems*, Ph.D. thesis, Katholieke Universiteit Leuven, 2003.
- [48] Dahl, P. R., “A solid friction model,” Tech. rep., Aerospace Corp El Segundo Ca, 1968.
- [49] Haessig, D. A. and Friedland, B., “On the modeling and simulation of friction,” *Journal of Dynamic Systems, Measurement, and Control*, Vol. 113, No. 3, 1991, pp. 354–362.
- [50] De Wit, C. C., Olsson, H., Astrom, K. J., and Lischinsky, P., “A new model for control of systems with friction,” *IEEE Transactions on automatic control*, Vol. 40, No. 3, 1995, pp. 419–425.
- [51] Swevers, J., Al-Bender, F., Ganseman, C. G., and Projogo, T., “An integrated friction model structure with improved presliding behavior for accurate friction compensation,” *IEEE Transactions on automatic control*, Vol. 45, No. 4, 2000, pp. 675–686.
- [52] Lampaert, V., Swevers, J., and Al-Bender, F., “Modification of the Leuven integrated friction model structure,” *IEEE transactions on Automatic Control*, Vol. 47, No. 4, 2002, pp. 683–687.
- [53] Lampaert, V., Al-Bender, F., and Swevers, J., “A generalized Maxwell-slip friction model appropriate for control purposes,” *Physics and Control, 2003. Proceedings. 2003 International Conference*, Vol. 4, IEEE, 2003, pp. 1170–1177.
- [54] Chao, H., Cao, Y., and Chen, Y., “Autopilots for Small Fixed-Wing Unmanned Air Vehicles: A Survey,” *Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation*, 2007.
- [55] Sawant, S., Davari, A., and Jin, W., “Trajectory tracking of UAV using robust inventory control techniques,” *System Theory, 2005. SSST '05. Proceedings of the Thirty-Seventh Southeastern Symposium on*, pp. 98–101.

- [56] Sadraey, M. and Colgren, R., *Robust Nonlinear Controller Design for a Complete UAV Mission*, Guidance, Navigation, and Control and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2006, doi:10.2514/6.2006-6687.
- [57] Capello, E., Guglieri, G., Quagliotti, F., and Sartori, D., “Design and Validation of an L1 Adaptive Controller for Mini-UAV Autopilot,” *Journal of Intelligent and Robotic Systems*, Vol. 69, No. 1-4, 2012, pp. 109–118.
- [58] Cook, R. G., Palacios, R., and Goulart, P., “Robust Gust Alleviation and Stabilization of Very Flexible Aircraft,” *AIAA Journal*, Vol. 51, No. 2, 2013, pp. 330–340.
- [59] Kaloust, J., “ESARCS: Enhanced Stall And Recovery Control System: A Nonlinear Model-Based Flight Control System for UAV,” *AIAA’s 1st Technical Conference and Workshop on Unmanned Aerospace Vehicles*.
- [60] Shao, K., Yang, C., Wu, Z., Liu, H., and Wen, B., “Design of a Gust-Response-Alleviation Online Control System Based on Neuro-Fuzzy Theory,” *Journal of Aircraft*, Vol. 50, No. 2, 2013, pp. 599–609.
- [61] Pashilkar, A. A., Sundararajan, N., and Saratchandran, P., “Neuro Controller for Aircraft Auto landing Under Severe Winds and Control Surface Failures,” *AIAA Aerospace Sciences Meeting and Exhibit*, 2005.
- [62] Grigorie, L. and Botez, R., “Adaptive Neuro-Fuzzy Inference Controllers for Smart Material Actuators,” 12 - 15 April 2010 2010.
- [63] Patil, M. and Taylor, D., *Gust Response of Highly Flexible Aircraft*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, may 2006, doi:10.2514/6.2006-1638.
- [64] Pisano, W. and Lawrence, D., “Autonomous Gust Insensitive Aircraft,” 2008.
- [65] Ricci, S. and Scotti, A., “Gust Response Alleviation on Flexible Aircraft Using Multi-Surface Control,” *51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*.

- [66] Su, W. and Cesnik, C., *Nonlinear Aeroelasticity of a Very Flexible Blended-Wing-Body Aircraft*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2009, doi:10.2514/6.2009-2402.
- [67] Love, M., Zink, P., Wieselmann, P., and Youngren, H., “Body Freedom Flutter of High Aspect Ratio Flying Wings,” *46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, AIAA.
- [68] D’Eleuterio, G. M. T. and Barfoot, T. D., “A Discrete Quasi-Coordinate Formulation for the Dynamics of Elastic Bodies,” *Journal of Applied Mechanics*, Vol. 74, No. 2, 2007, pp. 231.
- [69] Khot, N., Appa, K., and Eastep, F., “Actuating System for Enhancement of Rolling Maneuver of a Wing with Ailerons,” *Proceedings of the 40th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, AIAA/ASME/AHS Adaptive Structures Forum and AIAA Forum on Non-Deterministic Approaches*.
- [70] Khot, N. S., Appa, K., and Eastep, F. E., “Optimization of Flexible Wing Without Ailerons for Rolling Maneuver,” *Journal of Aircraft*, Vol. 37, No. 5, 2000, pp. 892–897.
- [71] Khot, N. S., K.Appa, and Ausmarr, J., *Deformation of a Flexible Wing Using an Actuating System for a Rolling Maneuver Without Ailerons*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 1998.
- [72] Kojima, R., Ogawara, K., and Shingin, H., “Micro UAV Holonomy Control System Robust for Gust Wind,” *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*.
- [73] Kureemum, R. and Bates, D., *Aircraft flight controls design using constrained output feedback - An H-infinity loopshaping approach*, Guidance, Navigation, and Control and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2001, doi:10.2514/6.2001-4281.

- [74] Raza, S. A. and Etele, J., “Simulation Tool for Testing and Validating UAV Autopilots in Wind Gust Environments,” *AIAA Atmospheric Flight Mechanics Conference*.
- [75] Regisford, S. J. S. and VanderMey, J. T., “Perching a Minimally-Actuated Micro Air Vehicle,” 2013.
- [76] Rowe, J., Smith, S., Simpson, A., Jacob, J., and Scarborough, S., *Development of a Finite Element Model of Warping Inflatable Wings*, Structures, Structural Dynamics, and Materials and Co-located Conferences, American Institute of Aeronautics and Astronautics, 2006, doi:10.2514/6.2006-1697.
- [77] Vos, R., Gurdal, Z., and Abdalla, M., “Mechanism for Warp-Controlled Twist of a Morphing Wing,” *Journal of Aircraft*, Vol. 47, No. 2, 2010, pp. 450–457.
- [78] Lee, S., Tjahjowidodo, T., and Moon, S. K., “Flexible membrane wing warping using tendon-sheath mechanism,” *Control and Automation (MED), 2015 23th Mediterranean Conference*, June 2015, pp. 624–629.
- [79] Kaneko, M., Yamashita, T., and Tanie, K., “Basic considerations on transmission characteristics for tendon drive robots,” *Advanced Robotics, 1991. 'Robots in Unstructured Environments', 91 ICAR., Fifth International Conference on*, IEEE, 1991, pp. 827–832.
- [80] Tjahjowidodo, T., “Theoretical analysis of the dynamic behavior of presliding rolling friction via skeleton technique,” *Mechanical Systems and Signal Processing*, Vol. 29, 2012, pp. 296–309.
- [81] Hassani, V., Tjahjowidodo, T., and Do, T. N., “A survey on hysteresis modeling, identification and control,” *Mechanical systems and signal processing*, Vol. 49, No. 1, 2014, pp. 209–233.
- [82] Minh, T. V., Tjahjowidodo, T., Ramon, H., and Van Brussel, H., “Control of a pneumatic artificial muscle (PAM) with model-based hysteresis compensation,” *Advanced Intelligent Mechatronics, 2009. AIM 2009. IEEE/ASME International Conference on*, IEEE, 2009, pp. 1082–1087.

- [83] Minh, T. V., Tjahjowidodo, T., Ramon, H., and Van Brussel, H., “Non-local memory hysteresis in a pneumatic artificial muscle (PAM),” *Control and Automation, 2009. MED’09. 17th Mediterranean Conference on*, IEEE, 2009, pp. 640–645.
- [84] Hassani, V. and Tjahjowidodo, T., “Structural response investigation of a triangular-based piezoelectric drive mechanism to hysteresis effect of the piezoelectric actuator,” *Mechanical Systems and Signal Processing*, Vol. 36, No. 1, 2013, pp. 210–223.
- [85] Wang, D. P., Bartley-Cho, J. D., Martin, C. A., and Hallam, B. J., “Development of high-rate large-deflection hingeless trailing-edge control surface for the Smart Wing wind tunnel model,” *SPIE’s 8th Annual International Symposium on Smart Structures and Materials*, International Society for Optics and Photonics, 2001, pp. 407–418.
- [86] Kaneko, M., Wada, M., Maekawa, H., and Tanie, K., “A new consideration on tendon-tension control system of robot hands,” *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on*, IEEE, 1991, pp. 1028–1033.
- [87] Lin, C.-J. and Lin, P.-T., “Tracking control of a biaxial piezo-actuated positioning stage using generalized Duhem model,” *Computers & Mathematics with Applications*, Vol. 64, No. 5, 2012, pp. 766–787.
- [88] Rakotondrabe, M., “Bouc–Wen modeling and inverse multiplicative structure to compensate hysteresis nonlinearity in piezoelectric actuators,” *IEEE Transactions on Automation Science and Engineering*, Vol. 8, No. 2, 2011, pp. 428–431.
- [89] Wang, D., Zhu, W., and Yang, Q., “Linearization of stack piezoelectric ceramic actuators based on Bouc-Wen model,” *Journal of Intelligent Material Systems and Structures*, Vol. 22, No. 5, 2011, pp. 401–413.
- [90] Hoblit, F. M., *Gust loads on aircraft: concepts and applications*, AIAA, 1988.
- [91] Do, T., Tjahjowidodo, T., Lau, M., and Phee, S., “A new approach of friction model for tendon-sheath actuated surgical systems: Nonlinear modelling and parameter identification,” *Mechanism and Machine Theory*, Vol. 85, 2015, pp. 14–24.

- [92] Choi, E. C., “Wind characteristics of tropical thunderstorms,” *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 84, No. 2, 2000, pp. 215–226.
- [93] *Ansys Fluent Software*.
- [94] Jones, W. and Launder, B., “The prediction of laminarization with a two-equation model of turbulence,” *International journal of heat and mass transfer*, Vol. 15, No. 2, 1972, pp. 301–314.
- [95] *FLUENT Documentation*, 2005.
- [96] SARIOĞLU, M. and Yavuz, T., “Vortex shedding from circular and rectangular cylinders placed horizontally in a turbulent flow,” *Turkish Journal of Engineering and Environmental Sciences*, Vol. 24, No. 4, 2000, pp. 217–228.
- [97] Tjahjowidodo, T. and Lee, S., “Tendon-Sheath Mechanisms in Flexible Membrane Wing Mini-UAVs: Control and Performance,” *International Journal of Aerospace Engineering*, Vol. 2017, 2017.
- [98] Raymer, D. P., *Aircraft Design: A Conceptual Approach and Rds-student, Software for Aircraft Design, Sizing, and Performance Set (AIAA Education)*, AIAA, 2006.
- [99] Sadraey, M. H., *Aircraft Design: A Systems Engineering Approach*, John Wiley & Sons, 2012.
- [100] Schwarz, B. J. and Richardson, M. H., “Experimental modal analysis,” *CSI Reliability week*, Vol. 35, No. 1, 1999, pp. 1–12.
- [101] CRGIS, N. L., “A Wind Tunnel Gust Response Technique,” <https://youtu.be/ahjkA1u52Vw?t=2m10s>, Accessed: 2016-05-08.
- [102] Tang, D., Cizmas, P. G., and Dowell, E., “Experiments and analysis for a gust generator in a wind tunnel,” *Journal of aircraft*, Vol. 33, No. 1, 1996, pp. 139–148.
- [103] Xu, H., Xing, S., and Ye, Z., “Numerical Study of an Airfoil/Rotating-Slotted-Cylinder Based Flutter Exciter,” *Journal of Aircraft*, Vol. 52, No. 6, 2015, pp. 2100–2105.

List of publications:

International Journals:

1. Lee, S, Tjahjowidodo, T., Lee, H. C., Lai, B., “Investigation of a robust tendon-sheath mechanism for flexible membrane wing application in mini-UAV”, *Mechanical Systems and Signal Processing*, Accepted for publication.
2. Tjahjowidodo, T. and Lee, S., “Tendon-Sheath Mechanism Actuated Flexible Membrane Wing Mini-UAV Characterization, Control and Flight” *International Journal of Aerospace Engineering*, Vol. 2017, 2017.

International Paper Conferences:

1. Lee, S., Tjahjowidodo, T., and Moon, S. K., “Flexible membrane wing warping using tendon-sheath mechanism”, *Control and Automation (MED), 2015 23th Mediterranean Conference*, June 2015, pp. 624-629.
2. Lee, S., Tjahjowidodo, T., and Lee, H. C., “Wing Warping Control of Flexible Membrane Wing Under Gusty Conditions”, *International Conference on Noise and Vibration Engineering (ISMA)*, September 2016.