DEVELOPMENT OF A SERVO-DRIVEN FLAPPING-WING AIR VEHICLE WITH FOLDING-WING MECHANISM

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Abstract

This study endeavors to achieve a heightened fidelity in emulating avian flight principles by developing a flapping-wing air vehicle (FWAV) with the capability to perform an extensive wing motion. For this purpose, flapping-wing motion is implemented using servo motors, consequently augmenting the degrees of freedom in wing movement. Initially, a folding-wing mechanism for enhancing lift is designed, followed by the establishment of a flapping-wing flight simulation environment to assess the feasibility. To accomplish this, aerodynamic and dynamic models are formulated and subsequently validated. Additionally, a prototype is manufactured for flight testing, enabling an analysis of flight control and performance. This study aims to more accurately mimic avian flight principles by developing a FWAV capable of various wing movements. By giving the main wing an additional degree of freedom, it provides information on new design methods and performance improvements. Furthermore, this study demonstrates the potential for the development of realistic FWAVs based on principles observed in nature.

Keywords: Flapping-Wing Air Vehicle (FWAV), Servo Motor Actuation, Folding-Wing Mechanism, Bird-Inspired Flight

1. Introduction

The flapping-wing air vehicle (FWAV) operates flapping motions in various ways, classified based on the driving method and wing structure. In terms of the driving method, it can be categorized into those using DC motors [1] and those using servo motors [2]. When using DC motors, the rotational motion of the motor needs to be converted into flapping motion through a gearbox and link mechanism. Servo motors are directly attached to both wings, generating flapping motion. Regarding wing structure, it can be divided into a single-joint wing [3] and a compound-joint wing [1]. The single-joint wing has a flat appearance, and its wing shape remains constant. The compound-joint wing has joints attached to the wing, allowing for wing folding or shape changes. Examples include Dove [3], a basic FWAV with a mass of 220 g, wingspan of 0.5 m, DC motor drive, and a single-joint wing. While it achieves a high speed of 12 m/s with rapid flapping frequency at 12 Hz, it has a relatively simple flapping motion as it cannot fold its wings. FESTO's SmartBird [1], weighing 450 g with a 2 m wingspan, uses DC motors and a link mechanism for flapping motion. It employs a compound-joint wing, enabling the folding of the main wing, but due to a 1-degree-of-freedom mechanism, it can only produce a single flapping motion without changing the flapping amplitude. Robo Raven [2], with a mass of 290 g and a wingspan of 1.17 m, employs servo motors for flapping motion. It can independently control both main wings, but the wings lack joints and are covered only with a flexible membrane, preventing active folding of the wings.

There examples have flapping motions with either constant or non-foldable wings. Currently, a FWAV capable of controlling both flapping and folding motions has not been developed. Therefore, replicating the flapping motion of actual birds, efficiently generating lift, or achieving agile maneuverability remains challenging. Therefore, this study aims to address these issues and focus on obtaining excellent maneuverability. The goal is to develop a FWAV capable of implementing various flapping motions through servo motor drive. Additionally, by applying a mechanism allowing the wings to actively fold, the study aims to more realistically mimic avian flapping and achieve agile flight maneuverability. To achieve this, the servo-driven FWAV with folding-wing mechanism is designed, simulated, and ultimately validated through flight tests.

2. Design of Flapping-Wing Air Vehicle

2.1 Conceptual Design

A servo-driven FWAV was designed to emulate the flapping motion of birds by actively controlling flapping and folding motions through the wing joints. The primary objective of this design is to achieve agile maneuverability by independently controlling the main wings, which improves aerodynamic efficiency for optimal flight performance. The lightweight nature of servo motors is anticipated to contribute to the stability of flight, particularly at low flapping frequencies. This design aims to closely mimic the wing movements of actual birds.

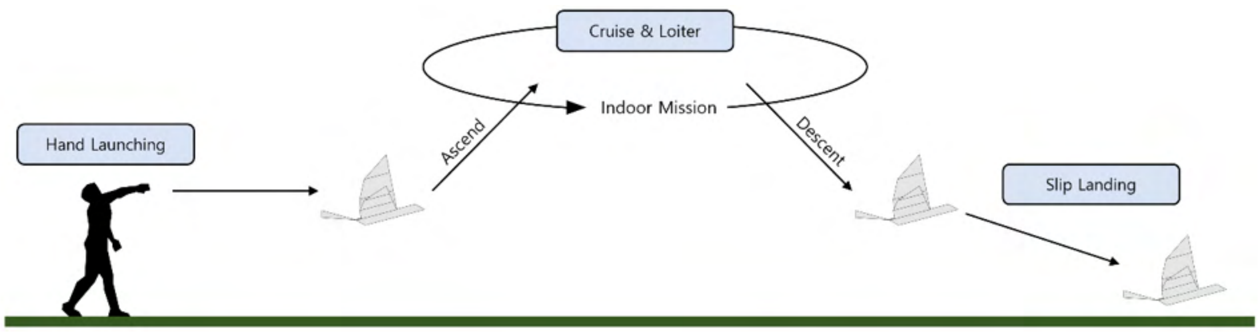


Figure 1 – Mission process

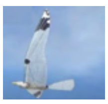
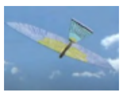
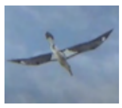
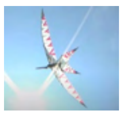
Unlike conventional fixed-wing aircraft, the FWAV takes off differently by being thrown by a person, gaining initial velocity through manual launch instead of using a runway. Once the FWAV achieves stable flight, it ascends while performing its designated mission. Upon reaching a certain altitude, it transitions into cruising and turning flight modes tailored to the specific mission, with the flight path varying based on the nature of the task.

Due to the FWAV's lightweight design powered by servo motors, the FWAV is sensitive to external environmental factors. Consequently, this FWAV is deemed suitable for indoor missions, characterized by low cruising speed, short turning radius, and high agility. After completing indoor missions, the FWAV gradually reduces altitude and lands on the ground without the need for additional landing gear.

2.2 Configuration Design

Prior to detailed exterior design of the FWAV, a foundational configuration design was undertaken. Initially, the overall wingspan was set at 1 m for ease of fabrication in the laboratory setting and compatibility with the installation of servo motor modules.

Table 1 – Wingspan and mass of servo-driven FWAVs

	eMotion Butterfly [4]	Bobo Raven [2]	USTBird [5]	SFO Seagull [6]	SFO Pteranodon [7]	SFO Kestrel [8]	SFO Albatross [9]	SFO Pterodyactyl [10]
Figure								
Wingspan	0.5 m	1.168 m	0.8 m	1.02 m	3.04 m	1 m	1.41 m	1.07 m
Mass	32 g	290 g	83.2 g	36 g	384 g	45 g	57 g	33.5 g

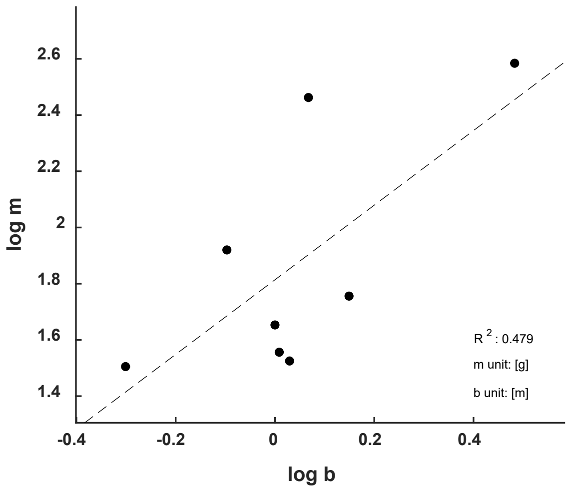


Figure 2 – Regression analysis for wingspan and mass

Table 1 summarizes an extensive survey of various servo-driven FWAV, consolidating their wingspan and masses. Through regression analysis, a relationship equation between wingspan and mass was estimated. Based on this, the estimated mass of a 1 m wingspan FWAV is about 65 g.

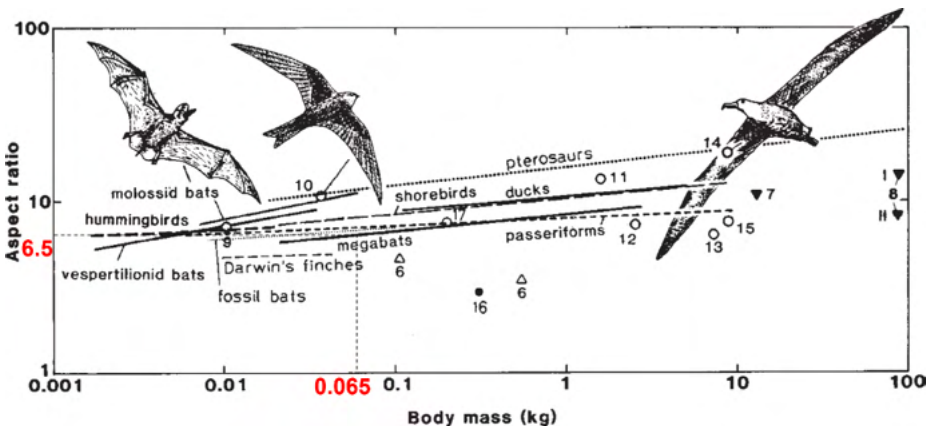


Figure 3 – Aspect ratio and mass of flying animals [11]

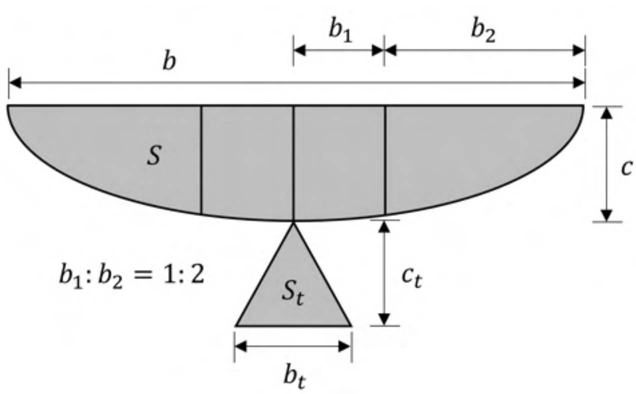


Figure 4 – Basic configuration of FWAV

Table 2 – Configuration design specifications

	Wingspan b	Wing Area S	Root Chord c	Mean Chord c_m	Aspect Ratio AR
Main wing	1 m	0.1571 m^2	0.2 m	0.1571 m^2	6.4
Tail wing	0.2 m	0.018 m^2	0.18 m	0.09 m	2.2

Furthermore, predicting the aspect ratio of goose wings yields approximately 6.5. Assuming the estimated total mass of the FWAV is 65 g with assumed semi-elliptical wing shape, which minimizes induced drag, and aspect ratio of 6.5, the estimated wing root chord length will be 0.2 m. These assumptions serve as the basis for the detailed exterior design of the FWAV.

2.3 Flapping-Wing Mechanism Design

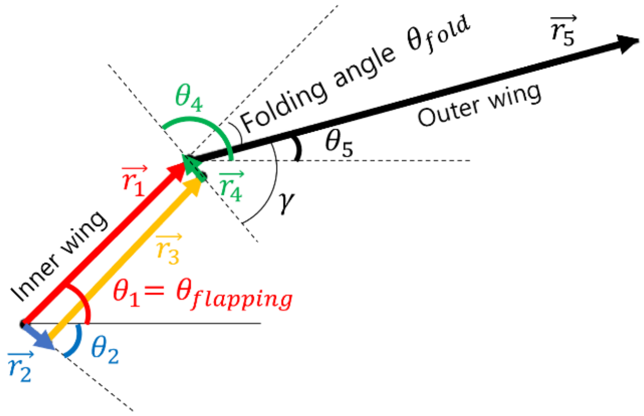


Figure 5 – Main wing link vectors

One side of the FWAV is equipped with two servo motors, responsible for controlling the flapping and folding motion separately. The first servo motor, attached to the body of the FWAV, is directly connected to the inner wing (highlighted in red in Fig. 5) to generate the flapping motion. To create the folding motion, the second servo motor must be configured to induce the outer wing's rotational motion. However, attaching the second servo motor to the inner wing would impose a significant torque on the first servo motor, which was responsible for generating the flapping motion, due to its weight.

To address this issue, the second servo motor is attached to the body at the same location as the first servo motor. In this configuration, the second servo motor does not directly attach to the outer wing; instead, it transmits power through and a 4-bar linkage from the body side. Consequently, as depicted in Fig. 5, the effective control input variables are the angles θ_1 of the first servo motor and θ_2 of the second servo motor.

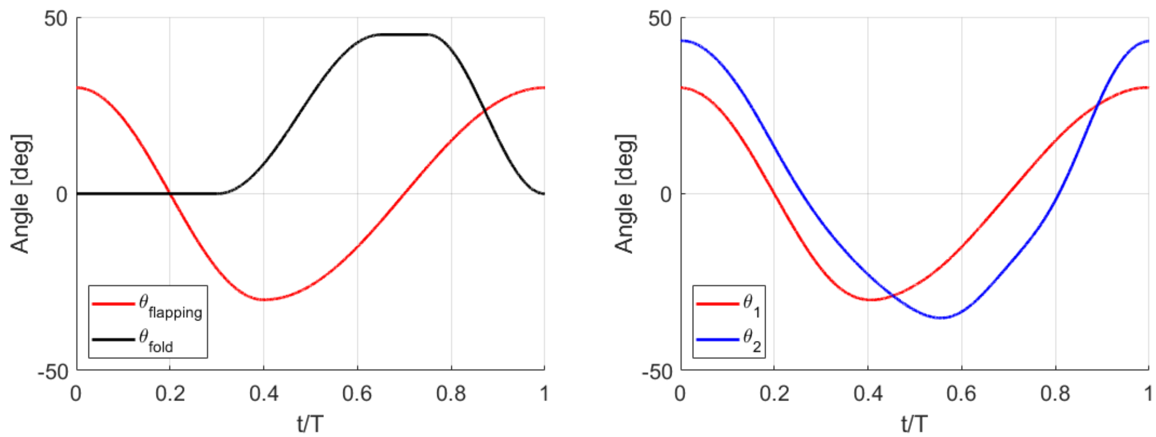


Figure 6 – Convert from flapping and folding angles to servo input angles

Therefore, by setting the flapping angle $\theta_{flapping}$ and folding angle θ_{fold} for one flapping cycle, the servo motor angles θ_1 and θ_2 can be determined.

3. Flight Simulation

3.1 Dynamic Model

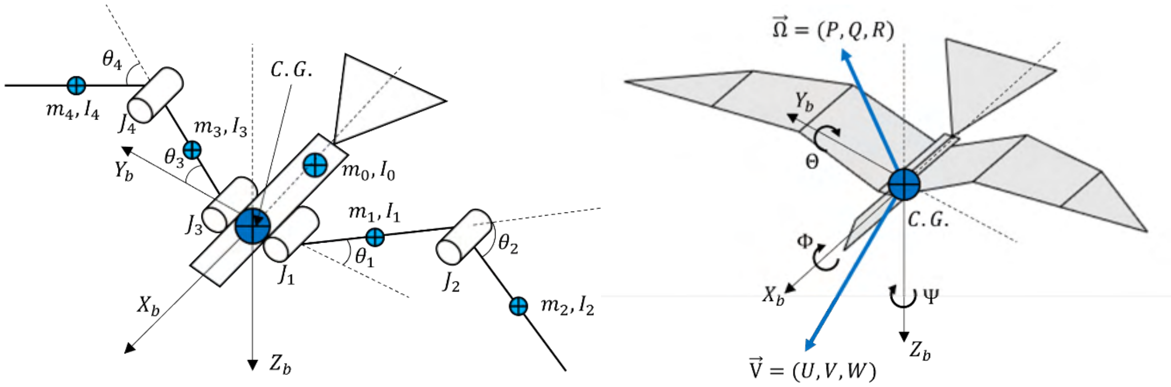


Figure 7 – Schematic diagram of rigid body model

The FWAV can be assumed to have a rigid body model, except for the flexible membrane comprising the wing surface. To achieve this, the proposed servo-driven FWAV in this study can be configured as a rigid body model system, consisting of a total of four wing joints and five links representing the body, inner wings, and the outer wings. The schematic diagram of the rigid body model of the FWAV and the mass and length of each link are illustrated in Fig. 7. Although the position of the center of gravity varies slightly with the angle of the wing joint, however, due to the significantly lighter weight of the wings compared to the body, it can be assumed that the center of gravity remains nearly constant. Therefore, by fixing the position of the center of gravity on the body link and establishing the center of the coordinate system at this point, a body-fixed coordinate system for the FWAV can be defined. The main wing of the FWAV can unfold completely and fold back, leading to a relatively large variation in the moment of inertia. Utilizing the mass, moment of inertia, and the body-fixed coordinate system of the FWAV, the equations of motion for the 6 degrees of freedom in three-dimensional space can be formulated.

3.2 Aerodynamic Model

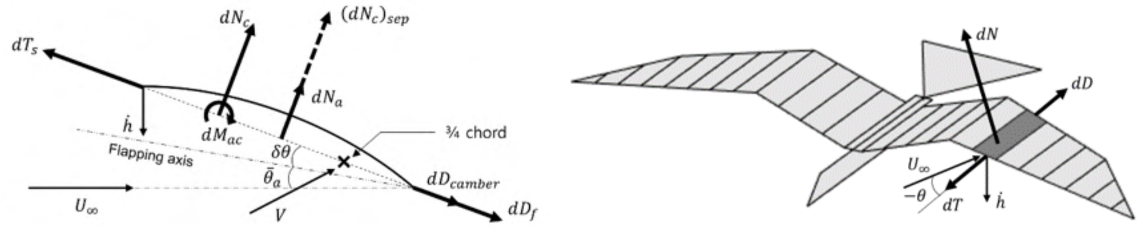


Figure 8 – Aerodynamic model applied on FWAV

The Modified Strip Theory (MST) [12] is a theoretical framework that predicts changes in the angle of attack acting on the wing cross-section by considering the wake effect, flow separation, effects due to viscosity, and the velocity induced by flapping. By applying this aerodynamic model, the lift force can be accurately calculated, and when integrated into the equations of motion, it enables an accurate simulation of the dynamic characteristics of the FWAV. As illustrated in Fig. 8, the main wing is divided into thin strips in the longitudinal direction, and the corresponding incremental aerodynamic forces are integrated to calculate the final aerodynamic forces at each time step.

3.3 Flight Control

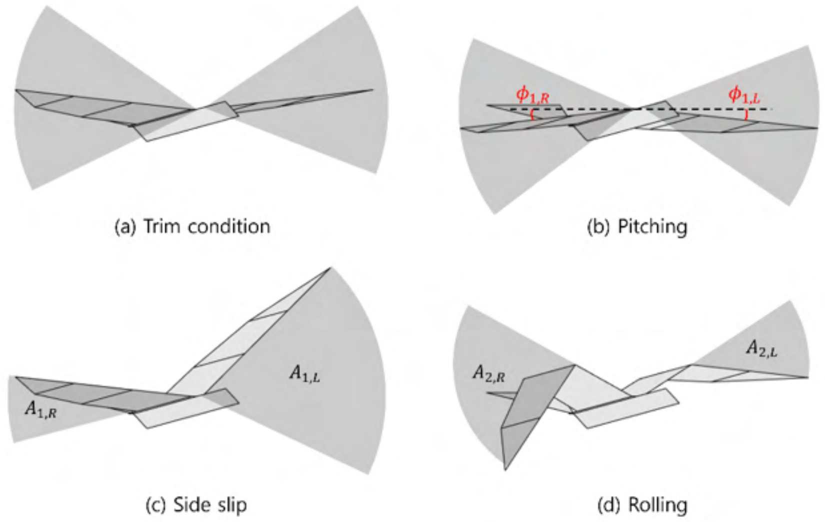


Figure 9 – Control force generation method

The method depicted in Fig.9 allows for the modification of flapping patterns to generate aerodynamic forces and moments. Let's consider a scenario where the FWAV is assumed to be flying at a constant speed under trim conditions as shown in Fig. 9(a). Adjusting the dihedral angles of the left and right wings as shown in Fig. 9(b) induces a pitching moment. Also, varying the flapping amplitudes, as illustrated in Fig.9(c) allows for control to prevent side slip by generating lateral forces. If the folding angles are changed asymmetrically as seen in Fig. 9(d), a rolling moment is generated. Additionally, increasing the flapping frequency can enhance cruising speed and facilitate altitude gain. By applying these strategies to modify the flapping motions, control over the flight maneuverability of the FWAV can be achieved.

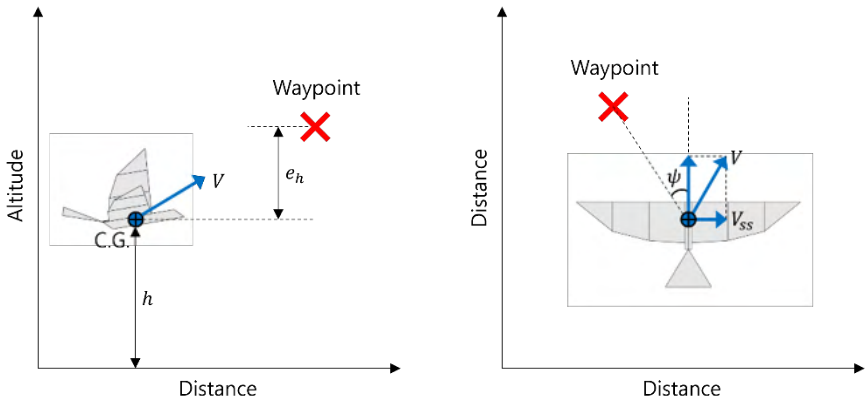


Figure 10 – Waypoint tracking

After establishing the aerodynamic and dynamic models of the FWAV, flight simulations were conducted. The simulation was divided into two main parts: first, the longitudinal control adjusted the altitude and speed, and second, the lateral control modified the flight direction.

The left side of Fig. 10 illustrates how the aircraft tracks waypoints during longitudinal control. In this case, altitude error and velocity error are controlled. The right side of Fig. 10 depicts the tracking of waypoints during lateral control. In this case, direction angle and side slip are controlled.

Flight control is based on a closed-loop control system, employing the classical PID control techniques. The controller received errors in flight data, such as altitude or velocity of the FWAV, as input and generated the control commands. Control inputs included flapping frequency, dihedral angles of both main wings, flapping amplitude, and folding angles. These control input variables determined the flapping motion at each time step.

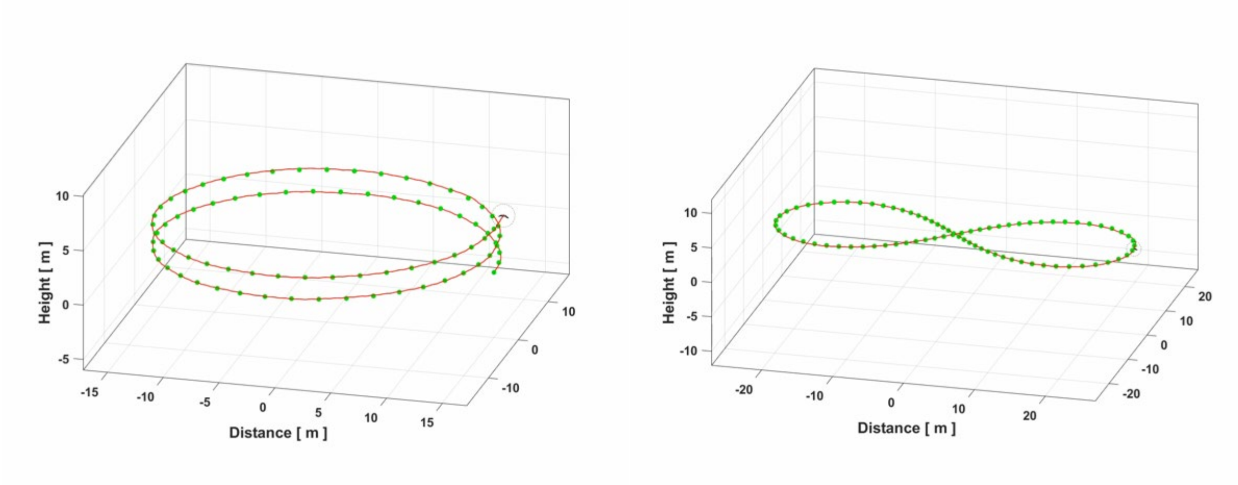


Figure 11 – Simulation of trajectory tracking with flight control

As shown in Fig. 11, the FWAV could exhibit a helical ascent trajectory while simultaneously performing turning flight and altitude ascent. The simulation demonstrated that the FWAV had the capability to follow the desired trajectory accurately. Through the flight simulations, the anticipation of the control strategies and flight performance can be made.

4. Flight Test

4.1 Fabrication

Figure 12 – Servo-driven FWAV CAD design(left) and fabrication(right)

To conduct flight tests, detailed design of the FWAV was undertaken. The designed configuration depicted in Fig. 12 (left) was achieved using the Computer Aided Design (CAD) software. Lightweight materials were primarily utilized to ensure the low weight of the prototype FWAV. The shape of the main wing was semi-elliptical. Four servo motors, responsible for flapping motion, were arranged for the flapping mechanism, and were attached to the body. The triangular-shaped horizontal tail maintained a consistent angle relative to the body.

The wing frame was constructed with carbon rods while the remaining body and joint components were produced using polylactic acid (PLA) material from a 3D printer. Additionally, polyethylene foam was employed for the wing membranes. Through these material choices and configuration design, a balance between the lightweight nature and robust durability of the FWAV was achieved. The completed FWAV is illustrated in Fig. 12 (right) with a total mass of 65 g and a wingspan of 1 m.

4.2 Flight Performance

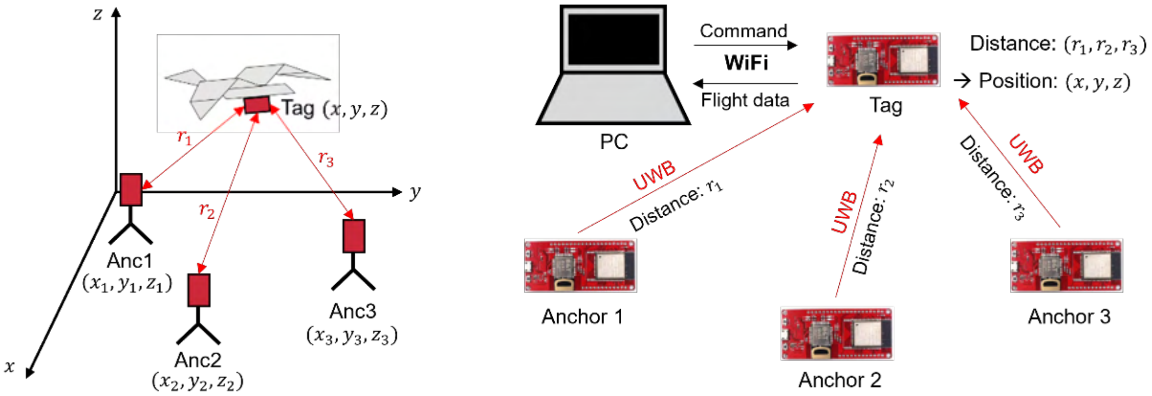


Figure 13 – Position measurement environment

An environment was established to collect flight data by installing three anchors in the ground coordinate system as shown in Fig. 13. The distances from the tags attached to the FWAV were used to calculate its position. The ultra-wideband wireless communication module was employed for this purpose. The calculated position information from the tags was transmitted to a PC via Wi-Fi, and the PC sent control commands back to the tags. This experimental setup allowed real-time measurement of the position and the speed within an indoor space.

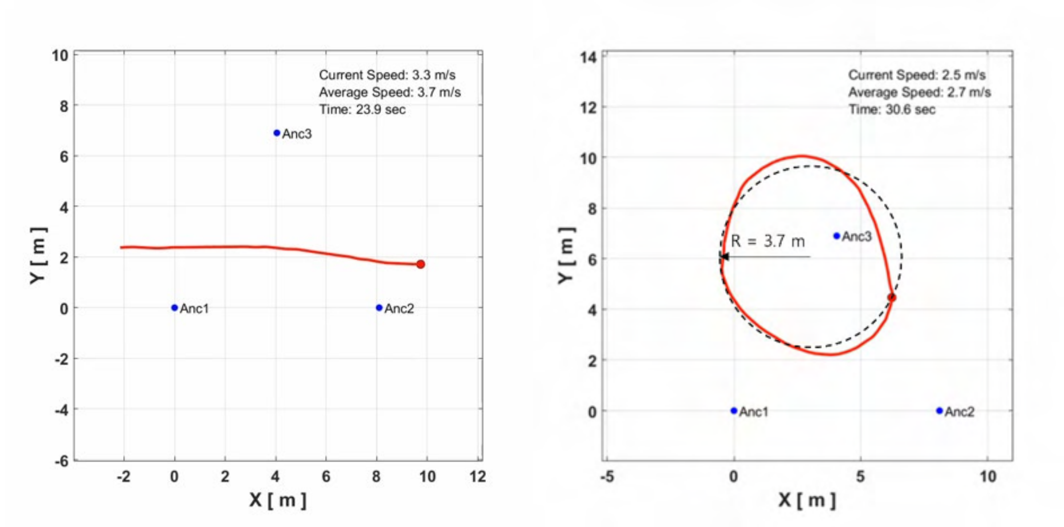


Figure 14 – Flight test measurement of the forward and circular trajectory

Fig. 14 shows the flight data measurements for forward flight performances. With a flapping frequency of 3.2 Hz, the FWAV maintained an average flight speed of 3.7m/s and a body pitch angle of 10 degrees, enabling level flight. The observed trim conditions in the experiments were found to be similar to the simulation results. Furthermore, it was verified that the FWAV could maintain altitude stably and perform turning flight. The turning radius was 3.7 m, and the previously designed control logic was successfully applied for smooth flight. Through flight tests, the confirmed minimum turning radius was 2 m.

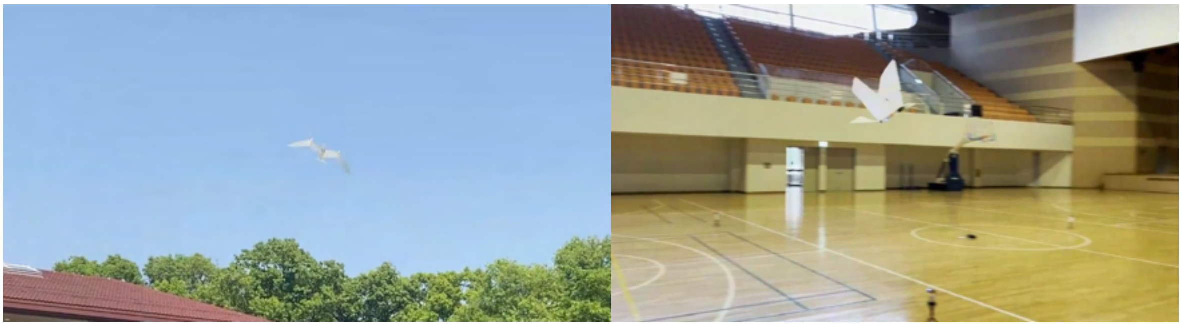


Figure 15 – Outdoor and indoor flight tests

Figure 15 depicts the indoor and outdoor flight tests. The FWAV flew at low speeds, making it suitable for indoor flight, which is where it is relatively safe. In addition, due to the FWAV's lightweight, it is well-suited for indoor flight but under windless conditions. Nevertheless, the FWAV still demonstrated decent outdoor flight capabilities. In outdoor flight tests, a maximum flight time of 3 minutes was recorded. The flight tests confirmed that the FWAV can fly freely in both indoor and outdoor spaces.

5. Conclusion

In this study, a flapping-wing mechanism that is powered by servo motors was proposed to realistically emulate avian wing movements. To achieve this, a 4-degree-of-freedom mechanism that utilized four servo motors was developed to control flapping and folding motions simultaneously. To create a servo-driven FWAV, the initial design configuration was conducted by examining various avian species to determine the weight and body length needed for a 1m wingspan flapping vehicle. The study focused on emulating goose wing movements. Additionally, flight simulations were performed to confirm the feasibility and control strategy of the FWAV. Dynamic and aerodynamic models were developed, and parameters for wing motion function were defined. Based on these models, the flight trajectory during flight was successfully controlled.

Finally, a prototype was fabricated for flight tests. Through these tests, it was confirmed that the FWAV exhibited compliant altitude ascent rates and stable flight at a relatively low speed of approximately 3.7 m/s. The vehicle demonstrated a flight endurance of up to 3 minutes, with a minimum turning radius of 2 meters. This confirms that the proposed servo-driven FWAV can closely mimic actual avian wing movements, resulting in enhanced maneuverability.

Figure 16 – Folding wings of birds

6. Acknowledgments

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8. Copyright Statement

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