Biomimetic FOC Cable Driven Variable Amplitude Flapping Wing Robot

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***Abstract*—From the inception of human flight, engineers have sought to mimic and replicate flapping-wing flight. Given birds exhibit superior efficiency and advantageous characteristics such as low noise and high maneuverability compared to conventional UAV technologies, advancing flapping-wing aerial vehicle (FWAV) designs is essential. The continued development of FWAV technology aims to refine performance and enhance capabilities, bringing them closer to those of their biological counterparts.**

This paper aims to show a path forward to variable amplitude flapping wing drive mechanism with a unique cable-driven mechanism mimicking the bird's pectoralis and supracoraoideus muscles. Without variable amplitude flapping (VAF), it is impossible to achieve the flight capabilities of birds across all flying regimes. Variable amplitude flapping is a critical feature that will be necessary for fully articulated and multi-modal FWAVs moving forward. Current focus is on achieving a symmetric flight for "pigeon" class birds. This entails the development of the first-of-its-kind implementation of drive mechanism for FWAVs that employs a Field-Oriented Control (FOC) drive for a Brushless Direct Current (BLDC) motor and a biomimetic cable-driven system to achieve variable amplitude and frequency flapping strokes.

***Index Terms*—Biomimetic, Variable Amplitude Flapping Wing, Cable-Driven, Field-Oriented Control, Flapping Wing Aerial Vehicles (FWAVs), Ornithopter**

I. INTRODUCTION

Birds are very competent creatures in many flight regimes. This is partly due to the complex musculoskeletal system evolutionarily optimized for flapping flight, far surpassing feats of performance relative to modern UAVs [1]. The flight of birds continues to put many people in awe today including many engineers who have also taken the challenge to replicating it.

New designs in industry and academia frequently move closer to mimicking bird flight. Many aspects, such as wing design, drive system design, electronics, tail design, and more, are iterated consecutively from prior work with higher fidelity.

Flapping mechanisms for FWAVs have been an aspect that has largely stayed the same over multiple years of FWAV development. Most flapping mechanisms are fixed-gear systems that can vary the frequency of flapping, although are unable to vary the amplitude. This puts fixed amplitude systems optimized for one flight regime, generally cruise. Birds, on the other hand, are fully capable of varying the frequency and amplitude of flapping. This allows birds to perform characteristic maneuvers that require different flapping amplitudes in takeoff, landing, etc.

This leads to the inference that, without variable amplitude flapping, it is impossible to mimic bird flight in all regimes. The sparrows undergoing a spiraling dive to catch its prey or taking an abrupt u-turn are some maneuvers of interest. A variable amplitude flapping wing will enable differential roll and yaw capabilities during the up-stroke and down-stroke by adequately vectoring the lift force. Such a design is a starting point for future higher fidelity designs on having a fully articulated motions. While the engineering design choices are often limited by the mass budget, endurance, and range which improve over time, the improved FOC motor technology is one step closer to fully mimic a bird.

The objective of this paper is to provide an overview of the development of K1, an FWAV with an FOC-driven VAF drive mechanism paired with a biomimetic push-pull cable system to produce flapping motion. FOC boards enable precise control over the motor's torque and speed, and accurate modulation of wing flapping angles in FWAVs. Thanks to the implementation of FOC, cable-driven mechanisms can now be effectively employed. Utilizing a biomimetic push-pull configuration offers a lightweight, efficient, and flexible method for precise motion transmission.

The background of bird flight, field-oriented control (FOC), and cable-driven systems are discussed. Following this, a review of the related work and the proposed current drive mechanism will be presented, including an introduction to K1, the first FOC-driven, cable-driven FWAV system.

II. BACKGROUND

A. Natural Flight Mechanisms

Birds utilize Variable Amplitude Flapping (VAF) to adapt their wing motion for different flight modes, optimizing aerodynamic performance see Fig. 1. This adaptability is enabled by their musculoskeletal system, particularly the coordinated actions of the pectoralis and supracoracoideus muscles, which control the downstroke and upstroke, respectively [4].

During takeoff, birds rely on large wingstroke amplitudes and high wingbeat frequency to generate sufficient lift and thrust. In pigeons (Columba livia), the downstroke amplitude and sweep velocity are at their highest during this phase [1], [2]. The wings sweep through a large vertical range, accelerating a greater volume of air, which increases the lift force necessary to overcome body weight [3]. This large amplitude is critical for achieving the upward force required to lift off from a perch at low speeds.

In high-speed flight, birds reduce their wingstroke amplitude while maintaining or increasing wingbeat frequency. This adjustment minimizes drag and improves aerodynamic efficiency [5]. Studies on pigeons and black-billed magpies show that reduced amplitude, combined with optimized stroke angles, enables sustained high-speed flight with efficient force production [9].

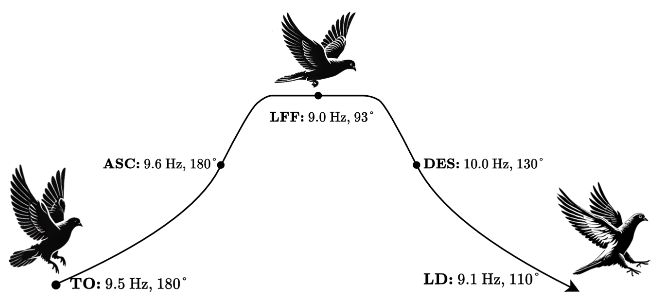

Fig. 1. Pigeon Flapping Amplitude and Frequency Over Takeoff, Ascent, Level Flight, Descent, and Landing [1]

During landing, birds adjust wing amplitude to decelerate and stabilize their descent. The downstroke is directed forward, generating rearward forces that produce drag to slow the bird [3], [7]. However, downstroke sweep velocity remains lower than during takeoff, indicating a focus on precise control rather than maximizing force output.

Although not a topic explored in this paper's developments, birds employ asymmetrical variations in wingstroke amplitude to achieve directional control. By increasing amplitude on one wing while reducing it on the other, birds can execute complex maneuvers such as banking and turning [9], [10]. This dynamic modulation of amplitude allows for precise navigation in cluttered environments.

The ability to vary flapping amplitude across these flight modes is essential for birds to achieve versatile and efficient flight. Fixed-amplitude FWAV's lack this capability, limiting their performance to specific flight regimes. Incorporating VAF into FWAV designs, through mechanisms like field-oriented control (FOC) and push-pull cable systems, is necessary to replicate the full range of avian flight dynamics [4], [11].

B. Field-Oriented Control (FOC)

FOC is a technique of controlling Brushless DC(BLDC) motors by manipulating the magnetic fields directly. Unlike ESCs (Electronic Speed Controllers) found in many traditional FWAVs, FOC allows for the independent control of torque, speed, and orientation of the brushless motor.

Generally, commercial brushless motors are modified with a radial magnet, or other attachment that allows the input of a position sensor for precise position feedback into the FOC board. This effectively enables Brushless motors to be converted into lightweight and high-performance closed-loop servos.

FOC-driven BLDC motors are commonly used in applications within robotics that require precise and high-speed positioning of actuators. Recently companies like ODrive, MJ Bots, and various others are providing robust user-friendly packages to implement FOC control on any project. In the context of FWAVs, FOC enables accurate and adaptable flapping motions necessary for Variable Amplitude Flapping (VAF). By offering precise control over motor dynamics, FOC can adjust the full position waveform to mimic flight performance across different modes, such as takeoff, cruising, and landing.

C. Cable-Driven Actuation

Cable drive systems usually consist of a flexible but non-stretchable wire or braided material to transmit actuator force over extended distances. Tension force is often routed through the use of pulleys and guides, and various configurations of transmitting the force exist.

Cable-driven actuation systems are effective in translating motion silently compared to gear-driven systems as friction is minimal, making them ideal for applications requiring a smooth and quiet operation. They also provide an efficient method for translating motion while keeping the mechanism lightweight, a critical aspect of FWAVs. In many cases of design, due to cables not needing much hardware on the actuation surface to transmit the force, inertia-sensitive areas like wings can take advantage of cable-driven mechanisms.

III. Related Work

A. Flapping Mechanisms

Many of the existing FWAV designs today continue to have flapping mechanisms that are driven by fixed gear systems [12]. Fixed gear systems drive systems rely on 3 components. A motor with variable speed control, a reduction gearbox, and a cam/linkage system to convert the rotational energy to translational for flapping.

The issue with fixed gear flapping mechanisms lies in the fact that since the linkages and gears do not change, the flapping amplitude is fixed. Due to this, most FWAVs have been optimized for a cruise with amplitudes tuned to Strouhal numbers between .2 and .4 [13]. Apart from this, the designs for these fixed gearboxes have been refined extensively, making for very reliable and repeatable results.

Even with the refinement of a fixed gear mechanism, the FWAV sphere of work in academia and industry will need to turn towards VAF for higher-fidelity models of birds in the future.

B. Existing VAF Designs

Variable amplitude flapping has been around for a very long time, although has not had the same traction as fixed gear systems due to performance drawbacks of the existing methods. Within bird scale projects ($Reynolds\# > 15000$), few tested systems exist for developing VAF.

Variable linkage systems are the first option that allows for changing stroke by changing the lever arm lengths of a crank attached to a motor. These systems are generally complex due to fixed cycling amplitudes being unable to produce the extended actuation needed from VAF. One example is a theorized version of a variable linkage system proposed by Peter Valentine in 1996, see Fig. 2, although no designs have been shown to fly using a similar system in research. Often to produce VAF using variable linkages complexity and weight outweigh the potential benefits.

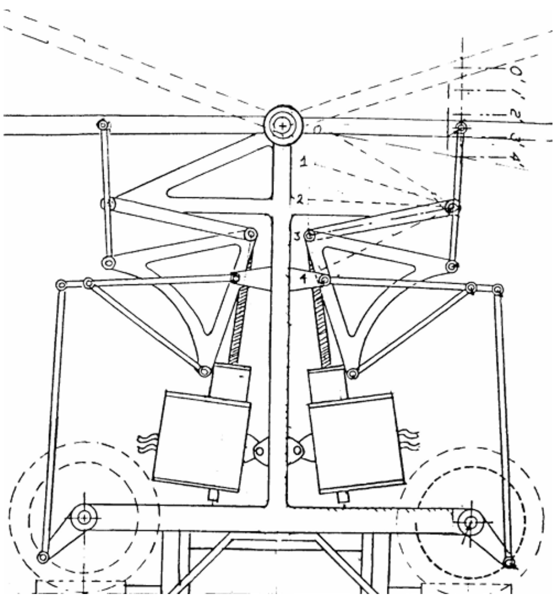

Fig. 2. Variable Stroke Linkage Mechanism [14]

Enclosed servo-driven methods are the most common form of VAF today. Servo-driven ornithopters utilize a pair of high-performance servos that can fully actuate given a control input. RoboRaven and USTBird are recent examples that allow the exploration of VAF advantages [17], [18]. These systems are easy to implement, yet face a few drawbacks. Due to multiple gear reductions embedded in servos, heat generation reduces flapping efficiency, and potentially limits the number of cycles the servo can carry out. Options are also largely limited to commercially made servos, limiting sizing.

Spring-assisted flapping drives are another mechanical method of providing variable amplitude flapping. These systems use a motor(direct or indirect drive) that oscillates back and forth, paired with an elastic rebound system to counter the inertia on the ends of the cycle [15]. Paul MacCready implemented a spring inertial system that flew briefly on the QN Pterosaur in 1986, but most of these systems today are limited to smaller-scale projects [18].

IV. Proposed Design

This section will delve into the VAF drive mechanism to be implemented on K1. The design of the proposed system has 2 parts, the drive mechanism, and the flapping mechanism. Please utilize Fig. 3 as a reference for components within the system.

A. Drive Mechanism

The ODrive S1 board generates the high-frequency and varied amplitude oscillations needed for the FWAV flapping motion. The ODrive S1 itself is a high-powered board capable of supporting 1600W for the control of a single brushless motor.

In order to perform closed-loop position control of the motor and hence the flapping angle, a radial magnet has been attached to the motor shaft, and the ODrive's onboard MA702 magnetic encoder is used.

The motor itself is a 3506 460kV brushless motor. The sizing is large, although it has been sized to accommodate for higher torque due to the lower gear ratio that will be provided by the bio-mimetic flapping mechanism. A more oblate motor also increases the inertial load by a significant factor, although through testing and simulation, the inertial load of the motor is minimal to that of the entire system and the aerodynamic loads.

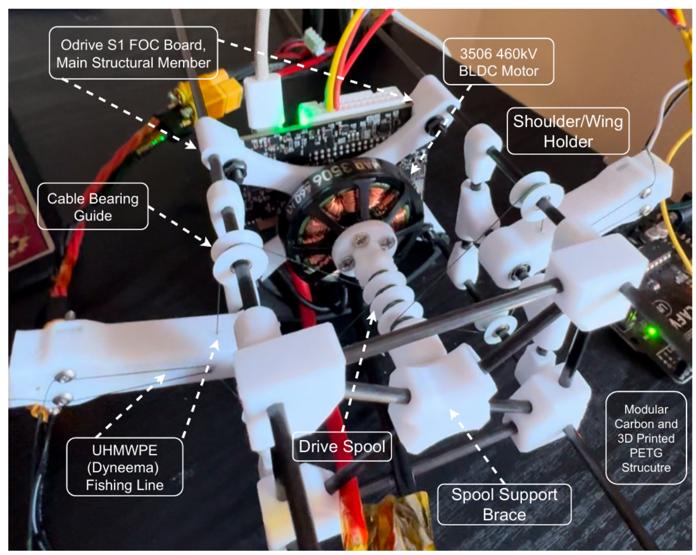

Fig. 3. K1 Drive Mechanism

The motor is mounted with a 1mm gap between the radial magnet and the encoder surface on the ODrive unit In order to offset the weight(35g) drawback of the ODrive S1 unit, the board is used with the second purpose of serving as the main structural base of the FWAV.

B. Structure

The general structure builds off of the ODrive, as four 3mm carbon fiber tubes are used as the surrounding structure tied to each corner of the ODrive. 3D printed parts in PETG are used to hold the carbon tube structure together and provide an incredibly stiff yet lightweight internal frame. Not shown in Fig. 3, the carbon tube structure is bent and jointed at the ends preloading the structure. This has increased the stiffness immensely and provides for a large volume for the placement of any payloads.

The structural design of the FWAV drive mechanism solely utilizes 3mm standard jointing giving a very modular design, allowing rapid prototyping of the design to be possible. Embedded in the spool support brace, the shoulder, and the cable guides are miniature bearings that allow the free rotation of the respective components. Alongside this, in the shoulder joints, tensioning bolts have been placed to allow for the tightening of the cable.

C. Flapping Mechanism

Since FOC control allows for high-performance rotating oscillatory motion, new flapping mechanism designs unable to be produced with standard fixed gear systems can be introduced.

In Fig. 4, general variations of different drive mechanisms are highlighted that are capable of transmitting torque to the wing shoulder joints.

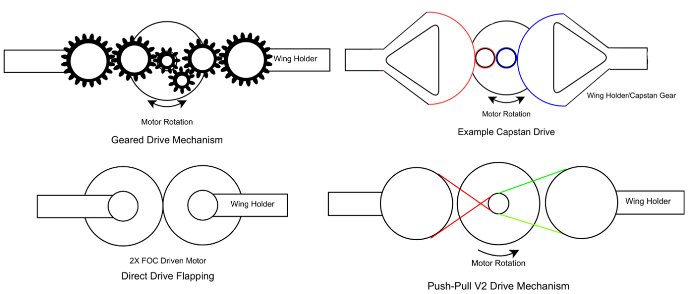

Fig. 4. Flapping Wing Mechanism Examples with FOC Driven Brushless Motors

Capstan drive, and direct drive methods are potential flapping mechanisms that may be chosen based on the needs of the user. The capability of providing an oscillatory mechanism as such opens the door for multiple more advanced for translational mechanisms for flapping wing mechanisms.

Due to a need to minimize the inertial load from the flapping mechanism, to provide the correct mechanical advantage, and to design a method that ties well into the existing carbon structure, a push-pull cable drive mechanism was chosen shown in Fig. 5.

This system uses a pair of Dyneema cables that are guided above and below the motor in opposing yet mirroring pairs. The set of cables on the bottom shown in blue and grey spool in for clockwise rotation during the downstroke. This set of strings is analogous to the role that the Pectoralis muscle in bird wings down during downstroke. Similarly, the set of cables on the top shown in red and green act as the Supracoracoideus muscles pulling the shoulder joints up for the upstroke on counterclockwise motor rotation.

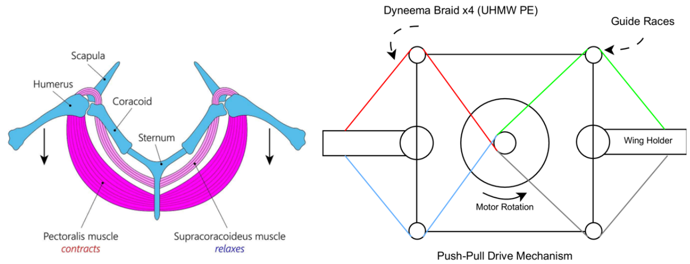

Fig. 5. K1's Biomimetic Push-Pull Cable Drive Mechanism

This cable routing design mimics the geometric layout of the avian muscular system and provides sufficient mechanical advantage for the maximum load on the system in the cycle (maximum induced drag at max velocity during the center cycle). The advantage of this system also allows for a very simple shoulder joint minimizing inertial additions.

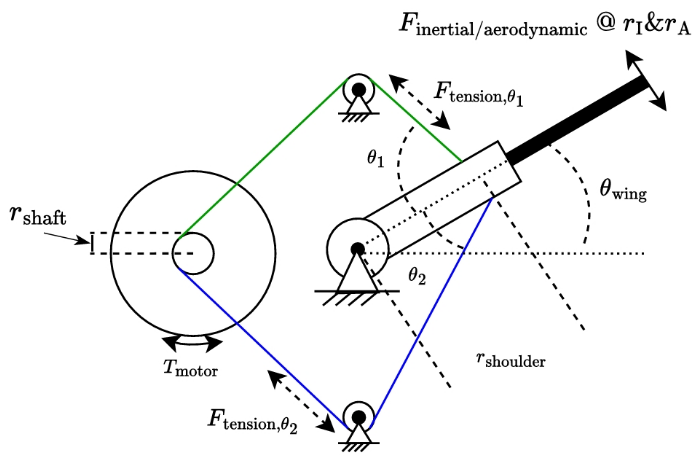

Fig. 6. Half Mechanism Dynamics Diagram

Since the cables are pulling on the shoulder joints with constant translational motion, the non-linear path of the connection point on the shoulder provides for interesting issues in tension if not properly designed.

The set of equations below are used to model the kinematics and dynamics of half of the biomimetic cable drive system shown in Fig. 6 and are used to size the radius of the shoulder joint connection point accordingly

$$\theta_{\text{wing}} = \frac{2r_{\text{shaft}}}{r_{\text{shoulder}}} \sin\left(\frac{\phi}{2}\right) \tag{1}$$

$$T_{\text{motor}} = r_{\text{shaft}}\left(F_{\text{tension},\ \theta_2} - F_{\text{tension},\ \theta_1}\right) \tag{2}$$

$$I_{\text{wing}}\ddot{\theta}_{\text{wing}} = r_{\text{shoulder}}\left(F_{\text{tension},\ \theta_2}\cos\theta_2 - F_{\text{tension},\ \theta_1}\cos\theta_1\right) - \tau_{\text{aero}} \tag{3}$$

The current range of motion as modeled for this drive mechanism is between a maximum of $\pm 60^\circ$ from horizontal, with further iterations expected to reach $\pm 90^\circ$ accommodating for all bird flight regimes

D. System Architecture

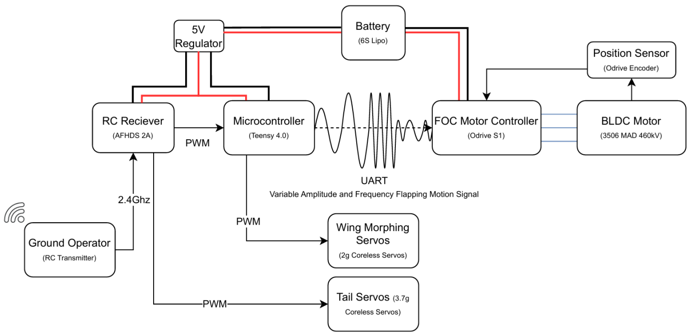

Fig. 7. Electronics Architecture

On K1, the system architecture is as seen on Fig.7. Ground-based manual control is given via an RC transmitter to the onboard RC receiver, this generates a PWM signal that is read by the microcontroller that is being used. The microcontroller then generates a pre-programmed UART signal for the given PWM value, producing a sinusoidal (any signal with variable frequency and amplitude) control command of position to the ODrive. This position control is then controlled and adjusted for by the ODrive itself. This system architecture meets the current needs to perform rapid and iterative prototype testing for tethered flights and possibly measure aerodynamic forces.

V. Further Work

In order to test the novel drive mechanism, a FWAV by the name of K1 is under development that utilizes the novel FOC drive mechanism, and a cable-driven flapping mechanism. Current ongoing work will show the achievable flapping frequencies and wing range of motion produced by K1 in flight testing. These two parameters will further lead to classifying tuneable frequency and amplitude for a symmetric flight from near vertical take-off, climb, cruise, and landing. In addition, Such metrics are a crucial step in furthering work that incorporates morphing wings which are outside the scope of current studies although will be implemented in future iterations of the project. Current video updates of the project and testing can be found on this GitHub page: https://github.com/Geourg/K1-FWAV

VI. Conclusion

The paper presents a novel drive mechanism that shows a new path forward to achieving a fully articulated flapping-wing robot for control of flight over multiple flying regimes. FOC motor control has shown prominence in robotics and is deemed to be an appropriate addition to current FWAV drive mechanisms for seamlessly achieving variable amplitude and flapping frequencies. In addition, the proposed architecture of using the cable drive mechanism not only mimics the bird muscles but also shows pathways to achieving higher fidelity in flapping wing articulation.

References

[1] K. P. Dial, "Activity patterns of the wing muscles of the pigeon (*Columba livia*) during different modes of flight," *J. Exp. Zool.*, vol. 262, pp. 357–373, 1992.

[2] G. N. Askew, R. L. Marsh, and C. P. Ellington, "The mechanical power output of the flight muscles of blue-breasted quail (*Coturnix chinensis*) during take-off," *J. Exp. Biol.*, vol. 204, pp. 3601–3619, 2001.

[3] A. M. Berg and A. A. Biewener, "Kinematics and power requirements of ascending and descending flight in the pigeon (*Columba livia*)," *J. Exp. Biol.*, vol. 211, pp. 1120–1130, 2008.

[4] B. W. Tobalske and A. A. Biewener, "Contractile properties of the pigeon supracoracoideus during different modes of flight," *J. Exp. Biol.*, vol. 211, pp. 170–179, 2008.

[5] B. W. Tobalske, T. L. Hedrick, and A. A. Biewener, "Wing kinematics of avian flight across speeds," *J. Avian Biol.*, vol. 34, pp. 177–184, 2003.

[6] K. D. Earls, "Kinematics and mechanics of ground take-off in the starling *Sturnis vulgaris* and the quail *Coturnix coturnix*," *J. Exp. Biol.*, vol. 203, pp. 725–739, 2000.

[7] P. R. Green and P. Cheng, "Variation in kinematics and dynamics of the landing flights of pigeons on a novel perch," *J. Exp. Biol.*, vol. 201, pp. 3309–3316, 1998.

[8] R. H. C. Bonser and J. M. V. Rayner, "Measuring leg thrust forces in the common starling," *J. Exp. Biol.*, vol. 199, pp. 435–439, 1996.

[9] B. W. Tobalske and K. P. Dial, "Flight kinematics of black-billed magpies and pigeons over a wide range of speeds," *J. Exp. Biol.*, vol. 199, pp. 263–280, 1996.

[10] K. P. Dial, B. E. Jackson, and P. Segre, "A fundamental avian wing-stroke provides a new perspective on the evolution of flight," *Nature*, vol. 451, pp. 985–989, 2008.

[11] M. Rosen, G. R. Spedding, and A. Hedenström, "The relationship between wingbeat kinematics and vortex wake of a thrush nightingale," *J. Exp. Biol.*, vol. 207, pp. 4255–4268, 2004.

[12] J.-H. Han, Y.-J. Han, H.-H. Yang, S.-G. Lee, and E.-H. Lee, "A review of flapping mechanisms for avian-inspired flapping-wing air vehicles," *Aerospace*, vol. 10, no. 6, p. 554, 2023.

[13] M. Hassanalian, A. Abdelkefi, M. Wei, and S. Ziaei-Rad, "A novel methodology for wing sizing of bio-inspired flapping wing micro air vehicles: theory and prototype," *Acta Mechanica*, vol. 228, no. 3, pp. 1097–1113, 2017.

[14] N. Chronister, *Flapper Facts*, Newsletter of the Ornithopter Modelers' Society, no. 15, Summer 1996.

[15] M. Park and A. Abolfathi, "Direct drive or slider-crank? Comparing motor-actuated flapping-wing micro aerial vehicles," *Drone Systems and Applications*, vol. 12, pp. 1–8, 2024.

[16] J. Gerdes, A. Holness, A. Perez-Rosado, L. Roberts, A. Greisinger, E. Barnett, J. Kempny, D. Lingam, C.-H. Yeh, H. A. Bruck, and S. K. Gupta, "Robo Raven: A flapping-wing air vehicle with highly compliant and independently controlled wings," *Soft Robotics*, vol. 1, no. 4, pp. 275–288, 2014.

[17] H. Huang, W. He, J. Wang, L. Zhang, and Q. Fu, "An all servo-driven bird-like flapping-wing aerial robot capable of autonomous flight," *IEEE/ASME Transactions on Mechatronics*, vol. 27, no. 6, pp. 5484–5494, Dec. 2022.

[18] L. H. McCarty, "Latter Day Pterodactyl Flaps its High-tech wings," *Flapper Facts*, Newsletter of the Ornithopter Modelers' Society, no. 16, 1986.