Development of a Butterfly Inspired Micro Aerial Vehicle with Figure 8 Wing Motion

Caroline Waugh[1], Jorge Mares Zamora[1] and Chang-kwon Kang[2]
University of Alabama in Huntsville, Huntsville, Alabama, 35899, USA

The use of biomimetics in micro aerial vehicle design allows for smaller, more efficient designs that take advantage of flight characteristics not commonly seen in modern flight vehicles. This is especially relevant for potential applications in planetary exploration on planets like Mars since it allows for more flexible and compact drone designs. In terms of energy efficient flight on a small scale, the Monarch butterfly, *Danaus plexippus*, is well known for its annual migration that can span over 4000 km despite its mass of only around 1 g. This study focuses on mimicking the unsteady flight dynamics of the Monarch butterfly in a micro aerial vehicle design, with wing flexibility and flight motion dynamics being of particular interest. In this paper, a flexible wing design and two different butterfly inspired micro aerial vehicle designs are reported along with simultaneous measurements of the wing motion and aerodynamic properties. Prototype and model results for both designs show promise in terms of achieving the desired dynamic motion on a small scale without the use of active controls. Although the current prototype is unable to power its wings with the on-board motor and power supply, further design refinement and the development of a smaller wing will likely remedy this issue, theoretically allowing for un-tethered powered motion, which would be the first step in achieving un-tethered flight. Additionally, wing motion measurements show favorable flexibility properties, with the wing displaying a slight figure 8 motion despite being tested with a setup that only controls the stroke angle.

I. Introduction

Aviation inherently traces its roots back to biology and nature, and throughout history, humanity has turned to birds, bats, and insects when seeking to understand flight and achieve it for ourselves [1]. However, mimicking the flapping flights seen in nature is no simple feat, so it is no surprise that the much simpler, fixed wing aircraft became commonplace in modern skies rather than their flapping wing counterparts. Despite this, from prominent historical figures like Leonardo da Vinci, the Wright Brothers, and Sir George Cayley, all the way to modern day engineers, the fascination with flapping wings and biological flight has persisted, and not without due cause [1, 2]. As technology and our understanding of flight improves, so does our understanding of the countless benefits and intricacies of biological flight when compared to fixed or rotary wing flight. Beyond mere novelty, from aeroelasticity and interactions between dynamic wing motion and the air to general unsteady flight mechanisms that yield more efficient flight performance, flapping wing flight presents several advantages over traditional flight vehicle designs if harnessed properly [3, 4, 5]. While the complexity needed to achieve biologically inspired flapping wing flight isn't suited for large scale or commercial flight with our current technology, it is ideal for micro aerial vehicles, especially given the scale flight typically takes in nature. Insects and birds make use of unsteady aerodynamics to achieve efficient and maneuverable flight, and by emulating these through biomimetics, more advanced flapping wing micro aerial vehicle (FWMAV) designs can be developed [3, 4].

While ornithopters have been more well studied in terms of micro aerial vehicle development, insect inspired flight vehicles, or entomopters, have been increasingly popular in research all over the world. In just the past 20 years, there have been FWMAV designs like TU Delft's Delfly projects, the various vehicles from Shinshu University's Aono Lab, and even the MarsBee project for flight beyond our planet [6, 7, 8]. Generally, entomopters fall into one of three categories: dragonfly or fly inspired, beetle or cicada inspired, or butterfly inspired. Of these categories, the dragonfly inspired vehicles make up a fairly large portion of existing designs given their speed and efficiency, which makes them ideal candidates for biomimetic designs [4]. Although somewhat less common, there still have been several

---

[1] Undergraduate Student, Mechanical and Aerospace Engineering, AIAA Student Member

[2] Associate Professor, Mechanical and Aerospace Engineering, Technology Hall N266, AIAA Associate Fellow.

projects and studies focused on butterfly inspired vehicles and flight. Existing literature has revealed a multitude of influential factors in butterfly flight, including the figure 8 wing motion, flexible wing interactions that aid in flight efficiency, stroke angle and the motion of flapping itself, body position, and many more [3, 5, 9, 10]. Different butterfly inspired micro aerial vehicle (BIMAV) designs have focused on different sets of these features to varying degrees. Vehicles like the FESTO eMotion butterfly and the USTButterfly-II feature active mechanisms like a mass shifter or individually controllable wings to allow for steerable flight [9]. These designs often end up larger than what would be considered a micro aerial vehicle due to the added mass needed for the kinds of motion they produce and increased power requirements. Having a low mass and high power efficiency are typically the key factors in micro aerial vehicle designs, which is why steerable flight is much less commonly seen in the smaller vehicle designs, which instead focus more on flapping flight dynamics and lift production. The robo-butterfly Shinshu, for example, has a design focused largely on stroke and lead-lag angle motions, and despite featuring an on-board power supply, it weighs only 2.7 g with a wing area comparable to that of actual butterflies. However, while the design can produce sufficient lift for flight on downstrokes, it produces an equal force downwards on upstrokes, rendering it incapable of flight [8].

Looking at existing literature and research for BIMAVs and micro flapping wing vehicles in general, there are several clear trends and limitations for their design. First, while designs with multiple points of actuation and powered control often perform better, it comes at the cost of increased mass and size. Second, designs that have shown the most success typically have a very dynamic wing motion that either passively or actively allows the wings to move with three or more degrees of freedom to trace either an elliptical or figure 8 wing tip path. Finally, for scope and simplicity reasons, many of the existing designs feature rigid wings, although multiple studies have analyzed the potential benefits of flexible wings in flapping wing applications [5, 6, 8, 9, 11].

With these features in mind, the goal of this research was to develop a BIMAV design that utilizes complex bio-inspired motion to develop the necessary lift for flight on a relatively small scale without being tethered to a power source on the ground. This paper reviews two biomimetic designs that are in development. The designs were created to optimize the complex wing motion of other successful FWMAVs and attain the signature figure 8 wingtip motion of actual butterflies without the need for active controls. Passive mechanisms were a large focus in the creation of the designs in order to achieve complex motion with only one motor and limited mechanical complexity. Additionally, flexible wings were developed that mimic the variable rigidity of a butterfly's wing, with the Monarch butterfly being used as the reference given the abundance of data on the species and its energy efficient flight evolved for long migrations.

The first design is based largely off of the robo-butterfly Shinshu and features a single motor driven spur gear and a lever arm to produce a relatively simple flap motion to test the flexible wings on. The second uses a two-gear system to approximate the figure 8 wing motion of a butterfly in nominal flight. Designs were modeled and simulated in a 3D Computer Aided Design (CAD) environment, and prototypes were 3D printed using both stereolithography (SLA) and fused deposition modeling (FDM) printing techniques. Design performance for the wings was analyzed using a Vicon motion tracking system to measure their movement and a force sensor was used to measure resulting forces when flapping. The wings were predominantly made from flexible plastic film material and carbon fiber rods. The two vehicles were designed to accommodate an on-board power supply and control board for un-tethered flight. For simpler analysis of the flexible wing performance, both designs use only forewings and have no hindwings in their current iterations.

II. Materials and Methodology

A. Design Prototyping and Development

Designs were modeled in a CAD environment using SolidWorks, and motion analysis was done within the program before physical models were made. Select components were 3D printed using FDM and SLA techniques. Other materials and components used in the design and fabrication of the vehicles include: plastic gears, carbon fiber rods, plastic film, specialty lightweight control boards, micro motors, and Lithium-ion batteries.

The first design was based on research done by the Aono lab [8], with modifications being made based on motion simulation results and prototype performance. The second design was focused on mimicking the characteristic figure 8 motion of butterfly flight, and iteration of the design followed the same procedure as the first.

B. Wing Performance Testing

Wings were constructed and tested both on and off the vehicle prototypes, with a custom-made test stand being used for general performance testing of a singular wing. The stand uses gears and 3D printed mounts with a motor connected to a power supply to generate a simple flapping stroke motion for the wing. Reflective markers on the base of the flapping stand serve as the thorax and abdomen reference points (T1 and T2) for an axis of rotation for wing angle calculations. A specific version of the wing was made with a more matte surface and black coloration to limit reflectiveness, and reflectors were placed on the wing, as is shown in Figure 1. A total of 11 Vicon motion tracking cameras, shown in Figure 2, were set up at varying angles and heights around the test stand to record the wing motion using the reflective markers. Figure 3 shows the measurement setup within the Vicon program, with a special subject skeleton frame being used for the wing marker tracking. Additionally, a force sensor was used to measure the forces generated by the wing when flapping on the test stand.

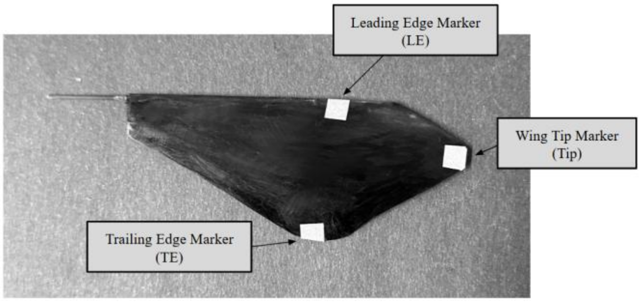

Fig. 1 Wing with reflective markers for motion tracking.

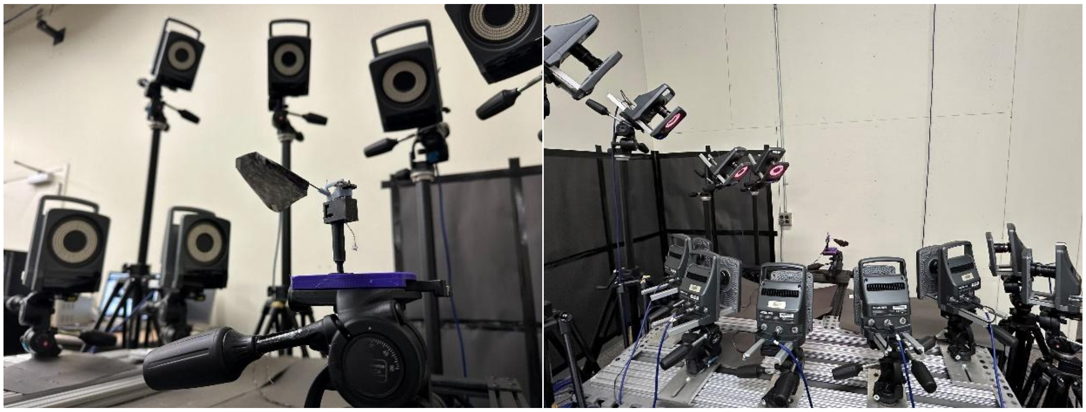

Fig. 2 Vicon motion analysis setup and with wing flapping test stand.

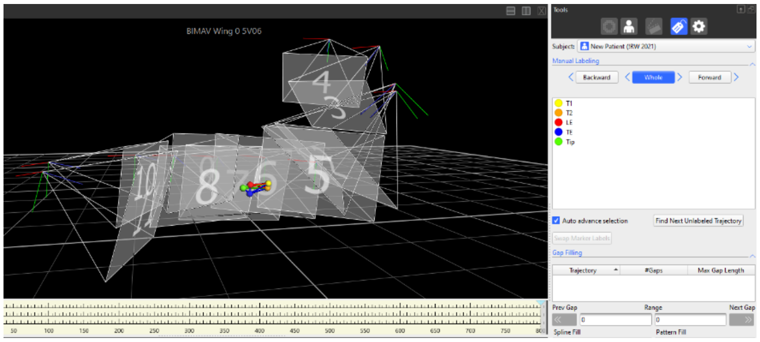

Fig. 3 Vicon wing motion tracking system setup

III. Design and Development

A. Design A: Simple Flapper System

Design A is based on designs from Shinshu University's robo-butterfly [8], shown in Figure 4, and features a single motor driven spur gear and a lever arm to control wing motion. It uses flexible film material for power transferal to the wings and is mostly 3D printed. Several concepts for a rigid connection between the lever arm and wings were created. However, motion simulations for each of them revealed issues with the limited freedom of movement that would likely result in components binding or breaking if re-created physically or would be unnecessarily complex. Initial models of one of the designs featuring a rigid power transferal design are shown in Figure 5.

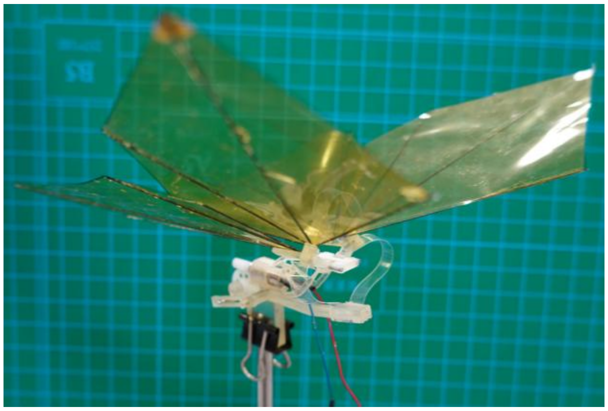

Fig. 4 robo-butterfly Shinshu micro aerial vehicle [8].

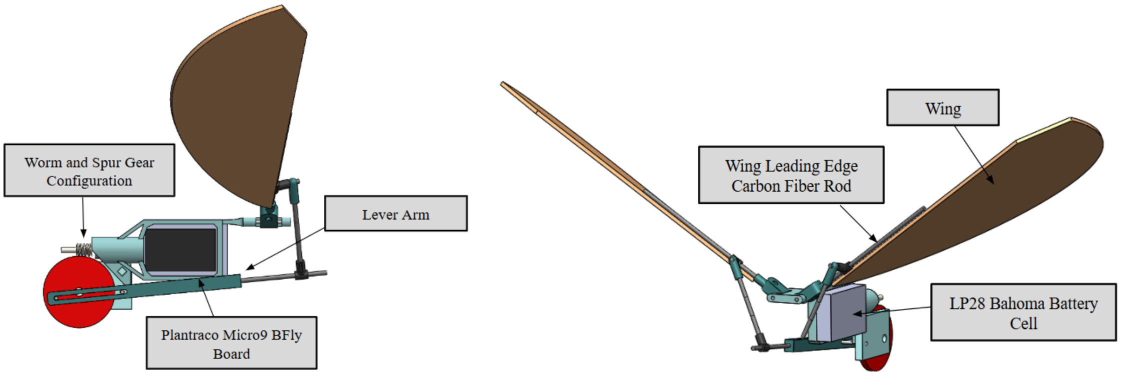

Fig. 5 Preliminary CAD models and components for Design A.

Based on the model results, only the flexible wing connector designs were further developed and prototyped for this design, and the improved CAD models for this version are shown in Figure 6.

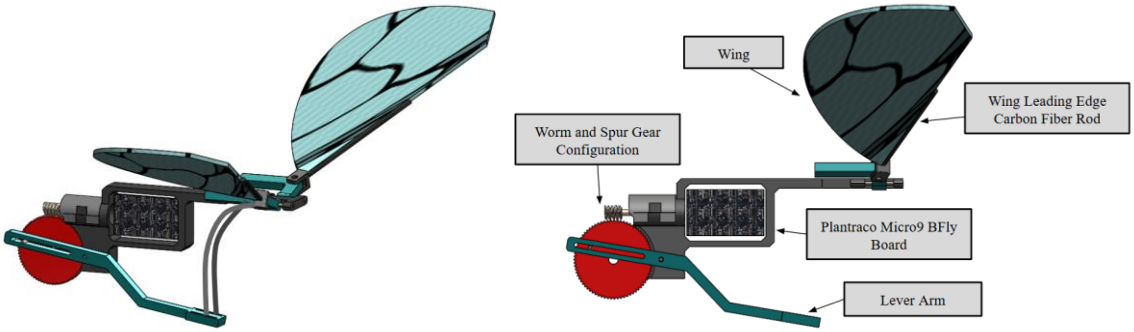

Fig. 6 Improved Design A model for flexible connections.

Initial prototyping and construction for Design A revealed that the resin being used to print it was too brittle and flexible for proper power transferal. Many early iterations broke once the motor was powering the wings due to this issue, as is shown in Figure 7, so the second phase of designs were printed using polylactic acid (PLA) to provide more rigidity to the gears and motor. Additionally, the design was improved to strengthen the weaker areas where breaks were happening. The resin and PLA versions of the prototype design are shown in Figure 8. The fully assembled resin version weighs 6.55 g, and the PLA version weighs 6.74 g.

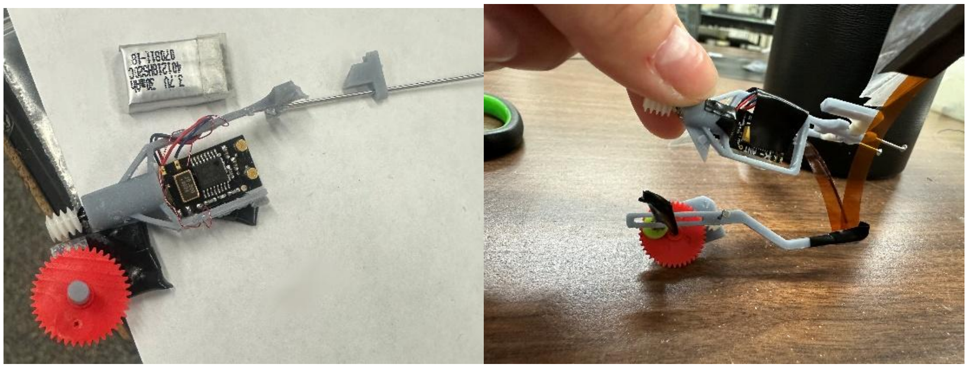

Fig. 7 Design A resin prototype failures.

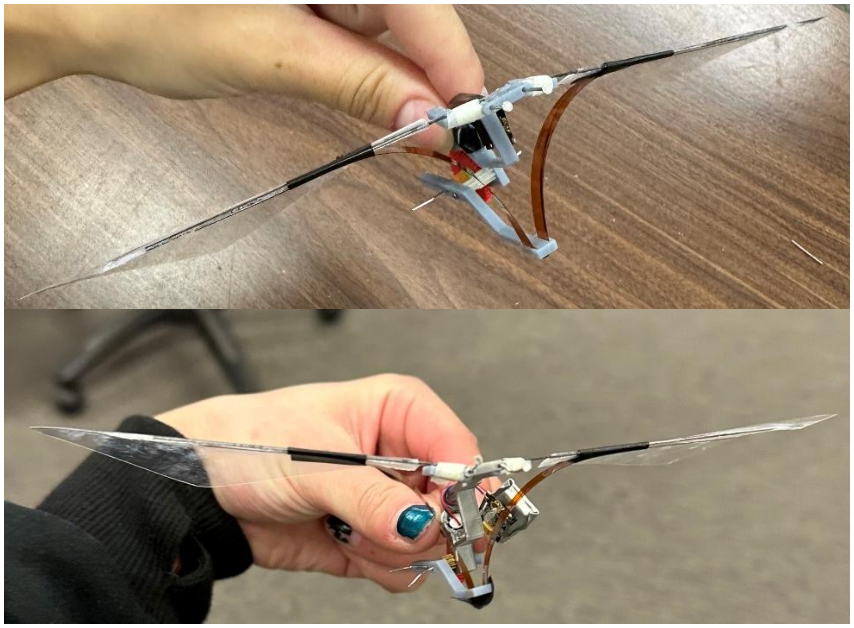

Fig. 8 Design A resin (Top) and PLA (Bottom) assembled vehicles.

B. Design B: Figure 8 Motion

The development of Design A was used as the starting point for Design B, but with the addition of a two-gear mechanism, shown in Figure 9, to produce the desired figure 8 motion. Where Design A was focused on re-creating and refining an existing design with the addition of a flexible wing, Design B was created as an entirely new BIMAV design concept using passive mechanisms to constrain the flight motion and wing angles in a way that mimicked biological flight. A concept model of the mechanism and wing configuration is shown in Figure 10, and shows the two-gear linkage system, as well as a curved slot that constrains wing motion in a way that generates multi-dimensional motion. Flat cutouts on the connecting rod between the wing and shoulder joint are guided along the slot to adjust angle of attack, the curve of the slot results in a greater upstroke angle than downstroke, and the length of the slot controls the lead-lag angle. All of these features are attained passively and are tunable using the specific dimensions and features of the guiding slot. Motion simulations done in the CAD software showed favorable wing movement with this design, displaying a figure 8 motion and general dynamic flight pattern with only a singular motor powering the gears.

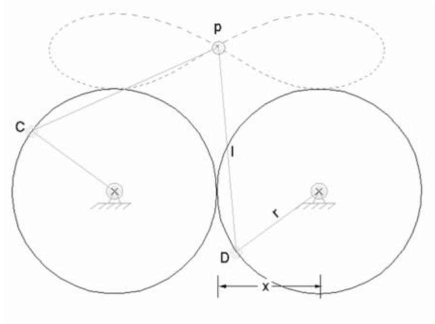

Fig. 9 Figure 8 motion drive diagram[*].

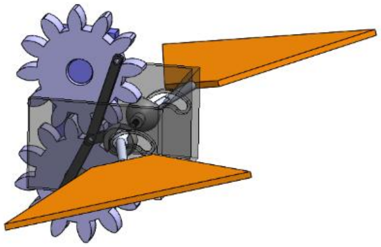

Fig. 10 Early concept model for Design B mechanism.

C. Wing Design

Monarch butterfly wings were rehydrated using isopropyl alcohol analyze their deformation properties and how the wing veins interact with the membrane. The artificial wings were designed to be mostly rigid, but still capable of slight deflection and deformation like how actual butterfly wings behave. They feature a carbon fiber leading edge to mimic the robust forewing vein on a butterfly's wing, and the body of the wing is made of a flexible plastic film material to allow for deformation while still being rigid enough to support the vehicles in flight theoretically. The carbon fiber leading edge does not extend across the entire length of the wing to allow for more wing tip deflection, as well as to mimic the properties of the strongest forewing vein on an actual butterfly. Future iterations of this wing will feature additional flexible veins on the main body of the wing in a material like TPU to mimic the properties of the other veins on the wing in terms of rigidity and compressibility. The constructed wing models for the micro aerial vehicle assembly are shown in Figure 11. The wings have a length of 90 mm and are 37 mm at their widest point.

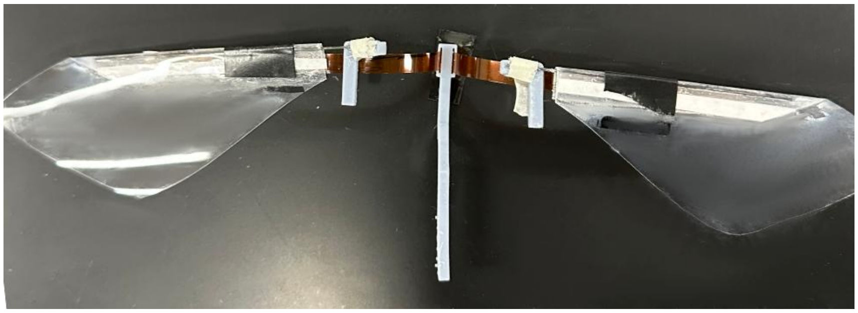

Fig. 11 Wing prototypes assembled for Design A.

IV. Results and Discussion

For the BIMAV designs discussed, Design A was physically constructed and tested, while Design B has only been modeled and simulated virtually. Design A had continued issues with power transfer from the on-board motor to the wings due to material properties and the weight of the wings in comparison to the torque the micro motor was capable of outputting. Tighter tolerancing and continued design iteration will likely solve some of the problems, although a smaller wing or a more powerful motor may be needed as well. The CAD models and motion simulations for Design

---

[*] Sansoy, Figure Eight Motion Drive, https://www.instructables.com/Figure-Eight-Motion-Drive/

B served as a proof of concept for a fully passive mechanism with dynamic figure 8 flight, and the next steps will be constructing physical prototypes of the design as was done for Design A. The premise of using a guiding slot in tandem with a two-gear figure 8 drive has proven to be quite promising for further BIMAV design and development using simple passive mechanisms. The design achieves the same dynamic range of motion that other vehicles require active control or complex joint systems to attain [11].

Tests were run at a flapping frequency of 1 Hz and 10 Hz for the flexible wing design performance analysis. Figures 13 and 14 show the marker locations from the Vicon motion tracking system for one flapping cycle. The thorax and abdomen, or T1 and T2, markers shown in the top set of graphs are the fixed reference markers on the flapping mechanism for the reference axis of rotation, and the three wing markers correspond to the leading edge, trailing edge, and wing tip markers on the wing are shown in the bottom set of graphs. While T1 and T2 are meant to remain stationary, vibrations in the test stand during the trial resulted in slight movement from them, particularly in the 10 Hz trial. The different colored lines in Figures 13 and 14 each correspond to different reflective markers for the wing and thorax sections respectively.

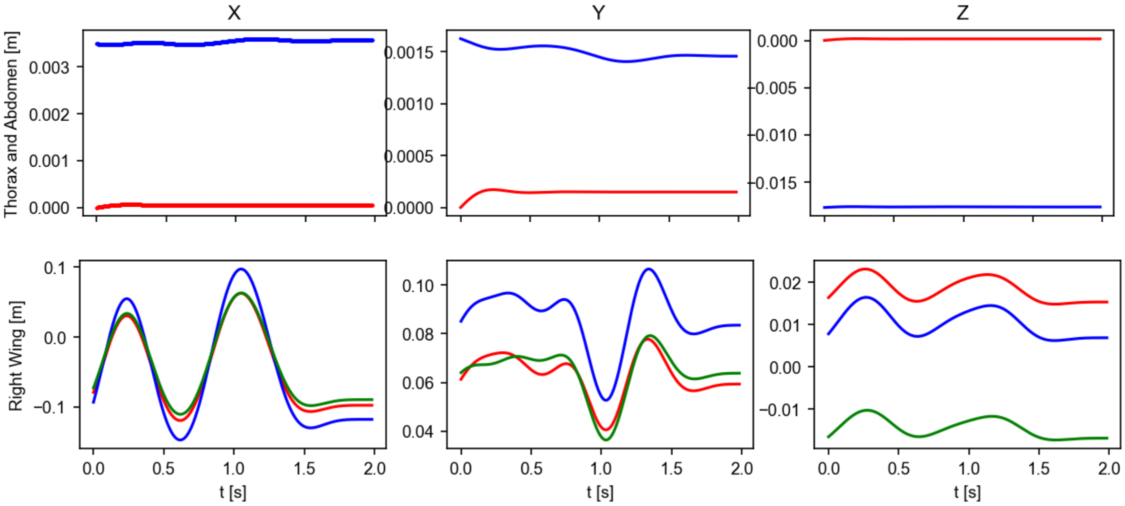

Fig. 13 1 Hz flapping frequency wing motion analysis tracker locations.

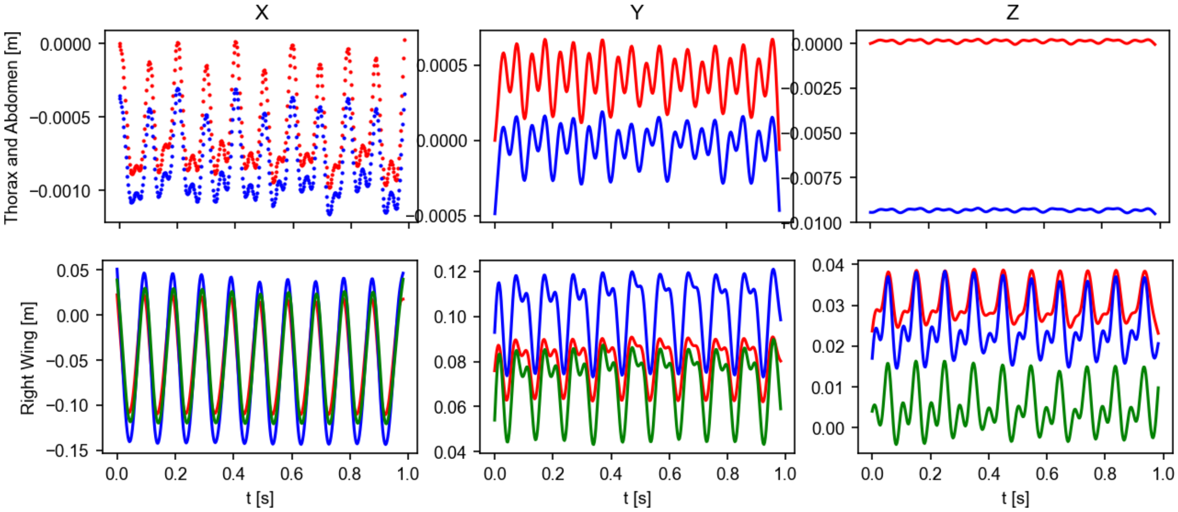

Fig. 14 10 Hz flapping frequency wing motion analysis tracker locations.

Figure 15 shows what the stroke/flap, feathering, and deviation angles on the wings correspond to on an actual model, where ϕ is the stroke or flap angle, Ω is the feathering angle or angle of attack, and Θ is the deviation angle. Figures 16 and 17 show the calculated angles for the wing in a 1 Hz and 10 Hz trial respectively. As can be seen by the shape of the deviation angle graphs, the flexible wing displayed a slight figure 8 wing tip trajectory in the 1 Hz trial that became more distinct in the 10 Hz trial, despite being setup in a way that was purely changing the stroke angle. Additionally, the negative angle bias for the flap angle was likely due to the curvature of the wing prototype making the markers appear to be slanted despite the wing being mounted mostly vertically. As can be seen in the graphs, the performance of the wing improved between the 1 and 10 Hz trials, with the motion becoming much more fluid with more favorable wing motion in the higher frequency trials.

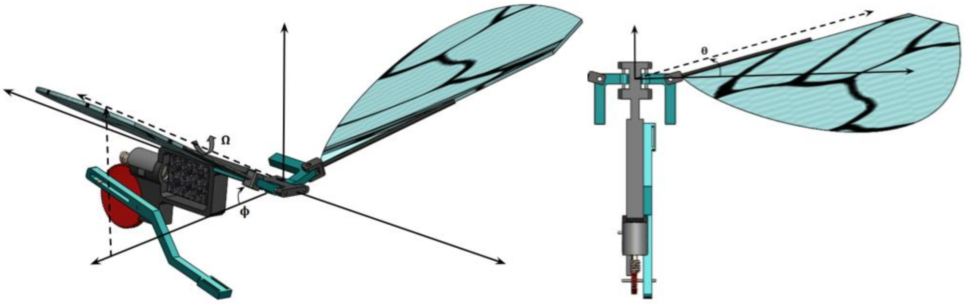

Fig. 15 Wing angle references.

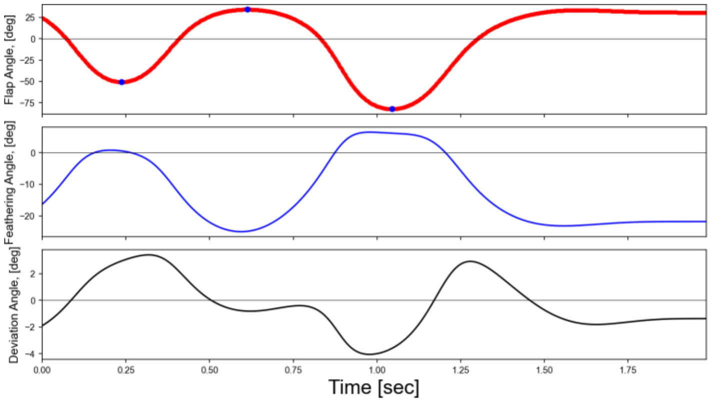

Fig. 16 1 Hz flapping frequency wing angles.

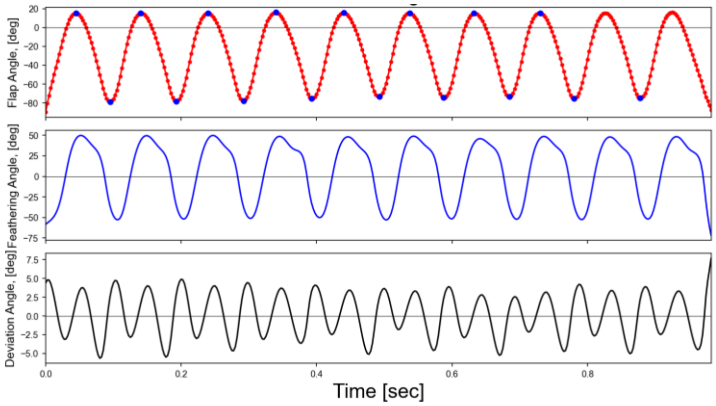

Fig. 17 10 Hz flapping frequency wing angles

Figure 18 shows the forces generated by the wing when powered by 2V on the test stand. The positive x-direction corresponds to the lift generated by the wing in the orientation it was tested in, and the positive z-direction corresponds to thrust production. The forces in the y-direction can likely be attributed to the torque that the offset mass of the wing applied to the stand when flapping, rather than any significant aerodynamic effects. Additionally, these forces should balance out in a two-wing configuration on an actual vehicle model. The lift generated mostly balanced out in the positive and negative directions, although there was still a slight bias towards positive lift values, with the average being 0.065 g. The same can be said for the thrust generation, which had an average value of 2.638 g. At its peaks, the lift generated in the positive direction was well above the weight of the current BIMAV designs, so theoretically, it would be able to support itself in flight if not for the lift in the negative direction. The figure 8 design motion is intended to help reduce the negative lift effects, so future plans include further testing and potential first flights using that design.

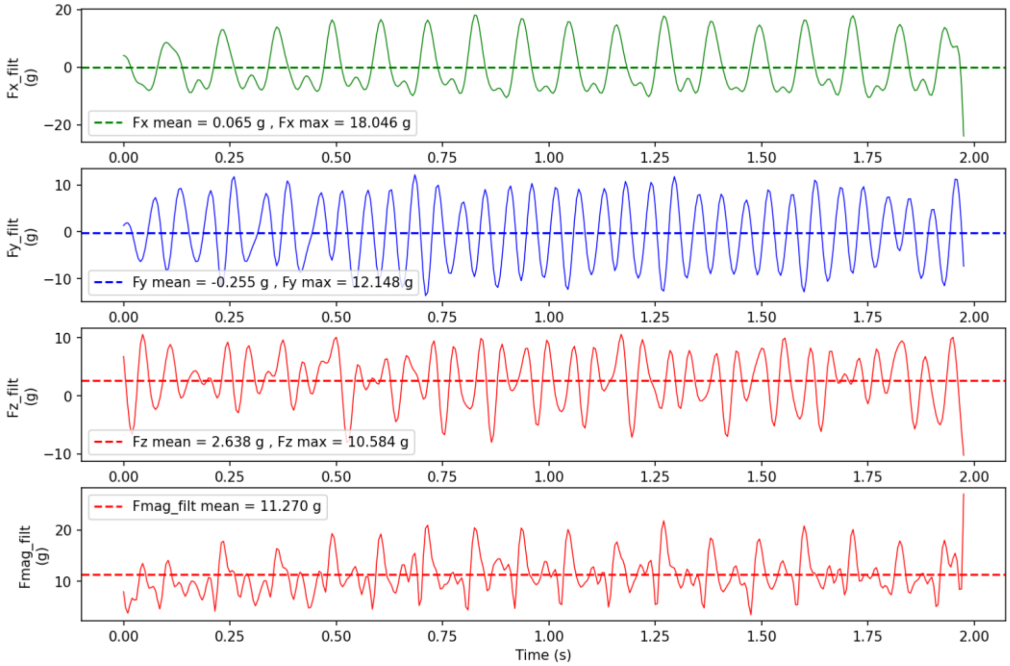

Fig. 18 Force production of the flexible wing with 2 V.

V. Concluding Remarks

The flexible wing and figure 8 motion BIMAV designs show great promise for further micro aerial vehicle development. Future plans include refining the figure 8 design and constructing prototypes for testing, as well as further analysis of the flexible wing's properties at higher flap frequencies. Next steps for the design of the flexible wings will include experimenting with the use of TPU or other flexible material veins on the wing as well as folding the wings so that they are somewhat collapsable and can compress and stretch mid-flight like how real butterfly wings do.

While the designs are still in the early stages of development, they present several potential features that would prove very useful for exploration, science, and surveying missions both on Earth and beyond. First, their small size and mass would make them very versatile and easy to transport to locations, and the flexible nature of the wings means that they could easily fold up into an even smaller volume if needed. By perfecting the passive mechanisms that govern the wing motion of the figure 8 BIMAV design, flapping wing micro aerial vehicles can be made with the same dynamic wing motion presented by projects like the Delfly and the Jilin province FWMAV at fractions of the size and mass, leaving more room for on board cameras, sensors, and controls [6, 11]. Additionally, since the designs mimic the much slower flapping frequency of a butterfly as opposed to the faster dragonfly or hummingbird flapping frequencies, they might be better suited for flight in a Martian environment given the faster flapping or blade rotation frequencies that would be needed for flight in Mars' thinner atmosphere [7, 12]. Although these are theoretical advantages that have not been achieved yet, the early results for these designs still show potential as the basis for a novel biomimetic micro aerial vehicle with applications in missions both on Earth and other planets like Mars.

Acknowledgements

The authors would like to thank Dr. Hikaru Aono of the Shinshu University in Japan for his support.

References

[1] Christina Harvey, Guido de Croon, Graham K. Taylor, Richard J. Bomphrey; *Lessons from natural flight for aviation: then, now and tomorrow*. J Exp Biol 25 April 2023; 226 (Suppl_1): jeb245409. doi: https://doi.org/10.1242/jeb.245409

[2] Gibbs-Smith, C. H. (1962). *Sir George Cayley: "Father of Aerial Navigation" (1773-1857).* Notes and Records of the Royal Society of London, 17(1), 36–56. http://www.jstor.org/stable/531013

[3] Shyy, W., Aono, H., Kang, C., and Liu, H., *An Introduction to Flapping Wing Aerodynamics*, Cambridge University Press, New York, 2013.

[4] Dong, H., Bode-Oke, A. T., & Li, C. (2018). *Learning from Nature: Unsteady Flow Physics in Bioinspired Flapping Flight.* InTech. doi: 10.5772/intechopen.73091

[5] Twigg, R.S., Sridhar, M.K., Pohly, J., Hildebrandt, N., Kang, C., Landrum, D.B., Roh, K., & Salzwedel, S. (2020). *Aeroelastic Characterization of Real and Artificial Monarch Butterfly Wings*. AIAA Scitech 2020 Forum.

[6] Croon, G.C.H.E., Perçin, M., Remes, B.D.W., Ruijsink, R., De Wagter, C., "The DelFly: Design, Aerodynamics, and Artificial Intelligence of a Flapping Wing Robot," Springer Dordrecht, Cham, Switzerland, 2016.

[7] Kang, C., Fahimi, F., Griffin, R., Landrum, D. B., Mesmer, B., Zhang, G., Lee, T., Aono, H., Pohly, J., McCain, J., Sridhar, M., Dunne, H., Palma, G., Doneshwar, S. S., Starchman, K. L., Cavalheiro, G. M., Iriyama, T., & Kaufman, E. "Marsbee - Swarm of Flapping Wing Flyers for Enhanced Mars Exploration.," NASA 20190002496, 2019

[8] Miyasaka, S., Kang, C., and Aono, H., "Experimental Analyses of Aerodynamic Force Generation and Wing Motion Associated with a Single-motor-driven Butterfly-inspired Flapping-wing Robot," *Sensors and Materials*, Vol. 35, No. 9, 2023, pp. 3097–3108, https://doi.org/10.18494/SAM4343

[9] Huang H., He W., Chen Z., Niu T., and Fu Q., "Development and experimental characterization of a robotic butterfly with a mass shifter mechanism," *Biomimetic Intelligence and Robotics*, Vol. 2, No. 4, Dec. 2022, https://doi.org/10.1016/j.birob.2022.100076

[10] Chen, Q., Lu, T., Tong, Y., Luo, G., Jin, X., and Deng, Z., "A Practical Model for Realistic Butterfly Flight Simulation," *ACM Transactions on Graphics*. Vol. 41, No. 3, June 2022, https://doi.org/10.1145/3510459

[11] Jiang, S., Hu, Y., Li, Q., Ma, L., Wang, Y., Zhou, X., and Liu, Q., "Design and analysis of an innovative flapping wing micro aerial vehicle with a figure eight wingtip trajectory," *Mechanical Sciences*, Vol. 12, No. 1, pp. 603–613, https://doi.org/10.5194/ms-12-603-2021, 2021.

[12] Grip, Havard Fjaer; Johnson, Wayne; Malpica, Carlos; Scharf, Daniel P.; Mandic, Milan; Young, Larry; Allan, Brian; Mettler, Berenice; San Martin, Miguel, 2017, "Flight Dynamics of Mars Helicopter", https://hdl.handle.net/2014/47585, 43rd European Rotorcraft Forum, Milan, Italy, September 12-15, 2017, JPL Open Repository