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Design and Manufacturing of Flapping Wing Mechanisms for Micro Air Vehicles

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Stringent size, weight, and power constraints imposed on flapping-wing micro-air-vehicles (FWMAVs) make their design quite challenging. In particular, the flapping actuating mechanism represents a corner stone in the design of the whole vehicle, if not the most challenging task. In this paper, we provide a review on the several designs of flapping mechanisms in literature and compare their performances. We also provide our design and manufacturing iterations that culminated in a novel design of a FWMAV actuating mechanism that actively controls both the wing flapping (back and forth) and pitching motions using only one drive motor. In this design, we use a parallel crank rocker mechanism. Synthesis and optimization of the parallel crank rockers allowed independent control of the wing flapping and pitching angles. That is, the two angles are allowed to simultaneously follow specific independent functions using only one drive motor. The designed mechanism is manufactured (3D printed), tested, and found to successfully achieve the desired wing motions that mimic the motion of a hummingbird wing.

I. Introduction

FORthe last decade, flapping-wing micro-air-vehicles (FWMAVs(have been the focus of intense research within the scientific community. DARPA (Defense Advance Research Project Agency) has set the definition for micro air vehicles (MAVs) as an autonomous flying machine whose maximum dimension is smaller than 15 cm that is capable of performing a variety of civil and military applications. These miniature vehicles are mostly meant for indoor reconnaissance and surveillance. A special type of MAVs is the flapping-wing type that flies like birds or insects. Flapping insects exploit unconventional aerodynamic mechanisms to generate high lift at ultra-low Reynolds numbers.[1–4] They also exploit unconventional stabilization mechanisms to stabilize their bodies in flight and overcome gust disturbances.[5,6]

There have been a multitude of unique designs developed independently by several universities and organizations. The smallest FWMAV was designed and built by Harvards engineers, while Aerovironments FWMAV has set the standard in terms of flight performance and control. Similar to their corresponding biological flyers,[7] FWMAVs can typically hover using a horizontal stroke plane;[8,9] i.e., without an out-of-plane motion. This design allows two degrees of freedom for the base rigid wing: back-and-forth flapping and pitching. To comply with the stringent size, weight, and power (SWaP) constraints imposed on the design of FWMAVs, most of the previous designs[8–11] adopted passive control for the pitching angle.

While most of the previous studies on the dynamics and control of FWMAVs have concluded inherent hovering instability,[12–19] the recent research efforts at the University of California, Irvine have discovered an unconventional stabilization mechanism;[5,6] namely vibrational stabilization. This unconventional stabilization technique ideally require continuous active pitch control. In addition, several efforts[4,20] on the kinematic optimization of FWMAVs also recommend active control for the wing pitching angle. However,

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the SWaP constraints imposed on the design of FWMAVs may not allow for the use of two-motors to independently manipulate the wing flapping and pitching angles. As such, there is a need for designing actuation mechanisms that allow such an independent control using only one drive motor, which is the objective of this effort.

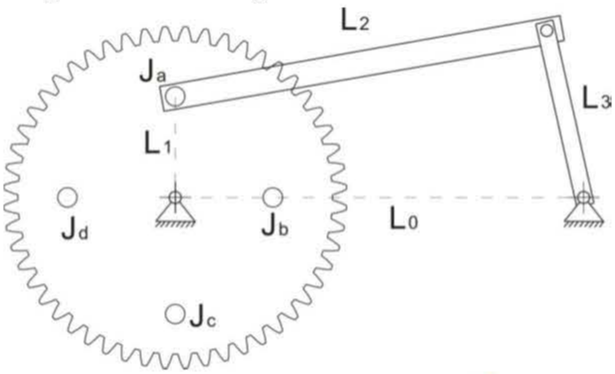
Active pitch control increases the complexity of the flapping mechanism. Working through an iterative design process allowed for extensive testing of previously known and novel design of flapping mechanisms as well as various materials and manufacturing processes. Through this heuristic process, we developed a novel flapping mechanism that actively controls the wing flapping and pitching motions. In this paper, we provide a review on the different designs found in literature, our heuristic design iterations, and our final design for the flapping mechanism.

II. Literature Review

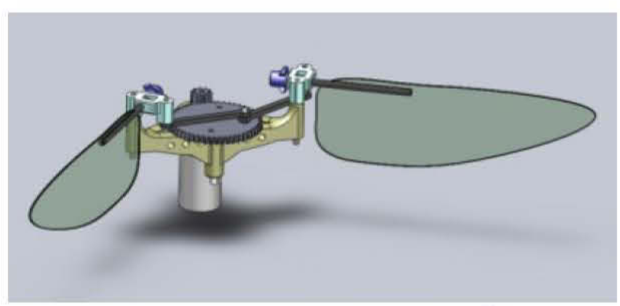
The driving mechanism for FWMAV's vary from peizoelectric motors that vibrate to complex mechanisms. Whitney[21] presents a comprehensive investigation of new MAV design and manufacturing methods. In his thesis, Whitney studied the feasibility of passive pitch rotation control and concluded that lacking full direct control of wing pitching angle hinders control of the vehicle. In order to maintain close control of the pitch and swing of the wing a specific mechanism needed to be developed. Four mechanisms were reviewed as a basis for the design, the Purdue mechanism,[22] the Aerovironment Nano Air Vehicle,[23] the Bristol Mechanism,[24] and the DelFly mechanism.[25]

A. Purdue Mechanism[22]

Hu has recently developed a 2.61 gram vehicle capable of hovering. The dc drive motor transmits power to the wings using a crank-rocker mechanisms with a gear acting as the input crank as shown in Figure 1(a). The drive train consists of two gears with a gear ratio of 5.2:1. Each wing has a symmetric four-bar mechanism with independent outputs that share the gear crank. The mechanism allows the wings to freely rotate due to the presence of a housing for the wings as shown in Figure 1(b). Mechanical stoppers limit the maximum angle of attack to 45 degrees, which was found to be aerodynamically optimal. Due to the simple structure and acceptable lift and drag coefficients, passive pitch structures are often adopted as the default FWMAV testing platform. However to apply the novel systems developed by Taha et al.,[26] the pitch of the wings must be actively controlled.



(a) Crank-Rocker with Gear Crank[22]



(b) Assembly of Purdue Mechanism[22]

Figure 1. The Purdue Mechanism and the Four Bar.

B. AeroVironment Mechanism[23]

DARPA funded the development of several nano air vehicle systems, which resulted in the AeroVironment hummingbird. The vehicle developed has a life-sized hummingbird wing-flapping mechanism which provides controlled precision hovering and fast forward flight. The vehicle has on board the batteries, communication systems, motor and video camera while only weighing 19 grams, see Figure 2.

The hummingbird depends on a continuously rotating crankshaft driven by a motor. Two strings connect the crankshaft, and the two pulleys mounted at the wing hinge flapping axis. Two additional strings are used to connect the pulleys as shown in Figure 3(a). As the motor turns the crankshaft, the pulleys oscillate driving the wing flap shown in Figure 3(b). This design minimizes vibration while maximizing Thrust.

In addition to an effective design the materials chosen for the construction created a light weight and durable structure. The gears were PEEK, a strong and light weight plastic, the main structure is an aluminum alloy, the wing arms are carbon fiber and the wings are a flexible membrane.

Figure 2. AeroVironment Mechanism[23]

This design like the Purdue Mechanism utilizes passive pitch control through employing the natural flexure of the wing as it beats through the air to adjust the pitch. There are mechanical stops that then control the maximum pitch angle. However, without active pitch control, the design still falls short of the experimental requirements.

(a) Isometric View[23]

(b) Top View of Flapping Action[23]

Figure 3. The AeroVironment Hummingbird Nano Air Vehicle Flapping Mechanism[23]

C. Bristol Mechanism[24]

Conn designed a parallel crank-rocker flapping mechanism. A biomimetic design approach was introduced to develop the parallel crank-rocker mechanism as shown in figure 4. The parallel crank-rocker has an upper and lower mechanism that are phase shifted from each other and are connected via a cylindrical joint giving the system the needed two degrees of freedom. Thus the Bristol Mechanism has successfully implemented active pitch control.

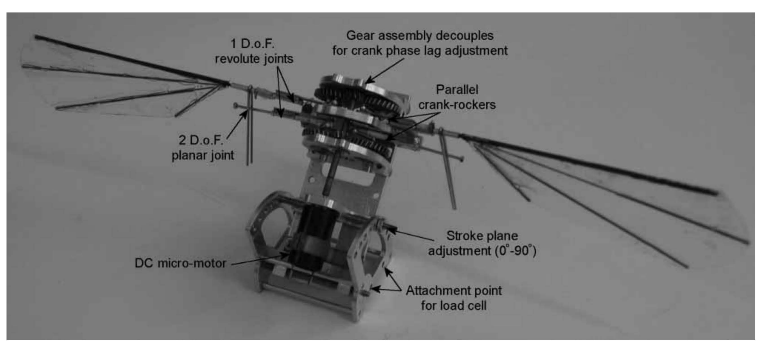
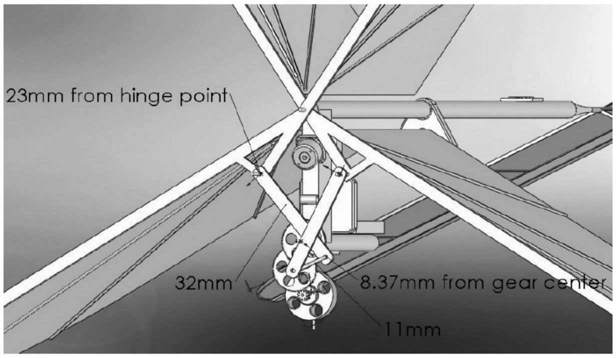


Figure 4. Bristol Mechanism[23]

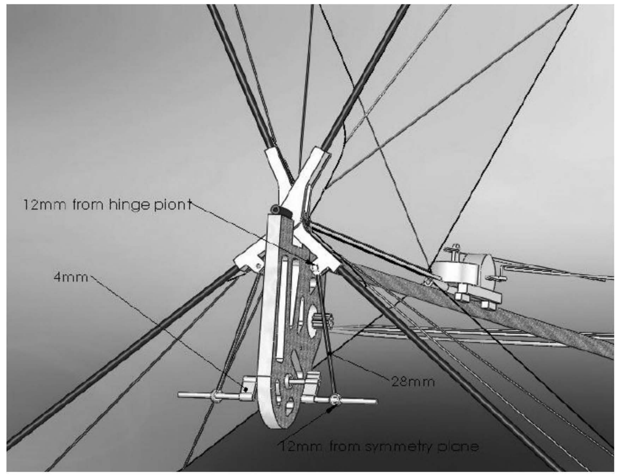
However, the wing beat frequency of this mechanism was insufficient to generates enough lift to raise the whole body. Moreover, the mechanism was designed to test the behavior of FWMAVs, but not to fly. The heavy structure prevents the possibility of flight. Though active pitch control was achieved, this design will not fly with out significant modifications.

D. DelFly Mechanism[25]

De Croon design the mechanisms and controls of the DelFly. A crank mechanism is used to transmit motion from the motor to the wings as shown in Figure 5(a). The disadvantage of this design was that the two sets of wings were asymmetric in movement, which led to a rotational reaction. To overcome this lack of symmetry, the drive train is modified to be perpendicular to the flying direction as shown in Figure 5(b).



(a) The DelFly 1[25]



(b) The DelFly 2[25]

Figure 5. The DelFly FWMAV

E. Air Force Mechanism[27]

Anderson designed a mechanism that mimics the movement insect's wings. The design uses a mechanism driven by piezoelectric materials. The advantages of this technology and design include: an extremely small size envelope, high speed performance and very a low weight. Version 3 of the Air Force Mechanism is shown in Figure 6. The design and development of the wing and structure demonstrated the advantages to specific construction methodologies and materials.

A novel control technique called Bi-harmonic Amplitude and Bias Modulation (BABM) was applied. Utilization of this technique can generate forces and moments in 5 vehicle degrees of freedom with only two actuators. However, the lack of active pitch control renders this design unsuitable for testing of the vibrational stabilization theory.

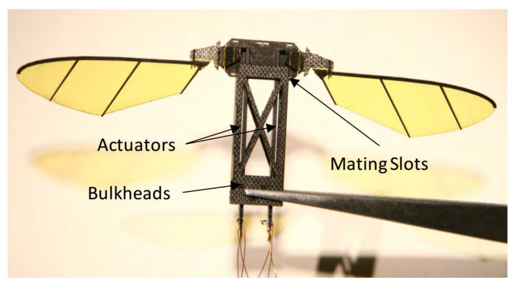


Figure 6. Version 3 of the Air Force Mechanism[27]

III. Design Iterations

Since the design criteria of being able to fly with active pitch control has not been met by any of the existing design, development continued on a novel mechanism.

A. Test Apparatus

The test apparatus is shown in Figure 7. The apparatus hangs the FWMAV vertically on a pendulum and measures the angle that the FWMAV is able to swing the pendulum.

B. Prototype 1.1

The first prototype was based off of the Purdue Mechanism[22] with a crank rocker and passive pitch control. The mechanism was constructed using light weight plastics, 3D printed plastic parts, carbon fiber and plastic film, see Figure 8(a). The vehicle fit within the desired envelope and had a flapping wing range of 100 degrees. At 40 Hz wing beat frequency some lifting force was generated. This prototype confirmed the feasibility of these manufacturing techniques. However, as did not had an active pitch control, the next prototype (Prototype 1.2) was focused on the mechanical control of the pitch.

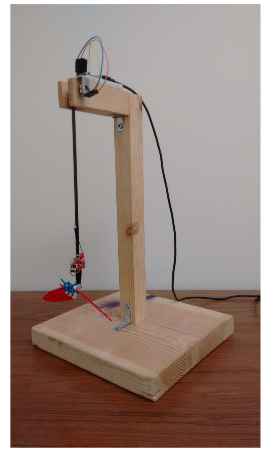
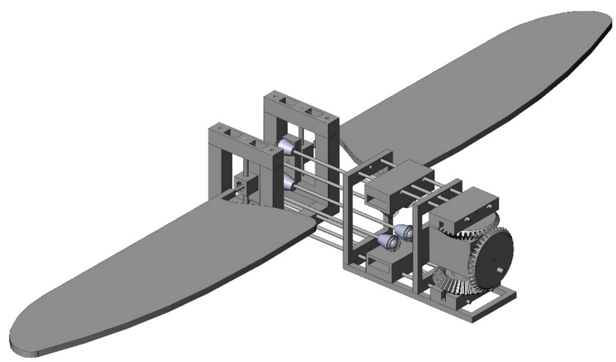


Figure 7. The Lift Test Apparatus with Prototype 1.3

C. Prototype 1.2

The second prototype was adapted from the Bristol Mechanism[24] by implementing a dual parallel crank system. This prototyped utilized parallel crank slider mechanisms rather than crank rocker mechanisms, see Figure 8(b). This design succeeded in providing active pitch and wing flapping control. However due to the geometry, the plastic model resulted in excessive flexure and was subject to high manufacturing error. Transitioning to aluminum would have remedied the flexure problem, but then mechanism would exceed the weight limit. As a result of the problem of complex design and materials lack of resistance, the research goal focused on a more a simple and robust mechanism design.

(a) Prototype 1.1 Top View



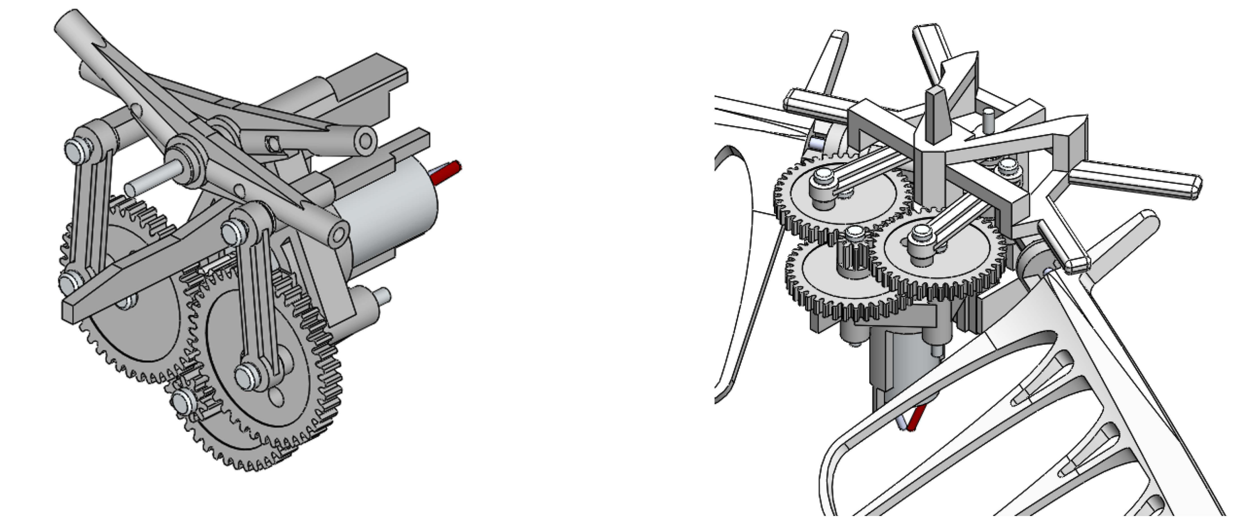
(b) Prototype 1.2 Isometric View

Figure 8. Prototypes 1.1 and 1.2

D. Prototype 1.3

Prototype 1.3 utilized a commercially available mechanism found in many flapping wing toys. The mechanism consists of two crank rockers utilizing gears as the input crank as seen in Figure 9(a). These mechanisms only control the swing of the wing. An additional outer frame was designed that provided mechanical stops to control the maximum wing pitch, see Figure 9(b). The wings were redesigned to include arms that would run along guides on the frame to control the rate of change of the wing pitch, see Figure 10(a). The final prototype utilized the the commercial mechanism with a 3D printed external frame and 3D printed wings with a plastic film, see Figure 10(b).

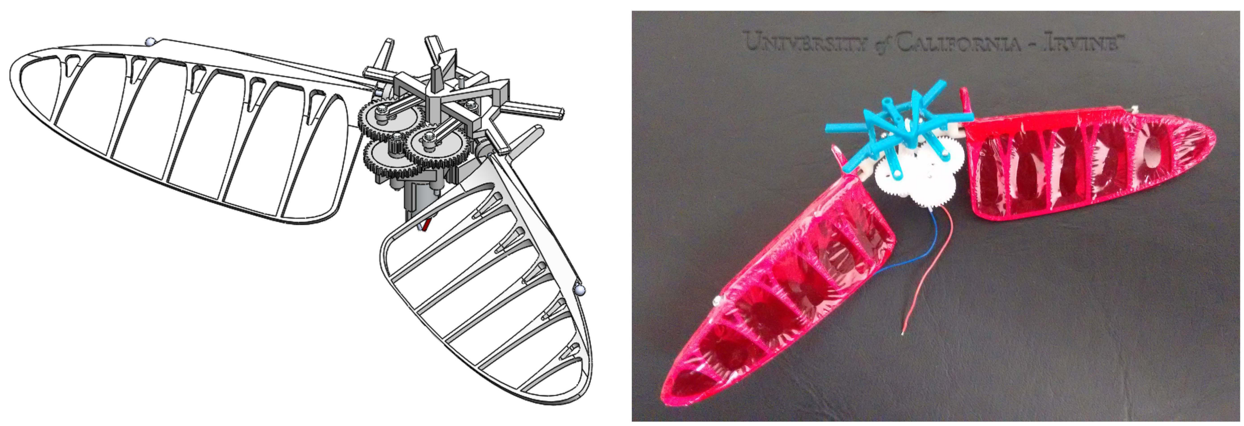
Prototype 1.3 during testing exhibited an active pitching angle of 40 degrees even though it was designed to retain a 30 degree pitching angle. This was due to the reliance on guides and stops rather than continuous pitch control. The stops and guides also resulted in a significant amount of energy loss due to the impacts and sliding friction. Also due to the sudden changes in angle when hitting the stops the wing changes pitch too rapidly. In addition, the wings were too heavy. Though some lift was generated the majority of the energy was lost do to the internal interactions of the mechanism. To improve the performance, a continuous control of the pitch is needed to reduce internal friction and energy loss.



(a) Prototype 1.3 Commercial Mechanism

(b) Prototype 1.3 Commerical Mechanism with Customizations

Figure 9. Prototypes 1.3 Commercial Mechanisms vs Customized Mechanism



(a) Prototype 1.3 Isometric View Mechanism

(b) Prototype 1.3 Completed Prototype

Figure 10. Prototypes 1.3 Model and Physical Prototype

E. Prototype 1.4

Prototype 1.4 employed parallel crank rocker mechanisms driven by a timing belt. The goal of this prototype was to develop a mechanism that could follow the theoretical ideal curves for the wing swing and wing pitch. The goal for the wing swing was to follow:

$$-60^o \cos(\omega * t) \tag{1}$$

where ω a is the frequency of wing beats, which was desired between 50 Hz and 70 Hz. The wing pitch's ideal curve follows:

$$\pi/2 - 60^o \sin(\omega * t) \tag{2}$$

The ratio of the link lengths in the crank rocker were determined by the following equations from Shigley,[28] see Figure 11 for the link numbers. t_n represents the length of link n, ϕ is the output crank angle, and γ_{min} is the transmission angle.

$$\frac{r_3}{r_1} = \sqrt{\frac{1-\cos\phi}{2\cos^2\gamma_{min}}} \tag{3}$$

$$\frac{r_4}{r_1} = \sqrt{\frac{1-(r_3/r_1)^2}{1-(r_3/r_1)^2\cos^2\gamma_{min}}} \tag{4}$$

$$\frac{r_2}{r_1} = \sqrt{(\frac{r_3}{r_1})^2 + (\frac{r_4}{r_1})^2 - 1} \tag{5}$$

Using a transmission angle of 30 degrees, the minimum recommended for operation,[28] an output angle of 115 degrees was found. This total angle swing lies within the acceptable range for the mechanism. Next an offset distance between the planes of the two crank rockers was chosen which allowed for calculation of angular offset between the top and bottom cranks. The pitch angle could then be simulated, plotted and compared to the ideal. Manipulation of the offset angle between the top and bottom cranks adjusted the pitch angle curve until a curve was found to be within the design tolerances. In Figure 12 the simulated pitching angle to vary from the ideal sine curve, but was close enough for the purposes of this prototype.

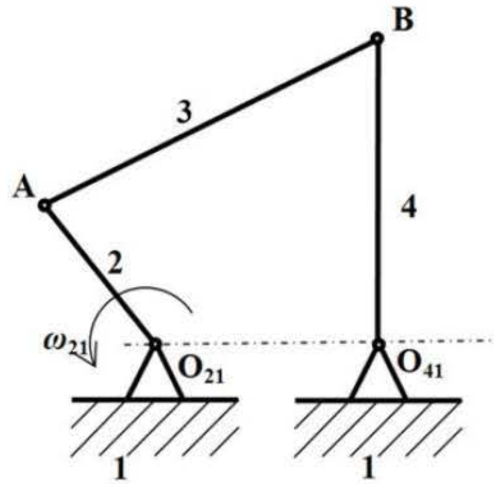


Figure 11. Crank Rocker with the Links Labeled

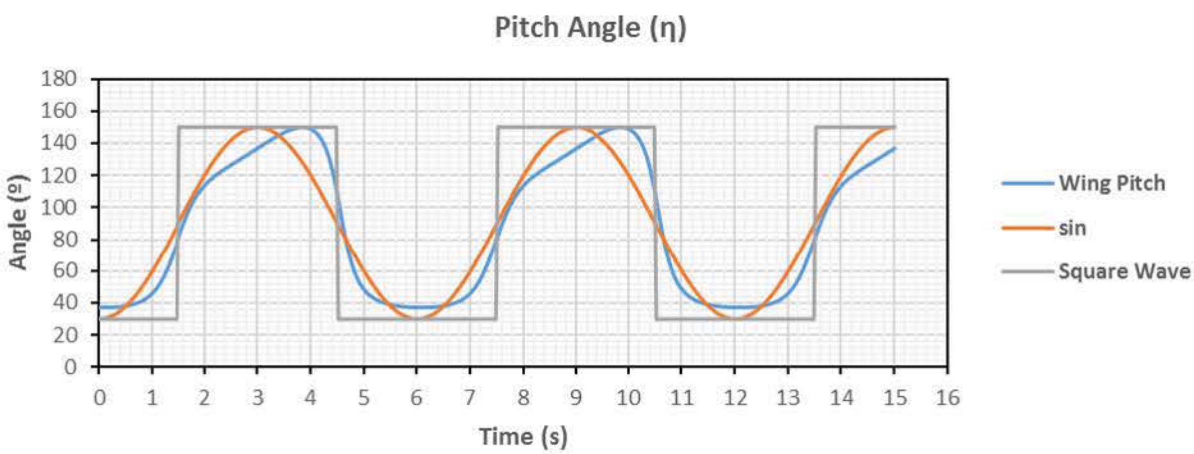


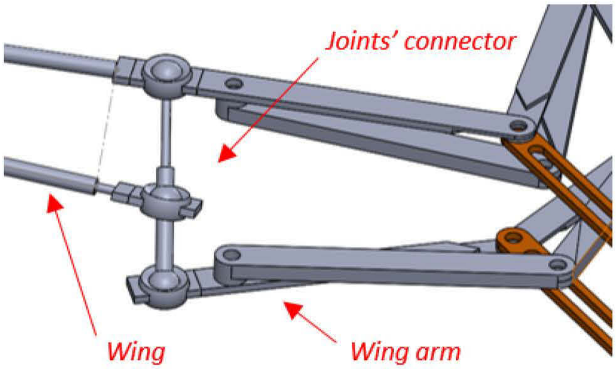
Figure 12. Prototype 1.4 Pitching Angle Simulation vs Theoretical Curves

The prototype was then modeled in SolidWorks and a linkage was applied to mirror the movements of the original crank rocker mechanism. This allows for symmetrical movement of the wings swing and pitch angles, though the assymmetry may cause balance issues during flight. The wing's pitch is controlled via a telescoping connector that allow for a limited range of three degree of freedom movement for the lower wing joint. In this manner the pitch of the wing is continuously controlled by the mechanism without relying on mechanical stops.

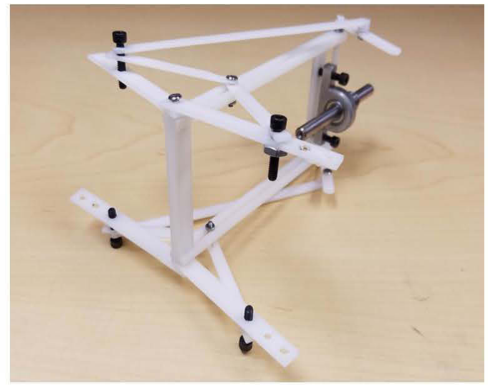
The entire set up was driven by an electric motor which drove timing belts. Gears were not chosen due to constraints of the geometry of the design and mounting position of the motor. The set up can be seen in Figure 14.

The prototype was constructed using a laser cutter to create the links and utilizing commercial available parts for the joint connections. The prototype can be seen in Figure 13(b).

The mechanism was able to generate the desired movement. However, due to the flexibility of the plastic used and the long offset of the motor from the center of gravity of the system due to the belt driving system, full speed testing at 50 Hz could not be performed.



(a) Prototype 1.4 The connection between the wing arm and wings.



(b) Prototype 1.4 Constructed Prototype

Figure 13. Comparison of Pitch Curves for Prototype 1.4 and Prototype 1.5

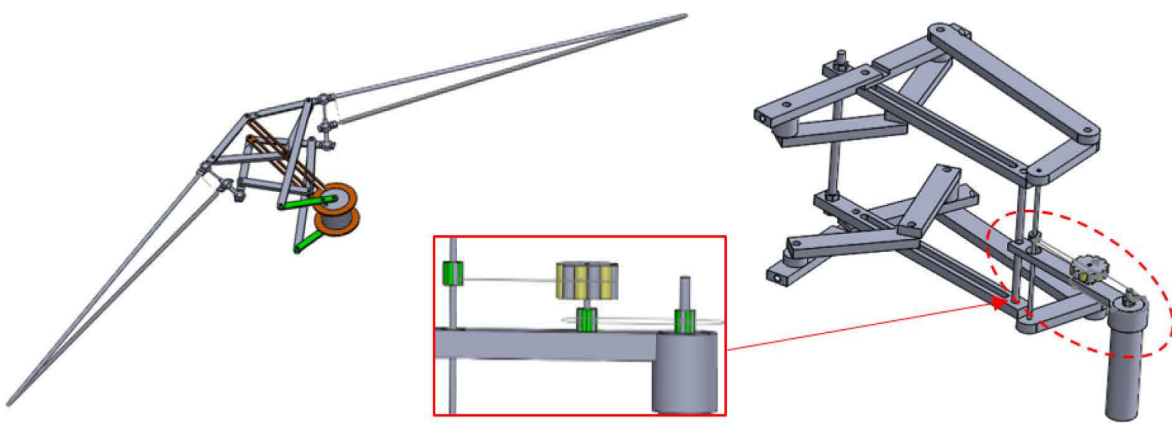
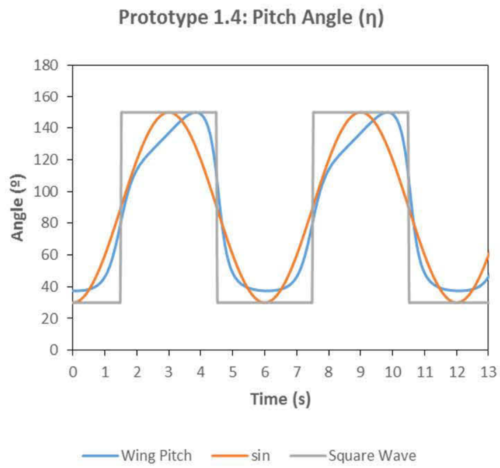


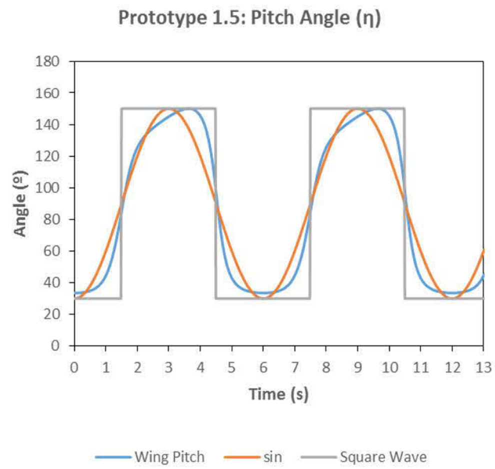
Figure 14. Prototype 1.4 Full Assembly Model (Left) and Details of the Flapping (Right) and Driving Gears, Belts and Motor (Center)

F. Prototype 1.5

Prototype 1.5 combines the strengths of Prototypes 1.3 and 1.4. The compact design and smooth motion from the gear driven system is adopted from Prototype 1.3. The dual level design with precise active pitch control and the wing mounting mechanisms were adopted from Prototype 1.4. Combining these characteristics mitigated the major weaknesses from the previous two iterations.



(a) Prototype 1.4 Pitch Curve



(b) Prototype 1.5 Refined Pitch Curve

Figure 15. Comparison of Pitch Curves for Prototype 1.4 and Prototype 1.5

The further refinement of the design of the crank rocker mechanism through varying the transmission angle, offset distance between the two crank rockers, and the crank offset angle achieved the ideal 120 degree swing for the wing and improved the path of the wing's pitch. From Figure 15 the pitch angle's path has been improved significantly and now lies mostly within the sin wave and square wave, the ideal upper and lower bounds of the behavior, with the sin wave producing the ideal lift and control characteristics.

Further refinement included offsets in the wing mounting system and the location of the gears. The modifications and layout of the relevant link lengths can be see in Figure 16. The gears are acting as the input cranks for this mechanism as denoted by the r2. Custom gears were designed using GearTeq Design Software.

The fabrication of this mechanism was performed on a 3D printer using ABS plastic. This resulted in a significant weight reduction from Prototype 1.4 at 48 grams to Prototype 1.5 at 19 grams, a 60 percent reduction. The core part of the mechanism functions as expected and is shown in Figure 17.

Figure 17. Prototype 1.5 Printed Prototype

G. Current Development and Future Work

Prototype 1.5 still needs to have a motor attached to the mechanism as well as the wings to be completed. Developing an improved design for the wings has already begun. Several different wing architectures were tested for the lift generated while flapping. The results revealed that a profile very similar to the Hawk-Moth

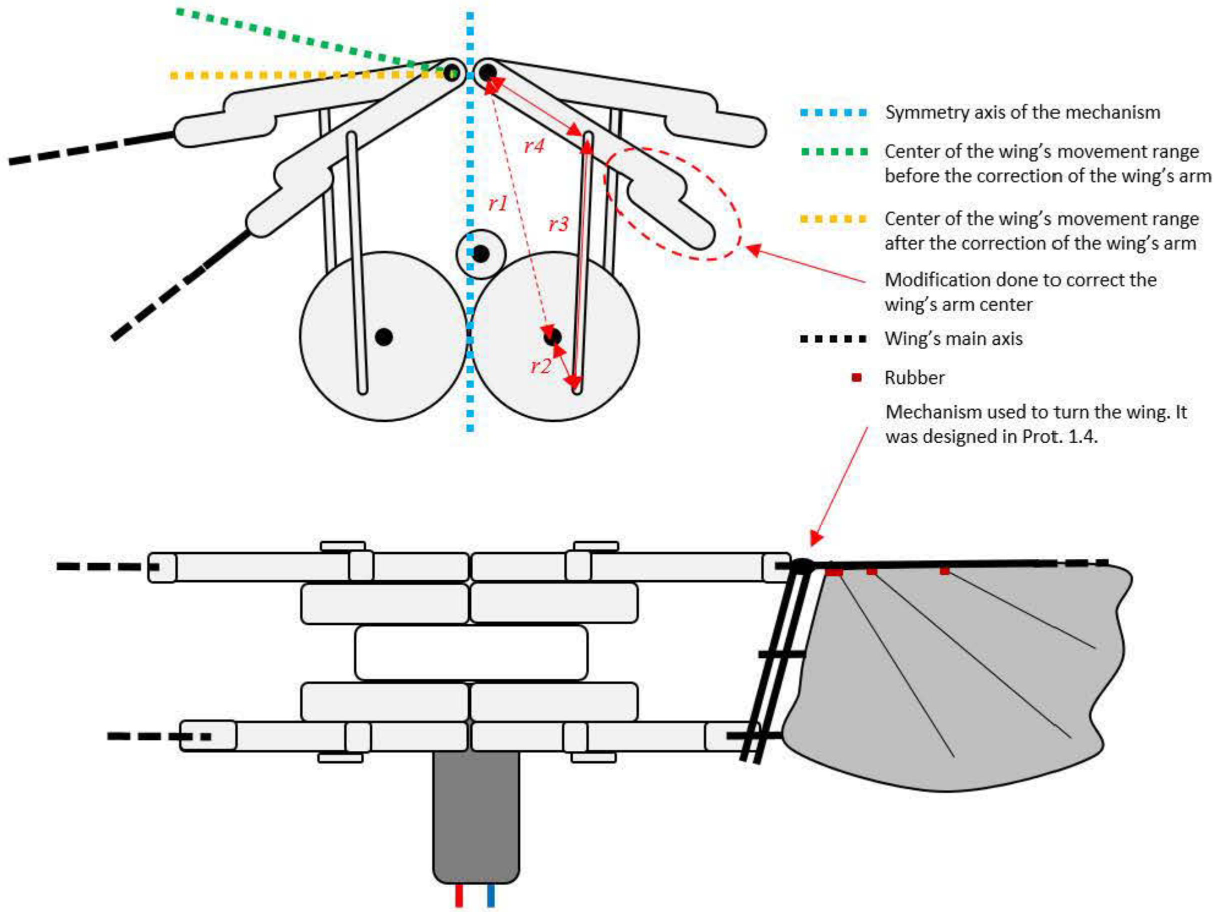


Figure 16. Prototype 1.5 Sketch of the mechanism in a top and front view

Hummingbird was optimal. The best performing structure was the one with two diagonal stiffeners as seen in Figure 18. The proposed material to use will be carbon fiber bars for the stiffeners and main structure which will reduce weight and provide additional stiffness, and a flexible plastic material for the trailing edges of the wing. This will further improve the performance of the wing in addition to more closely mimicking nature.

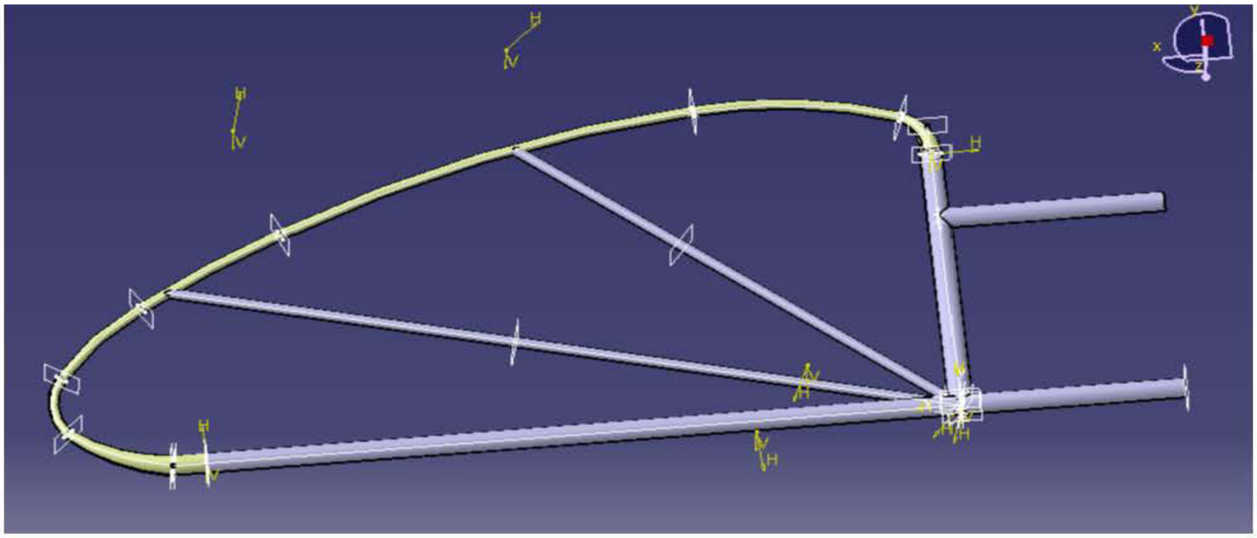


Figure 18. Prototype 1.5 Proposed Wing Structure

IV. Materials and Manufacturing

The advantages, disadvantages and applications of the manufacturing process and material utilized in the prototyping are reviewed in the following sections.

A. Materials

The appropriate materials for the structure vehicles depends strongly on the application. The most common materials used are Plastics such as PEEK and ABS, Aluminum and Carbon Fiber

PEEK is a polymer with a very high strength, low density and also a low coefficient of friction. It can effectively make light weight and durable gears and was the material used by AeroVironment. However, it is significantly more expensive than other building materials.

ABS is a polymer with a mid range strength and a low density and very low cost. However, due to its high coefficient of friction it will generate excess heat and decrease efficiency of a mechanical system when used in a high speed component.

Aluminum is highly machinable, and cost efficient. It is also considerably lighter than most other metals, while maintaining a significantly higher strength and stiffness than most polymers. This makes it ideal for long members with small cross sectional areas that will experience high stresses and require rigidity.

Carbon Fiber is a composite material that has a high stiffness, and tensile strength as well as a low density. It is highly effective in usage in these microstructures where stiffness, and strength are critical and due to their low density are able to out perform Aluminum in most applications. Though carbon fiber components are expensive, the improvements to performance justify its application.

B. Manufacturing Processes

The components for the microstructures of the MAV's are unique and need to be custom manufactured. The four primary methods of creating the components are through 3D printing, laser cutting, machining and modification of commercially available parts.

3D Printing is an additive manufacturing technique which will create a component through laying material until the final geometry is acquired The material can be either a thermoplastic polymer or a metal. The primary disadvantage is that 3D printing has a relatively low accuracy which creates rough surfaces and inaccurate joints, which are unsuitable for high speed applications.

Laser Cutting cuts with high accuracy detailed shapes from sheets of material. However, the thickness of the parts are limited by the sheet thickness and the edges are rough due to burning.

Machining allows for the creation of highly accurate detailed components from metal or polymers. However as complexity increases so does the machining time, and certain geometries are not possible to create as a single part when machining.

Modifying commercially available parts provides reliable components at a higher price, but due to the difficultly in manufacturing the long term time saving benefits can out weigh the expense.

V. Conclusion

We provided a review on several designs of actuation mechanisms for flapping-wing micro-air-vehicles (FWMAVs) in literature. We also showed our design and manufacturing iterations that lead to the development of a novel design of a flapping mechanism that actively controls both wing flapping (back and forth) and pitching motions using only one drive motor. The proposed design relies on a parallel crank rocker mechanism. Synthesis and optimization of the parallel crank rockers allowed independent control of the wing flapping and pitching angles. The designed mechanism is manufactured (3D printed), tested, and found to successfully achieve the desired wing motions that mimic the motion of a hummingbird wing.

The adopted iterative process allowed optimization of not only the mechanism design for active pitch control, but also manufacturing processes and materials used for implementation of the design. The final design, a combination of parallel crank rockers in which the gears replace the crank, created a compact configuration that provides smooth continuous active wing pitch control as well as optimum wing swing. The closeness of the fit of the pitch and swing curves to the theoretical ideal curves will allow accurate testing of the active pitch control hypothesis in FWMAVs. The future work involves completing the manufacturing of the wing to begin testing, followed by significant weight reduction of the overall design, and finally allowing asymmetric wing motions for lateral maneuvers.

VI. Acknowledgments

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