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Hummingbird-Inspired Wing Drive Mechanism

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Abstract

Hummingbirds have very distinct and unique flying characteristics which are unlike that of any other bird. While the hummingbird flaps its wings, it simultaneously feathers or rotates its wings in order to attain its hovering ability. The main goal of this project is to come up with a novel and simple design for an ornithopter that is capable of generating the same wing motion as a hummingbird. In designing this mechanism, different components such as gears, joints, actuators and structural supports were considered in order to obtain a fully functioning mechanism.

I. Introduction

Biologically inspired robots are a new frontier in autonomous systems. Over the past several years, engineers have looked to nature for new and unique robot designs, which offer many advantages over traditional designs [1]. Bio-inspired robots have shown to be highly maneuverable and have the ability to function in a variety of environments. As a result, these robots can be used for a number of different real-world applications ranging from search and rescue missions to planetary surface exploration. Thus far, there have been robots designed to mimic the behavior of cockroaches, snakes, lizards, and even birds.

These bird-inspired robots are called ornithopters which fly by flapping their wings, Figure 1 [2]. Over the years there has been a growing interest in ornithopters by universities, which has led to a variety of novel and innovative ornithopter designs. Recently, researchers at Georgia Tech have designed a small flying robot called the Entomopter which closely imitates animal flight muscles by using a reciprocating chemical muscle system [3].

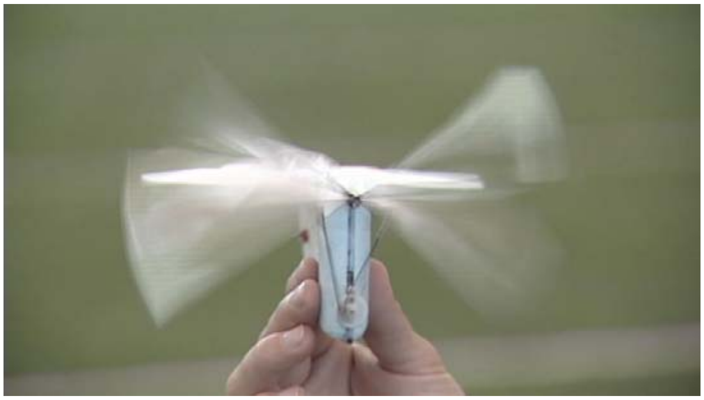


Figure 1: The photograph above shows an ornithopter with its flapping wings.

Additionally, in 2002 engineers at Chalmers University of Technology in Sweden, constructed a flapping wing robot that was capable of learning flight techniques. The ornithopter was driven by machine learning software known as a steady state linear evolutionary algorithm. This software was able to “evolve” in response to feedback on how well it performs at a given task. As a result, this mechanism evolved the ability for horizontal movement and maximum sustained lift force [3].

Ornithopters offer a number of advantages as compared to fixed-winged vehicles. Flapping airfoils produce both lift and thrust, thus minimizing the drag-inducing structures and ultimately increasing the efficiency. Another advantage of flapping-winged flight is that it also allows for high maneuverability. While fixed wings depend on forward velocity in order to generate maneuvering forces, flapping wings can produce large maneuvering forces at any given time [4].

The primary purpose of this project is to design an ornithopter which mimics the wing motion of hummingbirds. A hummingbird inspired ornithopter has already been designed by researchers at the University of Delaware, Newark. However, our goal was to come up with a new and simpler design that would allow the flapping-winged robot to generate enough lift force in order to hover. In order to design a robot that posses the same flight movements of a hummingbird it was first necessary to understand in detail exactly how these birds fly.

II. Hummingbird Flight

Hummingbirds have very unique flight characteristics which are unlike that of any other “ordinary” bird. Although the hummingbird has the same physical structure as most birds, it uses many of the same aerodynamic tricks as insects in order to gain its hovering ability. These birds typically fly at top speeds of 26 mph and beat their wings 60-80 times per second during normal flight. However, during acceleration they are able to beat their wings up to 200 times per second [5].

The hummingbirds’ notable flying characteristics are largely the result of their unique bone structure. Figure 2 shows the similarities as well as the differences between the bone structure of a pelican’s wing and that of the hummingbird. From the figure it is clear that the hummingbirds’ wing structure is similar to the human arm. The upper and forearms are small and rigid, and the wings consist almost entirely of feathers and muscles. In fact, 25% of a hummingbird’s body weight consists of flight muscles. As this figure shows, the wing mostly consists of the hand. While most birds can articulate the wing at the wrist, elbow, and shoulder, the hummingbird can only articulate its wing at the shoulder. The upper and forearms are in the shape of a V and the elbow is permanently bent making it a rigid structure that can articulate freely in all directions at the shoulder joint. This combination of rigidity at the elbow and mobility at the shoulder is the result of their high level of efficiency and maneuverability [6]. The structure of the wing also allows the hummingbird to generate propulsion and lift during both the upstroke and the downstroke.

Overall, hummingbirds have very flexible wings. As the hummingbird flies and the wing moves, a “depressor” muscles powers the downbeat and an “elevator” muscle powers the upbeat. The leading edge is rigid, while the feathers which form the surface of the wing are able to twist and bend. Consequently, the angle of attack of the wing varies from shoulder to the wing tip during every instant of the wing beat cycle. Overall, there are three distinct types of flight maneuvers for the hummingbird which consist of forward flight, backward flight, and hovering.

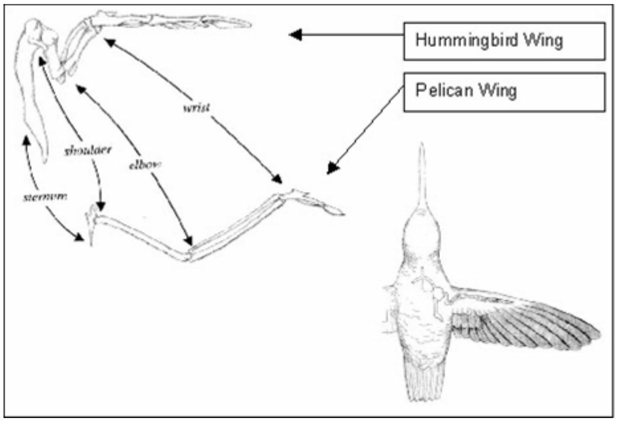


Figure 2: The wing bone structure of a pelican and a hummingbird. The wing structure of the humming is much like that of the human arm.

During the forward full speed flight position, lift is provided by both the down and upbeats as the bird rapidly flaps its' wings. However, forward thrust is limited to the downbeat. In this position, the wing beats in a vertical plane, orthogonal to the ground. On the downbeat the wing tip travels in a straight line, while on the upbeat the wing describes an arc so that throughout the duration of the wing cycle the tip moves in the shape of a flattened ellipse [6]. This can be seen in Figure 3 below.

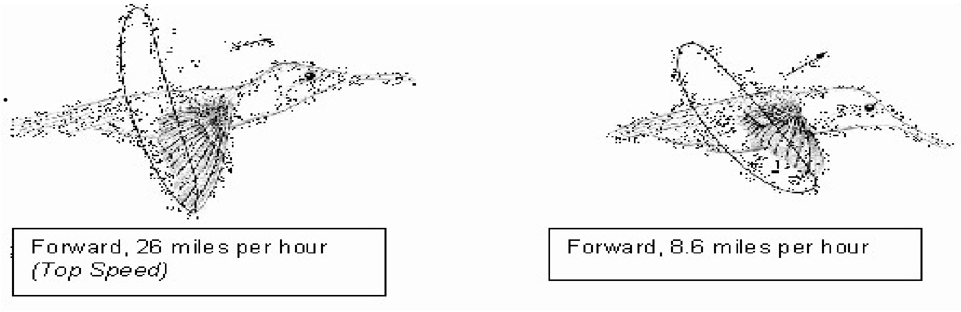


Figure 3: The wing motion of the hummingbird during forward flight.

Hummingbirds also have a so called "reverse gear" which enables them to fly backwards. In order to make this maneuver, the body of the bird is vertical and it is able to achieve backwards thrust by moving its wings in a circular path above its head, Figure 4. The wing surface is inverted on the back stroke in order to decrease the amount of air resistance the hummingbird experiences [6]. As the wings are inverted, air is pushed forward allowing the hummingbird to fly backwards in the opposite direction.

In the hovering position, its wings move forward and backward to generate lift in a plane perpendicular to the ground with the leading edge upward. In this position, its wings trace a sideways figure 8, Figure 5, while keeping its body vertical and rotating its wings 180 degrees during the wing beat cycle [6]. The figure 8 motion allows the hummingbird to maintain equilibrium, rather than producing lift during the forward and returning paths of the wings.

Figures 6 and 7 show both the top and side views of the motion of the hummingbirds' wings while in the hovering position. In order to hover the wings move forward and backward in a horizontal plane. On the forward stroke, the wing moves with the leading edge forward, the feathers trailing upward to produce a small positive angle of attack.

On the back stroke, the leading edge rotates nearly 180 degrees and moves backward, the underside of the feathers now uppermost and trailing the leading edge in such a way that the angle of attack varies from wing tip to shoulder, producing a substantial twist in the profile of the wing [6].

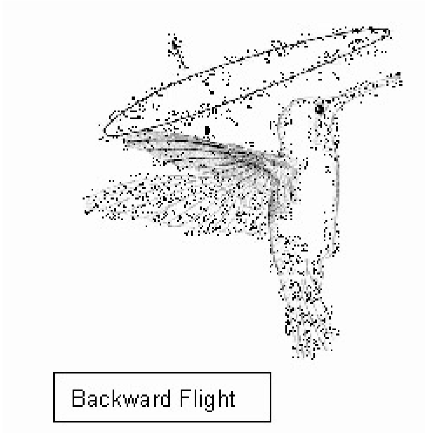


Figure 4: The motion that the hummingbirds' wing tips make during backwards flight.

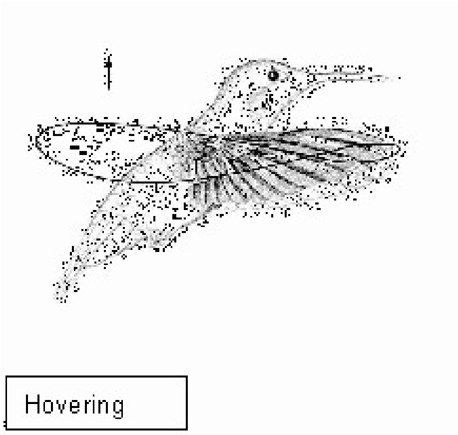


Figure 5: In the hovering position, the wings of the hummingbird move in a figure-8 motion.

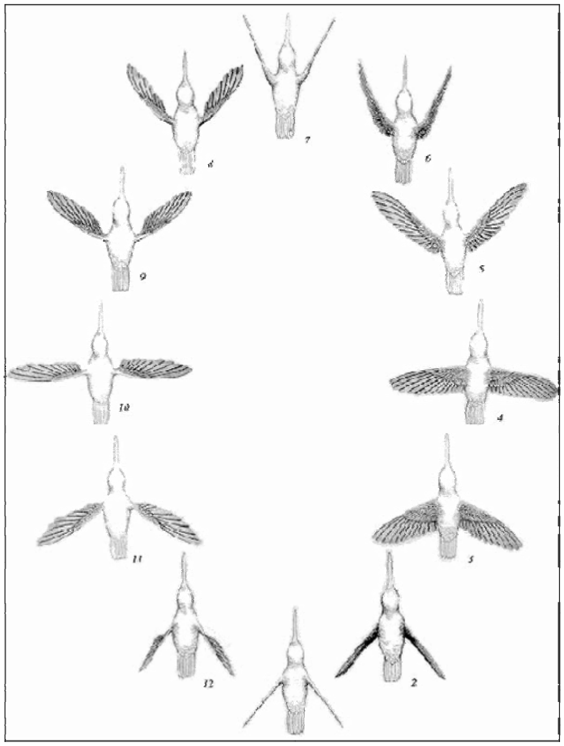


Figure 6: Top view of the hummingbirds' wing motion during hovering as the wing articulates through an angle approaching 180 degrees.

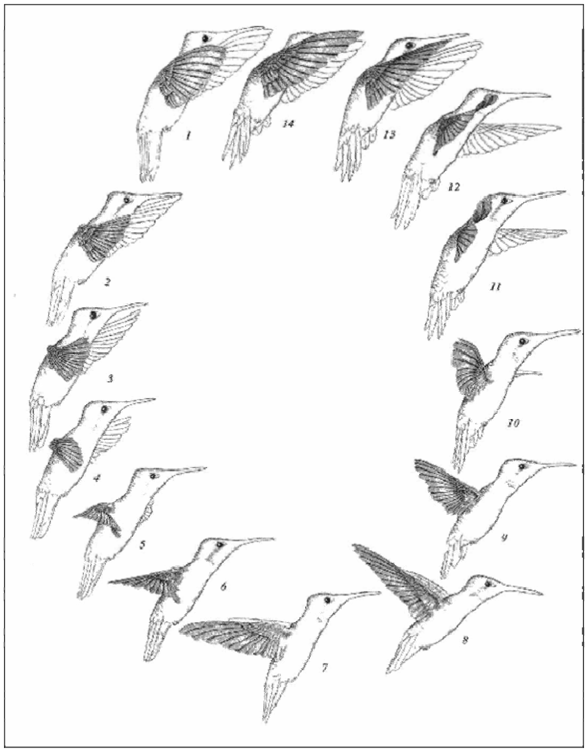


Figure 7: Corresponding side view showing the different stages of the wing beat cycle while hovering as the hummingbird traces the figure 8 motif.

Hummingbirds support 75% of their entire body weight during the downstroke and 25% of their body weight during the upstroke while in the hovering position. Insects on the other hand, support their body weight equally during both the upstroke and the downstroke and ordinary birds support 100% of their body weight with the downstroke alone [7].

III. Design Considerations

The most distinctive characteristic of hummingbird flight is the ability for the bird to both flap and rotate its wings in order to hover. Over the years there have been many improvements in flapping-winged robots. However, to this date little scientific research has been done that incorporates both flapping and rotating wings into one single design due to the complexity in the integration of these two features. Because the rotation of the wings is still a fairly novel design concept for ornithopters, three different mechanisms were considered that would allow the wings to attain optimum rotation of ± 180°.

1. Cam-follower System

Researchers at the University of Delaware, Newark have designed a light-weight compact ornithopter inspired by the wing motion of hummingbirds. The micro-air vehicle (MAV), Figure 7, has the potential to generate enough lift to hover by using a single actuator and rotating each wing about two orthogonal axes.

The flapping-winged mechanism named the Mechanical Hummingbird Project is able to attain biaxial wing rotation by using a cam-follower system. This system consists of a torsion spring, a bending spring, a follower, and a guide, Figure 8. In order to achieve full wing rotation, the follower moves around the path of the guide. The top edge of the guide is slightly in front of the follower axis while its bottom edge lies slightly behind the follower axis. There is a slant in the guide which forces the follower to move along the backside of the guide while moving down and along the front side of the guide while moving upward. The follower initially begins at the top edge of the guide. As it moves down and contacts the guide the follower is forced to rotate, thus rotating the entire wing. The follower then continues to move down the back edge of the guide while the torsion spring is compressed. The bending spring forces the follower to keep contact with the guide until the follower has moved below the bottom edge of the guide. At this point, both the bending and the torsions springs are released, causing the wing to rotate back to its initial position and realigning the follower axis with the wing spar axis. The follower is then forced along the front edge of the guide, moving in the opposite direction, while still in its fully pronated position [8]. Figure 9 illustrates the motion of the follower as it travels around the guide.

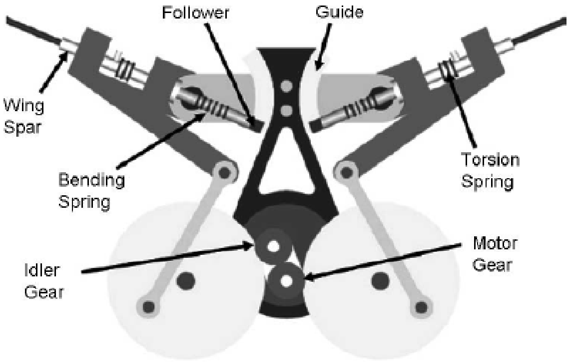


Figure 7: The front view of the ornithopter, showing the four-bar mechanism which drives the wings. The motor gear drives both the right gear wheel and idler gear.

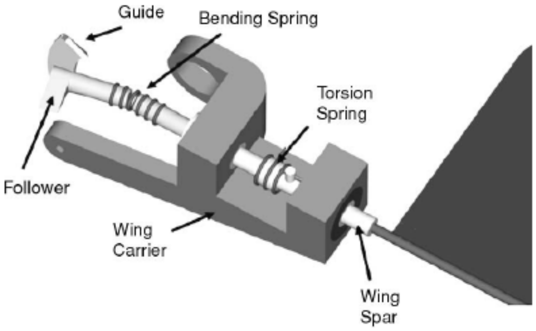


Figure 8: A schematic diagram depicting the wing carrier assembly. The torsion spring is attached to the wing spar and the bending spring is bent allowing follower to move along the guide.

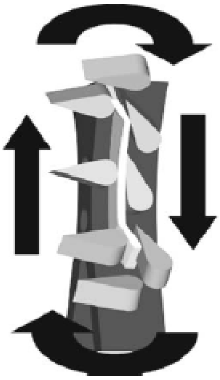


Figure 9: The path that the follower makes as it travels around the guide.

2. Four-bar Linkage System

The four-bar linkage system is another system that was considered in order to achieve the feathering of the wings. The four-bar linkage system also known as the crank-rocker is one of the most widely used and simplest movable mechanisms. The four-bar consists of four rigid bodies which are attached to one another by pivot joints to form a closed-loop, Figure 10 [9]. One of the links in the mechanism is fixed, while the input link is a crank and continuously rotates a full 360 degrees. The middle bar is referred to as the coupler bar and the output link is the rocker. As the crank moves in its circular path, the rocker link follows the motion as determined by the motion of the input and coupler bar. One of the fundamental concepts in modeling a four-bar is the concept of critical dimensions [10]. In order to achieve optimum rotation, the output angle needs to be maximized (as close to 180 degrees as can be attained). All the links must be of the correct proportions and dimensions to maximize the rocker angle. As a result, the crank-rocker must follow Grashoff's condition which states that the sum of the lengths of the crank and coupler bars (the shortest and longest links respectively) must be less than or equal to the sum of the lengths of the rocker and the fixed bar for the input link to experience full continuous motion.

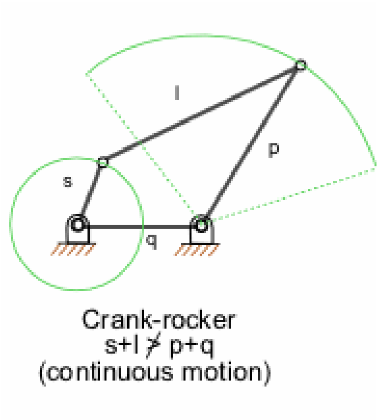


Figure 10: The crank-rocker mechanism. According to Grashoff's condition the addition of the lengths of the shortest (s) and longest (l) links (the crank and coupler bars respectively) cannot be greater than the sum of the lengths of the rotator (p) and fixed (q) links, if continuous motion is desired.

3. Spring and Pulley System

The third and final mechanism that was considered in order to generate the feathering of the wings was a spring and pulley system. This system consists of highly tensioned strings attached to the wings. While the wings are in the fully pronated position, the strings would be in tension. Then the spring would release, thus reducing the tension in the strings and causing the wings to rotate. When the spring snaps back into place the strings would once again be under tension, thus bringing the wings back to their initial position.

After evaluating these different mechanisms it was decided that the four-bar linkage system would be used in order to produce the feathering of the wings. An improvement could have been made to the cam-follower system which has already been designed, but this is a very complicated system and many of are skeptical if it will even allow the mechanism to fly. The spring and pulley system was also rejected because there was no effective and efficient way proposed that would incorporate this concept into a design which would generate maximum wing rotation. Because of this, the four-bar linkage system was selected. Even though this mechanism does not produce the amount of rotation desirable (maximum output angle that can be achieved is less than 180 degrees), it still produces a large enough output angle that is sufficient without over complicating the design.

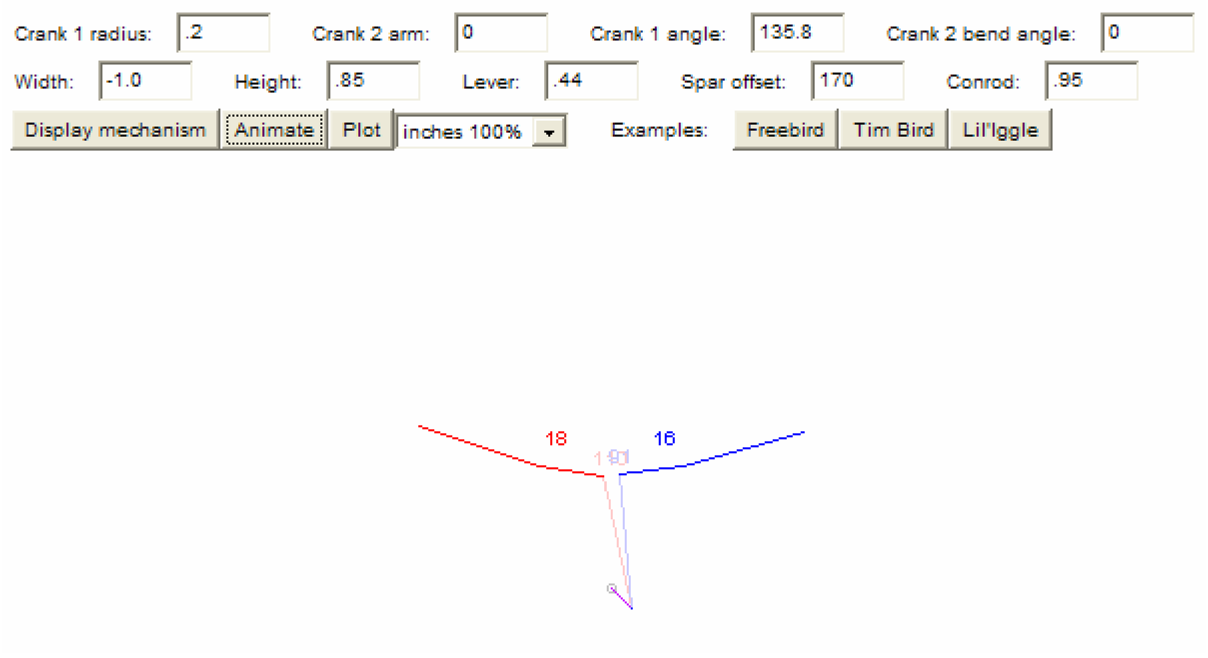
IV. Design Components

Many different components were considered in designing this robot to accurately mimic the unique flight characteristics of the hummingbird. A small DC motor .273 inches in diameter and .65 inches long is used to drive the ornithopter. The initial speed of the motor is 29,000 rotations per minute (rpm) which allows the mechanism to flap its wings at 11.9 Hertz. The body consists of different gears, joints, and structural supports that work together with all the mechanical components in order for the mechanism to function effectively. In designing a robot that mimics the flight patterns of hummingbirds, both the flapping and rotating mechanisms were first modeled separately using ProEngineer Wildfire 3.0. Afterwards, these two features were then integrated together into one single and final design.

1. Flapping

The flapping mechanism consists of two four-bars which are used to generate the up and down flapping motion of the ornithopters' wings. The single actuator runs with an initial input speed of 29,000 rpm and a final output speed of 1,087.5 rpm which is equivalent to a gear reduction ratio of 1:26.667. The DC motor directly drives the pinion with 48/12 teeth by being in contact with 9 of its teeth. The pinion in turn rotates a wheel with 60/12 teeth. As the wheel rotates, the crank moves in a circle, thus forcing the coupler and output links to move relative to this motion. Because the output link is connected to the wings, as the bar rotates it causes the wings to flap up and down.

In order to figure out the correct dimensions for the two four-bars which generate the flapping an online simulator known as FlapDesign, Version 2.2 [11] was used, Figure 11. By plugging the different dimensions into this simulator and running the animation we able to see if the mechanism would flap as desired. From this simulator we were also able to obtain plots for the wing angle versus the conrod (coupler) angle, Figure 12. This plot shows the synchronization of both of the two coupler bars, which is necessary for the wings to flap. Figures 13 and 14 show different views of the flapping model designed in ProEngineer.



Crank 1 radius: .2
Crank 2 arm: 0
Crank 1 angle: 135.8
Crank 2 bend angle: 0
Width: -1.0
Height: .85
Lever: .44
Spar offset: 170
Conrod: .95
inches 100%

Figure 11: The flapping mechanism modeled in the online simulator.

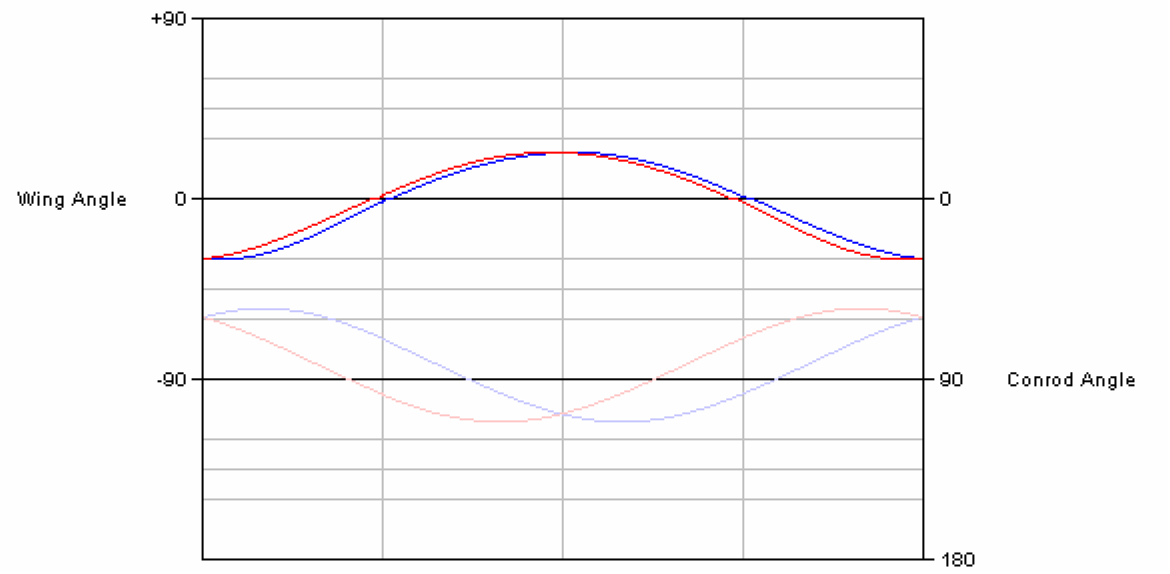


Figure 12: A plot for the wing angle versus conrod angle for both of the coupler bars in the flapping mechanism.

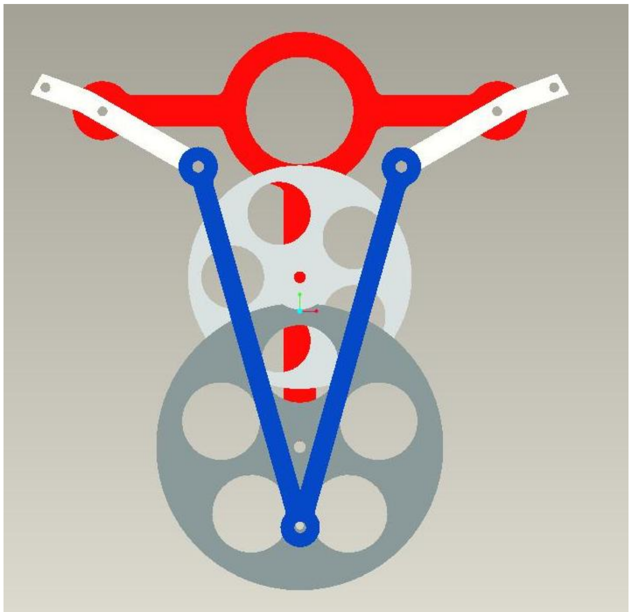


Figure 13: Front view of the flapping mechanism which clearly displays the four-bar linkage system used to move the wings up and down.

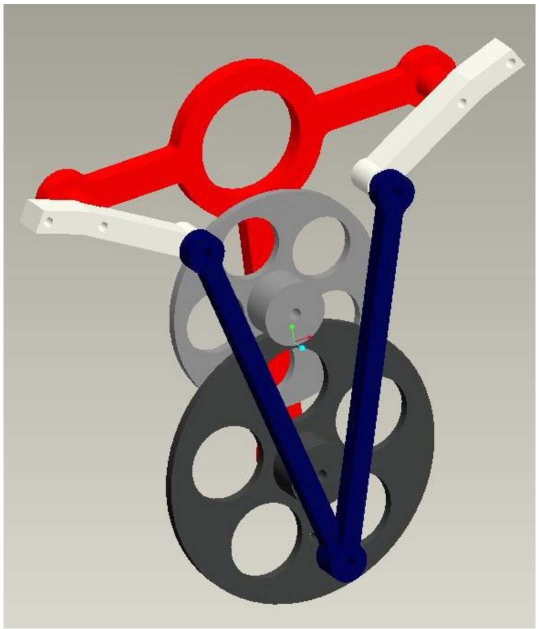


Figure 14: Another view of the flapping mechanism.

Table 1 in the Appendix shows the various dimensions for the different components used in the design.

2. Rotating

In order to achieve the feathering of the wings another four-bar linkage system was used in the form of a crank-rocker. The dimensions for these links were calculated by using the Flash Four-bar Linkages online simulator [12]. The simulator would allow you to change the lengths of the bars in reference to the length of the fixed bar, Figure 15. By adjusting the lengths of the crank, coupler, and rotator bars it was possible to see which proportions produced the maximum output angle achievable. Using these proportions in the design we were able to attain fairly accurate dimensions to produce the rotation of the wings. Although, the mechanism doesn't rotate at the desired 180 degrees (maximum achievable output angle is approximately 130 degrees) it is still sufficient. (It is important to note here that some rotation had to be sacrificed to obtain small enough proportions for the crank and rotator links so that the design would be possible based on the gear dimensions.)

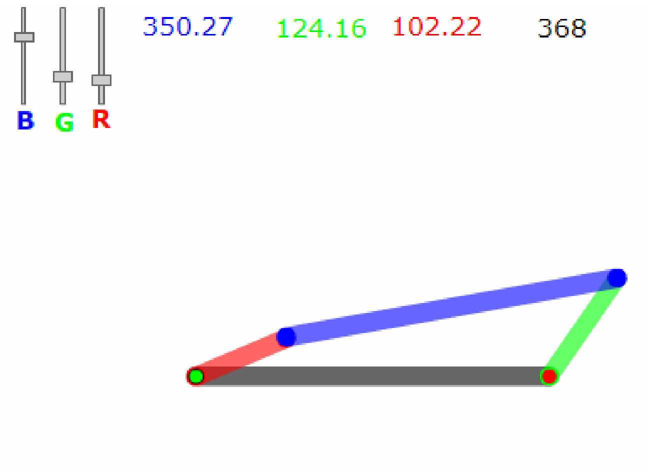


Figure 15: The online simulator used in order to calculate the accurate proportions for the links in order for the crank-rocker to generate optimum rotation. The red bar is the crank, the blue link the coupler, the green bar is the rotator, and the gray is the fixed bar.

Another important component that was incorporated into the design for the rotating model is the use of the worm gear. A worm is a gear that resembles a screw and its body is usually fairly long in the axial direction. A worm is usually meshed with a disk-shaped gear called the "gear" or the "wheel." In a worm-and-gear set the worm can always drive the gear, but the gear cannot drive the worm [13]. This gear was used because the motion from the motor needed to be transferred from one plane to a perpendicular plane, Figure 16 [14]. The bevel gear was also considered as a means of finding a right angle solution since the gears can be place at 90 degree angles from one another, Figure 17 [15]. However, the worm gear was chosen for the design instead because it allows for the maximum speed while using relatively few parts and in a small space.

Figure 16: Worm and worm gear.

Figure 17: Bevel gears.

In order to achieve the synchronized flapping and feathering of the wings the worm-and-gear set must have the same gear reduction as the gears used in the flapping model. For the rotating-winged mechanism a gear with 48 teeth and a standard pitch of 48 was used. The pressure angle of the teeth is 20 degrees which is one of the most common angles for worm gear teeth. After taking these factors into account it was then possible to calculate the number of teeth that need to be on the worm to acquire a gear reduction of 1:26.667. By performing the necessary calculations it was found that the worm needs approximately 1.8 teeth.

The rotating model works as follows: The motor drives the worm which in turn drives the worm gear. As the worm gear rotates, this causes the crank-rocker system to move forcing the rocker to rotate back and forth from 0 to 130 degrees. Because the output link is attached to the wings, as this bar rotates feathering is generated in the wings of the ornithopter. Figures 18 and 19 show different views of the rotating mechanism modeled in ProEngineer.

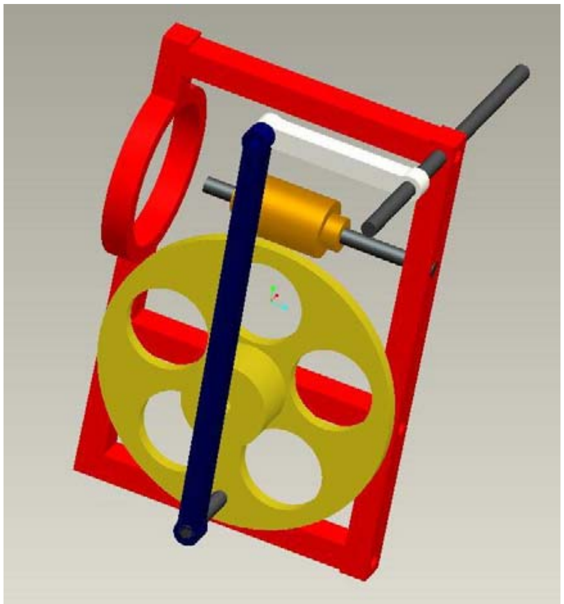


Figure 18: A clear view of the rotating mechanism. The crank-rocker mechanism is evident and so is the worm-and-gear set. As the motor drives the worm, the gear causes the crank-rocker to move back and forth. Because the rotator is attached to the wing, this ultimately causes the entire wing to rotate.

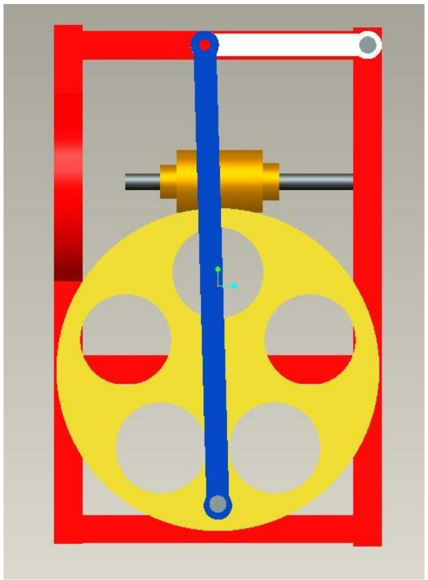


Figure 19: The side view of the rotating mechanism.

Table 2 in the Appendix shows the different proportions of the four-bar relative to the fixed bar. Table 3 in the Appendix lists the different dimensions for the components used in the design of the rotating mechanism. Figures and show various views of the rotating model in ProEngineer.

3. Combined Mechanism

The combined mechanism integrates these two designs into one single mechanism which is capable of flapping and rotating its wings. For flapping to be achieved in this model the same four-bar linkage system was used along with the same sized gears. In addition, the same four-bar was used in the rotation of the wings and the worm-and-gear set was again utilized as well so that the motion could be transferred to a plane orthogonal to the motion of the motor. The only new feature that was incorporated into this design is the use of the universal joint. The universal joint is a joint in a rigid rod which allows the rod to bend in any direction. It consists of a pair of ordinary hinges located close together, but oriented at 90 degrees relative to one another, Figures 20 and 21 [16].

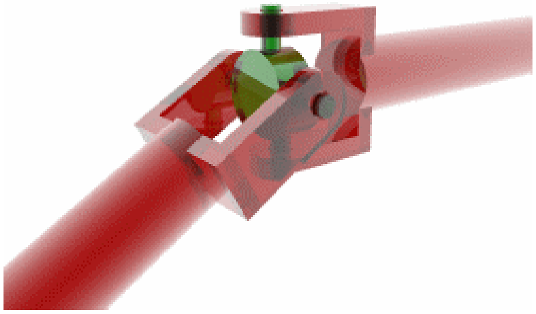


Figure 20: The universal joint.

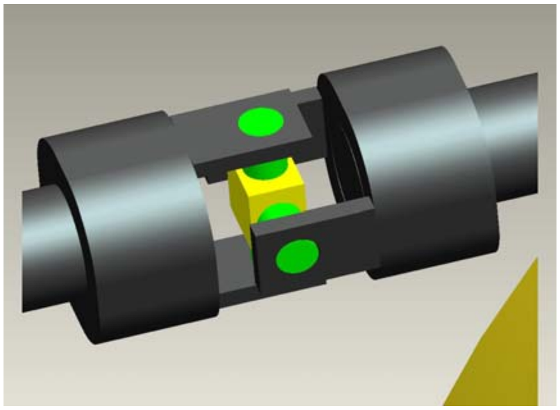
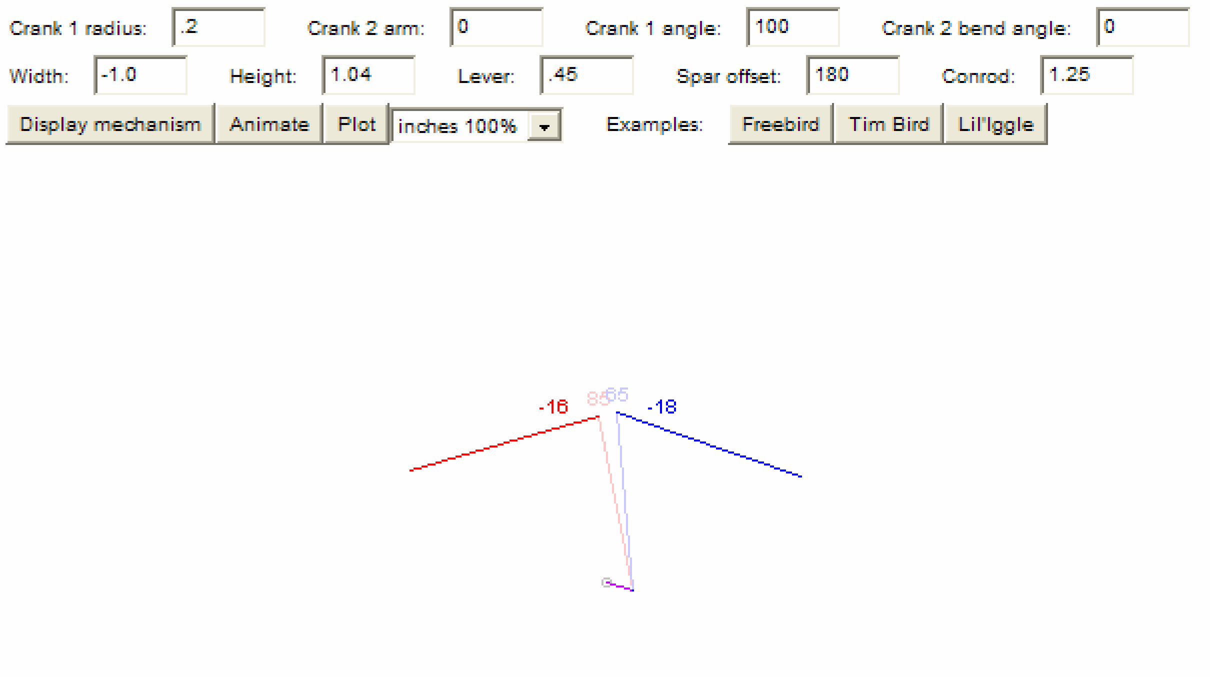


Figure 21: The universal modeled in ProEngineer.

The way the mechanism works is as follows: The motor rotates the pinion which in turn drives the wheel. As the wheel rotates the two wings flap up and down as the crank moves in a circular path around the gear. At the same time that the motor drives the pinion, it also rotates the worm which in turn drives the gear. The crank-rocker mechanism attached to the gear rotates the rod along the wing axis from 0 to 130 degrees. As the rod rotates, the universal joints at both ends of the rod bend in different directions, thus causing the entire wing to feather. Figure 22 shows the simulation for the flapping of the combined mechanism and Figure 23 shows the plot of the wing angle versus the conrod angle. Because both of these both coupler bars are synchronized, the mechanism is indeed capable of flapping its wings. Figures 24 and 25 are various views illustrating the completed final design.



Crank 1 radius: .2
Crank 2 arm: 0
Crank 1 angle: 100
Crank 2 bend angle: 0
Width: -1.0
Height: 1.04
Lever: .45
Spar offset: 180
Conrod: 1.25
inches 100%

Figure 22: The online simulation for the parameters for the combined mechanism.

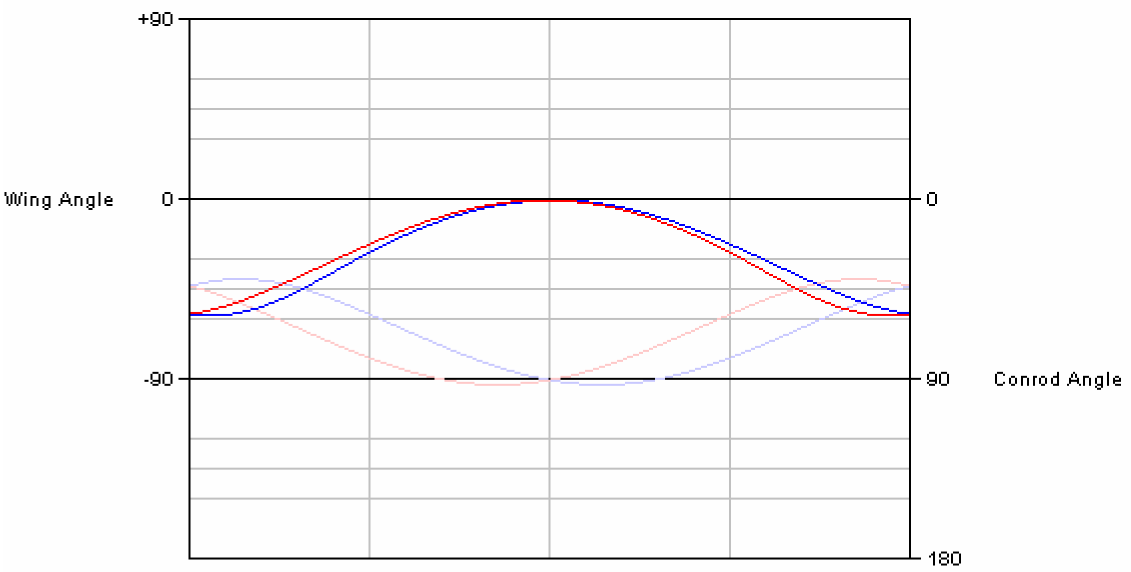


Figure 23: The plot for the wing angle versus the conrod angle for the combined mechanism. It is clear to see that the two coupler bars are aligned during the flapping cycle.

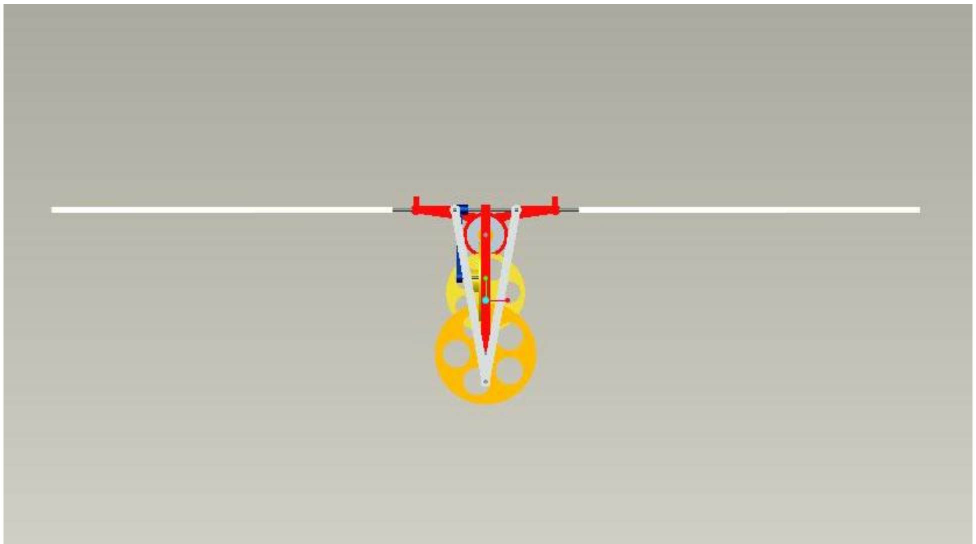


Figure 24: Front view of the combined mechanism. This view shows the four-bar mechanism that causes the wings to flap.

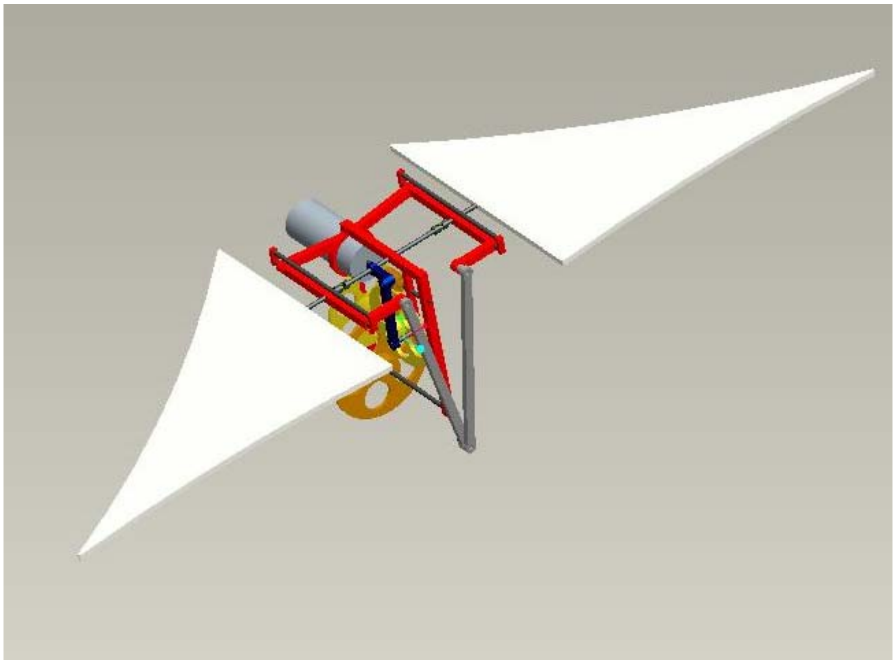


Figure 25: This shows another view of the completed design. The four-bar used to generate the flapping and the four-bar used for rotation are evident.

Tables 4 and 5 in the Appendix lists the different dimensions used for the design of the combined mechanism.

V. Future Work

There is still much future work that needs to be done in order to fully complete the design of this hummingbird inspired ornithopter. Firstly, the dimensions for the crank-rocker system used need to be of more accurate proportions for rotation to be optimized. A better simulator should be used or a Matlab program could be written in order to optain extremely precise dimensions for the linkage system to see if an output angle above 130 degrees and closer to 180 degrees can be achieved. In addition to this, further work needs to be done in order to find accurate dimensions for the length and diameter of the worm. Once all of the dimensions are very precise the ornithopter can then be constructed and tested to see if it will indeed fly or not. Last but not least, a Matlab program should also be written to control and synchronize both the flapping and feathering of the wings.

VI. Conclusions

It is evident that biologically inspired robotics is a rapidly growing field since these robots offer many advantages over older traditional designs. As new and improved robotic designs keep being invented, bio-inspired robots can be used for more and more real-world applications.

Overall, the goal of this project was achieved. A new and simple design was proposed in order to mimic the wing motion of the hummingbird. Even though much work still needs to be done on the ornithopter before it is completed, the preliminary calculation done thus far show that this model should flap and rotate its wings thereby generating enough lift in order to hover.

VII. Acknowledgements

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VIII. References

1. Regli, W.C., Drexel University. “Bio-Inspired Robot Design.” (2006). http://gicl.cs.drexel.edu/wiki/Bio-Inspired_Robot_Design_(Fall_2006)
2. Yeates, E., KSLTV. “Engineers Build Tiny Flying Ornithopter.” (2006). http://media.bonnint.net/slc/6/685/68510.jpg
3. Wikipedia, Online Encyclopedia. “Ornithopters.” (2007). http://en.wikipedia.org/wiki/Ornithopter
4. Ornithopter Zone. “Why Flapping Wings.” (2007). http://www.ornithopter.org/
5. Vanhorn, M., Apologetics Press on the World Wide Web. “Hummingbirds—Float Like a Butterfly, Pollinate Like a Bee.” (2004). http://www.apologeticspress.org/modules.php?name=Read&itemid=2533&cat=11
6. Greenewalt, C.H. *Hummingbirds.* Chapter 3. General Publishing Company. Toronto, Ontario. (1990).
7. Ornithology, Lecture Notes- Bird Flight. (2005). http://www.people.eku.edu/ritchisong/554notes3.html
8. McIntosh, S.H., Agrawal, S.K., Khan Z. (2006). “Design of a Mechanism for Biaxial Rotation of a Wing for a Hovering Vehicle.” *Transactions on Mechatronics*. Vol.11, No. 2. p. 145-153.
9. Wikipedia, Online Encyclopedia. “Four Bar Linkage.” (2007). http://en.wikipedia.org/wiki/Four_bar_linkage
10. Olson, D. University of Rhode Island, College of Engineering. “Analysis of a Four-bar Linkage.” (1996). http://www.mines.edu/fs_home/dgolson/mce302-1.html
11. FlapDesign Software, Version 2.2 http://www.ornithopter.org/flapdesign1.shtml
12. Flash Four-bar Linkages Simulator. http://www.mechanisms101.com/fourbar01.shtml
13. Wikipedia, Online Encyclopedia. “Gears.” (2007). http://en.wikipedia.org/wiki/Gear
14. Nice, Kim. How Stuff Works. “How Gears Work- Worm Gears.” (2007). http://science.howstuffworks.com/gear5.htm
15. Most Common Types of Gears. http://www.virtualsciencefair.org/2006/seef6s2/common.htm
16. Wikipedia, Online Encyclopedia. “Universal Joint.” (2007). http://en.wikipedia.org/wiki/Image:Universal_joint.gif

Appendix

Table 1: Dimensions for the flapping mechanism.

Crank 1 Radius	0.2 inches
Crank 2 Arm	0
Crank 1 Angle	135.8 degrees
Crank 2 Bend Angle	0
Width	-1.0 inches
Height	0.85 inches
Lever	0.44 inches
Spar Offset	170 degrees
Conrod	0.95 inches
Pinion	0.567 inches
Gear	0.728 inches

Table 2: Proportions used to generate the maximum amount of rotation for the crank-rocker system.

Crank	27.78% of fixed bar
Coupler	95.18% of fixed bar
Rotator	33.70% of fixed bar

Table 3: Dimensions for the rotating mechanism.

Fixed Bar	0.85 inches
Crank	0.236 inches
Coupler	0.81 inches
Rotator	0.286 inches
Worm Diameter	0.11 inches
Worm Length	0.15 inches
Worm Gear Diameter	0.567 inches

Table 4: Dimensions for the flapping of the wings for the combined mechanism.

Crank 1 Radius	0.2 inches
Crank 2 Arm	0
Crank 1 Angle	100 degrees
Crank 2 Bend Angle	0
Width	-1.0 inches
Height	1.04 inches
Lever	0.45 inches
Spar Offset	180 degrees
Conrod	1.25 inches
Pinion	0.567 inches
Gear	0.728 inches

Table 5: Dimensions for the rotating of the wings for the combined mechanism.

Fixed Bar	0.51 inches
Crank	0.141 inches
Coupler	0.485 inches
Rotator	0.172 inches
Worm Diameter	0.11 inches
Worm Length	0.13 inches
Worm Gear Diameter	0.567 inches