A Study on the Control, Dynamics, and Hardware of Micro Aerial Biomimetic Flapping Wing Vehicles

Siara Hunt
A STUDY ON THE CONTROL, DYNAMICS, AND HARDWARE OF MICRO AERIAL
BIOMIMETIC FLAPPING WING VEHICLES

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Siara Hunt

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A STUDY ON THE CONTROL, DYNAMICS, AND HARDWARE OF MICRO AERIAL

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by

Siara Hunt

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SYMBOLS

\( \theta \)  
angle of wing with respect to body

\( T \)  
thrust

\( L \)  
lift

\( D \)  
drag

\( F_{\text{downstroke}} \)  
lift force from the downstroke of flapping (likewise \( F_{\text{upstroke}} \))

\( M \)  
pitching moment

\( m \)  
mass

\( I_{yy} \)  
pitching moment of inertia

\( I_{xz} \)  
product of inertia

\( \omega \)  
angular velocity or flapping frequency

\( g \)  
gravitational acceleration

\( x \)  
horizontal position

\( z \)  
vertical position

\( u \)  
forward velocity in body coordinates

\( w \)  
vertical velocity in body coordinates

\( \sigma \)  
Strouhal number

\( S \)  
surface area of wing

\( \rho \)  
density of air

\( A_r \)  
aspect ratio

\( c \)  
chord

\( \alpha \)  
angle of attack

\( C_L \)  
.lift coefficient

\( C_D \)  
drag coefficient

\( K \)  
aspect ratio coefficient

\( v \)  
velocity of vehicle through the air

\( f \)  
flapping frequency

\( L_1 \)  
length of first wing panel

\( L_2 \)  
length of secondary wing panel

\( v_z \)  
vertical speed

\( P_{\text{aero}} \)  
power needed in actuation

\( P_{\text{dynamic}} \)  
dynamic pressure

\( d_{\text{sym}} \)  
symmetric wing dihedral

\( V_{\text{inf}} \)  
freestream velocity

\( K_p \)  
proportional controller gain

\( K_D \)  
derivative controller gain

\( \delta_0 \)  
free displacement/actuation of an ideal bimorph actuator

\( V \)  
input voltage
# ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>MAV</td>
<td>micro aerial vehicle</td>
</tr>
<tr>
<td>NAV</td>
<td>nano aerial vehicle</td>
</tr>
<tr>
<td>PAV</td>
<td>pico aerial vehicle</td>
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<tr>
<td>ECS</td>
<td>electronic control system</td>
</tr>
<tr>
<td>LiPO</td>
<td>lithium polymer</td>
</tr>
<tr>
<td>IPMC</td>
<td>ionic polymer metal composite</td>
</tr>
<tr>
<td>NiMh</td>
<td>nickel metal hydride</td>
</tr>
<tr>
<td>ESC</td>
<td>electronic speed control</td>
</tr>
<tr>
<td>PI</td>
<td>proportional integral controller</td>
</tr>
<tr>
<td>PD</td>
<td>proportional derivative controller</td>
</tr>
<tr>
<td>PID</td>
<td>proportional integral derivative controller</td>
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<tr>
<td>VCCTEF</td>
<td>variable camber continuous trailing edge flap</td>
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<tr>
<td>SMA</td>
<td>shape memory alloy</td>
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**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Biomimetic</td>
<td>drawing inspiration from biology</td>
</tr>
<tr>
<td>Piezoelectric/PZT</td>
<td>lead titanate (PbTiO3)</td>
</tr>
<tr>
<td>Supination</td>
<td>insect wing flapping-twisting dynamic</td>
</tr>
<tr>
<td>Delayed stall</td>
<td>bio-wing operating at angle of attack that causes aircraft stall</td>
</tr>
<tr>
<td>Wake capture</td>
<td>using vortices for lift</td>
</tr>
<tr>
<td>Alula</td>
<td>feathered thumbs</td>
</tr>
<tr>
<td>Feathering</td>
<td>variable wing mechanism</td>
</tr>
<tr>
<td>Clap-Fling</td>
<td>bio-wings that make contact and exceed the Kutta condition</td>
</tr>
<tr>
<td>Quad-launch</td>
<td>pterodactyl takeoff by jumping from all fours</td>
</tr>
<tr>
<td>Compliant</td>
<td>design method of organic, integrated whole structures</td>
</tr>
<tr>
<td>Variable camber flap</td>
<td>aircraft with multi-segment flaps resembling feathers</td>
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ABSTRACT

Hunt, Siara, MSAE, Embry-Riddle Aeronautical University, December 2017. A Study on the Control, Dynamics, and Hardware of Micro Aerial Biomimetic Flapping Wing Vehicles.

Biological flight encapsulates 400 million years of evolutionary ingenuity and thus is the most efficient way to fly. If an engineering pursuit is not adhering to biomimetic inspiration, then it is probably not the most efficient design. An aircraft that is inspired by bird or other biological modes of flight is called an ornithopter and is the original design of the first airplanes. Flapping wings hold much engineering promise with the potential to produce lift and thrust simultaneously. In this research, modeling and simulation of a flapping wing vehicle is generated. The purpose of this research is to develop a control algorithm for a model describing flapping wing robotics. The modeling approach consists of initially considering the simplest possible model and subsequently building models of increasing complexity. This research finds that a proportional derivative feedback and feedforward controller applied to a nonlinear model is the most practical controller for a flapping system. Due to the complex aerodynamics of ornithopter flight, modeling and control are very difficult. Overall, this project aims to analyze and simulate different forms of biological flapping flight and robotic ornithopters, investigate different control methods, and also acquire understanding of the hardware of a flapping wing aerial vehicle.
1. Introduction

In this thesis, a literature search of flapping wing robotics is conducted, the aerodynamic dynamics of biological flight is investigated, several models of flapping wing flight are developed and simulated, and different control methods are considered and developed. First, a simple model that accounts for the most reduced possible system is developed. Subsequently, further models with increasing complexity are developed. After the development of several possible flapping models and equations of motion, the models are simulated with MATLAB in threefold progression; a single panel flapping wing, a two-panel flapping wing, and a two-panel flapping wing with three dimensional translational motion. In the single panel model, flat-plate drag was used without forward motion and the final two-panel model allows forward motion. Different control methods are investigated and ultimately a proportional derivative controller with feedback and feedforward control is used to control the two-panel flapping wing. Overall, an innovative flapping wing model and control is derived. The thesis additionally discusses the application of smart materials in flapping wing robotics and possible applications. The vast evolutionary history of bird and insect flight, the ideal application of bio-Micro Aerial Vehicles (MAVs) for surveillance, and the increasing presence of biomimetic design in engineering are the primary inspirations for this work.
Evolution has been furthering the efficiency of flight for about 400 million years. In contrast, human efforts to advance fixed-wing aircraft are a little more than 100 years old- a mere infant to the workings of evolution. Therefore, it is in the interest of aircraft design to take advantage of the 400-million-year-old ingenuity of evolutionary flight by mimicking biological modes of flying. Moreover, the beginnings of fixed-wing aircraft were not the original dream of aviation. Humanity’s original dream of flight was to fly like the birds and many attempts to build human-powered ornithopters were made before the Wright brothers (Goodheart, 2011). George Caley’s fixed-wing aircraft design was a movement away from ornithopters and away from the original dream of flying like the birds. Now, aviation and aerospace engineering may be able to realize the original dream of flight like the birds because smart materials and advancing technologies have the potential to make the human-piloted ornithopter not only possible, but potentially more efficient than fixed-wing aircraft.

A seamless, integrated, and more flexible wing may boast reduced drag and greater fuel efficiency according to NASA researchers (Nguyen, Trinh, et al, 2013). Many modern aircraft designs involve morphing wings, variable wings, and more dynamic flaps and ailerons. All of these modern designs appear to illustrate a movement towards flight that is more bird-like. Indeed, several researchers at the NASA Ames Research Center claim that an aircraft wing modeled more like a seagull wing with variable camber continuous trailing edge flaps (VCCTEF) -essentially feather-like flaps for an aircraft as shown in Figure 1.1- can reduce drag by 50% and “significantly reduce fuel burn for long-range cruise” (Nguyen, Trinh, et al, 2013). A related NASA study determined that the bend-twisting motion of birds can be applied to commercial aircraft:
Highly flexible wing aerodynamic surfaces can be elastically shaped in-flight by active control of wing twist and bending deflection in order to optimize the local angles of attack of wing sections to improve aerodynamic efficiency through drag reduction during cruise and enhance lift performance during take-off and landing (Nguyen, Precup, et al, 2015).

Moreover, the researchers from NASA and Boeing believe that elastic, flapping wing and VCCTEF flight is potentially the next revolution for commercial aircraft:

Elastically shaped aircraft, therefore, may be viewed as a biologically-inspired concept that could potentially revolutionize the conventional airframe design. Taking a cue from birds’ efficient shape-changing wings, this concept may be able to bring future aircraft concepts to the next level in terms of performance, efficiency, and maneuverability (Nguyen, Trinh, et al, 2013).

The VCCTEF is mimicking bird feather spreading by dividing the wing into several camber varying segments, thus transforming the commercial airfoil into something strikingly bird-like. While NASA’s “aeroelastic” wing is not a full replication of a bird wing, it is taking characteristics of bird flight to achieve improved cruise performance.
Figure 1.1 Models of VCCTEF from NASA Ames and Boeing using 15 flap segments with SMA to more resemble bird flight for the purposes of more efficient commercial transport aircraft. They also have developed a “drooped” seagull wing for commercial aircraft and have tested these designs in a wind tunnel (Nguyen, Precup, et al, 2015).

However, current materials and structures in aerospace engineering may never be able truly replicate bird flight. Moreover, the engineering challenge of designing lightweight bio-Pico Aerial Vehicles (PAVs) and bio-Nano Aerial Vehicles (NAVs) is dramatically different from the construction of human-carrying ornithopters or biologically inspired commercial aircraft. Engineering innovation will need to move from the design of systems of parts to the design of
organic, integrated, “compliant” wholes for full-scale piloted ornithopters to truly be realizable. While full-scale piloted ornithopter-aircraft are of interest and will be briefly discussed, an understanding and proof of concept of unmanned-aerial-vehicle-scale ornithopters is necessary prior to the consideration of larger designs.

Many researchers are pursuing the development of flapping MAV and PAV ornithopters due to their wide applications in commercial and military use. Equipped with cameras and sensors, such vehicles can be used for emergency search and rescue missions, surveillance, operations in hazardous and dangerous environments, and reconnaissance. Vehicles that are as small as some of the robotic insects and birds being developed could perform missions unseen and undetected due to their small size as well as their natural disguise. Moreover, the ability to hover makes them more advantageous than fixed-wing MAVs and the characteristic of quiet flapping flight makes them more advantageous than loud rotary wing aircraft. Interestingly, some researchers express that there are no limitations to scaling such robotic insects upward to large insect-like aircraft as well. For example, some engineers claim it is not impossible to imagine smart technologies and materials that could lift payload limitations on insect MAVs (Abas, 2015).

While there are many practical applications to small flapping vehicles, the driving motive of this research is to analyze flapping robotics for the potential development of bio-inspired aircraft that can take advantage of the greater efficiency of flapping flight. For example, compared to a quadcopter used for surveillance, a small flapping MAV used for the same purpose can potentially offer a vehicle of reduced weight and greater fuel efficiency, especially if
flapping thrust can replace propeller thrust. Likewise, researchers at The Department of Aerospace Systems and Artificial Muscle Research Center of Seoul, Korea state:

_Biological flight systems, known as the most efficient flight mechanism, are superior to engineering flight systems at all small scales for their better power supply, better stability and control systems, and ability to fly in fluctuating conditions and at low Reynolds numbers_ (Park & Yoon, 2008).

This thesis desires to be a contributor to the emergent field of bio-inspired flight that has been relentlessly pursued in recent engineering and MAV research. If an aircraft can derive its propulsion from flapping, there may be a reduced need for aircraft engines. If an aircraft can use ailerons and flaps that mimic bird feathers (similarly to the compliant design created by FlexSys Inc. (Hetrick, J., Osborn, R., et al, 2007)), then drag could be dramatically reduced by a seamless structure. If a commercial aircraft can perch like a bird, there may be no need for airports or runways. Thus, one primary interest in this focus on natural modes of flight is the efficiency that flapping flight offers over fixed wing flight. Through evolution, the flapping flight of birds, insects, and bats has developed perfect adaptation to the air, whereas fixed wing aircraft are not always perfectly aerodynamically adapted and often have to fight against wind or wake turbulence. Biological flight takes advantage of unsteady aerodynamics, rather than working against it.

Moreover, a secondary interest in flapping wing aircraft is to provide an alternative design possibility for SpaceShipOne’s feathering mechanism. SpaceShipOne was designed to
stabilize for reentry into earth’s atmosphere with a variable wing mechanism. Burt Rutan was inspired by the maneuverability of a badminton ball (Fig. 1.2) for this feathering mechanism (Guthrie, Willumsen, et al, 2004). And the badminton ball is merely a simplified, epoxy version of a diving bird lifting its wings upward. Thus, a flapping or flexible wing mechanism could also work for space re-entry or could help lift a rocket for an air launch to orbit. The flapping wing rocket could use a tow-assist takeoff, flap to 50,000 feet, and then jettison the flapping wings for space or retract the wings for a feathering re-entry. These statements may be controversial, require additional practical proof, and may never be implemented. The purpose of these statements is to encourage alternative ideas about aerospace engineering as unconventional ideas have often driven the frontier of engineering and led to practical innovative solutions.

Figure 1.2 Badminton ball
1.1. History of the Ornithopter

Aviation began with the ornithopter and will likely continue to pursue an advanced form of ornithopter because the dream of flight is not encapsulated by fixed-wing airplanes and yearns to experience the sky like a bird. While fixed-wing flight has claimed a century of success, many researchers, engineers, and scientists are now developing an increasing interest in robotics and aircraft that are more biologically inspired. The first humans to take the imagination of flight into their own hands built wings that they could attach to their bodies. Many so-called “tower-jumpers” beginning from 60 A.D., strapped on makeshift wings made of feathers and jumped from towers while attempting to fly (Goodheart, 2011).

In 1060 in England, the first attempt to somewhat successfully fly with wings strapped to the body was accomplished by a monk who glided 200 yards after jumping from a religious tower and was seriously injured. Several centuries later in 1742, these attempts were still being made and a French inventor attempted to fly with wings over the Seine River. In the 1400s, the first known written description of a flying machine was recorded by Franciscan monk and empiricist Roger Bacon and later in 1486 Leonardo Da Vinci sketched out the first ornithopter machine to be powered by man. Da Vinci’s sketch was dramatically different from the preceding ideas of flight because it introduced the idea of a pilot and a vehicle to carry him, powered by him. He even considered retractable landing gear for the aircraft (Goodheart, 2011). Thus, the first vision of a human pilot may have been one intended to control a flapping wing ornithopter, not a fixed wing aircraft.
By the end of the 1700s, aviation was steering away from ornithopters and became driven by ballooning. Balloons were a simpler and easier way to fight the binds of gravity, but ultimately delayed the progress of heavier-than-air craft. However, in 1799 George Cayley was inspired by ballooning to develop an alternative and created the first designs of a fixed-wing aircraft that are still evident in today’s modern aircraft. But Cayley called ornithopter flight “ridiculous” and subsequently determined widespread movement away from flapping wing flight. Nevertheless, ornithopters continued to be built in nearly every decade up to today in a determined effort to fly like the birds. In 1810 a clockmaker named Jacob Degan, probably unaware of fixed-wing developments, created an ornithopter with umbrella-like wings. In the mid-1800s, a French sea captain named Jean-Marie le Bris built two elaborate ornithopters with fuselages that never flew and were accidentally destroyed by horses pulling the craft to get them to take-off speed. In the late 1800s, some inventors attempted building ornithopters and tried to fly them by having the devices lifted by balloons. In the early 1900s during the time of the Wright Brothers, the president of the Royal Aeronautical Society also built ornithopters (Goodheart, 2011).

Notably, Otto Lilienthal, the “flying man” who was the first to successfully fly gliders, also had a keen interest in ornithopters. Despite his revolutionary work with gliders, Lilienthal often abandoned the glider experiments that would make him a historical figure in aviation to work on ornithopters. Lilienthal said:
Man longs to soar upward and glide, free as the bird … and enjoy [the earth] as fully as only a bird can do. The observation of nature constantly revives the conviction that flight [like birds] cannot and will not be denied to man forever (Goodheart, 2011).

He claimed that “birdflight was the basis of aviation” as was the title of his 1889 masterpiece. Lilienthal died from a stalled glider before he finished his second ornithopter, but work in ornithopters continued. In 1929, Alexander Lippisch, the first to design a delta wing that flew and the first to create a mass-produced rocket fighter, built an ornithopter that flew with human-powered glides after being catapulted. In 1959, a human-powered ornithopter was built by Emil Hartman, but could not maintain sustained flight. In the 1980s, Paul McCready built an incredible pterodactyl ornithopter that flew momentarily. James DeLaurier built a Cessna-like piloted ornithopter that flew for 14 seconds and is considered the first successful ornithopter by The World Air Sports Federation, which they call “Ornithopter No.1” (Goodheart, 2011). (Note that all historical information came from Benjamin Goodheart’s article “Tracing the History of the Ornithopter; Past, Present, and Future”).

Thus it can be argued that if some of the greatest minds and inventors of human history and aviation have had a keen interest in ornithopters, and since the design and development of ornithopters has been pursued with an unwavering interest throughout most of human history, then ornithopters will probably be the focus of some schools of thought in aerospace engineering for the unforeseeable future.
2. **Avian and Insect Flight**

Prior to discussing the design of small flapping wing robotic aircraft, a study of insect and bird flight is necessary to motivate and guide the understanding of robotic flapping wing aircraft. Insect flight was poorly understood until recently due to the small and rapid nature of insect flight mechanisms. Advances in technology and high-speed videography have allowed for a greater examination of the subtle kinematics of insect wings. Bird flight, however, has been thoroughly studied and bird wings are known to simultaneously create lift and thrust by twisting their wings forward on the downstroke in order to create a large normal force that propels them forward. During the downstroke, the wings are pivoted backward in such a motion that creates lift but can negate thrust. Bird wings are especially efficient in their ability to optimize lift and thrust by changing the speed, camber, and angle of varying parts of the wing (Sane, 2003). Also, the complex motions of feather spreading, varying the span of the wing, and fore-and-aft swinging maximize the efficiency of flapping flight (Rashid, 1995). However, overall, the incredible characteristic of biological flight is its ability to create a wing that acts as an airfoil and propeller simultaneously.

Flight in animals and insects developed as a mechanism for species to escape predators and more quickly acquire food resources. Insects and birds depend on flight performance for their survival and thus evolution has ensured a rigorous and reliant flight performance. Thus,
basing robotic aircraft on such mechanisms may guarantee the most adept performance. To engineer a flight mechanism requires replicating certain biological functions and transforming them into robotic means. For example, in insect flight, three parts of the insect create the flight apparatus— the flight muscle, thorax, and wing. In order to fly, an insect warps the thorax in such a way to amplify the muscle contraction which allows large flapping angles (Mateti, 2012). In a flapping robot, an actuator becomes the flight muscle that allows amplification of the wing flapping that is found in the thorax.

Insect flight is particularly maneuverable, in which some insects have the ability to take-off backwards, fly sideways, and even land upside down. Insects often have camber in both the spanwise and chord directions, which allows agile control of wing deformation. One difference from fixed wings and flapping insect wings is that a leading edge vortex remains attached to the wing in insects and does not dissipate into an unstable wake like in fixed wing aircraft (Sane, 2003). Thus, insects can float on their own wing-tip vortices, creating lift and allowing them to hover or maneuver abruptly. Insects use delayed stalling, rotational circulation, and wake capture to enhance the maneuverability of their flight dynamics. In wake capture, the insect can rotate its wings backward to capture the energy from the vortices and whirlpools left behind from the flapping wing and use that energy for lift (Park & Yoon, 2008). In delayed stall, birds use their alula, or feathered thumbs, as leading edge slats that can allow the bird to operate at higher angles of attack, generate greater lift, and thus prevent stalling (Lee, Kim, et al, 2015). This is shown in Figure 2.1.

Additionally, flapping insect wings not only exhibit the bending motion of flapping, but also simultaneous twisting of the wings, called supination and pronation (Figure 2.2). This
twisting-flapping motion is more able to adjust to and take advantage of the dynamics of the air. The twisting action adjusts the angle of attack and tilts the resulting force forward to provide the animal with both propulsion and lift (Weis-Fogh, 1975).

Figure 2.1 For two different wings, it is shown that with the *alula* (solid lines) more effective lift area is generated (y-axis) than for wings without an *alula* (dashed lines) for varying velocities (Lee, Kim, et al, 2015).

Moreover, insects, birds, and bats take advantage of any non-steady flows over their wings, whereas in fixed-wing aircraft non-steady flows over an airfoil need to be minimized to keep flight efficiency and prevent unwanted and possibly dangerous vibrations and flutter modes. Insects especially excel in non-steady flows and actually have cells and hairs on their wings that tend to maximize non-steady airflow (Park & Yoon, 2008).

Due to the small size and high-frequency wing motion of insects, it has been challenging to quantify the kinematics of insects. For example, an average insect such as the fruit fly *Drosophila melanogaster*, is about 3mm in length and beats its wings with a 200 Hz frequency (most insects use a 35-100 Hz wing beat frequency (Mateti, 2012)). Until high-speed
videography, single-image film attempted to capture such tiny motions but failed to understand the aerodynamics of the insect. Prior to computational modeling, scientists tried tethering insect wings to understand their flight but often interfered with the condition of the insect, making it hard to distinguish inertial and aerodynamic forces. In terms of the frequency of flapping for birds, larger birds tend to spend a large proportion of their flight time soaring and gliding and use a low frequency flapping to gain altitude. Smaller birds tend to use higher frequency flapping. Hummingbirds in particular use a very high frequency flapping and their flight is more akin to insect flight than bird flight (Park & Yoon, 2008).

Insects alter many parameters of their wings such as wing tip trajectory, stroke amplitude, angle of attack, frequency, and deviation from main stroke plane from wing stroke to wing stroke. Thus, it is difficult to understand the dynamics of insect flight and many scientists have thought that insect flight defies the laws of aerodynamics. Furthermore, insects and birds can change the movements of each wing separately and simultaneously to further complicate their motion (Sane, 2003). However, there are several commonalities between animal flight and fixed wing aviation. For instance, the cellular structure of some insect wings have veins that act as wing spars that provides the weight support and flight load of the wing.

Insects use *clap-fling* flight (discovered by Weis-Fogh in 1973), Figure 2.3, in which the wings are held tightly above the body of the insect in contact and are then flung apart. After moving apart after the clap position, the wings open at a high speed in a v-shape, encouraging air to move inward between the wings in a triangular gap between the wings. Then the wings separate from their v-shape and sweep horizontally apart with each wing carrying a vortex of air that formed during the flinging motion and that contributes to the lift of the insect (Sane, 2003).
After the fling, the wings do not clap beneath the body of the insect, but instead flip upward through 120 degrees in a twisting motion, like the flipping of a pancake. This clap-fling-flip motion is what allows for hovering flight. *Clap-fling* flight also permits bound circulation over the wing beyond that normally allowed by the Kutta condition (Mueller, 2000). Although insects primarily use the clap-fling-flip mode of flight, some birds, such as pigeons, will use this method for hovering or for vertical takeoff (Weis-Fogh, 1975).

![Figure 2.2](image.png)

Figure 2.2  The kinematics of insect flight (Sane 2003). The downstroke to upstroke of flight is the mode of supination that produces the most lift and propulsion. The upstroke to downstroke of flight is the mode of pronation that produces some lift but no propulsion and possibly creates a negative component of propulsion. However, this effect is most pronounced in avian flight, whereas in insect flight, both the downstroke and upstroke tend to produce significant lift.
2.1. Physics of Flapping Flight

While the focus of this project is primarily on the control of ornithopters and not the specific details of a perfectly developed physics model, some knowledge of the physics of flapping flight is necessary to help drive the modeling. In general, the flapping wing is typically producing lift on the downstroke and thrust on the upstroke. When the wing lifts upward, there is less lift because the wing is collapsed downward, thus has less effective wing area, which is a major component of lift generation. Another consideration in the physics of flapping is the angle
of attack. As the angle of attack changes, the lift and drag generated will also change. Also, the wing will generally have the greatest speed and angle of attack at the wing tips. The ornithopter modeling that will be developed will ultimately find that successful flight and control of a flapping wing vehicle is highly dependent on the flapping frequency.

The average thrust, lift, and power generated from a rigid flapping wing are as follows (Mishra, Tripathi, et al, 2014):

\[
T = 0.3KS\rho\sigma^2v^2 \\
L = 0.5KS\rho\alpha v^2 \\
P = 0.16KS\sigma^2v^3
\]

where \( \sigma \) is the Strouhal number, which describes the oscillating motion of the wing and should be between 0.2 and 0.4 for a bird in flight, with a value of 0.2 for cruise flight. \( K \) is the aspect ratio coefficient, \( S \) is the surface area of the wing when the wing is fully stretched out, \( v \) is the velocity of the bird through the air, and \( \rho \) is the density of air.

Several researchers have also have developed relations between the mass, speed, and flapping frequency of birds. The following are empirical relations derived from biologists. For flapping frequency (in Hertz), relations with respect to mass have been derived for large and small birds, respectively, as follows (Park & Yoon, 2008):

\[
f = 116.3m^{-0.16}
\]

\[
f = 28.7m^{-0.3}
\]

A relation between flapping frequency and wing length, \( l \), has also been found as (Park & Yoon, 2008):

\[
f l^{1.16} = 3.54
\]
And perhaps most interestingly, a relation between the typical flight speed and mass (in grams) of a bird has been developed (Park & Yoon, 2008):

\[ v = 4.77 m^{0.16} \]

According to this empirical relation, the ornithopter hardware for this project (see Section 7) should fly at approximately 13 m/s. This relation exactly predicts the maximum velocity found from the 1 kg mass simulated in Section 6 to be 14 m/s.
3. A Review of Select Ornithopter Prototypes

While attempts to build ornithopters historically have happened about once per decade throughout human history, today the construction of small scale robotic ornithopters is commonplace at many universities. Here some successful ornithopters will be reviewed, including the DeLaurier ornithopters, the H2Bird, the perching plane, and the Microrobotic Fly. Dr. DeLaurier and his students at the University of Toronto are thought of as the leading innovators of piloted, full-scale ornithopter aircraft and two of his developments are discussed here. Additionally, another company, Festo, has developed remarkably life-like seagull, butterfly, and dragonfly ornithopters that primarily use classical mechanical systems.

3.1. The Piloted DeLaurier Ornithopters

In 1991 at the University of Toronto, a full-scale remotely-piloted ornithopter reminiscent of a Cessna style aircraft, successfully achieved flapping test flight for 3 minutes and landed without failure, as shown in Figure 3.1. Later in 1999, the same team achieved a very brief liftoff with a similar, but piloted, design. While the design was intended to mimic bird flight as much as possible, it did not have any structures resembling the intricate dynamics of bird flight such as feather-spreading and wingspan variation. In order to best replicate bird flight, the wings were made into 3 movable panels. The panels counteract each other in which the center panel moves opposite the outer flapping panels in order to balance lift and power variation (Robinson, 2003).
Later the team also developed another full-scale piloted ornithopter called the “Snowbird.”

The researchers at the University of Toronto have developed a full scale model of ornithopter flight as necessary for conducting manned missions. In order to develop a full model, researchers considered the equations of motion for each wing and the body separately and then matched those equations with the kinematics to derive 18 equations of motion describing the ornithopter. Still this model only considers the ornithopter to have rigid wings and body and also considered the wings as only flat plates without any aerodynamic parameters. The model considers the wing flapping to be only sinusoidal without any twisting dynamics (Rashid, 1995). Simply to demonstrate the complexity of modeling ornithopter flight, part of this full model is shown in Figure 3.2.

![Figure 3.1 James DeLaurier’s piloted ornithopter](http://www.ornithopter.net/)
\[
X_{\text{en\textsubscript{w}}} - m_w g \sin \Theta - m_w (Q_w W_b - R_y V_b) = m_w \ddot{U}_b - R_{xbl} - R_{xb2}
\]
\[
Y_{\text{en\textsubscript{w}}} + m_w g \cos \Theta \sin \Phi - m_w (R_y U_b - P_y W_b) = m_w \ddot{V}_b - R_{ybl} - R_{ybl2}
\]
\[
Z_{\text{en\textsubscript{w}}} + m_w g \cos \Theta \cos \Phi - m_w (R_y V_b - Q_w U_b) = m_w \ddot{W}_b - R_{zbl} - R_{zb2}
\]
\[
L_{\text{en\textsubscript{w}}} = (I_{zb} - 1) \dot{\phi}_b + I_{zb} P_x Q_b
\]
\[
= I_{zb} \dot{\phi}_b - I_{zb} \ddot{\phi}_b + d_{ zb1} R_{yb1} - d_{ zb1} R_{yb1} + d_{ zb2} R_{yb2} - d_{ zb2} R_{yb2} - M_{lb1} - M_{lb2}
\]
\[
M_{\text{en\textsubscript{w}}} = (I_{zb} - 1) P_x R_b - I_{zb} (P_b^2 - R_b^2)
\]
\[
= I_{yb} \dot{\theta}_b - I_{zb} \ddot{\theta}_b + d_{ zb1} R_{ybl1} + d_{ zb1} R_{ybl1} - d_{ zb2} R_{ybl2} + d_{ zb2} R_{ybl2} - M_{nb1} - M_{nb2}
\]
\[
N_{\text{en\textsubscript{w}}} = (I_{yb} - 1) \dot{\theta}_b + I_{zb} \ddot{\theta}_b + d_{ ybl1} R_{xy1} - d_{ ybl1} R_{xy1} + d_{ ybl2} R_{xy2} - d_{ ybl2} R_{xy2} - M_{nb1} - M_{nb2}
\]

\[
X_{\text{en\textsubscript{w}}} = m_w g \sin \Theta - m_w [2Q_w^2 (D_{zw1} - d_{ zb1}) + 2R_y^2 (D_{zw1} - d_{ yb1})]
\]
\[
+2P_y Q_w (d_{ yb1} - D_{yw1}) + 2R_y R_b (d_{ zb1} - D_{zw1}) + 2Q_w W_b - 2R_y V_b
\]
\[
-3P_{yw} (Q_b D_{yw1} + R_b D_{zw1})]
\]
\[
= m_w \ddot{U}_b + m_w (D_{zw1} - d_{ zb1}) \dot{\phi}_b + m_w (D_{yw1} - d_{ yb1}) \ddot{\phi}_b + R_{xbl}
\]

\[
Y_{\text{en\textsubscript{w}}} = m_w g \cos \Theta \sin \Phi - m_w [2P_y^2 (D_{yw1} - d_{ yb1}) + 2R_y^2 (D_{yw1} - d_{ yb1})]
\]
\[
+2P_y Q_w (d_{ yb1} - D_{yw1}) + 2Q_w R_b (d_{ yb1} - D_{zw1}) - 2P_y W_b + 2R_y U_b
\]
\[
-P_{yw} (Q_b D_{yw1} + R_b D_{zw1})]
\]
\[
= m_w \ddot{V}_b + m_w (D_{zw1} - d_{ zb1}) \dot{\phi}_b + m_w (D_{yw1} - d_{ yb1}) \ddot{\phi}_b + R_{ybl}
\]

\[
Z_{\text{en\textsubscript{w}}} = m_w g \cos \Theta \cos \Phi - m_w [2P_y^2 (D_{zw1} - d_{ zb1}) + 2Q_w^2 (D_{zw1} - d_{ yb1})]
\]
\[
+2P_y R_b (d_{ yb1} - D_{yw1}) + 2Q_w R_b (d_{ yb1} - D_{zw1}) + 2P_y V_b - 2Q_w U_b
\]
\[
+P_{yw} (R_b D_{yw1} + d_{ yb1})]
\]
\[
= m_w \ddot{W}_b + m_w (D_{zw1} - d_{ zb1}) \dot{\phi}_b + m_w (D_{yw1} - d_{ yb1}) \ddot{\phi}_b + R_{zbl}
\]

\[
L_{\text{en\textsubscript{w}}} = I_{xw} \dot{\theta}_b - I_{xw} \ddot{\theta}_b + D_{yw1} \dot{\phi}_b + D_{zw1} \dot{\phi}_b + M_{lb1}
\]
\[
M_{\text{en\textsubscript{w}}} = I_{yw1} \dot{\phi}_b - I_{yw1} \ddot{\phi}_b + D_{yw1} \dot{\phi}_b - D_{zw1} \dot{\phi}_b + M_{lb1}
\]
\[
N_{\text{en\textsubscript{w}}} = I_{xw} \dot{\phi}_b - I_{xw} \ddot{\phi}_b - D_{yw1} \dot{\phi}_b + D_{zw1} \dot{\phi}_b + M_{lb1}
\]

Figure 3.2 Part of the full scale model of ornithopter flight (Rashid, 1995)
Another piloted ornithopter developed by DeLaurier team at the University of Toronto Institute for Aerospace Studies was the Snowbird Ornithopter that flew in 2010. This ornithopter, with a very high aspect ratio, was made primarily out of foam, balsa wood, and carbon fiber, as shown in Figure 3.3. The Snowbird was not able to take-off on its own and required a tow-assist to fly. However, it was subsequently powered by human motion alone and is perhaps the ornithopter that has most closely realized the ornithopter sketches of Leonardo da Vinci.

![Figure 3.3 Test flight of the tow-assist piloted “Snowbird” DeLaurier ornithopter](http://www.aerovo(lo.com/ornithopter-summary/)

The Snowbird ornithopter has a 32 meter wingspan, weighs 44 kilograms, and was developed and tested from 2006 to 2010. It was the vehicle developed for the Human-Powered Ornithopter (HPO) project.
3.2. The H2Bird

The H2Bird of the University of California, Berkeley, shown in Figure 3.4, was the original inspiration for this work. These researchers modified a commercial toy ornithopter to be controllable via laptop and then made the ornithopter autonomous. The researchers used the following model of the x and z direction dynamics to perform simulations of the robot where \( \delta \) is pitch, \( Q \) is angular velocity, \( m \) is mass, \( T \) is thrust, and \( L \) is lift:

\[
\begin{align*}
\dot{x} &= v_x \cos \delta + v_z \sin \delta \\
\dot{z} &= v_x \sin \delta - v_z \cos \delta \\
\dot{v}_x &= -v_z Q + \frac{1}{m}(T - mg \sin \delta) \\
\dot{v}_z &= v_x Q + \frac{1}{m}(-L + mg \cos \delta) \\
Q &= \dot{\delta}
\end{align*}
\]

In this formulation, positions are in world coordinates and velocities are in body coordinates (Rose 2013).

Figure 3.4 The H2Bird Ornithopter (Rose, 2013).
3.3. Aerial Perching Robot

In order to optimize ornithopter interaction with humans, a perching mechanism has been developed in some micro aerial vehicles, as shown in Figure 3.5. The perching is achieved by maximizing the upward elevator or tail deflection and by attaining a high angle of attack approaching a stall in order to abruptly stop the flight path and land. Perching aircraft, despite their low speed, maintain their controllability even with disturbances like wind. The robot in Figure 3.3 demonstrated that a flapping mechanism can be considered as a wing dihedral that can control longitudinal and lateral-directional motions relevant to flight maneuvers such as perching. This perching ornithopter uses articulated, panel wings similarly to the DeLaurier ornithopter. The ability to vary the asymmetric wing dihedral was used to control the flight path and heading of the ornithopter. Trailing edge flaps were also used on this ornithopter to ensure that the wing dihedral provides uniform yaw control effectiveness.

The researchers who developed this robotic aircraft primarily used proportional integral (PI) and proportional integral derivative (PID) controllers to control the robot. The researchers used varying symmetric and asymmetric wing dihedral to control the vehicle. One of the PID controllers they developed was as follows:

$$d_{sym}(x) = - (k_p \frac{de_z}{dx} + (ak_p + k_i)e_z(x) + ak_i \int_0^x e_z(x)dx)$$

where $d_{sym}$ is the symmetric wing dihedral, $a$ is the desired rate of convergence from some altitude $z$ to a desired altitude, $e_z$ is the error in the $z$ trajectory from desired, and $k_i, k_p$ are the integral and proportional gains, respectively (Aditya, 2012).
3.4. The Microrobotic Fly

Harvard University and UC Berkeley have been developing tiny quarter-sized insect robots that fly using piezoelectric actuation (see Figure 3.6). These engineers hope to usher in a new era of highly maneuverable, undetected, hovering aerial robots used for reconnaissance. Researchers working on these tiny robotic flies generally take an engineering development paradigm of body, brain, colony- a body of smart materials, a brain of smart sensors, and a coordination algorithm to allow several vehicles to form a swarm that acts in synchrony.
However, thus far, these tiny robots have needed external power in order to fly. The Harvard Microrobotic Fly powers flight with a piezoelectric bimorph actuator, a smart material that creates electric power through mechanical stress. These researchers find that the power needed in the actuation is related to the flapping frequency, where $L$ is the lift generated (Karpelson, 2014):

$$P_{aero} = f^{1/2}L^{5/4}$$

Thus, in this prototype, the high dependence on flapping frequency for the thrust and lift needed to keep the ornithopter in flight is taken note of for the development of a model.

It may be the case that engineering materials will never be able to match the agility and versatility of insect or bird flight. Thus, some researchers, like those at Draper Inc. and the Howard Hughes Medical Institute, are genetically modifying the nervous systems of real insects to respond in predictable ways to pulses of light in order for such insects to be subsequently as controlled as PAVs (http://www.draper.com/news/equipping-insects-special-service).
3.5. The Kestrel Ornithopter

The Kestrel Ornithopter, or *Spybird*, is the RC ornithopter purchased for hardware exploration as related to this project shown in Figure 3.7. This RC vehicle uses all the normal inputs of a RC fixed wing aircraft with a tail for an elevator and motors and servos that control the flapping flight.

![The Kestrel Ornithopter](image)

Figure 3.7 The Kestrel Ornithopter (Jackowski, 2009)

3.6. The Nano Hummingbird

The Nano Hummingbird, using special proprietary motors, can fly sideways, backwards, and clockwise/counterclockwise, as shown in Figure 3.8. This ornithopter uses a continuously rotating crankshaft with oscillatory pulleys that use additional strings to stay in phase in order to achieve its unique robotic flight abilities. The same company that developed this MAV,
AeroVironment, also built a huge pterodactyl ornithopter. The pterodactyl ornithopter could not quad-launch and had to takeoff with a tow-assist via vehicle.

Figure 3.8 Nano Hummingbird
(http://www.airforce-technology.com/projects/-hummingbird-nano-air-vehicle/)
4. A Model of Flapping Flight

4.1. Aerodynamic Model of Fixed Wing Aircraft

Prior to developing a model of flapping flight, the nine equations of motion governing fixed wing flight mechanics are considered. Fixed wing flight is simpler than flapping flight and thus a basis of fixed wing flight will assist subsequent concerns in flapping flight. Also, when large birds fly, the gliding and soaring phases of flight mimic fixed wing flight because flapping in this case is only used occasionally to help gain altitude. Thus, the translational dynamics equations governing fixed wing flight can govern an ornithopter during these periods of flight. The translational dynamics equations are:

\[
\dot{U} = VR - WQ + \frac{1}{m} \sum F_x \quad \text{with } U(0) = U_0
\]

\[
\dot{V} = WP - UR + \frac{1}{m} \sum F_y \quad \text{with } V(0) = V_0
\]

\[
\dot{W} = UQ - VP + \frac{1}{m} \sum F_z \quad \text{with } W(0) = 0
\]

\(U, V,\) and \(W\) are the velocity components of the aircraft’s velocity vector in the \(x, y,\) and \(z\) axes respectively and \(m\) is the mass of the aircraft. \(P, Q,\) and \(R\) are the angular velocity components in the \(x, y,\) and \(z\) axes of the body frame. See Figure 4.1.
Figure 4.1 Airplane schematic showing $U$, $V$, $W$ components of velocity and $P$, $Q$, $R$ components of angular velocity (Rashid, 1995).

The rotational dynamics equations are:

$$
\dot{P} = \frac{I_x}{D}(I_x - I_y + I_z)PQ + \frac{1}{D}(I_yI_z - I_x^2 - I_{xz}^2)QR + \frac{I_x}{D} \sum L + \frac{I_w}{D} \sum N
$$

$$
\dot{Q} = \frac{I_y - I_z}{I_y}PR + \frac{I_w}{I_y}(R^2 - P^2) + \frac{1}{I_y} \sum M
$$

$$
\dot{R} = \frac{1}{D}(I_x^2 - I_xI_y + I_{xz}^2)PQ + \frac{I_w}{D}(I_y - I_x - I_z)QR + \frac{I_w}{D} \sum L + \frac{I_w}{D} \sum N
$$

all with initial conditions in angular velocity of $P(0) = P_0$, $Q(0) = Q_0$, and $R(0) = R_0$ and

where the term $D$ is given by:

$$
D = I_xI_z - I_{xz}^2
$$

where $I_{ij}$, $i = x, y, z$ and $j = x, y, z$ are the moments and products of inertia.
The Kinematic Equations in terms of the Euler Angles are:

\[
\dot{\theta} = Q \cos\phi - R \sin\phi
\]
\[
\dot{\varphi} = P + Q \sin\phi \tan\theta + R \cos\phi \tan\theta
\]
\[
\dot{\psi} = Q \frac{\sin\phi}{\cos\theta} + R \frac{\cos\phi}{\cos\theta}
\]

where the traditional notation for roll, pitch, and yaw as \( \varphi \), \( \theta \), and \( \psi \) were maintained for familiarization, but note that elsewhere in this research \( \theta \) and \( \varphi \) refer to the angles that a bird wing makes with respect to the body.

Flapping wing kinematics will need to consider a stroke plane in the \( yz \) plane that includes the point of wing pivoting motion and the range of the final upstroke and downstroke points. However, the modeling for this thesis will be over-simplified because the final goal is a functional control algorithm and not a perfectly defined physics model. Indeed, when birds fly, their brains are not circulating through a complex mathematical calculation, but are merely following simple rules of oscillatory motion probably directed by sensory signals from feathers flexing, acceleration, and other dynamic indications.

4.2. A Simplified Model

To begin generating a model of flapping flight, a simplified model that considers hovering flight with no forward motion is used. This simplified model will be built upon with added complexities in subsequent models. Thus the general modeling approach is to take an approximated system in which varying coefficients will absorb certain aerodynamic parameters that will later be expanded upon in more detail.
In the following model formulations, it is acknowledged that complete specifications of ornithopter flight may not be necessary because only a control algorithm is what is desired. Thus, in this model, it is assumed that the flapping motion is some form of a sinusoidal force that can effectively incorporate all the complex dynamics of flapping to simulate bird flight. In other words, here the model will effectively replace the true behavior of the bird in order to create a simplified model for mathematical and control purposes.

Figure 4.2 Diagram of 2-panel ornithopter constants and variables

The following model, which is assumed to be the simplest possible model that can effectively describe flapping flight, was used to create and sustain flapping flight in a MATLAB animation where the ornithopter is taken to hover and rise above the origin and only considers the vertical, z direction with one-panel wings:

\[
\dot{z} = v_z
\]

\[
v_z \equiv \frac{1}{m}(-mg + F_z)
\]

\[
F_z \equiv C_L \rho S \cos(\theta) \omega^2 \cdot \text{sgn}(\omega)
\]

\[
C_L \rho S = \text{constant}
\]

\[
\omega = \dot{\theta}
\]
\[
\theta = \theta_{\text{max}} \cdot 2^{\frac{1}{n}} \arctan (A \cdot \sin(2\pi \frac{t}{T}) + b)
\]

\[
b = b^* - k_1 (z - z^*) - k_2 v_z
\]

In this model, \( \theta \) is not pitch, but the angle the wing panel makes with the horizontal surface, shown in Figure 4.2. It varies periodically with frequency \( \omega \) between \( \pm \theta_{\text{max}} \), however this motion is asymmetric so the faster downstroke creates a lift force that exceeds gravity and the drag produced from the upstroke. The “bias” parameter \( b \) helps to regulate this asymmetry and thus can be considered as a PD control used to maintain the desired altitude. Also note that this model assumes no wing twisting. The vertical force, \( F_z \), is dependent on the flapping frequency of the wing, \( \omega \), the aerodynamic parameters (coefficient of lift \( C_L \), air density \( \rho \), and wing area \( S \)) are considered constant, and the coefficients \( A \) and \( b \), which were initially taken as constant and found using trial and error to sustain flight. Later it was found that the system was highly dependent on the value of coefficient \( b \) and thus it was chosen as a control variable. Thus the later development of this coefficient incorporated \( b^* \), the feedforward control, and a proportional derivative formulation with \( k_1, k_2 \) as the controller gains. Note that for forward flight, \( C_L \) would be a function of \( v_x \) and \( \omega \) because \( \omega \) changes with angle of attack. However, this first simple model assumes no forward motion and then \( C_L = C_D \), for a flat plate, which would be approximately constant and \( \equiv 1 \).

This simplified system was used to make a single segment (non-articulated) flapping wing simulation in MATLAB. With the controller added into the model, the model will be as follows:
\[ v_z' \equiv \frac{1}{m}(-mg + C_L \rho \cos(\theta)(\frac{d}{dt}(\theta_{max} \cdot \frac{2}{m} \arctan(A \sin(\frac{2\pi}{T} t) + (b^* - k_1 (z - z^*) - k_2 v_z))^2 \cdot \text{sgn}(\omega))) \]

To initiate the derivation of this simple model, it was observed that flapping flight is highly dependent on how fast the wings are flapping. The wings need to be flapping at a certain rate in order to create enough lift and thrust to compensate gravity. The wings are flapping in an oscillatory motion reminiscent of a sinusoidal function. The motion was modeled with more of a sawtooth dynamic of \( \frac{df}{dt}(\arctan(\sin(f(t)))) \) due to the dramatic up and down trajectory of the wings.

Most bird wings are not a single, fixed panel, but really consist of two segments, as shown in Figure 4.2. To create a system of two panels, two different angles need to be considered and the rates of those angles are assumed to be the controls for the system. Note that \( \phi \) is not roll, but is the angle of the secondary link in the wing. The following model with two degrees of freedom along the x and z axes, with fixed pitch and no rotational motion of the body, is considered:

\[
\begin{align*}
\dot{z} &= v_z \\
\dot{x} &= v_x \\
v_z' &= \frac{1}{m} F(v_z, \theta, \phi, \dot{\theta}, \dot{\phi}) - g \\
v_x' &= m^{-1}(v_x^2 - D)
\end{align*}
\]

\[ F \equiv c \cdot \cos \theta \cdot \dot{\theta}^2 \cdot \text{sgn}(\dot{\theta}) + d \cdot \cos \phi \cdot \dot{\phi}^2 \cdot \text{sgn}(\dot{\phi}) \]

An approximated version of the force is given above (with \( c \) and \( d \) as coefficients), but the full
physical model of that force will be calculated in the following integration. So, the force in the z direction is as follows:

\[ F(v_z, \theta, \varphi, \dot{\theta}, \dot{\varphi}) = \int_0^{L_1} k_{f1}(l_1 \dot{\theta} \cos \theta - v_z)^2 \cos \theta \cdot \text{sgn}(\theta) \, dl_1 \]

\[ - \int_0^{L_2} k_{f2}[L_1 \dot{\theta} - v_z - l_2(\varphi - \dot{\theta})]^2 \cos(\varphi - \theta) \cdot \text{sgn}(\varphi) \, dl_2 \]

Evaluating the integral terms yields for fixed values of \( \text{sgn}(\dot{\theta}) \) and \( \text{sgn}(\dot{\varphi}) \):

\[ k_{f1}(\frac{4}{3} L_1^3 \dot{\theta}^2 \cos^2 \theta - L_1^2 \dot{\theta} \cos \theta + v_z^2) \cos \theta + k_{f2}[L_1^2 \dot{\theta}^2 + v_z^2 + \frac{4}{3} L_2^3 (\varphi - \dot{\theta})^2 \]

\[ - 2L_1 \dot{\theta} v_z - L_1 L_2^2 \dot{\theta} (\varphi - \theta) + v_z L_1 L_2^2 \dot{\theta} (\varphi - \theta) \cos(\varphi - \theta) \]

In this system, \( L_1 \) and \( L_2 \) are the lengths of each panel in the wing, respectively, and \( \theta \) and \( \varphi \) are the angles of the wing panel with respect to the body. The integrals are constructed by considering infinitesimal components of each panel, \( dl_1 \) and \( dl_2 \), respectively. Here the values \( k_{f1} \) and \( k_{f2} \) are drag coefficients that incorporate the span and chord of each panel of the wing, respectively. These coefficients will include the angle of attack, \( \alpha \), and aspect ratio, \( A_r (= \text{wingspan}^2/\text{wing area}) \) as follows:

\[ k_f = 2\pi \alpha (1 + 2/A_r)^{-1} \equiv \pm 1 \]

This is because if there is only vertical speed, then the angle of attack is constant. It is only if there is translational motion or wing twist that there will be a variable angle of attack.

Since \( F(v_z, \theta, \varphi, \dot{\theta}, \dot{\varphi}) \) is the total upward force (and can be downward force in certain conditions), this is the total lift. The system can be turned into a state space system in which further analysis can be performed through a simple substitution. Through this substitution, the
model can be fit to the basic controls model $\dot{x} = F(x, u)$. In this model, $x$ is the set of variables and $u$ is the set of controls.

The following substitution can be made:

$$x = [x_1 = z, x_2 = v_z, x_3 = v_x, x_4 = \theta, x_5 = \phi]$$

$$x^* = [x_1^* = z^*, x_2^* = v_z^*, x_3^* = v_x^*, x_4^* = \theta^*, x_5^* = \phi^*]$$

$$\dot{x} = [x_1 = x_2, x_2 = \frac{1}{m}F_z(x_2, x_3, x_4, u) - g, x_3 = \frac{1}{m}F_x(x_3, u), x_4 = u_1, x_5 = u_2]$$

$$u = [u_1 = \dot{\theta}, u_2 = \dot{\phi}]$$

$$u^* = [u_1^* = \dot{\theta}^*, u_2^* = \dot{\phi}^*]$$

where $u$ is the matrix of controls, which is the rotation rate/frequency of the angle relating to the first panel of wings. $x^*$ is the desired trajectory where $z^*$ and $v_z^*$ may be constants, but $\theta^*$ and $\phi^*$ are periodic functions of time. The deviation from the desired trajectory is $\bar{x} = x - x^*$ and $u^*$ is the control in the steady state. The system can then be linearized into a state space system of

$$\frac{d\bar{x}}{dt} = A(t)\bar{x} + B(t)\bar{u}$$

with matrices $A(t)$ and $B(t)$ that are periodic functions of time. This is further discussed in Section 5.1. This may be assumed to be a good choice of control because in considering a complex biological system where an organism must control several joint angles to move, the change of one primary joint or muscle often subsequently controls the secondary joints.

4.3. Model Considering Pitch

The angle of attack is the angle between the relative wind and wing chord line, whereas the pitch is the angle between the chord line and the horizon. There is a critical angle of attack
that produces that greatest coefficient of lift, but at a greater angle of attack, an airfoil stalls. During a stall, increased non-steady aerodynamics cause an airfoil to lose lift. Birds and insects do not stall because their wings can actually create more lift and thrust from non-steady aerodynamics and because the agility and flexibility of their feathers and anatomical structures delay stall, as discussed in Section 2. Therefore, pitch and angle of attack may not be as crucial for flapping vehicles as they are for fixed wing aircraft. However, in order to accurately model an ornithopter that is able to maintain straight and level flight, the pitch of the aircraft needs to be considered. An infinitesimal lift force is typically taken as:

\[ dL = P_{\text{dynamic}} C_L dA = 0.5 \rho v^2 2\pi c \cdot dr \]

where \( c \) is the chord length, \( \rho \) is the air density, and \( dr \) is an infinitesimal length of the wing. This formulation assumes a symmetrical airfoil with a lift curve slope of \( 2\pi \). The normal component of force to the airfoil is:

\[ F_{\text{Normal}} = \cos \theta \cos \alpha dL \]

where \( \theta \) is the same angle from the simple model describing the angle created by the wing with respect to the body. Thus the total lift for a full model considering pitch is:

\[ L = 2 \int_0^{L_1} \cos \theta \cos \alpha dL = \rho \pi c \int_0^{L_1} \cos \theta \cos \alpha v^2 dr \]

where the lift is multiplied by 2 to account for the contribution of each wing and \( v \) is a function of the free stream velocity, \( V_{\text{inf}} \), and \( \theta \) as follows:

\[ v = \sqrt{(u^2 + w^2)} = \sqrt{V_{\text{inf}}^2 + (r \cdot \dot{\theta})^2} \]
\[ \theta = \theta_{\text{max}} \cdot \cos(\omega t) \]
\[ r \cdot \dot{\theta} = -\theta_{\text{max}} r \omega \cdot \sin(\omega t) \]
where $r$ is a vector length of the wing. See Figure 4.3. Using these relations, a full lift equation for a flapping wing is as follows:

$$L = \rho \pi c \int_{0}^{L_1} \cos \theta \cos \alpha (V_{\text{inf}}^2 + (V_{\text{max}} r \omega \cdot \sin(\omega t))^2) dr$$

Figure 4.3 Components for derivation of lift force involving angle of attack

Figure 4.4 Illustrative sample of how angle of attack may vary along the span of an ornithopter wing. The actual distribution of the angle of attack depends on $\theta$, $v_x$, and $v_z$. 
5. Controls Engineering

Controls engineering has the ability to govern the full dynamics of a system with only a simple or partial model of the system that does not necessarily take all of the disturbances of the system into account. In other words, to achieve suitable feedback control of a system it is sometimes only necessary to use the core part of the system, not the full mathematical model. With flapping wing flight, designing the system around the oscillatory force of natural flight, it is found that all of the complexities of the system are inside of the oscillation. In terms of biology, the bird’s brain is not constantly using a full mathematical system of airflows and flight disturbances, but is instead following natural instinct to achieve the same control of a full model.

Due to the complexities of ornithopter flight, several control methods needed to be investigated to find an algorithm that was suitable. A linear and nonlinear controller were pursued and the nonlinear control proved to be most suitable. Ultimately, a proportional derivative controller with feedforward and feedback control was chosen to control the altitude of a simulated flapping vehicle.

Controls engineering is primarily concerned with driving a plant, or system, from an initial state to a desired state, $x^*$. To do this, the plant, which in this case is nonlinear, ideally needs to be linearized around an equilibrium or operating point. Then a controller can be built in order to produce the appropriate control signal to yield $x^*$.

To design a feedback controller for the matrix state space system developed in Chapter 4,
controller gains $K$ such that $u = -Kx$ are needed to govern the equation $\dot{x} = Ax + Bu$. Firstly, to determine if the system is indeed fully controllable, we consider the Controllability Matrix:

$$CO = [B \ AB \ A^2B \ A^3B \ldots \ A^{(n-1)}B]$$

If the Controllability Matrix has full rank of $n$, where $n$ is the dimensions of the $A$ matrix, then the system is fully controllable. One of the simplest ways to design a controller is to use the pole placement method. In this method, the desired poles of the system need to be determined, which often correspond to the eigenvalues of $A - BK$, which are chosen to create a stable response with desirable transient properties. The integrated value of $x$ can then be plotted versus time to show that the calculated gain $K$ brings the system to a steady state rapidly and thus controls the system.

5.1. State Space Formulation

Overall, the basic system being considered is approximated as follows:

$$\ddot{v}_z = m^{-1}F_z - g$$

$$\ddot{v}_x = m^{-1}F_x$$

As developed in section 4.2, the state vector of the system is

$$x_1 = z, \ x_2 = v_z, \ x_3 = v_x, \ x_4 = \theta, \ x_5 = \varphi$$

and the controller is $u = [\dot{\theta}, \ \dot{\varphi}]$ so the state space formulation of $\dot{x} = A(t)x + B(t)u$ would have time dependent matrices in which the states are tied up in trigonometric functions. This is because in most developments of an ornithopter system, $\dot{x}_2$ and $\dot{x}_3$ are complex functions and dependent on many of the states. Since the states are coupled in many instances and nonlinear, a more simplified, linear formulation of the
ornithopter needs to be developed.

In general, \( F_z \) and \( F_x \) depend on both the angles of each panel of the wing with respect to the body, \( \theta \) and \( \varphi \), the rates of those angles, and the angle of attack, \( \alpha \). However, it can be assumed that \( \varphi \) and \( \alpha \) are functions of \( \theta \). Thus, \( F_z = F_z(\theta, \dot{\theta}, v_z) \) and \( F_x = F_x(\theta, \dot{\theta}, v_x) \).

Then the desired state vector of the system can be denoted as \( v_{z*}, v_{x*}, \theta^* \). Thus, the desired system becomes:

\[
\begin{align*}
\dot{v}_{z*} &= \frac{1}{m} F_z(\theta^*, u^*, v_{z*}) - g \\
\dot{v}_{x*} &= \frac{1}{m} F_x(\theta^*, u^*, v_{x*}) \\
\dot{\theta} &= u^*
\end{align*}
\]

\( v_{z} = v_z - v_{z*} \), \( v_{x} = v_x - v_{x*} \), \( \theta = \theta - \theta^* \), and \( u = u - u^* \)

where \( u^* \) will be the feedforward control. After subtracting the original system from the desired system and denoting \( v_{z} = v_z - v_{z*} \), \( v_{x} = v_x - v_{x*} \), \( \theta = \theta - \theta^* \), and \( u = u - u^* \) then the system can be linearized.

Therefore, the following can be created as a simplified and linearized plant:

\[
\begin{bmatrix}
\frac{\partial F_z}{\partial v_z} & 0 & \frac{\partial F_z}{\partial \theta} \\
0 & \frac{\partial F_x}{\partial v_x} & \frac{\partial F_x}{\partial \theta} \\
0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\frac{\partial F_z}{\partial u} \\
\frac{\partial F_x}{\partial u} \\
1
\end{bmatrix}
\]

However, even when using this reduced Jacobian of the system, the matrices still retain some time-dependent and trigonometric terms as follows with considering \( F_x \equiv C_2 v_x^2 \cos \theta \) and
\[
F_z = C_1 \cos \theta \cdot \dot{\theta}^2
\]

(which are approximated x and z force components that are used in subsequent simulations, see Section 6.1 and 6.2):

\[
\begin{pmatrix}
\ddot{v}_z \\
\ddot{v}_x \\
\ddot{\theta}
\end{pmatrix} = \frac{1}{m} \begin{pmatrix}
0 & 0 & -C_1 u^2 \sin(\theta) \\
0 & 2C_2 \cos(\theta) & -C_2 v_x \sin(\theta)
\end{pmatrix} \begin{pmatrix}
\ddot{v}_z \\
\ddot{v}_x \\
\ddot{\theta}
\end{pmatrix} + \frac{1}{m} \begin{pmatrix}
2C_1 \cos(\theta) \\
0 \\
1
\end{pmatrix} u
\]

One approach was to assume that the small angle approximations of \( \sin \theta \cong \theta \) and \( \cos \theta \cong 1 - \frac{\theta^2}{2} \) could be applied to get the A and B matrices to be linear. However, if this is done, the controllability matrix becomes a non-full rank matrix, indicating the uncontrollability of the system. And this makes sense, because if the wing is not able to flap at large angles, it will not maintain enough lift or thrust to fly. Therefore an alternate approach was taken to get numerical values for the A and B matrices. In this approach, it is observed that the complex arctangent function used to drive theta that is shown in the first, simple model formulation (and propagated into the more complex models), can be modeled as a square root function, as shown in Figure 5.1.

After many attempts to acquire a linear time invariant (LTI) system, it appears preferable to work with the nonlinear model for control purposes. Therefore, the classical state feedback controller cannot be designed due to the time-varying linearized system. Since the system is time-varying, eigenvalue placement control is not applicable. Therefore, a form of PID controller was designed for the nonlinear system model.
Figure 5.1 Graph illustrating that the arctangent (blue) can be approximated as the absolute value of the square root (red).

The methodology for controlling this system is as follows. It can be assumed that the desired states of the system are periodic with period $T$. Thus for any $T$, the time dependent states will be as follows:

$$v_z^*(t) = v_z^*(t + T)$$

$$v_x^*(t) = v_x^*(t + T)$$

$$\theta^*(t) = \theta^*(t + T)$$

where $\theta^*(t)$ represents the periodic motion of the wings. This implies that the feedforward part of the controller is also periodic.
The feedback controller is linear in the form of $\bar{u} = -Kx$. The feedforward controller will be in the form of $u(t) = U(sin2\pi t T^{-1})$, where $U(t)$ is a function mapping the interval $[-1, 1]$ to $[u_{\text{min}}, u_{\text{max}}]$. The feedforward and feedback controllers will be additive, so the total controller will be $u = u^* + \bar{u}$. Thus the controller will take the form:

$$u = U(sin\frac{2\pi}{T}t) - K \cdot [x_1, x_2, x_3]^T$$

where $x_1 = v_x$, $x_2 = v_z$, $x_3 = \theta$. A schematic of an ideal linearized controller setup is shown in Figure 5.2. This was the method explored for a linear feedback and feedforward controller, but a nonlinear controller was ultimately used for the ornithopter, as explained in the following section.

![Figure 5.2 Reduced schematic of linear controller with a step disturbance representing wind dynamics that may disrupt bird flight altitude from a desired trajectory](image-url)
5.2. Feedback and Feedforward Control

For this system, two controllers will be used, a feedforward and feedback control that are applied to a nonlinear model. A classical LTI system is not used for this controller because of the time-dependent A and B matrices. In the first simple formulation of a flapping model controller, a feedback and feedforward control were integrated in the system, given as follows:

\[
b = b^* - k_p (z - z^*) - k_D v_z
\]

In which \( b^* \) is the feedforward control and \(- k_p (z - z^*) - k_D v_z \) is the PD feedback controller with gains of \( k_p, k_D \). This PD controller was integrated into a MATLAB simulation developed in Section 6 to plot a closed loop response of the system as shown in Figure 5.3. Thus, first the ornithopter model was simulated, then the controller was added into the simulation to control the altitude of the ornithopter. The altitude is the only parameter controlled. The controller gains were plotted for several values and tuned to find gains that provide an altitude stability that oscillates around a level flight altitude as birds do. The gains were selected by varying them until a desirable overshoot and settling time were achieved. The closed loop response with tuned gains after exploring outputs of Figure 5.3 is shown in Figure 5.4.
Figure 5.3 Implementation of feedback and feedforward control in order to investigate controller gains with light blue gain values producing the best closed loop response.
Figure 5.4 Final controller for ornithopter system with tuned proportional and derivative gains to achieve stable altitude across 20 seconds.

5.3. Alternate Proportional Derivative Control

In another method to practically implement and simulate a controller for this complex, time-dependent, nonlinear system, it is necessary to consider a reduced system as follows:

\[ \dot{z} = v_z \]

\[ v_z = m^{-1}(F_{lift} + F_{drag, z} - mg) \]

\[ F_{lift} = \pm c \cdot \cos \theta \cdot \dot{\theta}^2 \]

\[ \theta = \theta_{max} \sin(\omega t) \]
To control the ornithopter, altitude is the primary concern. In order for the ornithopter to maintain altitude, it must maintain a certain flapping frequency, \( \omega = 2\pi T^{-1} \), and thus it must maintain a certain period, T. This dependence of altitude, frequency, and period can be used to create a controller. It is known that to control the ornithopter, it must maintain some constant average velocity as follows:

\[
\frac{1}{T} \int_{t-T}^{t} z(t') dt' \cong \text{constant}
\]

\[
\dot{z}_{\text{avg}} = z(t) - z(t + T)
\]

Therefore \( z_{\text{avg}} \) and its derivative are only different by some inverse quantity of the period, which is really the frequency. Thus, a governing equation of the system becomes:

\[
\Delta \omega = -k_1 z_{\text{avg}} - k_2 \dot{z}_{\text{avg}}
\]

This system is in the form of a proportional derivative controller that can be tuned to control the ornithopter. To tune the gains of this system, the Laplace transform is implemented. The Laplace transform is essentially a method of expressing a differential equation into algebraic equation. The Laplace transform of this governing equation is found as follows:

\[
\Delta \omega = -k_1 X(s) - k_2 \dot{X}(s) = F(s)
\]

\[
\frac{X(s)}{F(s)} = \frac{1}{(s + K_d)K_p} = \frac{1}{(s + K_d)K_p}
\]

where \( K_d \) and \( K_p \) are the derivative and proportional gains respectively and where this expression yields the transfer function. This transfer function can be simulated and tuned to produce the desired control. To decrease the rise time in the control response, \( K_p \) should be increased and to decrease the overshoot and settling time, \( K_d \) should be increased. This control design is integrated into the 3-dimensional simulation in section 6.1 and helps yield the altitude
output simulated in Figure 6.5. These gains were tuned by initially setting them to zero and subsequently increasing and decreasing the values until a stable response was achieved. Once a stable response was acquired for altitude, the same gains were used for all other parameters since the altitude is the primary parameter desired to control.
6. Simulation of Flapping Flight

To simulate a one-panel winged ornithopter, the initial simple model is used:

\[ \dot{z} = v_z \]

\[ v_z \equiv \frac{1}{m}(-mg + F_z) \]

\[ F_z \equiv C_D \rho Scos(\theta)\omega^2 \cdot \text{sgn}(\omega) \]

\[ \omega = \dot{\theta} \]

\[ \theta = \theta_{\text{max}} \cdot 0.6 \arctan(A \cdot \sin(2\pi T^{-1} t) + b) \]

where the coefficients A and b are initially adjusted with trial and error to maintain flight in the simulation. Later b becomes the parameter that absorbs the control algorithm. In order to animate this simulation, a for loop for a time step of 0.01 is run through theta and omega with theta initiated at 45 degrees. To make the flapping wings, two lines are simulated with x coordinates of \([x, x + L \cdot \cos \theta]\) and z coordinates of \([z, z + L \cdot \sin \theta]\), where L is the length of the wing. This simulation assumes no forward motion of the ornithopter and it is found that values of \(b = 2\), \(A = 2\), and \(c = 0.3\) allow for the ornithopter to flap and maintain altitude. In this model, the mass is assumed to be 1 kilogram, gravity is taken as 10 \(m/s^2\), and the wings are assigned an arbitrary length of 10 meters.
Figure 6.1 Two time captures of the initial simulation showing altitude and flapping of model with the model centered on an arbitrary origin
6.1. Articulated Flapping Wing Simulations

In order to simulate flapping flight with two panel, articulated wings, where $\theta$ is the angle the wing makes with the body, $\varphi$ is the angle the secondary panel makes and the force becomes a function of these two angles as follows:

$$F_{\text{downstroke}} = c \cdot \cos \theta \cdot \dot{\theta}^2 + d \cdot \cos \varphi \cdot \dot{\varphi}^2 = C_{L,1} \rho S_1 \cos \theta \cdot \dot{\theta}^2 + C_{L,2} \rho S_2 \cos \varphi \cdot \dot{\varphi}^2$$

$C_{L,1}$, $C_{L,2}$, $S_1$, $S_2$ are the coefficients of lift for each panel and wing areas for each panel, respectively. When the wings are moving down, the lift generated is positive and for when the wings are moving up, the lift generated is negative:

$$F_{\text{upstroke}} = -c \cdot \cos \theta \cdot \dot{\theta}^2 - d \cdot \cos \varphi \cdot \dot{\varphi}^2 = -C_{L,1} \rho S_1 \cos \theta \cdot \dot{\theta}^2 - C_{L,2} \rho S_2 \cos \varphi \cdot \dot{\varphi}^2$$

It is assumed that the angle $\theta$ is time dependent and following an oscillatory dynamic as follows:

$$\theta(t) = -(\pi/3) \sin(\omega t)$$

$$\omega = 2\pi T^{-1}$$

$T$ is the period from peak to peak of oscillation, $T = (\text{frequency})^{-1}$. Thus, with no motion in the $x$-direction, the total force is modeled as follows:

$$v_z = m^{-1}(-mg + F_{\text{lift}})$$

The resulting simulations with $c = 2$ and $d = 1$ are shown in Figures 6.2 and 6.3. The length of
each wing panel is given an arbitrary length of 10 meters and the mass remains 1 kilogram. Note that it would be more realistic to have a 10 meter structure have a weight of 100 kilograms, but the simulations would need further tuning to accommodate that. The wings are constrained to move from 0 to 60 degrees. The simulation uses an if/else statement due to the dependent nature of the wing links (see Appendix A). When the wing performs the upstroke, the secondary wing angle will converge to zero. When the wing performs the downstroke, the secondary wing angle will converge to that of the primary wing angle. This dynamic is necessary to simulate the fluid, seamless motion of avian flight.
Figure 6.2 Flapping simulation on the upstroke (creating more thrust, less lift) with two panel wings that is centered on the origin
Figure 6.3 Flapping simulation on the downstroke (creating more lift, less thrust) with two panel wings that is centered on the origin.
To simulate the two-panel flapping wing in 3 dimensions, the forward motion is needed. Thus, the previously used $F_{\text{downstroke}}$ and $F_{\text{upstroke}}$ ($= \pm F_{\text{lift}}$) will continue to dictate the vertical motion, but another force, $F_{\text{aero}}$, will dictate the forward motion. The aerodynamic force for the simulation is used as the following:

$$F_{\text{aero}} = (C_1 \cos \theta + C_2 \cos \phi) \cdot v_x^2 = (C_{L,1}\rho S_1 \cos \theta + C_{L,2}\rho S_2 \cdot \cos \phi) \cdot v_x^2$$

where in this case, $c = d = 0.35$ and $C_1 = 0.06$ and $C_2 = 0.02$. The forces in the $x$ and $z$ direction are modeled as follows, respectively:

$$v_z = m^{-1}(-mg + F_{\text{lift}} + F_{\text{aero}} - F_{\text{drag},z})$$

$$F_{\text{aero}} = (C_1 \cos \theta + C_2 \cos \phi) \cdot v_x^2$$

$$F_{\text{drag},z} = C_D v_z^2$$

$$v_x = m^{-1}(-F_{\text{drag},x} + \text{Thrust})$$

$$F_{\text{drag},x} = C_D v_x^2$$

where the thrust is either 200 or 0 Newtons to represent the high-thrust generating downward flap and the low or even negative upward flap motion, respectively.

This 3 dimensional flapping motion is animated as shown in Figure 6.4. The flight dynamics of this simulation are oscillatory, where the altitude of the ornithopter follows a trigonometric wave as shown in Figure 6.5. As shown in Figure 6.6, this simulation does match the actual flight of some small birds like finches. However, this simulation does not agree with
the gliding flight of larger birds, who tend to maintain constant altitude, as shown in Figure 6.7. Nevertheless, the fundamental dynamic of flapping and its compensation of gravity cause the bird generally to oscillate up and down at some point in the flight trajectory. When the bird is gliding, a nearly constant altitude is maintained because flapping is less necessary to flight. Figures 6.8, 6.9, 6.10 show the complex dynamics of the ornithopter’s forward and vertical velocities and the primary and secondary angles. Notably, the ornithopter dramatically increases its forward and vertical velocity on the downstroke compared to the upstroke.
Figure 6.4 3D simulation of two-panel ornithopter with motion in x, y, and z directions
Figure 6.5 Trajectory of flight generated from the translational simulation, showing deviation of altitude from origin.

Figure 6.6 Trajectory of small birds like finches are oscillatory as their body rises and falls during flight as they transition between gliding and flapping (http://www.birds.cornell.edu/)
Figure 6.7 Most birds maintain a nearly constant altitude and fly straight and level by varying pitch
Figure 6.8 Plot showing the forward translational velocity of the ornithopter. Here the dramatic change in upstroke and downstroke velocities are apparent. The ornithopter increases its forward velocity component by over 10 m/s on the downstroke to create lift. However, on the upstroke the ornithopter’s forward velocity slows to nearly 2 m/s.
Figure 6.9 Plot showing the vertical velocity of the ornithopter, where negative values show the ornithopter moving downward. On the downstroke the ornithopter gains vertical velocity, but when the upstroke begins, the wings go up and the ornithopter drops in a slight temporary diving motion, like a badminton ball. Some complex motion on the upstroke velocity is occurring due to the motion of the secondary wing panel.
Figure 6.10 Time dependence of the primary and secondary wing angle links, showing how the secondary angle straightens out and becomes constant when the primary angle peaks.
7. Micro Aerial Vehicle Hardware

A partial goal of this research is to gain more understanding of technological hardware, so some micro aerial vehicle hardware was purchased and explored. A Spybird Eagle Ornithopter, Figure 7.1, with a 1.2 meter wingspan and 450 gram weight was purchased in order to investigate and modify its electronics and hardware. A few different types of Arduino were additionally purchased in order to modify the Spybird in order to attempt to control the MAV autonomously. The Spybird is run with a 3 cell, 11.1 volt lithium polymer battery and a nickel metal hydride battery. The dynamics of the ornithopter that were evident during the test flights helped inform the aerodynamic models that were developed.
In the store-bought system, there are four main components- the electronic control system (ECS), the receiver, the lithium polymer (LiPO) battery, and the hardware components such as motors, gears, and servos. The LiPo 3 cell battery inputs direct current (DC) into the ECS, which then converts the DC into alternating current that powers the motors, gears, and servos. The receiver has 4 channel signal inputs of throttle, aileron, rudder, and elevator that go into the ECS.
In a generalized formulation for micro aerial vehicles, three main subsystems are necessary- the aerodynamic components such as the wings, the power actuators, and the energy source. These subsystems are joined by two transducer mechanisms, the mechanical transmission and the power electronics. The mechanical transmission interfaces between the actuator and the wings or aerodynamic components and the power electronics interfaces between the energy source and the actuator. Other systems involved in the MAV may involve controls, sensing, communication, and structural components.

The *Spybird* has a complex system of onboard electronics. The rudder and elevator system contain three servos that are joined into a multiplexer computer board to join the inputs of the three servos. Each one of these servos connects to the aileron, rudder, and elevator. These servos consist of an output shaft, a potentiometer, and control circuits. The multiplexer computer board includes a gyro and accelerometer system for orientation sensing.

The lithium polymer battery requires charging and its voltage was monitored by use of a
voltmeter. The battery recommended for the system came with the wrong connector for the Spybird, so a new appropriate connector had to be soldered on in order to power the ornithopter. Lithium polymer batteries require charging and after it was charged, it was found that it charged to over capacity when tested with a voltmeter. So a servo driver Mpi MX 8340 was purchased in order to test the systems to make sure none of the electronics were destroyed by an over-capacity battery. This servo driver flaps the wings of the ornithopter when connected to the throttle. The different control connectors were also checked with the voltmeter and it was found that the throttle uses about half of the battery power. Figures 7.2, 7.3, and 7.4 illustrate the hardware mechanics of the ornithopter.

Figure 7.3 Full schematic of operating hardware systems on the ornithopter. Notice that the servos that output the elevator, rudder, and aileron control are powered through the battery power that is intaken by the throttle.
Figure 7.4 Servo system attached to tail (top) that connects into a mixer circuit board (bottom)
7.1. Modifying the Ornithopter to Incorporate Autopilot

The 6 channel receiver and transmitter used to control the ornithopter has an open input to add a controller, in which an Arduino board will be attached to switch the transmitter between manual and autopilot modes. An Arduino Uno board, Figure 7.5, was purchased to begin familiarization with the Arduino software. An Arduino Mega 2560 Microcontroller, in which Ardupilot is installed, is used to attempt an autopilot function.

![Figure 7.5 Arduino Uno](image-url)
7.2. Test Flights of the Ornithopter

Prior to test flying the ornithopter, a servo driver, Figure 7.6, was attached to each of its controls to ensure all connections were functional and providing the correct voltages. For each control test, it is imperative to ensure all red control cables are attached to the positive input and all black control cables are attached to the negative or ground input.

Using a Spektrum DXe DSMX Transmitter, initial test flights were run with the transmitter and receiver in default mode for the throttle, rudder, aileron, and rudder. This proved to be insufficient for the ornithopter and the advanced option of programming the transmitter...
with a PC cable was required. In the default transmitter mode, the ornithopter was very difficult to control and was not able to fly for very long.

Consequently, the transmitter for the ornithopter needed to be programmed in order to trim the flight controls for stable flight. It was found that the circuit board that mixes the aileron and rudder control was causing an offset in the tail’s yaw orientation. So test flights were conducted again without the aileron and rudder mixer board, which allowed for successful flights. Careful placement of the LiPo battery was also necessary to create an appropriate center of mass for the ornithopter. This is crucial because the ornithopter tends to take a steep pitch down on takeoff due to gravity and without a proper center of mass cannot climb to altitude. But after climbout, the ornithopter maintains a very high altitude and its dynamics are almost impossible to distinguish from a real bird. A successful test flight is shown in Figure 7.7.

The test flights of the ornithopter helped confirm the accuracy of the previously created aerodynamic models by clearly showing the high dependence of lift force on flapping frequency. Without high flapping frequency, the bird could not gain altitude. There was not a high dependence on pitch, because even at launch of the ornithopter, the vehicle could be thrown straight without pitch up and still could take off.
Figure 7.7 Successful test flight of the ornithopter
8. Future Work

Future related applications to this work include the use of smart materials for flapping wing MAVs. MAV ornithopters have used many forms of actuation, such as rubber bands, electromagnetic motors, chemical muscles, shape memory alloy (SMA), ionic polymer composites, and piezoelectrics. Indeed, SMA are being used for biologically-inspired commercial aircraft (Nguyen, Trinh, et al, 2013) and for bat-like ornithopters (Bunget & Seelecke, 2009). While electromagnetic motors are widely used for larger ornithopters, smart materials have become popular for micro, nano, and pico air vehicles. All of these actuators are acting as the flight muscle of the insect or bird. The problem with motor-driven actuators is the added weight and complexity they tend to give to the system, whereas smart materials often make a system lighter, simpler, and more flexible.

8.1. Piezoelectric Flapping

Piezoelectric materials take a dramatic step towards more muscle-like dynamics versus motors and gears. The thorax or chest of an insect is often deformed as the muscle moves for flight and this deformation of the thorax is analogous to the amplification schemes used in combination with piezoelectric materials. Thus in addition to the wing, the piezoelectric material is the flight muscle, the transmission is the thorax, and the airframe is the exoskeleton. Piezoelectric materials are forcing researchers to think of aerial vehicle components in terms of biological parts.
Bimorphs are piezoelectric materials that exhibit organic motions and have the potential to replace motors as actuators. A bimorph is a smart material made of two piezoelectric (PZT) lead titanate (PbTiO3) layers sandwiched around a substrate that expands and contracts when a voltage is applied, causing the bimorph to bend and subsequently bend other materials attached to it, such as wings. Thus the bimorph will act as an actuator to induce the motion of other mechanical parts. One PZT layer contracts and the other will expand, which causes the bending motion. The bending frequency of the bimorph generates the frequency that produces the flapping motion of the aircraft. Bimorphs act under the reverse piezoelectric effect, in which electrical energy produces a mechanical reaction in the form of strain and amplification (Coleman, 2009). The free displacement or actuation movement of an ideal bimorph actuator (the substrate can be considered negligible) can be found with the following relation:

\[ \delta_0 = 3d_{13}l^2Vt^2 \]

where \( d_{13} \) is the piezoelectric charge constant specified in the type of PZT used, \( l \) is the length of the piezoelectric bimorph, \( V \) is the input voltage, and \( t \) is the thickness of each layer of the piezoelectric material.

The disadvantage of piezoelectrics is they have a high voltage demand and low actuation ability. But one large advantage for flapping wing flight is that piezoelectrics can be layered with additional perpendicular piezoelectric panels, so that motion can be created in multiple directions, in order to better mimic the bend-twist-flapping dynamics of bird flight (Chung, Kummaria, et al., 2008).
8.2. Ionic Polymer Metal Composite Ornithopters

Researchers are developing solid state aircraft that have no moving parts by incorporating ionic polymer metal composite (IPMC), thin film solar arrays, and thin film lithium batteries (an example illustration is shown in Figure 8.1). The IPMC, a type of electroactive polymer, acts as synthetic muscle in which an applied electric field causes the material to deform or flap. IPMCs consist of a thin electrolyte membrane and a noble metal that is plated on each side of the membrane. IPMCs have the ability to create a large bending motion when electricity is applied to its electrodes. IPMCs look like a plastic, but its core acts as an ion-exchange membrane. And when an electric field is applied to this membrane, it allows water molecules and hydrated ions to move across it. This flow of solvent creates a nonuniformity across the panel of IPMC in which one side contracts and one side expands, provoking a flapping mechanism (Mukherjee1 & Ganguli1, 2010).

Figure 8.1 Artist’s rendition of an IPMC bird
(https://spectrum.ieee.org/aerospace/aviation/fly-like-a-bird)
9. Conclusion

Current engineering designs are jeopardizing the planet with pollution and unsustainability, thus engineering must synchronize with ecological and biological modes of design for the interest of the planet. For example, MIT and Harvard are making bioplastic out of shrimp shells and Mercedes has a concept to grow organic, compliant cars. Evolution has perfected flight throughout hundreds of millions of years without polluting the earth, so aerospace engineering should aspire to clean energy and take note of the efficiency of biological flight instead of continuing to be one of the biggest unregulated contributors to worldwide air pollution. The Code of Federal Regulations states that “greenhouse gas emissions from aircraft cause or contribute to air pollution that may reasonably be anticipated to endanger public health” (40 CFR Part 87). Researchers from the NASA Ames Research Center claim that a transport aircraft inspired by the biological wing could reduce drag by 50% (Nguyen, Trinh, et al, 2013) and thus reduce fuel and pollution. While it is acknowledged that MAVs and aircraft will not use perfectly engineered replicas of a bird wing any time soon, many air vehicles will slowly incorporate some characteristics of bird flight in order to become more efficient.

The inspiration for this project was the movement of many researchers to work on biomimetically inspired aircraft and MAVs. The H2Bird, the perching plane, and the DeLaurier ornithopters are just a few examples of the many flapping wing robotic prototypes that have been recently developed. The work of this project was threefold; develop a model describing flapping
wing robotics, develop a control algorithm to stabilize the ornithopter’s altitude, and investigate the hardware of ornithopters. The modeling approach took other previously developed models of ornithopters into consideration and then the development of the simplest possible model was articulated. Subsequently, the simple model was built upon with increasing complexity and several control methods were investigated and modified to meet the parameters of the increasing complex models. It was found that a feedforward and a PD controller with proper gains applied to the nonlinear system, was able to control the ornithopter to bring it to oscillate around a stable altitude. However, it should be noted that due to the complex nature of the aerodynamics and mechanism of motion required to replicate bird flight, it is very difficult to accurately model ornithopters.

The Spybird ornithopter was the vehicle chosen to purchase, investigate, and modify. Many hardware adjustments and accommodations were needed to adjust typical remote control fixed-wing airplane configurations to work for the ornithopter. Several test flights were conducted and work on the development of an autopilot option for the transmitter is in process via control with an added onboard Arduino computer. However, the hardware component of the project was a side endeavor with the main focus of the research being on the literature search of ornithopters and the development of a model and control for the dynamics of flapping wing micro aerial vehicles.

While biomimetic flight is fascinating and the topic of widespread research, in practicality, engineering may never be able to truly mimic the agility of biological forms. However, aerospace engineering may be forced to mimic the bird wing in some aspects for increased efficiency as air travel becomes one of the leading causes of air pollution. In
conclusion, this research succeeded in meeting its objectives of developing and investigating models of flapping wing robotics.

10. Recommendations

1. A programmable transmitter should be used with a mechanical RC ornithopter to trim the flight controls.

2. A nonlinear controller should be anticipated with an ornithopter model.
REFERENCES


Paranjape, Aditya, Kim, Joseph, et al, “Closed-Loop Perching of Aerial Robots with Articulated Flapping Wings,” Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, IL.


A. Two Panel Flapping Simulation Code

A component of the MATLAB simulation code is shown here to illuminate how the two panel wings were generated in form and dynamics:

for k=1:T/dt

\[ t(k+1)=t(k)+dt; \]
\[ \text{The primary panel/link has a wing angle of } \theta(k). \text{ It is oscillating with frequency } \omega. \]
\[ \theta(k+1)=-\theta_1 \sin(\omega t(k)); \]
\[ \theta_{\text{ad}}(k)=(\theta(k+1)-\theta(k))/dt; \]
if \( \theta_{\text{ad}}(k) > 0, \)
\[ \phi(k+1)=\phi(k)+dt*10*(\phi(k)-\phi_1); \]
\[ \text{when the first link goes up, the second link } (\phi) \text{ converges to } \phi_1 \text{ (parameter)} \]
\[ F_l=-c \cos(\theta(k)) \times (\theta_{\text{ad}}(k))^2 - d \cos(\phi(k)) \times (\phi_{\text{ad}}(k))^2; \]
\[ \text{Fl is a negative force since the wings are moving up (generating negative lift)} \]
else
\[ \phi(k+1)=\phi(k)+dt*10*(-\phi(k)+\theta(k)); \]
\[ \text{corresponds to the first link going down} \]

\[ \text{Fl} \]
%when the first link is going down, the second link (phi) converges to theta(k)

\[ F_l = c \cdot \cos(\theta(k)) \cdot (\theta_d(k))^2 + d \cdot \cos(\phi(k)) \cdot (\phi_d(k))^2; \]

%Fl is a positive force since the wings are moving down (greater lift generated)

end

\[ \phi_d(k+1) = (\phi(k+1) - \phi(k))/dt; \]
\[ K_d = 1; \]
\[ x(k+1) = x(k) + dt \cdot 0; \]
\[ y(k+1) = y(k) + dt \cdot 0; \]
\[ v_z(k+1) = v_z(k) + dt \cdot (-g + F_l/m - K_d \cdot (v_z(k)^2) \cdot \text{sign}(v_z(k))); \]
\[ z(k+1) = z(k) + dt \cdot v_z(k); \]
\[ \text{plot}(y(k), z(k), '{r}') \]
\[ \text{xlabel('y')} \]
\[ \text{ylabel('z')} \]
\[ \text{grid} \]

%The following line command creates the coordinates for the wing links
\[ \text{line}([y(k), y(k) + L1 \cdot \cos(\theta(k)), y(k) + L1 \cdot \cos(\theta(k)) + (L2) \cdot \cos(\phi(k))], [z(k), z(k) + L1 \cdot \sin(\theta(k)), z(k) + L1 \cdot \sin(\theta(k)) + L2 \cdot \sin(\phi(k))]) \]
\[ \text{line}([y(k), y(k) - L1 \cdot \cos(\theta(k)), y(k) - L1 \cdot \cos(\theta(k)) - (L2) \cdot \cos(\phi(k))], [z(k), z(k) + L1 \cdot \sin(\theta(k)), z(k) + L1 \cdot \sin(\theta(k)) + L2 \cdot \sin(\phi(k))]) \]