ELECTROMAGNETIC ACTUATION FOR A DRAGONFLY INSPIRED FLAPPING-WING MICRO AERIAL VEHICLE

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science Graduate Department of the Institute for Aerospace Studies University of Toronto

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Abstract

Electromagnetic Actuation for a Dragonfly Inspired Flapping-Wing Micro Aerial Vehicle

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2017

Insect-scale microaerial vehicles is an area within microaerial vehicles which has seen recent growth due to new understandings of insect flight and the availability of new actuation technologies. Prominent flapping wing MAVs were surveyed and relevant observations taken to help guide the project. Alternative actuation technologies for the UTIAS Robotic Dragonfly project were assessed and an electromagnetic actuator was selected. A new design incorporating this actuator was fabricated and tested. The platform features a sub-gram at-scale prototype with independently driven wings, a mass of 222 mg and a wingspan of 75 mm. Experiments demonstrated that the prototype was capable of generating up to 1.34 mN of lift.
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Chapter 1

Introduction

Mankind’s long history has many accounts of aerial vehicles and devices from ancient tales of Icarus to the development of kites, hot air balloons, and rotor wings. While many of these inventions are fascinating, many of them were unmanned toys and controlled falling. The origins of what we tend to regard as the development of true flight able to carry passengers has much of its origins in a biomimetic flapping wing approach. Through the years there have been attempts at designing flapping wing contraptions using all manner of design. One famous design is Leonardo da Vinci’s flying machines using ropes and pulleys controlled by the pilot to actuate the device [8]. Otto Lilienthal’s kleiner Schlagflügelapparat design strapped wings to the pilots own arms [10]. Robert Hooke even worked on a design using springs as artificial muscles upon the realization that a human muscle power was insufficient for flapping flight [68]. Finally after centuries of different designs, attempts, and unfortunately a couple deaths, two brothers, Orville and Wilbur Wright succeeded where others had failed and were the first to achieve a sustained, powered, heavier-than-air, and manned flight [13]. On December 17, 1903, Wilburt Wright piloted the Wright Flyer for 59 s over a distance of 892 ft. Their success has been attributed to the development of aerodynamics, structure, power, and control.

Even many years after the Wright brothers’ famous flight and the explosion of air travel, insect flight was poorly understood and thought of as impossible to mimic. Some believe we are approaching a similar culmination of these four areas in regard to recreation of insect flight. Since the days of the Wright brothers there are now high-speed cameras available, many researchers are finally have the technology they require in the pursuit of understanding insect flight.

1.1 Motivation

Other than the technological and academic challenge, the development of MAVs has many potential applications. Applications of MAVs could range from search and rescue operations to drone surveillance. A controllable or autonomous MAV would gain certain advantages over currently used robotics. These include the ability to fly and cover adverse terrain as well as operate in close quarter urban settings which traditional UAVs are unable to do. Such a device would also enjoy the properties of being small and light weight excelling at discrete surveillance, or even extraterrestrial exploration.

MAVs have the potential to offer advantages over rover-type vehicles and current un-
manned aerial vehicles (UAVs). In a search and rescue situation, hazardous obstacles and general clutter around the search area may be present that would greatly reduce a traditional rover’s ability to manoeuver but not MAVs [139, 145]. In the field of crowd monitoring, some police departments often use solitary UAVs. These units can be quite expensive costing over $100,000. In the event of damage or malfunction the financial cost is very large along with the potential for complete failure of the missions [138]. Alternatively, a swarm of small MAVs could cover more area, and be more cost effective. If a small portion of the units were lost, the remaining units could continue the mission and the MAVs being so small would not pose any hazardous threat to civilians on the ground.

1.1.1 Mimicking Nature

Much of the early inspiration for flight came from birds, a relatively large creature which takes advantage of steady lift mechanisms (time independent flow). Insects, on the other hand have evolved to use unsteady lift mechanisms (time dependent flow) which can only be exploited at their small size. Owing to the wings being small, passive, rigid structures actuated from muscles within the thorax, insects are able to flap their wings at much higher frequencies than than birds can [38]. If one were to attempt to create a traditional fixed-wing aircraft that was the size of an insect, the vehicle would have to travel at speeds far beyond what is currently possible [37]. One obvious solution to this challenge is to attempt to exploit the unsteady lift mechanisms used by insects with flapping wings.

Insect wings have a unique place in the arena of flying animals. All other flying animals have evolved wings that are actually modified legs. In the case of birds and bats, their wings have the ability to change shape as well as fold up to be more compact while giving up a set of limbs. The insects on the other hand form wings from modified portions of their exoskeletons. The wings are fixed and nonliving much like human hair and fingernails are nonliving [22]. Insects were the first to develop flight and are quite different from other flying creatures. The earliest insects developed flight over 350 million years ago, and have a striking resemblance to currently extant dragonflies [54]. Both these ancient and modern insects the flight muscles were simple and were made up of two pairs. Modern dragonflies actually seem to be nearly identical in physical configuration [38]. Some insects like flies and bees, on the other hand, have evolved more recently and make use of more complex wing strokes such as the clap-and-fling or stroke-plan deviation, which is rarely observed in dragonflies. Despite potentially appearing to be less evolved than other insects, dragonflies are still considered to be some of the most manoeuverable and predatory flying insects in existence. It is interesting that many insects maximize efficiency by flapping at resonance based on the structure of the thorax. It seems insects have found a way to contrast starkly the many first year engineering lectures where resonance is often associated with the epic
failure with many projects. Similar to these types of cases, insects can create large flapping amplitudes from minimal energy cost [31].

In some cases, attempting to mimic nature may help understanding nature and lend weight to scientific hypotheses. Currently, the origins and development is still strongly contested. One theory that has been suggested is that running animals grew protrusions out of their thoraxes to increase inertial stability [38]. These protrusions could have allowed insects with this trait to move with more stability and have an advantage in escaping from predators, or accessing food and mates. Over time a membrane might develop turning what were once protrusions into wings allowing for insects to run and glide and eventually flap and take-off. In 2011, a team led by Ronald Fearing experimented with robotics that tested this idea. The team had developed a bipedal running robots that would lose stability and fall over when running at high speeds [1]. Consecutive modifications of the robot added spars, fixed wings and flapping wings which each gave the robot increased stability and improved its ability to run up steeper and steeper inclined planes [86]. The various hypotheses of insect wing origins only have limited fossil evidence supporting their claims, now this one theory has some form experimental robotic validation [85]. This kind of work demonstrates how ideas from one field can affect another and perhaps hint towards greater productivity if the fields of robotics and evolutionary biology collaborated in the future.

1.1.2 Robotic Biomimicry

While some have loosely described MAVs as being less than 30 cm and less than 100 g, the term MAV is most commonly applied to flying robots being less than 20 cm in largest dimension [135]. This is description is quite vague, but the simple size constraint has naturally led to the majority of projects towards biologically inspired flapping-wing MAVs.

Over the years there has been quite a few flapping-wing MAV projects. Only a few attempt to be truly biomimetic, while the remaining tend to be loosely mimicking insect flight. One MAV that fits into the latter category is the DelFly Micro from Delft University of Technology. The MAV features to pairs of flapping wings but also a rudder and elevator. The Delfly has gained some success in flapping flight but does not actively attempt to mimic any of the characteristics found in nature such as wing design, kinematics, mass, or control surfaces.

The earliest attempt to make a truly biomimetic MAV was in the 1990s by the University of California, Berkeley called the Micromechanical Flying Insect (MFI) [6]. The project aimed at being of a similar size and weight of real insects. It could control its wings with two degrees of freedom but was unable to achieve lift-off. The MFI project was instrumental in defining and developing the field of flapping wing MAVs. In fact, many of the researchers on the project are now leading researchers in the field at other universities.
Chapter 1. Introduction

The most successful project has been the RoboBee project at Harvard University led by Robert Wood who also worked on the MFI [6]. An early design made use of a single piezoelectric actuator achieved lift-off in 2007. The prototype only contained the bare essentials and was powered by a tethered off-board power supply. In the following years, the project has added the ability for roll, pitch, and yaw control and further development on on-board sensor integration. The flapping kinematics and mass are meant to imitate the honeybee for which the project is named [139].

1.2 Flapping-Wing Legacy at UTIAS

The University of Toronto Institute for Aerospace Studies (UTIAS) has had numerous projects related to flapping-winged vehicles. Research topics have been quite varied, ranging from modelling aerodynamics of flapping wings to a development of a man-powered ornithopter! Much of this work was led by James DeLaurier beginning in the early 1990s.

With the long-term goal of building a manned ornithopter, DeLaurier focused on developing of flapping-wing flight based on modified strip theory. The model also included the effects of vortex wake, leading-edge suction and post stall effects [41, 42]. Eventually these aerodynamic models were combined with wing deformation from twisting as well as wing folding [88]. These mathematical models were validated on relatively small ornithopters that could launched by hand as a proof of concept [43]. A vital component of this project was the development of an efficient flapping wing and a lightweight yet reliable drive mechanism to generate enough lift.

In 2006, Harris and DeLaurier flew the UTIAS Ornithopter No.1 to claim the title of
being the first ever manned ornithopter flight. The UTIAS Ornithopter No.1 was powered by a small engine was able to provide power to attain lift-off through its flapping mechanism. Only 5 years later, two students of DeLaurier, Todd Reichert and Cameron Robertson built and flew an ornithopter called the Snowbird. The Snowbird was the first human-powered ornithopter to take flight and was powered by the pilot using a leg-press type motion to flap the vehicle’s wings [88][10].

DeLaurier also led research projects on smaller flapping-winged robots. In 1997, the Defense Advanced Research Projects Agency (DARPA) called for a desire of small flapping-winged MAVs with size and mass constraints of a 15 cm wingspan and 50 g. A few years later, a small flapping wing vehicle called the MENTOR was built based on the hummingbird. The result was a four winged platform that could fly using either a gasoline powered engine or electric DC motors. These weighed 580 g and 440 g respectively and could not be considered to be true MAVs [145].

The most recent flapping-winged project led by DeLaurier, was a research project experimenting with ornithopter wings in tandem to study interactive effects of forewing and hindwing. Two wing pairs with their drive mechanisms were removed from a commercial toy ornithopter (Air Hogs Cyberhawk by Spinaster Corp.) and mounted together in a wind-tunnel. The wings were driven at varying phase differences while the net lift was recorded to determine if there was any benefit to mutual wake interference [126]. The total vehicle was not considered an MAV under constraints given by DARPA, but it was one of the first Tandem wing platforms tested at UTIAS and was also one of the closest to qualifying as an MAV with a mass of 28 g and wingspan of almost 30 cm.

1.3 UTIAS Robotic Dragonfly

Inspired by some much of DeLaurier’s later work with smaller ornithopters, the Space Robotics Group at UTIAS created the UTIAS Robotic Dragonfly Project. Peter Szabo began as the principal investigator under the supervision of Professor Gabriele D'Eleuterio, and was responsible for laying much of the groundwork of the project. The long-term goal was to one develop a flapping-winged MAV platform that would mimic the physical parameters and flight kinematics of a dragonfly. Many students have been involved in different areas of the project with the overarching vision of one day having autonomous flight.

Previous designs consisted of a minimal design driven by piezoelectric actuators. In this thesis the primary goal was to improve the lift generated by focusing on hover and using an alternative electromagnetic actuation, which at the inception of this work had not been attempted by anyone in the insect-scale flapping-wing MAV field yet. Since then, there have been two groups which have implemented electromagnetic actuators into a flapping wing MAV platform.
1.3.1 Contributions

In the following chapters the work leading up to an electromagnetically actuated flapping wing MAV is presented. A thorough literature review of prominent MAV projects is used as a frame of reference to provide insight into the field guide the choices of this project. Relevant background to the project is summarized highlighting previous design the motivation to find a new actuator. The suitability of various actuation technologies are researched and discussed resulting in selection of an electromagnetic actuator. A new flapping wing platform is designed to incorporate the new actuators is eventually fabricated. Finally, the prototypes were tested revealing simple methods that may help guide the future project.
Chapter 2

Literature Review

2.1 Dragonflies

Compared to many other bugs, dragonflies seem very tame to us humans and are not considered a pest. They don’t leave annoying cobwebs or infest and damage our homes, they don’t sting and aren’t poisonous, nor do they spread any of the multitude of insect borne diseases like malaria. To many it is just benign insect with a much lower “ick” factor. The perspective from many other flying insects is quite different. In fact, dragonflies are natural-born predators that hunt mosquitoes and other small insects while mid-flight. They achieve this by being very strong fliers that can glide, hover and have excellent maneuverability. It has even been reported that some dragonflies can make $90^\circ$ turns in just 3 wingbeats \[69\]. They have two relatively large pairs of wings that can each move independently which are powered by powerful muscles in the thorax. The rather long abdomen can contort and bend during acrobatic flight and their two large compound eyes which are very acute for hunting prey \[113\]. Much of dragonfly flight occurs so quickly that the human eye cannot track it, but high speed cameras have allowed researchers to document their flying capabilities. Research has found that some species of dragonfly can fly at speeds of 7 – 15 m/s \[24, 38\]. Most of the time the maximum speed is correlated with body mass with larger body masses resulting in higher maximum speeds \[117\].

Given all of the dragonfly’s capabilities, it may be surprising to some to find out that from an evolutionary perspective dragonflies are quite simple fliers. The fossil record indicates that dragonflies are descended from *Meganisoptera* formerly known as *Protodonata* which took flight ever 350 million years ago \[38\]. Like the shark, the dragonfly has ancient origins as a fierce predator and has remained almost unchanged for hundreds of millions of years \[110\].

More recent fossils show that many insects moved towards single wing pairs with hindwings evolving into halteres \[46\]. This change causes these insects to require more advanced wing mechanics than dragonflies \[118\]. The simple and consistent wing kinematics of dragonflies make them an excellent candidate for robotics to attempt to mimic.

2.1.1 Evolution of Dragonflies

Insects were the first in the animal kingdom to take flight more than 350 million years ago \[38\]. During the early days of the dragonflies ancestors, the earth was in the late Carboniferous and early Permian periods. During this time the atmosphere was extremely dense and oxygen
rich, which accounts for the gigantism experienced by arthropods and amphibians [14]. In fact, one genus *Maganeura* became terrifyingly large with some fossil specimens growing to an enormous 70 cm wingspan [77]. These creatures then experienced a reduction in size during the late Permian period believed to be caused by the drastic decrease in oxygen-rich atmosphere [49]. This size reduction is responsible for leaving with us with the dragonflies of today with wingspans of only 5 – 19 cm [77]. *Protodonata*’s most noticeable difference is the size differential as they have a virtually the exact same structure as modern dragonflies to today.

A contending theory for the origins of insect flight is that the wings were originally very basic extensions coming out of the thoracic wall. These extensions could have added inertial stability to running insects. The eventual addition of thin membranes might have added stability through damping on more adverse terrain. After another 100 million years it is thought that these refined protrusions from the thoracic wall might become fully fledged flapping wings capable of creating insect flight [38]. Some evolutionary biologists believe that the four-wing design was actually the basis for the entirety of insect flight that we now observe. In this respect, dragonflies are actually primitive in origins and have operated with four wings for the last 300 million years [114, 117]. Close inspection of more recently evolved “two-winged” insects reveals that they, just like dragonflies, actually once had four wings. In flies the hindwings have evolved into halteres. Halteres are tiny dumbbell shaped protrusions which oscillate during flapping which provide feedback to the fly about rotation and orientation. Beetles have hindwings that are adapted into a protective shell protecting the forewings when they are folded back. This trades increased protection for relatively poor aerodynamics [141].

(a) Casting of a *Maganeura* fossil 
(b) Supposed model of a *Meganisopteran*

*Figure 2.1: Examples of the order Meganisoptera dating to the Carboniferous period*

Dragonflies share the order *Odonata* with only one other insect, the damselfly. Damselflies are also predatory insects that seem, at least superficially, to be almost the same
as dragonflies. Because of their close common ancestry they share many physical features. Their eyes, thorax, abdomen and wings all have a strong resemblance to those of the dragonflies. Damselflies have slimmer bodies and most fold their wings along their bodies when at rest. The most notable difference occurs when looking at flapping kinematics. The dragonfly uses very consistent flapping along a well defined plane with the forewings and hindwings being able to flap in phase or out of phase. Damselflies on the other hand have developed more a more advanced flapping technique as the wings may move outside of a single stroke plane. Dragonfly wings actually follow a slight figure-eight path but this path is so close to a straight line, it is usually assumed to be a stroke plane. In the case of the damselfly, the wings do not follow a consistent stroke plane. The path of the wingtips can trace any path between the horizontal flapping plane and a 60° inclined plane. Damselflies also almost always flap all four wings in phase together and make use of the “clap-and-fling”. During the “clap-and-fling” each wing pair reaches above the body and touch (the clap), and then fling apart [117]. Dragonflies have not been observed performing this manoeuvre which is considered to be a more advanced method of lift generation. At the beginning of the “fling” a suction effect temporarily increases the lift generated and allows the damselfly to flap their wings at a lower frequency than dragonflies [118]. This allows the damselfly to have reduced muscle mass, but are less manoeuvrable than dragonflies and appear to be fluttering during flight.

### 2.1.2 Anisoptera Morphology

Together dragonflies and damselflies make up the entire order of *Odonata*. They each have their own suborder to themselves called *Anisoptera* and *zygoptera*. Their names are derived from the Greek roots of *anisos* meaning “uneven”, *zygo* meaning “joining” or “paired”, and *pteros* meaning “wings”. The reason for this is because damselfly wings have almost identical forewings and hindwings while dragonflies have forewings and hindwings with different size, venation, and planform. Dragonflies spend the majority of their lives in their nymph or naiad stage of development. At this stage they are purely aquatic and are but are still predators feeding on anything smaller than themselves, often other insects, tadpoles, and even small fish. The time spent as a nymph is most commonly 1–2 years but can reach 5 years in some species [24]. When ready to mature, the nymph climbs out of the water to begin moulting its skin, revealing the recognizable four-winged dragonfly. These wings are attached to the top of the thorax so that the body hangs below the wings allowing for a pendulum-like stability when flying [54]. Depending on seasonality, the dragonfly may only exist in this form for a few months before it mates and dies [32]. Despite not having wings prior to adulthood, dragonflies do not walk and only use their six legs to perch between flights [38]. This results in all motion of adult dragonflies being powered by the thorax where the flight muscle is located. This muscle can weigh anywhere between 15 - 49% of the total body mass [118].
modern dragonflies, wingspans can be as small as 5 cm, with 40 Hz flapping frequency, and body mass of 100 mg, with some of the largest specimens reaching 17 cm wingspans, with 20 Hz flapping frequency, and body mass of 1 g [24, 25, 77, 20, 117].

While birds and bats modify wingshape during flight, insects have no muscles inside their wings making use of purely passive structures [38]. If insects were to have muscle mass in the wings to actively deform, it would be very difficult to achieve the high flapping frequencies required to fly. Although passive, their wings have been observed to experience significant deformations while flying [36]. The flexible membrane of the wing is supported by rigid veins running longitudinally and radially creating a very structure that is strong but light [54, 140]. Longitudinal veins are very much like trusses adding strength and stiffness to the wing. The stiffest and most notable part of the wing is a thick vein along the leading edge which runs from the wing base all the way to the wingtip [141]. Venation of the wings is stiffened by making use of tube-like veins which increase structural stability without extra mass much like bones in mammals. The thin membrane which turns the truss-like veins into a fully fledged airfoil is only 2 - 12 $\mu$m [75, 77].

The design of the venation has a number of advantageous properties as flying is the dragonflies only method of locomotion. First, when bending forces are applied to the wing, forces are converted to tension or compression and the structure appears to optimize the distribution of internal forces. The complex structure of venation allows sections to yield and crumple under impact allowing some structural integrity to be saved [141]. Second, the wing surface is not smooth which is attributed to the venation structure which changes aerodynamic interactions. The raised venations channel air flow and trap vortices changing the effective profile of the wing [116]. Finally, wing venation in dragonflies appear to passively deform in a beneficial manner [36]. The venation adds rigidity to the wing but still allows it to flex giving the wings a cambered shape during flight [75, 140].

Another noticeable feature when examining dragonfly wings is the presence of pterostigma.
Pterostigma is a fluid filled sack near the wingtips of all four wings [20]. Pterostigma are actually present on many insects with high aspect ratio wings. Those insects that have pterostigma have been observed gliding at times during flight [116, 140]. While gliding, airfoils can be subject to the phenomenon flutter, which is an aerodynamic instability of an elastic structure in fluid flow. Flutter occurs at a critical speed and is caused by the wings deflection force and the force exerted by the fluid. The occurrence of flutter can be devastating and cause the insects flight to become unstable. To prevent flutter, researchers believe that pterostigma were developed which moves the wings centre of mass closer to the torsion axis offering passive pitch control. According to one experiment, the pterostigma is located in an almost optimal position [20]. When pterostigmas were removed from wings the critical flutter speed dropped. The pterostigma are estimated to augment the critical flutter speed by 10 - 25 %.

2.1.3 Flight Kinematics

The dragonfly is one of the earliest fliers in the entire animal kingdom. They remain quite similar to the primitive beginnings for the more modern insects in existence. Despite this, the dragonfly thrives to this day and can be found on every continent except for Antarctica [34]. Even with the evolution of more advanced lift generation, dragonflies make use of tried and true methods which still have proven effective for millions of years. Although they may be ancient, they are certainly not outdated.

The flight kinematics of dragonflies are very consistent and have proven to be successful making them ideal for robotic recreation. In particular, one species *Sympetrum sanguineum* has been extensively documented by Wakeling and Ellington allowing this species to serve as a foundational source material for this project.

The two pairs of wings on a dragonfly have the ability to flap at various phase differences. The base of both forewings and hindwings are attached to the thorax approximately one chordlength apart from one another [125]. While the two pairs of wings do not always flap in phase, they generally flap at identical frequencies. There was suspicion for a long time that the aerodynamic interaction between the two wing pairs might have significant effects on lift generation [118]. In recent work, it was shown that altering the phase difference between the forewings and hindwings influenced thrust and as well as power efficiency [114]. In most documentation the phase difference between the wing pairs is constant with phase difference alterations manifesting quite suddenly within the timespan of a single wingbeat [23]. Although dragonflies are capable of flapping at various phase differences, there are three that are primarily observed: parallel-stroking (0% phase), counter-stroking (180% phase), or phase-shifted [94]. From experimental observation, phase-shifted flight always has the hindwings leading the forewings anywhere from 0 - 180%. In simulation, Huang & Sun calculated
that lift generation decreases when the hindwings are led by hindwings, potentially explaining why has not been found in nature \[107\]. Previous calculations by Wakeling & Ellington showed that at a phase difference of 90% the hindwings would extract maximum energy from the wake produced by the forewings. It is also at this phase difference that the greatest lift was recorded from dragonfly specimens during forward flight. Counter-stroking with a 180% flapping has mainly been observed in cases of stationary hovering \[94\] \[125\]. Parallel-stroking, where the wings flapping with 0% phase is observed when performing severe aerodynamic manipulation such as taking-off, yaw rotations, or sudden direction changes \[24\] \[50\]. This generates a large amount of force but decreases efficiency. As a result, parallel-stroking is not used gratuitously and generally occurs for no more than six wingbeats \[23\] \[117\].

Dragonflies predominantly display consistent flapping frequencies with small variances and ranges between 20 - 40 Hz completely independent of the phase difference between the forewings and hindwings \[24\] \[77\]. Generally, flapping frequency and dragonfly size have an inverse relationship \[80\]. Flapping frequency is usually quite consistent with only a few rare cases observed by Rüppel \[94\]. In the case of *Sympetrum sanguineum*, the flapping frequency has been recorded as 39 Hz with little variation \[117\].

As mentioned earlier, one of the unique characteristics of dragonflies is how their flapping is restricted to a stroke plane \[54\]. Their wings flap along the plane with negligible displacement from straight line while pitching out of phase with the wing stroke \[117\]. Many modern two-winged flying insects flap in the horizontal plane during hovering such that the...
lift force is always opposing gravity. This is usually referred to as “normal hovering”, instead of this, dragonflies flap along an inclined plane relative to the body which is horizontal when hovering \[82, 123\]. When analyzing insect flight, the convention is to define lift as all force generated perpendicular to the stroke plane and drag to be all force generated parallel to the stroke plane. The resultant in normal hovering is that all lift force is applied directly against gravity and drag forces cancel out over the entire wingbeat \[123\]. Because dragonflies flap along an inclined plane, the force supporting the dragonfly in the air comes from both the generated lift and drag \[82\].

Specimens of *Sympetrum sanguineum* were measured to have, on average, stroke planes of 48° and 50° for the forewings and hindwings respectively \[117\]. During forward flight, the dragonfly it has been primarily observed that the stroke plane remains at a fixed incline. Only some fine manoeuvring is believed to be caused by adjustments to the stroke plane \[54, 94\]. As mentioned earlier, the wingtips actually do deviate from straight plane and trace a slim figure-eight path \[38, 118\]. Relative to modern day two-winged insects, this deviation is negligible, allowing for easier discussion on our part. Within the stroke plane, dragonflies can control a number of variables which allow them to be such excellent fliers. The amplitude of flapping along the stroke plane can be asymmetrical between the left and right wings of each wing pair. In fact, this asymmetry can be quite large as flapping amplitudes have been observed to have ranges anywhere from 73 - 150°. The dragonfly can also change the mean stroke angle such that each wing can have a different rest position either towards the dorsal or ventral position \[54\]. All of these variables are primarily manipulated without any change to the stroke plane or flapping frequency \[89\]. Despite the confines of a fixed flapping frequency and stroke plane, with four intact wings, the dragonfly still actively controls eight variables. A comparison between normal hovering and asymmetric hovering is shown in Figure 2.4.

Flapping is driven by the leading edge of the wing. Over the course of the wingbeat, the leading edge pronates and supinates at the maxima and minima of the stroke switching the angle of attack of the whole wing. Because the wings are not perfectly rigid, they twist along the span \[123\]. When twisting, the both the aerodynamic centre and centre of mass causes the trailing edge to lag behind due to inertial and aerodynamic damping causing the wing to pitch. As such, the angle of attack changes greatly over the course of a wingbeat \[94\]. Although dragonflies do sometimes control angle of attack, they are able to fly while passively controlling wing pitch \[32\].

### 2.1.4 Powering Dragonfly Flight

Since dragonflies have passively shaped wings, all flight is powered by muscles within the thorax \[38\]. Insect wings give up the ability to actively shape their wings with the benefit
Chapter 2. Literature Review

(a) Normal Hovering

(b) Inclined stroke plane

Figure 2.4: Comparison between normal hovering and inclined stroke plane during insect hovering [123]

of high-frequency flapping due to decreased inertia [140]. These muscles are almost entirely made up of aerobic tissue which has strong endurance capabilities [128]. This makes sense as the muscles within the thorax are the only source of flying power and flying is the dragonflies’ only method of transportation.

Flight muscles in insects are split into direct and indirect muscle. Direct muscle is considered to be more primitive of the two. The insect’s signal from the brain operates under 100 Hz and can directly control muscle for each wingbeat [53]. Direct muscle, also called synchronous muscle is found in insects with relatively low flapping frequencies like dragonflies, grasshoppers, and butterflies. To flap at higher frequencies than the brain can operate must make use of indirect muscle, also called asynchronous muscle [100]. It is thought that insects that make use of asynchronous muscle have muscle contractions that are decoupled which activate without a direct signal from the relatively high flapping frequencies such as beetles and bumblebees. Surrounding muscles can be used to restrict wing pitch and stroke amplitude [53].

Within the dragonfly’s thorax, direct muscles run parallel to one another in the dorsal-ventral direction. Each wing has a pair of muscles, one contracts during the upstroke and the other contracts during the downstroke powering each wing independent of the others [38]. The muscles attach to the thoracic wall as and sclerites which are at the base of the wing [74]. Keeping the wings, muscles and interior structure together are highly elastic structures referred to as resilin [53, 74]. It has been speculated that the elasticity within the dragonfly’s flapping mechanism creates conditions allowing for kinetic energy to be recovered as potential energy and then released in later part of the wing’s stroke [118]. Ellington has even claimed that power generated from the insect’s muscle would be inadequate without the aid of stored elastic energy [53].
Naturally, there have been a few attempts to quantify the power output of the insect’s flight muscles. One method attempted by Sun and Lan involved aerodynamic simulation to examine the work done on the air by the wings [108]. Ellington on the other hand, measured oxygen consumption assuming that all oxygen intake was being used to power the flight muscles [53]. Performance of each insect would of course be different, and calculations based on hover do not resemble the maximum capability of the specimen. Owing to this there has been some variability in the ranges estimated. General estimates of power density in insects for both direct and indirect muscle have been estimated to have ranges within 80-100 W/kg [74, 56, 132]. In Wakeling and Ellington’s analysis of *Sympetrum Sanguineum*, power output density was estimated to a minimum of 35.4 W/kg for steady hovering, and a maximum of 156.2 W/kg during more extreme flight. The total power output was then calculated to be 2.5 mW for hover and 10.5 mW for maximum effort [118]. Some power calculations have been done for some other larger species of dragonfly. *Aeschna juncea* and *Anax parthenope* were determined to have power outputs of 29.6 mW and 36.0 mW respectively [25, 104].

### 2.1.5 *Sympetrum sanguineum*

Experiments performed by Wakeling and Ellington produced extensive documentation on both physical parameters as well as flight characteristics of *Sympetrum Sanguineum*. The team caught wild specimens which were coerced into flying in laps inside a greenhouse. The flights were captured by orthogonally mounted high speed cameras. This set up would capture only a small area of flight which the dragonflies would pass through. Once the flights were conducted, the specimens were euthanized and dissected for measurement. The videos collected were then post-processed to extrapolate the wing kinematics and eventually the power output.

*Figure 2.5: Sympetrum Sanguineum [24]*

A summary of physical parameters measured by Wakeling and Ellington can be found in Table 2.1. Further observations and calculations can be found in Table 2.2. Most notable
Table 2.1: Average physical parameters of *Sympetrum Sanguineum* from Wakeling and Ellington [116, 118]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Mass</td>
<td>121.9 mg</td>
</tr>
<tr>
<td>Muscle Mass</td>
<td>61.4 mg</td>
</tr>
<tr>
<td>Forewing Length</td>
<td>27.5 mm</td>
</tr>
<tr>
<td>Forewing Area</td>
<td>163.8 mm$^2$</td>
</tr>
<tr>
<td>Hindwing Length</td>
<td>26.6 mm</td>
</tr>
<tr>
<td>Hindwing Area</td>
<td>216.4 mm$^2$</td>
</tr>
</tbody>
</table>

Table 2.2: Performance parameters of *Sympetrum Sanguineum* from Wakeling and Ellington [117][118]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke Plane</td>
<td>50°</td>
</tr>
<tr>
<td>Wingbeat Frequency</td>
<td>39 Hz</td>
</tr>
<tr>
<td>Forewing Max/Min Stroke Amplitude</td>
<td>$+45.3°/-45.2°$</td>
</tr>
<tr>
<td>Forewing Midstroke</td>
<td>$+0.1°$</td>
</tr>
<tr>
<td>Hindwing Max/Min Stroke Amplitude</td>
<td>$+44.9°/-56.7°$</td>
</tr>
<tr>
<td>Hindwing Midstroke</td>
<td>$+5.9°$</td>
</tr>
<tr>
<td>Muscle Power Density Hover</td>
<td>35.4 Wkg$^{-1}$</td>
</tr>
<tr>
<td>Muscle Power Density Max</td>
<td>156.2 Wkg$^{-1}$</td>
</tr>
</tbody>
</table>

from this data is that the muscle mass of *Sympetrum Sanguineum* is approximately half of the total body mass.

2.2 A Different Flight Regime

Much of mankind’s initial inspiration to fly came from large birds, and many attempts reflected that with some form flapping. Eventually man would abandon flapping altogether and build an entire industry around rigid wings based on steady air flow. It’s been over a century since the Wright brothers’ first flight, but in the recent years researchers have become interested in flapping flight again. Only this time inspiration is being drawn from the lowly insect.

Within the realm of insects, there is enormous diversity. Helicopter damselflies flap their wings at an low 5 Hz whereas midges flap with an incredible 1000 Hz [24, 45]. Despite flapping with frequencies of different orders of magnitude, all insects do make use of unsteady flow. The general trend is that the larger the insect, the slower it flaps, and the steadier the flow [128].

To quantify the steadiness of flow around a moving body we use the Reynolds number. The Reynolds number is a nondimensional parameter which characterizes the flow regime. It is defined as the ratio between the inertia of moving the fluid mass and the viscous dissipation
of motion [95]. It is commonly written in the form below

\[ R_e = \frac{\text{kinematic forces}}{\text{viscous forces}} = \frac{\rho V L}{\mu} \]  \hspace{1cm} (2.1)

where \( \rho \) is the density of the fluid, \( V \) is the velocity of the fluid, \( L \) is the characteristic length of the object, and \( \mu \) is the dynamic viscosity of the fluid [128]. A small Reynolds number indicates that viscous forces dominate while a large Reynolds number indicates the dominance of inertial forces. The latter is the regime where conventional aircraft operate [128]. A passenger jet will typically fly in a regime of \( R_e \approx 10^7 \) whereas insects fly in the ballpark of \( R_e \approx 10^{-10^4} \) [128, 95, 115].

Previously there has been some lack of knowledge in the low-Reynolds regime which insects occupy [47]. In recent decades this is no longer the case as analysis of insect flight has progressed in computer simulation, scaled model experimentation, and direct studies of insects.

### 2.2.1 Dragonfly Simulations

The Navier-Stokes equations govern fluid flow and the physics of flight. In the past, to arrive at something solvable simplifications and assumptions have been applied. In recent years this has changed drastically as advancements in computer technology now allow for more complex simulations.

Early flapping simulations used a quasisteady approach. Examples of this work come from Weis-Fogh and Jensen throughout the 1960s and 1970s [123]. Under this approach, it is assumed that the lift generated by the wing can be taken to be the summation of instantaneous measurements using conventional steady flow assumptions. This calculation involves the angle of attack of the wing, its geometry, and relative fluid velocity at each instantaneous time frame where all time-dependent causes are assumed to be negligible and ignored [47, 95]. These assumptions give a simulation that ignores previous events. The results may be sufficient when time-dependent effects are minimized during slow flapping, but the majority of insects do not fit well into this category [42]. It is now considered that time-dependent effects are not negligible and in fact are very important when analysing flapping wings [42, 53]. To reach a somewhat accurate estimation of flapping, detailed flight kinematics must be used in conjunction with the Navier-Stokes equations in a brute force computation to study the unsteady flow in simulation.

A high-order numerical tool to solve the Navier-Stokes equations to solve flow around a two-dimensional wing was developed by Wang [124]. Wang’s work was based on the simplified dragonfly kinematics. Data were based on a single wing of a single dragonfly’s flight. Other assumptions used for the simulation was that the wing flapped along a 50° inclined plane, had a sinusoidal amplitude and angle of attack, and flapped at 40 Hz. The wing was modelled
as a two dimensional cross-section of a flat plate with a 1 cm chord length. While the simulation was not extremely accurate pertaining to the exact wing path, pitching and flapping kinematics, and lack of span-wise effect, the results demonstrated that unique lift mechanisms existed when time dependent effects were accounted for. Furthermore, when the data were extrapolated to the size of a wingspan, the lift generated by four wings was calculated to be enough to lift a dragonfly. The simulation showed the generation of a pair of counter-rotating vortices which caused a large vertical force during the downstroke. Later, Wang and Russell expanded the two-dimensional solver to include both a forewing and a hindwing [125]. Once again, data was taken from a living specimen. The simulation included various phase differences including between 0 - 160°. The solver showed that 40 - 160° phase flight for hovering required minimal power output and that 0° phase flapping, often used for take-off, required much more power. Based on the simulation, the power output of the dragonfly would vary by 40% and the mean lift created would vary by 60%.

Sun and Lan performed a similar three-dimensional simulation of dragonfly flapping [108]. In this case, the simulation included both forewing and hindwing pairs modelled as flat plates. They also made similar kinematic assumptions and had the wings counter-stroking with exactly a 180° phase difference. The resulting data showed that, similar to Wang’s work, a large amount of vertical force was generated due to leading edge vortices present at the downstroke. It also revealed that the later wing-to-wing interactions, that is to say forewing-forewing and hindwing-hindwing interactions decrease lift but are not significant.

J.K. Wang and Sun worked to develop further Sun and Lan’s solver [120]. In this simulation the wings were no longer modelled a flat plates but as wings with varying chord length based on real dragonfly specimens. The hindwing led the forewing with phases of 0°, 60°, 90°, and 180°. The solution for 180° phase difference showed two force peaks each period while the others showed a single large force peak. Similar to the previously mentioned simulation, lateral wing-wing interactions also decreased performance but were not significant.

2.2.2 Scaled Flapping Experiments

Of course simulation does not guarantee what is happening in reality. The results obtained will only be as good as the theory, assumptions, and execution. To be confident in results of the simulation, experimentation must be done. Modern advancements in technology have allowed researchers to run experiments with high-speed cameras, force transducers, and particle image velocimetry (PIV) to directly study the flow around flapping wings.

To study air flow during dragonfly flight it would be ideal to use real living specimens. Unfortunately there are many obstacles that prevent this. Because dragonflies eat on the wing, it is very hard to feed them in captivity. It is also very difficult to get stimulate them to perform the desired task at hand such as flapping with a particular phase difference.
They also suffer from muscle fatigue and physical wear. In some attempts wings of deceased specimens where used but became brittle soon after death \[20\]. Owing to these challenges, researchers opt to use scaled flapping experiments. An artificial apparatus can mimic dragonfly wing kinematics and allow for more control and repeatable experiments. Sensors can be placed anywhere on an artificial wing and therefore are not solely reliant on camera footage. Scaling up from insect size also can be advantageous for ease of implementation, reduced cost, and ease of discerning flow features. To preserve the flow characteristics when scaling up the Reynolds number must be kept the same. When scaling up in size the other terms in Equation \[2.1\] must be modified by changing flapping frequency or the fluid used to balance inertial forces and viscous forces. There have been many scaled experiments using various insect wings. For the purposes of this project, we will focus on experiments based on the dragonfly.

Deubel et al. made an attempt with wings that were manufactured by milling a dragonfly’s venation pattern out of foam \[44\]. The wing was 8-times the size of an actual wing and was designed to accurately mimic the structure of a dragonfly.

Another group, Y. Wang et al., built a model 11-times the size of the dragonfly \textit{Aeshna juncea} made up of carbon fibre divinycell veins supporting a plastic wrap membrane \[122\]. The apparatus featured a six degree-of-freedom force/torque sensor at the wing base. The wing pitched passively with a variable stiffness spring. The flapping frequency was scaled down to 1 Hz. Lift coefficients were calculated from the collected data and seemed to match the three-dimensional Navier-Stokes solver by Sun and Lan \[108\].

Maybury and Lehmann built an experiment to examine forewing-hindwing interactions \[81\]. Wings of the species \textit{Polycanthagyna melanictera} where scaled up to 19 cm long and were driven at a reduced frequency of 0.67 Hz. The model operated in a bath of mineral oil and the flow recorded with a particle image velocimetry (PIV) system. Another experiment to test forewing-hindwing interaction was done by Deng \[69\]. Their wings were scaled to a similar size; 19.0 cm for the foredwing, and 18.5 cm for the hindwing. Their wings were also placed in mineral oil to recreate the appropriate \(R_e\) regime. Both groups reported superior lift generation with the hindwing leading the forewing.

2.2.3 Flight Mechanisms

As mentioned earlier, conventional aerodynamic theory for manned aircraft is based on rigid wings travelling through steady flow. This assumes time independence in modelling and is sometimes referred to as a translational lift mechanism. Insect wings do not flap in the steady flow regime and also behave quite differently than traditional airfoils. First, over the duration of a wing’s halfstroke, the mean angle of attack is greater than the stall angle. Second, pitch causes the angle of attack to change from positive to negative. Finally, owing
to the oscillating nature of flapping, insect wings accelerate and decelerate during stroke reversal [123]. Over the course of a stroke period there are two categories of lift generation. Translational mechanisms mainly occur in the middle of the upstroke and downstroke, whereas rotational mechanisms mainly occur at the top and bottom of stroke during stroke reversal.

An early explanation for insect lift generation is a translational lift mechanism called delayed stall. During the translational portion of the stroke, the large angle of attack creates a leading-edge vortex to form on the wing which increases circulation [115]. If the wing were to continue in that manner, the vortex would eventually detach from the wing and the lift generated would suddenly drop causing what is known as stall [95]. Insect wings actually transition into the next phase of the stroke through supination or pronation and avoid the stall. In the spanwise direction the leading edge vortex convects the vorticity towards the wingtip allowing the wing to have such a high angle of attack which would not be possible under steady conditions [54]. Dickinson was able to show that lift generation had a peak timed with delayed stall. Although this verified the presence of stall, simulation and experiment indicated that translational lift mechanisms did not fully account for insects’ ability to fly [45].

In his work on delayed stall, Dickinson hypothesized that there were other rotational lift mechanisms at work. He observed peaks in force generated during pronation and supination during stroke reversal which could not have been explained by translational lift mechanisms. They were called rotational circulation and wake capture. From his scaled up experiment, Dickinson estimated that these effects accounted for 35% of lift production.

At both ends of the wing’s stroke reversal occurs causing rotational circulation. The reversal behaves similar to the Magnus effect causing flow on one side to decrease and thus producing additional lift. The timing of the pitching during stroke reversal is very important.
Pitching early behaves much like backspin whereas later pitching essentially causes topspin [45]. Mistiming of pitching could actually harm rather than help overall lift generation. Dickinson also notes that if an insect could control the timing of pitching in individual wings, yaw and roll could be initiated.

Another peak in force distinct from rotational circulation is generated after stroke reversal known as wake capture. The wing passes through a large velocity field which was created by the previous halfstroke [45, 95]. Essentially the wing reaps the benefits of the wake that it previously generated only half a period ago [98, 115]. Wake capture causes a force peak which is completely independent of the phase relationship between the stroke angle and the pitch angle. Early flipping gives a positive lift whereas late flipping gives negative lift [45]. Well timed pitch flipping can allow an insect to maximize lift and recover previously spent energy.

Another method of lift generation is the previously mentioned “clap-and-fling” used by damselflies. This method works by having a pair of wings come together dorsally, referred to as the clap, and then fling apart beginning the downstroke [95, 98]. As the wings fling apart, the leading edge separates before the trailing edge causing a air to rush in and fill the void resulting in vorticity [115]. This lift mechanism was first identified by Weis-Fogh and has been shown to be applicable to large animals as well [128]. The clap-and-fling is an advanced form of flapping which dragonflies do not use as due to their restricted stroke amplitude relative to damselflies. Damselflies are able to flap at a significantly lower frequency when compared to dragonflies possessing similar physical parameters because of this ability [45].

Dragonflies make use of most of the above flight mechanism with the exception of the clap-and-fling. In the case of parallel phased flapping, the vortices from the dragonfly’s forewing and hindwing fuse together giving significant lift at a high energy cost [18]. Tandem wings also allow for out of phase flapping which improves efficiency with some phase shifts [114].
2.3 MAVs

Unmanned Aerial vehicles (UAVs), although often associated with modern drone strikes and more recently quadrotors, actually have a long history alongside manned flight. In fact, 54 years before the Wright Flyer took flight, Austria sent an unmanned bomb-laden balloon to attack Venice [2]. UAVs continued to develop as modern aircraft developed over the last century. Traditionally, UAVs were repurposed full-sized aircraft that were converted into radio controlled vehicles. This has changed drastically and the UAV trend is a decrease in size and weight. This has given rise to a new subset within UAVs known as microaerial vehicles (MAVs). MAVs take the form of any small flying aircraft; small fixed-wing planes, helicopters, quadrotors, and flapping-wing devices. Many MAVs are simply scaled down versions of UAVs that make use of traditional steady lift mechanisms. Scaling aircraft down causes the vehicles to fly in low Reynolds number regimes. To continue decreasing size of MAVs a subset of flapping-winged MAVs is attempting to make use of the unsteady lift mechanisms used by insects.

2.3.1 Motivation

Through recreating insect flight, we look to the future yet peer into the past and find greater understanding of earth’s oldest known fliers. The majority of man’s flight exploits simple aerodynamic mechanisms and left much to be discovered about the aerodynamic mechanisms used by insects. It has been known for some time that the Reynolds number is directly proportional to the characteristic dimensions of an object [130]. As flying vehicles or flying creatures decrease in size, flapping becomes more effective than conventional fixed-wing design [37]. Development of insect-sized flying robots is not just an academic exercise, it is a natural path for the field of MAVs to take. This technology will not only compete with other technologies, but will likely open up a whole set of niche applications that could not be filled before. Furthermore, in pursuing artificial insect flight, we can indirectly push the boundary on our understanding of aerodynamics and evolution.

2.3.2 Application

The possible applications for affordable and disposable flapping-winged MAVs are numerous. Previously suggested applications include surveillance, search and rescue, and exploration [89, 115, 139, 145, 37].

The application towards surveillance is probably the most obvious. In fact, flapping-wing MAVs have debuted in art before many of the projects that will be discussed even existed. One example of this is in the 2001 Dan Brown novel, Deception Point, where an insect-sized flying robot is used to spy on a secret operation [33]. Eventually, the MAV is
flown into an unwitting victim’s eye causing him to fall into a body of water and drown. Of course, this is an extreme case in a work of fiction and this author does not propose MAVs be used to assassinate. Nevertheless, the novel highlights that flapping-winged MAVs could be used disposably by the military and make for a very discreet method of surveillance.

One application that the public might enjoy is search and rescue. In the aftermath of a natural disaster such as an earthquake or tsunami, wheeled robots are presented with physical obstacles which flying robots can avoid. In some cases, large, solitary, and expensive UAVs have been used. In its place, a swarm of cheap and disposable MAVs could cover more area in an emergency when time is precious. A large swarm would also be able to continue the mission even if a large number were damaged or destroyed.

Another possible application is exploration both terrestrial and extraterrestrial. On earth, small flapping-winged MAVs could be used for exploration within constrained environments such as caves. As mentioned previously in Section 2.1.1, ancient relatives of the dragonfly lived successfully at very large sizes owing to the drastically different atmosphere. On another planet with an atmosphere with a different density and viscosity it may be difficult to explore with conventional aircraft as the atmosphere properties may not permit flying in the steady Reynolds number regime. Flapping-wing MAVs could succeed here and may not need to be as small as they are on earth if the atmospheric conditions were favourable.

2.3.3 Other MAV Projects

Over the past 15 years there has been a stream of research groups working on MAVs. This section will only summarize a select few thought to be distinguished and relevant.

Within the subset of flapping-winged MAVs there is already quite a bit of diversity. Some, like the DelFly from Delft University of Technology generate lift and thrust through flapping but do not focus on insect mimicry in their goals and design of the project [79]. Other groups at Carnegie Mellon University, the University of Delaware, and Chiba Institute of Technology work to recreate insect flapping kinematics with relaxed physical parameters [3, 146]. A rare number of groups projects such as the Micromechanical Fying Insect and Robobee project attempt to recreate all of the flight kinematics and physical parameters of insects [1, 6]. Because of this diversity Szabo found it useful to characterize three categories of flapping-winged MAVS, they are: superficial biomimicry, kinematic biomimicry, and true biomimicry [109]. Superficial biomimicry generally aims to use flapping as a source of lift and propulsion. The wing kinematics, aerodynamics, and physical paramters do not attempt to resemble biological examples. Kinematic biomimicry attempts to reproduce specific wing kinematics that are found in nature; however, the physical parameters are not strictly constrained to real insect. Finally, true biomimicry aims to achieve both physical specifications and flight kinematics of a real insect. Of course not all MAV projects fit neatly into these
categories; however, it is a useful classification to have in mind when examining the literature on the subject. Let us examine some of the most prominent and influential MAV projects from around the world.

**MFI, University of California, Berkeley**

An early project that can be credited with creating the flapping-wing MAV field is the Micromechanical Flying Insect (MFI) project at the Biomimetic Millisystems Lab at the University of California, Berkeley [1]. The team was lead by Ronald Fearing in 1998 with collaboration from Michael Dickinson and Robert Dudley. The two biologists researched insect flight for decades and were naturally suited to contributing to the MFI project.

As there had been no previous attempt to do something similar, there was no reference point for their proposed goals and the team aimed to attain what can be considered true biomimicry. This may have led to overambitious goals for the time. The common blowfly, *Calliphora*, was to be the model of the project. The goal of the MFI project was to develop a two-wing flapping MAV with a mass of less than 100 mg, a wingspan of 25 mm, a flapping frequency of 150 Hz, wingstroke amplitude of 140°, wing pitching of ± 45°, and deliver 8 mW of mechanical power to the wings [144]. The team also planned to include active wing pitch control as well as allow for independent control of each wing. The design contained the primary components of a thorax, actuators, wings, and even sensors. Piezoelectric actuators in conjunction with the thorax’s flexible structure generated flapping. The physical parameters of the Micromehcanical Flying Insect are shown in Table 2.3.

![Table 2.3: Physical parameters of the MFI platform](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>100 mg</td>
</tr>
<tr>
<td>Wingspan</td>
<td>25 mm</td>
</tr>
<tr>
<td>Actuator</td>
<td>Piezo (multiple)</td>
</tr>
<tr>
<td>Battery Life</td>
<td>N/A</td>
</tr>
<tr>
<td>Lift-off</td>
<td>No</td>
</tr>
</tbody>
</table>

During flight, real insects make use of mechanical resonance through a complex system of muscles and joints contained within the portion of the exoskeleton that is the thorax [56]. The MFI recreated the exoskeleton with a frame constructed of carbon fibre trusses. Within the frame there were multiple four-bar linkages and spherical joints powered by several piezoelectric actuators to flap the wings [99, 144]. The four-bar linkages would amplify the actuator deflection into the large wing deflection desired. Each wing had two actuators allowing for both wing stroke and wing pitch control. The system could also be tuned to resonate at different operating frequencies. At such a small size, conventional joints could not be used. Instead compliant joints were made of 12.5 μm thick polyester that would bend...
creating rotational stiff hinges [35, 99]. For the wing amplitude to reach 140°, the actuator interface of the four-bar linkages would need to be displaced by ±0.25 mm [144].

![Rendition of MFI](image1)

(a) Rendition of MFI [9]

![Artificial ocelli](image2)

(b) Artificial ocelli [143]

![Artificial haltere](image3)

(c) Artificial haltere [142]

Figure 2.8: MFI platform and custom developed sensors

Various piezoelectric actuators were experimented with. In one instance, an elastic extension was added to the actuator with the goal of reducing mass and augmenting actuator tip displacement in exchange for less blocked force. Another build included a secondary piezoelectric layer which would not actuate but to give sensory feedback and measure the state of the actuator [35]. After a number of iterations, the final actuator design was composed of one layer of PZN-PT piezoceramic to actuate and one layer of steel provide elasticity [99, 144]. The actuators had dimensions of 5 mm × 1 mm × 0.2 mm and weighed 15 mg. The PZN-PT piezoceramic layer was 150 µm thick and the steel layer was 50 µm thick. The actuators were expected to generate 7 mW of power when driven with an excitation voltage of 200 V [56].

The four-bar linkage was tested with the actuators and wings on a fixed test-bed. A single wing driven at 150 Hz with a stroke amplitude of ±70°, resulting in a mean lift of 506 µN. Unfortunately this would not be enough to lift the entire platform. It was also noted that the natural frequency was much lower than expected. To measure the force generated, tiny 1 mm strain gauges were added to the wing spars [144]. Later modifications led to an attempt to increase flapping to an extreme 275 Hz. This required much stiffer actuators weighing 100 mg each. After increasing the actuator stiffness and drive frequency, the mean lift increased to 1400 µN per wing [105]. This clearly demonstrated lift could be augmented with frequency but the cost of heavier actuators was too great and lift-off was not achieved.

Parallel to experiments, the MFI project also worked on dynamic simulations as well as sensor development. It was hoped that the project would one day lead to autonomous flight, so naturally some sensing ability would be required. Maintaining the biomimetic theme, several biologically inspired sensors were developed to one day aid in stabilization and navigation. These sensors needed to fit within very tight mass, size and power constraints to truly mimic their biological counterparts [143].

The first sensor developed was based on the ocelli which are light sensitive photosensors
that appear on the heads of some flying insects. In many insects, multiple ocelli are found on
the upper surface of the insect which detect light from the sky. Ocelli are used for horizontal
stabilization. In some species, it is thought that ocelli help follow areas of high light intensity
like the sun for migratory purposes. To recreate this, a multifaceted sensor containing four
photodiodes facing outwards was developed. This allowed the MAV to detect when the
vehicle was not in the upright position if there was a discrepancy in light intensity measured
between each photodiode. The artificial ocelli was quite small with dimensions 5 mm × 5 mm
× 5 mm and a mass of 150 mg [143]. Although this sensor was able to perform its intended
purpose, it was still too heavy to be used on a prototype. The artificial ocelli developed by
the Biomimetic Millisystems Lab can be seen in Figure 2.8b. The second sensor developed
for the MFI project was based on halteres. As mentioned previously, halteres are sensory
organs that are commonly found on two-winged insects and are believed to be evolved from
what were originally a pair of hindwings. Halteres are now tiny knob-like protrusions on
each side of the thorax which act as gyroscopes by measuring the insects body rotations.
The halteres oscillate 180° out of phase with the wings and are aligned such that they are
not coplanar and can sense rotation in three dimensions [143]. These artificial halteres had a
mass of 10 mg each and a length of 5.5 mm. The Coriolis effect influences the halteres when
the insect changes direction. Small strain gauges at the base of the artificial halteres allow
a signal to detect the MAV’s body rotations [143]. A diagram showing the artificial halteres
can be found in Figure 2.8c. Last, the eyes of the housefly can detect changes in contrast
even though their vision is quite poor. To mimic this, the group experimented with optic
flow arrays which was comprised of a low resolution camera. As a form of vision, the sensor
would send some feedback for significant changes in the environment [143].

The MFI project was the first to attempt to mimic insect flight to scale. Although it
did not achieve lift-off it is still extremely influential on current flapping-winged MAVs. Not
only was the foundation laid for the field, but many leading researchers at various university
began their work on the MFI project.

The DelFly Project, Delft University of Technology

One of the most notable flapping-winged MAV projects is the DelFly Project [79]. Leading
the project is Guido de Croon. The project aims to develop a lightweight flapping-wing
platform that is able to carry sensors on-board which travels at high speeds and is also
capable of hovering [40]. The project has undergone three iterations which were able to fly
and decrease in size each time. The project operates on a top-down approach, starting by
building a relatively large ornithopter with complete functionality and then generally scaling
down after study in the next iteration. The specifications of the three iterations of the DelFly
platform are shown in Figure 2.9 and Table 2.4.

The DelFly project can be considered to be superficial biomimicry. The project strives
to be a flapping-winged MAV but does not focus on imitating any particular creature found in nature in either kinematics or physical specifications. The resulting MAV has a unique design with stacked flapping biplanes. Two pairs of wing are stacked with all the wings’ leading edges being coplanar. The wings pairs are flapped with 180° phase shift resulting in a clap-and-fling occurring on the sides of the vehicle rather than above in the dorsal plane. The DelFly I has a V-tail whereas all other iterations have a rudder and elevator for a tail taken from conventional aircraft designs. All wings are driven by a single DC motor through a coupled motor-crank mechanism. Control is achieved by a conventional tail which is actuated through electromagnetics.

The DelFly approach has been quite successful. The DelFly’s relatively large size has allowed all iterations to have on-board lithium polymer battery, radio control receiver, as well as camera and transmitter. Iterations of the DelFly II and the DelFly Micro progressively decreased in mass and size. The DelFly Micro impressively was named the ”Smallest camera equipped aircraft in the world” by Guinness Book of Records in 2009. The most recent iteration, the DelFly Explorer, appears to be a modified version of the DelFly II with the addition of stereo vision camera as well as other sensors to aid in autonomous flight. These additions have allowed the DelFly Explorer to demonstrate path-following and obstacle avoidance.

The DelFly MAVs are well developed platforms which can fly, hover, carry sensors on board, and even contain sensors for autonomous control. The project, however, favours scaled down conventional control techniques versus a biomimetic approach. The sensors, when
implemented, are off-the-shelf components and do not resemble characteristics of biological insects.

Cornell MAVs, Cornell University

Another MAV project that could be considered superficial biomimicry comes from the Computational Synthesis Laboratory at Cornell University under Hod Lipson. The project achieved quick success producing two flapping-winged MAVs capable of flight in the last few years.

The goal of this project was to develop an MAV platform that would be capable of stable, hovering flight while using flapping wings at a small scale. The design produced had opposing wings flap with coplanar leading edges in normal hovering. Because all known hovering flight through flapping insects is unstable, pitching was retarded by damping of the body of the aircraft in order to add stability [89]. The two MAV platforms developed at Cornell are compared in Figure 2.10 and Table 2.5.

![Figure 2.10: Various MAV platforms developed at Cornell University][2]

![Figure 2.10: Various MAV platforms developed at Cornell University][3]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Large</th>
<th>3D Printed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>24.2</td>
<td>3.9 g</td>
</tr>
<tr>
<td>Wingspan</td>
<td>45 cm</td>
<td>14.3 cm</td>
</tr>
<tr>
<td>Actuator</td>
<td>Motor</td>
<td>Motor</td>
</tr>
<tr>
<td>Battery Life</td>
<td>33 s</td>
<td>85 s</td>
</tr>
<tr>
<td>Lift-Off</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The first platform was developed in 2008. This unusual design was the larger of the two and made use of four pairs of wings. All eight wings flapped in the same plane at a frequency of 20 Hz. The flapping was actuated by four 1.2 g DC motors, each driving a single
wing pair. The MAV was powered by two 3.7 V lithium polymer batteries that were rated at 90 mAh each weighing 3.1 g each. The wings were made up of a carbon fibre frame and a polyester membrane. The total mass of the platform was 24.2 g with a 45 cm wingspan. To impede body torques from pitching the vehicle, sails extended both above and below the flapping plane. The sails would passively delay pitching allowing for flights of up to 33 s \[115\]. No active control surfaces were included to reorient the vehicle.

The second platform was developed in 2010. The vehicle made use of 3D printing technology and was significantly smaller with a mass of 3.9 g and a wingspan of 14.3 cm. This time the design included just four wings, or two pairs, flapping in the same plane. All four wings were actuated with a single DC motor. Rather than assembling components, the bulk of the prototype was fabricated with 3D printing, which allowed for consistently fabricated, unique, and complex designs. While the project did not intentionally attempt to recreate a particular biological specimen’s flight, the wings were observed to twist and camber throughout the stroke in a similar fashion to insects. This was viewed as a shortcoming by the team and the wings were reinforced so they would behave more rigidly \[89\]. Passive stability was again achieved with sails above and below the flapping plane and no active stabilization was implemented. The final system had on-board batteries and could maintain flight for 85 s.

Both platforms were able to successfully perform unstable hovering flight. The project also demonstrated the value of 3D printing technology in scaling down as well as manufacturing reliability. It is possible that one day 3D printing will allow for very accurate recreation of insect wings as well as internal structural components. While the platforms are only superficially biologically inspired, they can provide insight in the goal towards insect sized flapping-winged MAVs.

**CMU MAV, Carnegie Mellon University**

The CMU MAV project is led by Metin Sitti at the NanoRobotics Lab at Carnegie Mellon University \[3\]. Originally this group aimed to develop an MAV platform that was truly biomimetic using small piezoelectric actuation. After many years of development, the group chose to relax those constraints and to aim for kinematic biomimicry allowing for larger actuators.

One of the main design goals of the project was include a method for future control of an insect-inspired MAV. Unlike the DelFly, to attain this, the platform would need to stabilize itself actively like real insects do. The design used passive wing pitch behaviour as well as resonant behaviour of the entire system \[66\]. The platforms were powered by an off-board source. Both platforms are compared in Figure 2.11 and Table 2.6.

The first CMU MAV platform was tested in 2010 and used piezoelectric actuation. Similar to the MFI project, bending beam piezoelectric actuators drove a four bar mechanism.
to displace the wings. Each wing was driven with its own piezoelectric actuator allowing them to be driven independently allowing for roll and pitch control. The vehicle had a mass of 705 mg, a wingspan of over 6 cm, and a flapping frequency of 55 Hz [64]. The piezoelectric actuators had a mass of 130 mg each and were largely based on piezoelectric actuators used for the RoboBee project at Harvard University. The actuators were powered externally and required custom power circuitry to operate at the required voltage. During experimentation, the mean lift generated was 1.4 mN, much less than what was required [67]. A much smaller iteration was planned to have half the wingspan and a mass of only 160 mg. Unfortunately, this was abandoned owing to fabrication challenges.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Piezo-Based</th>
<th>Motor-Based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>0.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Wingspan</td>
<td>&gt; 6</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Actuator</td>
<td>Piezo (dual)</td>
<td>Motor</td>
</tr>
<tr>
<td>Battery Life</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lift-off</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2.6: Comparison of MAV platforms developed at Carnegie Mellon University

The project was revamped making use of DC motors as actuators. DC motors were commercially available, but not nearly as small or light as piezoelectric actuators. Each wing was driven by a 1.2 g DC motor. Instead of utilizing cranks or gears like most other DC motor actuated projects, the motors were driven by a sinusoidal singal of up to ±5.5 V. The rotors were attached directly to the wing base which was outfitted with a spring system allowing the system to resonate [65]. Owing to the increased mass of the new actuators, the new MAV grew to a wingspan over 20 cm with a mass of 2.7 g. The platform flapped at a frequency of 1 Hz and was powered with an off-board power supply. The motor based MAV was able to attain lift-off and was measured to have a 1.4 lift-to-weight ratio [66].

The dynamics of both MAVs were simulated using a Lagrangian approach. The models assumed quasisteady approximations of the aerodynamic forces based on wing kinematics.
The simulation was reported to be a close prediction of the experimental results from the motor-based platform.

After being unable to achieve liftoff with a realistically biomimetic design, the CMU MAV project demonstrated that more could be achieved by relaxing the design constraints. This allowed the use of more conventional actuators, finally achieving liftoff but no longer being insect size.

**Dragonfly/Cicada MAVs, University of Delaware/Purdue University**

One project that has also focused specifically on a dragonfly inspired MAV is led by Xinyan Deng at the University of Delaware. As mentioned earlier, this group initially worked on scaled flapping experiments on dragonfly wings. The group developed three MAV platforms which are compared in Table 2.7.

The first platform was inspired by the dragonfly. A 7 g DC motor drove each pair of wings through a slider-crank mechanism. A model of the entire robot and the slider-crank mechanism is shown in Figure 2.12. The entire MAV was oversized relative to actual dragonflies. The wingspan was over 32 cm with a mass greater than 20 g. The vehicle would
flap at just 2 Hz. The platform did not include any on-board sensors or microcontroller. The prototype was powered from an off-board source and was shown to generate 93.7 mN which was insufficient for lift-off [48]. Although very far from imitating the specifications of an actual dragonfly, this platform may have fit true biomimicry with some of the dragonflies’ giant ancestors discussed earlier in Section 2.1.1.

Deng would later move to Purdue University to continue working on flapping-wing MAVs. A new platform was developed to resemble a cicada. A single DC motor actuated the wings through a similar slider-crank mechanism used on the dragonfly platform. The artificial cicada had a mass of 2.9 g with a wingspan of more than 10 cm. The cicada platform was unable to achieve lift-off as well [70].

![Cicada](image1) ![Electromagnetic platform](image2)

*Figure 2.13: Various MAVs developed at Purdue University*[70, 92]

Finally, a third platform was developed a two-winged robot utilizing custom built electromagnetic actuators to flap each wing [92]. A magnet was centered within a custom built coil which would accept a oscillating current causing the internal magnet to rotate the wings directly. The coil was constructed with a wedge shaped cross section to allow greater range of motion. Extra permanent magnets were placed outside the coil which acted as virtual springs which would allow the system to resonate. The actuators structure was fabricated with a rapid prototyper (Objet Eden350V, Stratasys Ltd.) with the exception of the traditional fasteners. Each actuator was 2.6 g each and required 5.76 W of power. Driving frequency varied from 10 - 160 Hz. Many different wings morphologies were tested however there was no particular biomimetic profile. This platform was the first under Deng to achieve lift-off. This while successful, is too large and massive to be considered a biomimetic flapping-winged MAV.

**RoboBee, Harvard University**

The most successful biomimetic flapping-winged MAV to date, without a doubt, is the RoboBee project led by Robert Wood at the Harvard Microrobotics Lab at Harvard Univer-
The project was previously called the MicroFly grown out of the MFI project at UC Berkeley. This group made a landmark achievement in 2007 as they demonstrated the first lift-off of a partial biomimetic MAV. This early platform was the Harvard Microrobotic Fly (HMF) was modelled after Diptera. Later in 2012, the project evolved into the RoboBee modelled after the honeybee. The HMF made use of a single piezoelectric actuator whereas the RoboBee had separate piezoelectric actuators for each wing. The project has been extremely influential in the field of flapping-winged MAVs in many aspects including design, fabrication methods, sensors, and control.

Both Diptera insects and honeybees move their wings with direct flight muscles attached to their exoskeletons. The muscles push and pull a system of joints that behaves like a four-bar link mechanism. Both the HMF and the RoboBee made use of four-bar mechanisms constructed out of carbon fibre segments and flexible joints made out of polymide. The piezoelectric actuators work as bending-beams whose tips have linear displacement for small displacements. The four-bar linkage amplifies the linear output of the actuators and converts it into angular motion to flap the wings. Both the joints and the actuator add stiffness to the system causing the system to resonate and increase stroke amplitude at particular frequencies.

For each platform the wing profile matched the insect that was being mimicked. The wings were originally constructed with polyester attached to simplified carbon spars; however, later iterations of the project utilized 3D printing which allowed for more complex venation imitation. Each wing was only 15 mm long with a mass of just 400 µg. Passive pitching was allowed by polymide hinge similar to those in the four-bar mechanism. Different hinge stiffness would allow different maximum pitching angles as desired. Although the pitching was not actively controlled, the wing kinematics were observed to strongly resemble that of real insects during hovering. A comparison between the two platforms can be found in Figure 2.14 and Table 2.8.

The HMF platform, while being the first biomimetic MAV to achieve lift-off, was still...
an incomplete MAV. Incomplete in that it had a frame, wings and actuator, but no sensors microcontroller or on-board power supply. The design was inspired by the *Dipteran* fly and had a mass of 60 mg, a total wingspan of 30 mm, and flapped at 250 Hz \[133, 132, 138\]. The platform was mostly carbon fibre with polymide film joints with a single custom built piezoelectric actuator. The actuator was fabricated with PZT-5H piezoceramic and had a mass of 40 mg. The tip of the actuator, displaced as from bending-beam, had a deflection of \( \pm 400 \mu \text{m} \) \[139\]. The actuator applied bidirectional force to the four-bar transmission and took the place of two of the pulling muscles inside an insect’s thorax. Carbon fibre spars and 1.5 \( \mu \text{m} \) polyester were used to replicate simplified versions of *Dipteran* wings \[132\]. The design of the four-bar transmission mechanisms resulted in a fixed stroke plane \[76\]. Recognizing that resonance was a vital component in the flight of real insects, the group also used an energy-based model to give an approximated resonant frequency of the system \[133\]. The system was designed to resonate at 250 Hz, the flapping frequency of real *Dipteran* flies; however, the observed resonant frequency of the HMF platform was closer to 110 Hz \[139\]. Despite this, the HMF was still able to flap with the desired stroke amplitude and even lift-off. Experiments showed that the lift generated was 1.14 mN, nearly double what was required \[133\]. High-speed cameras showed that the wing trajectory was almost identical to real living insects. The platform did not have any method of stabilization and was restricted by guide wires to ensure the MAV would only move in one dimension. Many years after achieving its first lift-off, two small piezoelectric actuators were added to the frame in an attempt to asymmetrically alter wing kinematics. The addition allowed for adjustments in the mean stroke amplitude to differ between one side and the other give a roll torque \[58\]. Unfortunately, this modification added to much mass and was unable to aid in-flight stabilization.

The second platform developed was the RoboBee. Although the RoboBee was modelled after its namesake, the common honeybee, it still shared many similar design requirements with its predecessor the HMF. The main exception to this was the reduced flapping frequency. The project was largely funded by the National Science Foundation with intent to potentially use a swarm of artificial honeybees to perform the task of crop pollination in light of decreasing honeybee populations \[19\]. The final design had a wingspan of 30 mm, a mass

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HMF</th>
<th>RoboBee</th>
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</thead>
<tbody>
<tr>
<td>Mass</td>
<td>60 mg</td>
<td>80 mg</td>
</tr>
<tr>
<td>Wingspan</td>
<td>30 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Actuator</td>
<td>Piezo (single)</td>
<td>Piezo (dual)</td>
</tr>
<tr>
<td>Battery Life</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lift-off</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Table 2.8: Comparison of MAV platforms developed at Harvard University [6]*
of 80 mg, and a flapping frequency of 120 Hz \cite{76}. Another major difference in the design was the use of two piezoelectric actuators which could independently drive the wings. This meant that each wing was able to have completely independent stroke amplitudes and mean stroke amplitudes from the other, thus giving the platform the ability to create pitch and roll torques. Similarly, four-bar mechanisms were used maintaining the fixed stroke plane \cite{76}. The platform comprised of a frame, two wings, and two actuators achieved lift-off with a measured maximum lift of 1.3 mN. To power the MAV, 19 mW was provided through a tether. The prototypes were fabricated with a careful laser-cutting process that surpasses the fabrication abilities of many other research groups. Despite this advanced fabrication, imperfections in construction manifested in the prototypes’ performances. Any misalignment or asymmetry in the flapping mechanism caused the platform to deviate from a vertical trajectory \cite{84}. To maintain free flight, the prototypes were flown in an environment including a network of eight high-speed cameras would provide feedback to an off-board controller which then fed drive signals to the back to the prototype. The RoboBee was able to hover at a stable altitude and attitude for over 20 s \cite{76}. The Robobee proved to be an at-scale platform capable of controlled stabilized flight.

Owing to the stringent size restrictions, conventional fabrication and construction was not used. Furthermore, these same size restrictions were also too large for the application of MEMS methods as well. The MicroFly and RoboBee as well as many other biologically inspired MAVs are at a scale without strongly established fabrication methods. The group developed a method where materials which layered materials, cut to size with a laser, added epoxy, applied compression, cured in an oven, and assembled the components \cite{134}. This approach allowed for complex structures which included rigid carbon fibre components and flexible joints to be fabricated relatively consistently. Also, a “pop-up” assembly technique was shown to diminish prototype variability. Flexible joint layers with adhesive would be sandwiched between carbon fibre to create a monolithic structure. Similar to the fabrication of printed circuit boards, a laser would cut the prescribed patterns. The cuts were designed to allow the assembly to “pop-up” into a three dimensional configuration which could easily be fixed with adhesives or soldering \cite{103}.

![Figure 2.15: Harvard Microrobotics lab's "pop-up" assembly from monolithic laminate](image)

*Figure 2.15: Harvard Microrobotics lab’s "pop-up" assembly from monolithic laminate* \cite{103}
The Harvard research group has made leaps in being able to apply piezoelectric actuation to MAVs. Starting with the modelling done by Smits [101], the team further experimented in areas of material selection, composite fabrication methods, and drive configurations specifically for micro-robotics [135]. Particular attention was given to the push/pull performance of the actuators at resonance in an attempt to truly mimic insect flight muscle behaviour [76]. For the RoboBee to become autonomous in the future it will eventually require an on-board power source. Piezoelectric actuators happen to have low power requirements but require high voltage to function. The Harvard research team noted that the power supply that would be low mass with the largest energy density would most likely be lithium polymer batteries. Unfortunately, these batteries generally output quite low voltages of around 3.7 V, not nearly enough for piezoelectric actuators. To solve this problem, Karpelson developed ultralight, high voltage power circuits to amplify the voltage. The circuit had a mass of 20 mg and could boost 5 V signal up to 200 V with the same 70 mW power output [72].

The Harvard research group also attempted to simulate the dynamics of the wings using quasi-static blade-element model. The equations of motion were derived for rotational dynamics of the wings which then gave estimates for aerodynamic force and moment. Unsteady effects such as wake capture were not included as the quasisteady nature only included instantaneous forces [131]. The team was also unsure if there was significant muscle involvement of wing flip and whether or not they were merely used for pitch adjustments or were used to actively control pitch continuously [131, 139]. Despite this lack of certainty, it was agreed that passive rotation of the wings would be effective and easy to implement on a robotic insect. This was the first use of simple wing hinge to passively allow pitching due to aerodynamic damping [131]. In the more basic platforms, these wing hinges were constructed in the same manner as the transmission joints, thin films of polymide acting as rotational springs sandwiched between rigid carbon fibre pieces. To estimate stiffness of the hinges, they were modelled as wide, thin, and short cantilevers [134]. If the hinges were too stiff, the wings would under rotate resulting in minimal pitching. If the hinge was too flexible, the wings could over-rotate and tend to flutter during flapping. Recently, the group developed a method to actively control wing pitch during flight. A small piezoelectric actuator along with a differential mechanism which could shift the resting orientation of each wing hinge thereby biasing the wing pitch [112].

With two partial flying biomimetic platforms the Harvard group also began work on biomimetic sensors to allow for on-board feedback. As the HMF was modelled after the Dipteron fly, an optical flow sensor was developed to match the visual capabilities of flies. The sensor had a very low resolution 4 x 32 pixel array which allowed for changes in contrast and therefore movement to be measured [51].

Like the team at UC Berkeley, the Harvard team also attempted to create artificial ocelli
Figure 2.16: Schematic of differential mechanism allowing active control of the mean wing hinge position of the Harvard RoboBee [112]

to measure light intensity of the sky to maintain the vehicles orientation. They demonstrated that simple estimate of angular velocity was all that was required to maintain a stable upright orientation. The sensor had dimensions of 4.0 mm × 4.0 mm × 3.3 mm and had a mass of 25 mg [59]. Off-board power and computational processing controlled signals sent to the MAV whose sole source of feedback information was the ocelli sensor.

A third sensor was used to stabilize the attitude of the RoboBee. For this purpose a the team was able to use an off-the-shelf inertial measurement unit (IMU). The IMU (MPU9150 from Invensense) has a mass of just 40 mg. The sensor includes a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer. It is one of the first MEMS sensors that is light enough to be carried on-board an MAV. With this added sensor, off-board computational processing, and tethered power, the RoboBee could stabilize attitude for 2 to 5 s when hovering in an environment with a camera a system which provided positional feedback [59].

The Harvard Microrobitics Lab has made monumental strides in the field of biomimetic MAVs. However, there are still many challenges to autonomous flight. Sensors, batteries, and microcontrollers still remain too massive to be carried on-board. Although the team has some of the most sophisticated fabrication techniques, minor imperfections must be compensated by control methods.

Bio-inspired MAV project, Shanghai Jiao Tong University

A final project of interest is led by Weiping Zhang at Shanghai Jiao Tong University [15]. Under Zhang, there have been number of recent biologically inspired flapping-winged vehicles. These include one based on electromagnetic actuation and one based on piezoelectric actuation. The two platforms are compared in Table 2.9
Table 2.9: Comparison of MAV platforms developed at Shanghai Jiao Tong University [148, 149]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EM-based</th>
<th>Piezo-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>80</td>
<td>84</td>
</tr>
<tr>
<td>Wingspan</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Actuator</td>
<td>Electromagnetic</td>
<td>Piezoelectric</td>
</tr>
<tr>
<td>Battery Life</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lift-off</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The first platform, appearing in 2016, makes use of electromagnetic actuation and is loosely based on *Eristalis tenax* also known as the hoverfly or dronefly. The platform was able to lift-off, had a mass of 80 mg and a wingspan of 3.5 cm. During experiments the platform had a flapping frequency of 80 Hz, a wingstroke amplitude of approximately ±7°, and a pitching amplitude of approximately ±60°. The actuator consists of a coil that was fixed to the airframe and magnet placed at the edge of the coil and oriented such that the magnetic field generated inside the coil would be parallel to axis of the permanent magnets poles. When the an oscillating signal is passed through the coil, the magnet moves in a linear fashion [148]. A four-bar link mechanism was used to convert this linear motion into rotational motion to the wings. The robot also employed passive rotation through wing hinges. Both the four-bar link mechanism and wing hinges behave similarly to those developed by the Harvard Microrobotics Lab.

![Schematic of transmission with actuator](image1)

![Realized prototype](image2)

*Figure 2.17: Electromagnetically actuated MAV platform developed at Shanghai Jiao Tong University [148]*

The second platform developed appeared in 2017 and made use of piezoelectric actuation. This platform is almost identical to the previous platform except for the change of actuator and airframe accommodation of the new actuator. The piezoelectric actuator works as a bending-beam to give a linear displacement which is then converted to rotational motion through the an appropriately dimensioned four-bar link mechanism in the same manner done on the electromagnetic platform. This platform had a mass of 84 mg and a wingspan of 3.5 cm. It was tested with a slightly higher driving frequency and reached similar flapping characteristics [149]. The team later added four lightweight legs made of a Ti6Al4Valloy...
which was treated with a one hour anodic oxidation process. These curved legs allow the robot to exploit water’s surface tension and is able to float and ‘skate’ on water in a similar fashion to insects like the water strider and mosquito.

![Folding assembly of frame and transmission](image1.png) ![Realized prototype](image2.png)

*(a) Folding assembly of frame and transmission  (b) Realized prototype*

*Figure 2.18: Piezoelectric actuated MAV platform developed at Shanghai Jiao Tong University [149]*

As both platforms were fabricated using flexible polymide film sandwiched between carbon fibre in the same manner done by the Harvard Microrobotics Lab. The frame and transmission were laser-cut out of a single laminated piece which included extra joints allowing for folding into a three-dimensional structure. The joints were then fixed with cyanoacrylate adhesive, thereby removing much of the error caused by manual assembly. The carbon fibre used was unidirectional and has non-uniform modulus. This meant that if the wing spar and veins were laser cut out of a single piece, leading edge spar or vein would not have the same properties along their respective directions. To solve this, the team laser cut the leading edge spar and venation patterns into two different pieces of carbon fibre such that the fibres would run parallel to the respective geometry. Predesignated location holes were also cut which are used to align the two layers as a polyester film is sandwiched between them and laminated.
Chapter 3

Project Background

Inspired by the recent lift-off of the RoboBee, the team at UTIAS decided to attempt to reproduce the flight of the dragonfly. Dragonflies are known for being excellent fliers. They also maintain a constant stroke plane which was ideal for robotic recreation. Bolstered by Wakeling and Ellington’s extensive research on morphology and kinematics, the dragonfly Sympetrum sanguineum was selected as the idyllic model for a flapping-wing MAV.

3.1 Original Goal

At the outset of the project a series of goals was defined with the ultimate long-term goal of developing a stabilized autonomous robotic dragonfly MAV that mimicked the physical parameters, wing kinematics, and dynamics of a real dragonfly [109]. The detailed species-specific research from Wakeling and Ellington as well as other literature mentioned in the previous chapter served as a foundation for design and fabrication of multiple iterations of prototypes. If and when a platform could successfully lift-off the focus could then shift towards sensors, power, and computation. These goals were very ambitious and many challenges were expected to be encountered on the way. Unfortunately, lift-off has not been achieved with any of the platforms developed.

3.1.1 Idealised Dragonfly

To guide the UTIAS Robotic Dragonfly, an Idealised Dragonfly was defined as collection of physical and performance specifications [109]. In the pursuit of true biomimicry, the major physical parameters and wing kinematics aimed to accurately mimic that of biological specimens taken from nature. The Idealised Dragonfly is based on the dragonfly Sympetrum sanguineum.

Physical and performance parameters were determined based on the measurements and observations listed previously in Table 2.1 and Table 2.2. Tables 3.1–3.3 list the performance specifications chosen to guide the UTIAS Robotic Dragonfly.

Table 3.1: Body parameters of the Idealised Dragonfly

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>140</td>
<td>mg</td>
</tr>
<tr>
<td>Body Length</td>
<td>40</td>
<td>mm</td>
</tr>
<tr>
<td>Wingspan</td>
<td>68</td>
<td>mm</td>
</tr>
</tbody>
</table>
Table 3.2: Physical parameters of the Idealised Dragonfly’s wings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Forewing</th>
<th>Hindwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>Maximum Chord</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Planform Area</td>
<td>180</td>
<td>240</td>
</tr>
<tr>
<td>Spar Thickness</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Membrane Thickness</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3.3: Performance parameters of the Idealised Dragonfly

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke Plane</td>
<td>50°</td>
</tr>
<tr>
<td>Storke Amplitude (fore/hind)</td>
<td>±45°</td>
</tr>
<tr>
<td>Stroke Midpoint (fore/hind)</td>
<td>0°</td>
</tr>
<tr>
<td>Wingbeat Frequency</td>
<td>40 Hz</td>
</tr>
<tr>
<td>Phase Shift</td>
<td>0°/90°/180°</td>
</tr>
</tbody>
</table>

With *Sympetrum sanguineum* as the project’s template, the power output for kinematic and dynamic mimicry was calculated. Based on the literature mentioned in Section 2.1.5, the muscle mass was assumed to be half of the body mass and the maximum muscle power density was taken to be 156.2 W/kg [118]. As the total mass of the Idealised Dragonfly was specified to be 140 mg, the resulting power output was calculated to be 10.5 mW during peak manoeuvring.

3.2 Prototype Design

This section discusses the early design of the piezoelectric-based UTIAS Robotic Dragonfly and its iterations.
3.2.1 Overview

Based on the available literature at the time, piezoelectric-based MAVs were fairly common and had achieved some success. As such, it was a strong candidate for actuation and was eventually chosen to actuate the platform. The major components of the design included: wings, actuator(s), transmission(s), and frame. Power was supplied from an off-board source via an umbilical tether.

The principle behind the design concept is that a piezoelectric bending-beam actuator would generate wing flapping through a transmission system. The piezoelectric bending-beam actuator is fixed at its base to frame and attached at the tip to the transmission. The actuator behaves as a vibrating cantilever beam excited by the piezoelectric effect under an oscillating signal causing the actuator tip to travel along an arc. By design, the tip displacement is significantly smaller than the length of the bending-beam actuator allowing the motion of the actuator tip to be modelled as a linear displacement. Paired with a four bar-bar link actuator-transmission-wing (ATW) system a single actuator would be responsible for the flapping of a wing pair. Coupling a single actuator to a pair of wings rather than having an actuator for each wing would help minimize mass but give up the ability to flap asymmetrically. Along the same reasoning, passively regulated wing pitch through aerodynamic damping was chosen and could be changed in the future. These choices appeared promising as passive wing pitch and two wings per actuator had been used in a platform capable of lift-off [133].

During the development of the piezoelectric-based UTIAS Robotic Dragonfly, several platforms underwent multiple iterations. These are split into a series of platforms which follow the naming convention #P#. The first number represents the platform while the second number represents the prototype iteration of that particular platform. There have been 3 series of iterations; the 1P#, 2P#, and 3P# series. The first platform, the 1P# series, was a very early platform used as a proof-of-concept of fabrication methods for the project. The second platform, 2P# series, was a platform designed to be an at-scale prototype in both dimension and mass where a single piezoelectric bending-beam actuated a single pair of wings. This platform enabled simplified fabrication as well as isolated wing pair performance. The last piezoelectric platform, 3P# series, was designed to be an at-scale prototype in both dimension and mass with two piezoelectric bending-beams actuated two pair of wings flapping in tandem. Because of the difficulties and slow nature of fabrication, the majority of effort in prototype development was placed on the 2P# series. For a comparison of the 2P# and 3P# series, refer to Figure 3.2.
3.2.2 Wings

The artificial wings for the robotic dragonfly needed to be constructed with existing technology and materials as well as a minimal design which would ease fabrication and assembly. The materials used for the artificial wings were carbon fibre, polymide film, polyester film. The carbon fibre would add stiffness to the wing and was chosen for its high strength to weight ratio, making it an excellent stand-in for natural venation. Polyester film is light and flexible in the place of the wing membrane, and polymide film is flexible but does not fatigue and is ideal for flexible hinges or joints.

The design of the wings is similar to that of the HMF at Harvard. The wing is meant to be rigid in the chordwise direction and pitching is passively permitted by a pitching hinge. Although this would not be completely biomimetic, it aids in the design process and has been suggested to produce nearly optimal lift in hovering [115]. Although passive pitching gives up some control, it was an obvious solution as active pitch control would entail complex implementation and additional actuators. In the context of the longterm goals of the project, control of body roll, pitch, and yaw could be attained through manipulation of wing stroke amplitude of each wing. The design of the wings was quite simple with the carbon fibre arranged as a frame. The frame design was described by Li et al. where it was shown that veins emanating from the leading edges radially along the chord was of importance [75]. Both wings have a larger spanwise spar making up the leading edge. The forewings and hindwings have three and four radial veins, respectively, attached to the leading edge. Wing sketches of typical specimens of *Sympetrum sanguineum* were used to simplify the vein structure such that they could be imitated by narrow straight lengths of carbon fibre. A thin 6 µm polyester film was bonded to the leading edge radial veins to form the final wing.

Artificial recreation of biological insect wing characteristics is quite a challenge. The structure has evolved for millions of years and all. The vein structure is very complex and difficult to reproduce. Because the main goal of the project is flight, only the major performance characteristics were focused on for the design. The leading edge was considered to be first and foremost the most importance piece in artificially recreating dragonfly wings.
as they are directly connected to the flight muscles and lead the motion of the wing. The artificial leading edge is created by a single carbon fibre beam with a rectangular cross-section whose stiffness can be calculated as a bending beam. The leading edge of the forewing was designed to have a cross-section of 150 $\mu$m $\times$ 150 $\mu$m and a length of 30 mm which resulted in a spanwise stiffness of $28.7 \times 10^{-6}$ Nm$^2$. Specific stiffness in the chordwise direction is difficult to recreate with multiple veins spaced apart. Instead for modelling purposes, the veins emanating chordwise were modelled as rigid members and a pitching hinge was connected to the transmission and the base of the wing. The pitching hinge allows the motion of a revolute joint but in reality is a bending beam which deflects passively under aerodynamic forces. The stiffness of the pitching hinge is an extremely important factor in lift generation. If the pitching hinge is too stiff, the wing does not pitch enough, decreasing lift and increasing drag. On the other hand if the pitching hinge is too flexible, the wing would pitch too much and in some cases flutter. These cases were all observed during experimentation. A detailed dynamic model to predict behaviour caused by various pitching hinges would ideally guide an optimal design. A simulation of this detail remains under development and the stiffness of the pitching hinge was designed as a combination of imitating chordwise stiffness in real dragonflies and trial and error among various prototypes.

The pitching hinges can be modelled as revolute joints with rotational stiffness $k_{rot}$ which was described by Wood et al as bending-beams

$$k_{rot} = \frac{E_k w_h l_h^3}{12 l_h}$$

where $E_k$ is the Young’s modulus, $w_h$ is the width, $t_h$ is the thickness, and $l_h$ is the length of the polymide film making up the pitching hinge. An example of the artificial wing properties are shown in Table 3.4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Forewing</th>
<th>Hindwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spanwise Stiffness</td>
<td>28.7</td>
<td>25.1</td>
</tr>
<tr>
<td>Pitching Hinge Stiffness</td>
<td>1.71</td>
<td>1.71</td>
</tr>
<tr>
<td>Mass</td>
<td>2.66</td>
<td>3.45</td>
</tr>
</tbody>
</table>

Wing Fabrication

Fabrication of the artificial wings for the UTIAS Robotic Dragonfly is a delicate in-house process which is loosely based on the method described by Wood et al. for the HMF platform [134]. Both the the leading edge and veins were made from 150 $\mu$m unidirectional pre-impregnated carbon fibre. The carbon fibre is pre-impregnated with uncured epoxy resin which bonds to the polyester membrane and becomes rigid when cured in an oven. Curing
must occur in a narrow temperature band. If the temperature is too low the epoxy in the
carbon fibre will not cure properly, and if the temperature is too high, the 6 $\mu$m polyester
film will warp and contract. The procedure for fabricating the pitching hinge is similar to the
method used for the transmission which will be described later. The wing fabrication begins
with laying the a venation template underneath polyester film. Extra long carbon fibre strips
are cut to width, and then laid onto the polyester film along the venation template and then
trimmed. The composite layers are then cured for 30 min at 125°C, and the excess polyester
is removed leaving the desired wing geometry.

### 3.2.3 Piezoelectric Actuators

Actuators need to be very low mass with high power density for insect scale MAVs. Piezo-
electric bending-beam actuators were selected as they fit these requirements and had a strong
precedence in MAV projects. Design of the actuators was based on existing models for piezo-
electric bending beams. The first iterations based on static models developed by Smits et al.
[101] and later iterations were based on Ballas’ model [26]. The actuators had to be custom
fabricated and went through many iterations throughout the project. Piezoceramic material
PZT-5H (T105-H4E-602 by Piezo Systems, Inc.) was cut to shape and bonded with con-
ductive epoxy in the desired configuration. Once permanently bonded, the actuators were
mounted to a frame and terminal electrodes were attached leaving the actuators ready to be
used. Over the course of the project the planform of the actuators changed from a rectangle
to a trapezoid which increased the power output to weight ratio. In an effort to further op-
timize the actuators output, work was spent developing a new piezoelectric actuator model
that could be used for alternative piezoelectric actuator designs.
3.2.4 Transmission

As mentioned previously, although the tip of an piezoelectric bending-beam actuator does travel along an arc, the maximum displacement is so small that it can essentially be considered a linear motion. This represents a challenge when the goal is to generate a relatively large flapping motion. Because the actuator is effectively linear, a transmission system is required to convert the motion into rotation of the wings. There have been numerous examples that make use of traditional geared transmission designs on superficially biomimicking MAVS [79, 60, 146, 7]. These approaches would not have met the size and mass requirements for true biomimicry and so a four-bar transmission was instead inspired by the designs used by the MAV projects at UC Berkeley and Harvard University [56, 132].

Transmission Iterations

As the project progressed, multiple iterations of drive actuators of various properties and physical parameters where fabricated. To match this, many dimensions of the transmission changed from prototype to prototype. Most significant were changes to the link which had the the greatest influence on the force and displacement conversion from the actuator to the wing.

3.2.5 Frame

A simple frame structure was used to house all of the prototype’s components. The structure acted as a fixed frame of reference for the transmission to be mounted to. The design was simplistic and minimal to reduce mass as much as possible. Alignment of the components to the frame was essential to prevent asymmetries in the lever arms and therefore flapping.

Frame Fabrication

The use of composite materials is ideal for MAV application due to the high strength-to-weight ratio when compared with metals [136]. As the frame is a meant to be a fixed rigid structure, pre-impregnated carbon fibre was not required. Thin strips of pre-cured carbon fibre were acquired with varying thickness and were cut to the desired planform and bonded with cyanoacrylate. Cutting and assembly was performed by hand. Frame dimensions varied due to changes in dimensions of the actuator and transmission.

3.2.6 Power

Piezoelectric actuators require low power at a high voltage to operate. The actuators developed were driven at 300 V and drew 28 - 83 µA. As the main focus was of the project was lift generation, the on-board power was not required. The prototypes were mounted
onto a lift sensor for testing and an umbilical tether was connected to provide the drive
signal. Off-board power allowed the use of inexpensive off-the-shelf component. A function
generator paired with a power supply and custom designed amplifying circuitry was chosen
to test the prototypes.

3.2.7 Summary of 2P# Platform

Because of the extreme difficulty in fabricating consistent prototypes components by hand,
much of the focus went into the 2P# prototype series as only a single pair of wings and
transmission was needed. All iterations in the 2P# series made use of the same forewing
planform. All other physical parameters exhibited great variance due to necessary modi-
fication and optimization. Actuator shape was either rectangular or trapezoidal with size
and mass varying greatly. Transmission parameters were modified to accommodate each
actuator but remained largely unchanged. Overall mass was mainly influenced by actuator
iterations and varied anywhere from 170 mg to 540 mg.

3.3 Modelling, Experiments and Discussion

In this section a brief summary is given of the simulation, experiments and results of the
2P# platform which was described by Szabo [109].

3.3.1 Modelling

The piezoelectric bending-beam actuator, transmission, and wings are the essential compo-
nents responsible for generating lift. Together, they constitute what was dubbed the ATW
(Actuator-Transmission-Wing System) [109]. While the kinematic relation of the ATW is
quite obvious, the dynamic behaviour was more complex. An energy based model was de-
volved to study the dynamic behaviour of the system. The actuator was represented as
a point mass with a translational spring related to the stiffness of the bending beam ac-
tuator. The wings were assumed to be flat plates that did not pitch allowing drag to be
crudely estimated for the purposes of analysis. Small angle approximations were applied to
the differential equation resulting in an estimation for the natural frequency.

3.3.2 Experiments

Experiments of the piezoelectric based platforms involved resonant testing as well as lift
testing. A brief discussion of both experiments is presented in this section.
Resonance Testing

The most important characteristic of each prototype is arguably its natural frequency. By driving prototypes at resonance it was hypothesized that lift generation could be augmented and power requirements diminished. The previously ATW model produced an approximate natural frequency for comparison. The Idealised Dragonfly prescribed a flapping frequency of 40 Hz, the prototypes needed to first and foremost prioritize stroke amplitude and lift generation. Owing to this, various 2P# prototype iterations were designed to operate with driving frequencies between 30-40 Hz.

To test the prototypes, a passive and active method was used. In the passive method, a displacement was applied resulting in the system oscillating with aerodynamic damping until it returned to rest. The period of the oscillations was recorded and the natural frequency calculated. The active method involved driving the prototypes and gradually changing the signal frequency. The frequency with the highest stroke amplitude was then observed and recorded. See Table 3.5 for a comparison of predicted and observed natural frequencies of select 2P# iterations.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2P12</td>
<td>22.2</td>
<td>21.0 Hz</td>
</tr>
<tr>
<td>2P13</td>
<td>40.2</td>
<td>38.1 Hz</td>
</tr>
<tr>
<td>2P16T</td>
<td>32.0</td>
<td>29.4 Hz</td>
</tr>
<tr>
<td>2P20</td>
<td>32.2</td>
<td>30.7 Hz</td>
</tr>
<tr>
<td>2P22T</td>
<td>44.6</td>
<td>42.3 Hz</td>
</tr>
</tbody>
</table>

Table 3.5: Body parameters of the Idealised Dragonfly

Lift Testing

To test lift generation, prototypes were mounted onto a load cell with a nylon bolt. Prototypes were driven via umbilical tether coming from the amplification circuit. A high-speed camera was positioned to record the overall kinematics of the lift test. Unfortunately, as resources were limited, the camera had low resolution and only qualitative information could be extracted from it. Early iterations performed poorly, but through with the ATW model and trial and error, the 2P# series demonstrated variable and increased performance. The highest performing iteration was 2P20 which was able to generate 1.22 mN of lift while being driven at 27.6 Hz. Although this was nearly sufficient lift for the Idealised Dragonfly, was only half that required to lift the 251.6 mg prototype. Attempts to improve on the 2P20 iteration by reducing actuator size resulted in a higher natural frequency resulting in higher aerodynamic forces which could not be overcome.
Chapter 3. Project Background

3.3.3 Discussion

The design and fabrication of at-scale prototypes was difficult but some of the goals were achieved. Many prototype iterations were able to generate lift albeit insufficient for lift-off. Some experimental lift curves were shown to be comparable to simulations from literature \[109\]. The conclusion was that the piezoelectric based design needed to shed weight or become more powerful. With the intent of developing more power dense piezoelectric actuators Szabo forwent further prototype development and shifted focus onto piezoelectric modelling.
Chapter 4

UTIAS Robotic Dragonfly and the Search for a New Actuator

As mentioned in the previous chapter, a single piezoelectric actuator was insufficient in a design strictly following the Idealised Dragonfly. Ideally, an increase in actuator power while maintaining mass, or decreasing mass while maintaining actuator power would result in lift-off. These are difficult directions to move in and it was decided that concessions on strict biomimicry needed to be made. It is worth noting, that although the Harvard platforms are the most accurate form of biomimicry to date, their platforms’ performance in wing kinematics and drive frequency do not match those of its living counterparts. Furthermore, the MAV project at Carnegie Mellon University was unable to lift-off when it had similarly strict parameters. When the team relaxed their design parameters the project was more open to other types of actuation and was eventually able to achieve lift-off. Based on this precedent, it was decided that UTIAS Robotic Dragonfly should also make design concessions rather than attempt to maintain true biomimicry.

4.1 Relaxation of Constraints

Taking a cue from the MAV project at Carnegie Mellon University, the major modification to the constraints was to change the overall body mass of the platform. An increased body mass and body dimensions would allow the substitution of other actuator types as well as the mechanical components required for them to function. The modifications to the overall body parameters are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>&lt;500 mg</td>
</tr>
<tr>
<td>Body Length</td>
<td>40 mm</td>
</tr>
<tr>
<td>Wingspan</td>
<td>68 mm</td>
</tr>
</tbody>
</table>

In an effort to conserve as much biomimicry as possible, the artificial wings aimed to be as close as possible to living dragonflies. The artificial wing design was therefore kept in line with the parameters outlined in Table 3.2.

The performance parameters were kept mostly the same as the previously defined Idealised Dragonfly. This decision was motivated by the desire to maintain biomimicry as
well as the knowledge that a dragonfly can lift significantly more than its own body mass. It has been observed that at certain points during the wing stroke dragonflies generate lift forces 15 - 20 times that of their bodyweight and on average generate well over 2 times their bodyweight [102]. To maximize lift generation it was believed that a switch to normal hovering would improve performance, therefore the stroke plane was changed from 50° to 90° from the horizontal plane.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Forewing</th>
<th>Hindwing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>Maximum Chord</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Planform Area</td>
<td>180</td>
<td>240</td>
</tr>
<tr>
<td>Spar Thickness</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Membrane Thickness</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

### 4.2 A New Actuator

With the immediate goal to improve lift generation it seemed a change of actuator is required. The different configurations and sizes of piezoelectric actuators had not been able to produce enough lift forces to overcome their own weight. Although the work done at Harvard University and Shanghai Jiao Tong University is encouraging for the use of piezoelectric actuators, both designs are significantly smaller and the UTIAS Dragonfly still aims to mimic the flapping of *Sympterum sanguieum* as closely as possible. Relaxation of the constraints allowed for a more open consideration of actuation technologies as well as rethinking of design.

#### 4.2.1 Commonly Used Actuators

When looking to switch actuation methods for the UTIAS Robotic Dragonfly it was natural to examine what other MAV projects have chosen. Upon examining the literature pertaining to MAVs it is quite clear that despite MAVs being incredibly diverse and varied, nearly every
MAV platform has actuated with electric motors or piezoelectric bending beams. Within this observation it should be noted that the two actuators have not been equally used. Electric motors form the overwhelming actuation method for MAVs in general. Electric motors are a firmly established technology with a vast supply in both quantity and variety for almost every application. On the other hand, piezoelectric actuators only become prominent in highly specialized MAVs applications in the last two decades.

The divide between MAVs that use electric motors and the MAVs that use piezoelectric actuators is a fine line contained within insect-sized flapping wing MAVS. When discussing others such as ornithopters or quadrotors, electric motors prevail uniformly. Within insect-sized flapping wing MAVs a line can be seen separating those that use electric motors and those that use piezoelectric actuators. This line appears to be somewhere between the categories of superficial biomimicry, kinematic mimicry, and true biomimicry defined by Szabo [109]. The smallest electric motors today are sub-gram units but still weigh hundreds of milligrams. Also it has been observed that electric motors are significantly less efficient when the become lighter than 10 g [105]. For these reasons piezoelectric bending-beam actuators have become attractive for insect-scale flapping wing MAVs.

The Biomimetic Millisystems Lab was the first to use piezoelectric bending-beam actuators for the MFI project. Since then, piezoelectric bending-beams have featured at some time in the majority of insect scale MAV projects.

The piezoelectric effect is considered to be a linear electromechanical interaction between the mechanical and electrical state in some crystalline materials [61]. The effect is a reversible process meaning that materials that exhibit the piezoelectric effect can both generate an electric charge from an applied mechanical force as well as generate mechanical strain due to an applied electric field. The piezoelectric effect has been used for sensory applications whereas the inverse piezoelectric effect is used for actuation [121]. Such materials will change produce measurable piezoelectricity when their structure is deformed by 0.1%. Similarly, when an external electric field is applied their structure can deform by 0.1%. Since piezoelectric materials exhibit such small deformations, a simple yet ingenious method must be used to amplify their effect.

Piezoelectric bending-beams are formed of bonded layers of piezoceramic with differing polarities. An expanding layer is bonded to another layer which can either contract or remain as an elastic component. With the appropriate orientation of layers and an applied voltage potential across the layers, the entire beam will bend. Applications of piezoelectric bending-beams are primarily energy harvesters, high power-density actuation in microbotics and MEMS sensors [109].

Piezoelectric bending-beams were chosen for the UTIAS Robotic Dragonfly for their high-power density and because the RoboBee had successfully implemented it into a flying platform. The HMF/RoboBee researchers had discounted electric motors but considered
other actuation methods \cite{71}. The piezoelectric actuators developed for the artificial dragonfly were unable to produce the required output while maintaining low mass. This likely has to do with the significant aerodynamic damping felt by the wings of the UTIAS Robotic Dragonfly. Although it is insect scale, it was modelled after *Sympetrum sagnuineum* which remains relatively large for an insect. Such devices exist in the mesoscale realm between MEMS scale devices and conventional components and it has been observed that piezoelectric beams are less effective at the macro-scale \cite{52}.

### 4.2.2 A New Search

Based on the 2P# series of the platform it seemed that piezoelectric actuation was not the best fit for the UTIAS Robotic Dragonfly. Moving forward electric motors were reconsidered along with electroactive polymers, thermal, electrostatic, and electromagnetic actuators. These technologies were investigated individually as well as compared to one another through the work of Bell et al. Although the motivation of their work was to compare various MEMS technologies, they also compiled macro-scale technologies for comparison. Their work produced performance maps which are shown in Figures 4.1 and 4.2. The survey was quite extensive and indicates which technologies fall under MEMS and the macro scale.

![Figure 4.1: Map of force versus displacement for MEMS and macro actuators by Bell et al.](image-url)
Chapter 4. UTIAS Robotic Dragonfly and the Search for a New Actuator

Thermal Actuation

Thermal actuation has been suggested as possible actuation methods for MAVs [71]. It is well known that materials exhibit expansion and contraction when subject to temperature change. One method is simply thermal expansion acting as a linear actuator. Another is with a thermal bimorph which offers larger displacement but lower force output. In the work of Bell et al. [29], a number of thermal based technologies are compared, they are: bimorph, solid expansion, topology optimized, shape memory alloy, fluid expansion, state change, and thermal relay. In Figure 4.1 it is shown that solid expansion, state change, shape memory alloys, and fluid expansion perform strongly in a space that is close to the other macro scale devices. Unfortunately these devices are limited in frequency owing to time required to transfer heat into and out of the actuator.

Figure 4.2: Map of frequency versus displacement for MEMS and macro actuators by Bell et al. [29]

Electrostatic Actuation

Electrostatic actuators are prevalent in microelectromechanical systems (MEMS). They operate based on the attraction and repulsion of electric charge. The family of electrostatic actuators are highly efficient and include: comb drive, parallel plate, repulsive force, and scratch drive to name a few. Generally electrostatic actuators have the ability to operate at
very high frequencies however with low force and deflection [71]. Although highly efficient, they are function on a very small scale and require MEMS manufacturing process and a high operating voltage. Owing to limited resources and the scale of the UTIAS Robotic Dragonfly, electrostatic actuation was rejected.

**Electromagnetic Actuators**

Electromagnetic actuation uses linear magnetic forces or rotational magnetic moments. Many linear solenoid actuators operate as an on/off system using electromagnetism to cause an active pull, and a spring to return the shaft to its original position. Such a device with properly tuned spring would be able to make use of resonant behaviour as well as the transmission system outlined in the previous section. Alternatively, a rotational spring can be used in conjunction with the magnetic moment on a permanent magnet in a magnetic field, operating on the same principle that electric motors use to rotate. In Figure 4.1 electromagnetic actuators have a similar performance to macro scale piezoelectrics with slightly higher maximum displacement. They have a maximum frequency significantly less than piezoelectrics but well above what is needed for a flapping wing MAV. There is a wide array of available linear electromagnetic actuators for various purposes. Generally they allow relatively large operating frequencies and displacement but the lack of demand for ultralight solenoids results in very few available sub-gram models. Possible solutions were bare-bones coil and magnet products or custom coil construction.

**Electroactive Polymers**

Electroactive polymers (EAPs) operate quite similar to piezoelectric actuators: a voltage is applied which induces mechanical deformation. They are divided into two categories, dielectric and ionic. Dielectric polymers function as compliant capacitor, where a passive elastomer film is sandwiched between two electrodes. A voltage is applied causing electrostatic pressure to squeeze and deform the middle elastomer film. In ionic EAPs actuation is
produced by the displacement of ions inside the polymer. They generally only require a few volts but require higher electrical power. Dielectric actuators overall appeared promising. The materials can obtain strains much larger than piezoelectric materials and can be used in a bending beam in a similar fashion. They are more limited in the frequency range in which they can function but still sufficient for flapping wing MAVs. Upon investigating further it was found to be very difficult to acquire an EAP material with known characteristics. One provider, when contacted for detailed electrical and mechanical properties of the material, indicated that there was no such data on the material and that the EAP film was meant for scientists and engineers to experiment with and extract their own parameters of interest. Such analysis and experimental modelling of the material could be an entire project on its own making it an unlikely candidate.

**Electric Motors**

Electric motors are a tried and true technology whose applications have been endless. Mass consumption has lead to a wide variety of motors that are available and affordable. Although researchers working on the HMF and RoboBee discounted electric motors as possible actuation methods [71], electric motors have been successful in multiple ornithopter projects and was able to perform sufficiently in the CMU MAV which was only 2.7 g. There are a number of lightweight options when considering motors for actuation of the UTIAS Dragonfly. One example of a lightweight motor is the 0308 Series Motor from Micromo. The 0308 Series Motor is a brushless DC micromotor that weighs 310mg which can deliver a torque up to 0.023 mNm. Such a motor could potentially result in a sub-gram design but required additional mechanics to function with the transmission discussed in Subsection 4.4.1.
Table 4.4: Comparison of sub-gram actuation technologies based on the work of Karpelson and Bell et al. \[71, 29\]

<table>
<thead>
<tr>
<th>Actuator Category</th>
<th>Maximum Deflection</th>
<th>Maximum Force</th>
<th>Speed of Actuation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Motor</td>
<td>Very high</td>
<td>High</td>
<td>Fast</td>
<td>Easily acquired but heaviest</td>
</tr>
<tr>
<td>Dielectric Polymer</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Capable of over 300% Strain, very high operating voltage</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>High</td>
<td>High</td>
<td>Fast</td>
<td>Easily acquired or fabricated</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>Low</td>
<td>Low</td>
<td>Very fast</td>
<td>Requires MEMS manufacturing processes, high operating voltage</td>
</tr>
<tr>
<td>Piezoelectric cantilever</td>
<td>Medium</td>
<td>Medium</td>
<td>Fast</td>
<td>Simple Planar structure, high operating voltage</td>
</tr>
<tr>
<td>Thermal</td>
<td>Medium</td>
<td>High</td>
<td>Slow</td>
<td>Versatile geometries, largest materials selection</td>
</tr>
</tbody>
</table>

4.3 Electromagnetic Actuation

Through much discussion it was decided that the main focus of this project was to work on new platform iterations rather than actuator development. It was felt that a consistent actuator throughout iterations would aid in the tuning of various prototypes. Eventually, electromagnetic actuation was chosen for the next steps of the UTIAS Robotic Dragonfly. Electromagnetic actuation is a mature well documented technology which would allow for sub-gram designs. Furthermore, at the outset of this work, electromagnetic actuation had never been attempted for flapping-winged MAVs. This made electromagnetic actuators highly appealing as they were available to acquire or fabricate with off-the-shelf components.

Although a few off-the-shelf solenoid-based actuators are sub-gram, none would be able to produce an overall MAV with sub-gram body mass. Custom built actuators were considered but disregarded owing to the cost and limited man hours that could be devoted towards actuator design from a small research team. This would appear to have left the project without any options however a solution was found in between these two options. Small coils and permanent magnets were acquired from Plantacro Microflight. The product is the NanoAct Magnetic Actuator kit. The kit is very minimal consisting simply of a coil and two disc shaped neodymium magnets. The coil has a mass of 70 mg and the permanent magnets were measured as having a mass of 10 mg. The product was ideal as it was readily available, affordable, and lacked any of the extra material that would have been part of a regular off-the-shelf actuator. The fact that the components were unassembled
allowed for direct integration into an MAV platform in either a linear or rotary configuration. The actuator can be seen in Figure 4.5 and the overall physical parameters are shown in Table 4.5:

<table>
<thead>
<tr>
<th>Component</th>
<th>ID (mm)</th>
<th>OD (mm)</th>
<th>Thickness (mm)</th>
<th>Mass (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil</td>
<td>3</td>
<td>3.8</td>
<td>2.8</td>
<td>70</td>
</tr>
<tr>
<td>Magnet</td>
<td>N/A</td>
<td>1.5</td>
<td>0.85</td>
<td>10</td>
</tr>
</tbody>
</table>

4.3.1 Actuator Characterization

While many MAV projects in the literature made great strides through trial and error, many including this project attempted to use mathematical models to guide the design process or validate the fabricated prototypes. Similarly, it was hoped that a simulation modelling the complex dynamics could be used to shed light on prototype design and compared to experimental tests. Of course, to do this, the performance or mechanical properties of the actuator would be required. Ordinarily, an off-the-shelf and custom built actuator would have properties supplied by the manufacturer or would be known based on the custom design. Unfortunately, the retailer could not provide any properties of the coils or magnets other than the dimensions and mass of the product.

To obtain this information, an experiment was performed to characterize both the
coil and permanent magnets. The behaviour of finite coils and permanent magnets can be quite complex, but for the purposes of this project, assumptions were made to simplify the characterization process. For the purposes of the experiment, both the coils and the magnets were modelled as individual magnetic dipoles. The equation for the magnetic moment of a coil is

$$\mu = NIA$$ (4.1)

where $\mu$ is the magnetic moment, $N$ is the number of windings of the coil, $I$ is the current flowing through the coil and $A$ is the area of the coil. Of most importance to the experiment is the magnetic field produced along the axis of the magnetic dipole which is

$$B_z = \frac{\mu_0}{4\pi r^3}$$ (4.2)

where $B_z$ is the magnetic field along the axis of the coil, $r$ is measured from the centre of the dipole and $\mu_0$ is the vacuum permeability constant ($4\pi \times 10^{-7}$). These equations let us estimate the properties of the coil and magnet.

The methodology behind the experiment was quite straightforward. Based on Equation 4.2, it is clear that the magnetic field along the axis of a magnetic dipole moment is linearly proportional to the magnetic moment, $\mu$, and that the field is also directly proportional to the inverse cube of the distance measured from the position of the magnetic dipole. In theory, many data points of the magnetic field and the inverse cube of position would have a relation whose slope can then used to determine the magnetic moment, $\mu$. Using a gaussmeter and calipers, the magnetic field was measured at varying distances from both the magnetic dipole being measured. The results can be found in Figure 4.6.
Figure 4.6: Magnetic field results of actuator characterization
From this process the magnetic moment of the permanent magnet could be directly determined. In the case of the coil, the magnetic moment was tested at two different voltages. In both cases the equivalent magnetic moment was calculated and then used to estimate the number of windings, $N$, of the coil using Equation 4.1. The results were that the permanent magnet had a magnetic moment of $0.396 \text{ Am}^2$ and the coils had approximately 222 windings.

4.3.2 Linear Actuation

Linear electromagnetic actuation involves alignment of the axes of both the coil and the permanent magnets. When a current is passed through the coil, a magnetic field is created which can attract or repel the permanent magnet. If the two components are constrained to a single axis, coaxial linear motion will follow. It is vital that the motion is constrained to a single axis as when the magnetic fields of the coil and magnet oppose each other, not only is there a repulsive force, but also an applied torque which is the basis for the rotational motion described in Section 4.3.3.

To maximize the output of a linear actuation system the components must be configured optimally. Contrary to ordinary intuition, the maximal force generated on the magnet does not occur in the centre of the coil where the magnetic field is the strongest. The force
on a magnet is actually proportional to the gradient of the magnetic field and is given by

$$\vec{F} = \nabla (\vec{\mu} \cdot \vec{B})$$  \hspace{1cm} (4.3)

To study the force production between the coil and magnet a solver in MATLAB was used. Robertson et al. had previously implemented a solver which calculated the force between coaxial cylindrical magnets and thin coils in MATLAB which was made publicly available [90]. The properties of the permanent magnet and the coil drawing 0.051 A were converted to the parameters required in the provided script. The resulting force-position curve is shown in Figure 4.7.

Based on the results of the electromagnetic force solver, it is clear that the peak forces are located the ends of the coil. Here the maximum force is approximately 45 mN. The resulting force can be linearly increased by increasing the current supplied. To maximize output, a system with one magnet placed at each end of the coil whose fields are arranged in opposite directions. Such a configuration might nearly double the actuating force with only the additional cost of a single magnet and the structure needed to secure it.

![Figure 4.8: Ideal magnet position for linear actuation](image)

4.3.3 Rotational Actuation

Rotational actuation involves the misalignment of the axes of the coil and permanent magnets. When a current is passed through the coil, a magnetic field is created which causes a torque on the permanent magnet. If the magnet is constrained by a joint on the correct axis, the desired rotation will follow. In this case, it is also vital for the motion to be constrained to one degree of freedom as the magnet is still subject to the forces described in Equation
The torque applied to the magnet is given by

\[ \vec{\tau} = \vec{\mu} \times \vec{B} \]  

(4.4)

where \( \tau \) is the torque applied to the magnet. In this case, the largest torque can be achieved at the location of the largest magnetic field. The magnetic field along the axis of the coil is

\[ B_x = \frac{\mu_0 n I}{2} \left( \frac{x - x_1}{\sqrt{(x - x_1)^2 + R^2}} - \frac{x - x_2}{\sqrt{(x - x_2)^2 + R^2}} \right) \]  

(4.5)

where \( B_x \) is the magnetic field along the coil axis, \( R \) is the radius of the coil, \( x \) is the position of interest, and \( x_1 \) and \( x_2 \) are the positions where the coil terminates. The field distribution of a generic finite coil is shown in Figure 4.9 where it can be easily inspected that the location where the magnetic field is greatest is at the very centre of the coil.

![Figure 4.9: Magnetic field along axis of coil](image)

### 4.4 Prototype Design & Fabrication

The goal of this thesis was to design a platform of the UTIAS Robotic Dragonfly using electromagnetic actuation methods to drive flapping wing pairs. Evolving out of the piezoelectric-based design the same major components were required, that is, the wings, actuator(s), transmission(s), and frame. Similarly, the frame was to house the actuator(s), transmission(s), and wings with an umbilical tether to provide off-board power.

Over the course of this thesis, two series of platforms with multiple iterations were developed. The naming convention follows the previously established structure in Subsection 3.2.1, yet it is easily distinguished from its predecessors. The prototypes followed the naming convention #EM#. The first number identifies the platform while the second identifies the iteration. Two platforms were designed and fabricated to date. The first platform, 1EM#
series, was developed to make use of a single linear actuator to drive a single pair of wings. The second platform, 2EM# series, was developed to use two rotational electromagnetic actuators, one for each wing. The majority of prototype development was with the 2EM# series.

4.4.1 1EM Series

The 1EM series was an early proof of concept design attempting to drive a single pair of wings with a single linear electromagnetic actuator. The idea was to have the operate the actuator in the manner discussed in Section 4.3.2. As the previous work on the UTIAS Robotic Dragonfly made use of approximately linear acting piezoelectric bending-beam actuators, it was only naturally to use this design as well for the 1EM series. The wings were designed and fabricated in an identical manner as described in Section 3.2.2. The transmission was based on a four-bar link mechanism where the bottom link was originally fixed to the tip of the piezoelectric actuator. For the linear electromagnetic actuator the permanent magnet was fixed to the link instead.

Transmission Design

The transmission followed the design outlined previously by Szabo [109]. The transmission was based on a four-bar linkage which would allow the very small displacement of a linear actuators to be converted into high angular displacement of the wings. The design consisted of two four-bar linkage mechanisms which were driven by the same actuator. A model and schematic of the design is shown in Figure 4.10. The dimensions of each link varied between prototype iterations. The equation governing the transmission motion derived by Wood [133] is

\[
\theta = \arccos \left( \frac{u^2 - 2ul_1 + 2l_2^2}{2l_2 \sqrt{(l_1 - u)^2 + l_2^2}} \right) + \arctan \left( \frac{l_2}{l_1 - u} \right) - \frac{\pi}{2}
\]  

(4.6)

where \(l_1, l_2\) are link lengths, \(u\) is the displacement of the actuator, and \(\theta\) is the resultant stroke angle. A schematic of the transmission is shown in Figure 4.10.

The transmission is composed of rigid linkages with flexible revolute joints. These joints not only allow motion, but also adds stiffness to the system. The joints are modelled as short, thin and wide bending-beams [134]. The stiffness of individual joints is modelled with elementary beam theory in the same manner as the pitching hinge and is given by Equation 3.1.

The actuator applies force to the bottom link and causes displacement \(u\). As the link displaces downwards, the wings rotate upward performing the upstroke. Likewise, as the tip displaces the link upwards, the wings rotate downwards performing the downstroke. This mechanism behaves with some parallels to the push/pull direct flight muscles in insects.
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Fortunately, the piezoelectric bending beam can create the push/pull functionality which is normally performed by two muscles in an insect.

Fabrication of Four-Bar Transmission

The transmission was fabricated with pre-impregnated carbon fibre and polymide film. The unidirectional carbon fibre prepreg was 150 $\mu$m thick and arrives embedded with uncured epoxy resin. When cured at a sufficient temperature, the epoxy becomes rigid and bonds to the polymide film before cooling. The 12.7 $\mu$m thick polymide film is very flexible and highly resistant to fatigue.

The fabrication method was loosely based on the technique presented by Wood et al. referred to as Smart Composite Microstructures (SCM) [134]. Owing to limited resources and lack of equipment, the SCM process was modified to be cut by hand without the use of specialized laser cutters. As such, the design was limited to less complex designs compared to
some of those outlined by Wood et al. The transmission was assembled from five subassemblies. Only one or two joints were fabricated in each subassembly allowing for replacement before final assembly if fabrication with a subassembly was incorrect or damaged. Each joint consisted of carbon fibre layers sandwiching polymide film. The outer layers of carbon fibre had coincident gaps of 0.5 m leaving the polymide film exposed which allowed bending to occur. The procedure for fabricating each subassembly required patience and fine motor control. First the polymide film was cut into segments to match the total planform of each subassembly.

Next, the carbon fibre prepreg was cut into segments which matched the desired planform of the rigid links. The carbon fibre segments were carefully mounted onto both sides of the polymide film ensuring the desired position of the joint and lightly clamped before curing in an oven at 150°C for 30 min. Once cool, any excess polymide was trimmed and the final assembly bonded with cyanoacrylate.

**Frame**

The frame structure was needed to hold all of the components firmly together. The design was a slightly modified version of the frame used for the piezoelectric-based platforms. The main addition was a mounting bracket made of the same pre-cured carbon fibre which held the coil of the actuator. This gives the actuator system a base frame of reference from which to drive the transmission system.

**Fabrication Challenges of the 1EM Series**

Fabrication of the 1EM series required an enormous quantity of diligent construction and time. Any misalignment of the transmission subassemblies, wing attachment, or transmission/frame connections, would ultimately lead to asymmetries in performance. Although these issues were significant, the most difficult challenges were correct orientation and positioning of the actuator components and spanwise wobble of the transmission.

As the entire fabrication and assembly was performed by hand, ideal positioning between the permanent magnet and the coil as seen in Figure 4.8 was very difficult to achieve. The actuator had a narrow space of optimal force output that needed to be achieved. This issue did not exist with the piezoelectric bending-beam actuators as they were a single physical component that was fixed to both the frame and the transmission.

Wobble in the transmission was also a new problem. With the piezoelectric actuators, the link that was attached to the actuator tip was therefore constrained to move along the actuator tip’s path. In the case of the electromagnetic actuator the link was not restricted in this manner as only the permanent magnet was fixed to it. As the oscillating signal passed through the coil, the magnet is linearly attracted and repelled. During the attractive portion
of the period, there is a linear force applied to the magnet without any applied torque. As the repelling portion of the period occurred, a torque is also applied to the magnet as described in Section 4.3.3 resulting in side to side wobbling of the transmission. The transmission swayed perpendicularly to the intended axis of motion, causing an augmentation in suboptimal position of the magnet as well as lost energy.

After a number of iteration attempts, no effective solutions were found and these challenges remained prevalent. This led to the discontinuation of the 1EM series and the birth of the 2EM series of electromagnetic actuator for the UTIAS Robotic Dragonfly.

4.4.2 2EM Series

The 2EM series was a design concept attempting to drive a single pair of wings with two rotational electromagnetic actuators. The actuators were made up of exactly the same components as the actuator in the 1EM series, however the design of the platform was to allow them to operate on the principles described in Section 4.3.3 instead. It was thought that this implementation of the actuator would provide certain advantages over the previous attempts.

The linear implementation of the actuator could not be properly constrained and therefore felt the effects of both Equations 4.3 and 4.4. On the other hand, a correct configuration of rotational implementation should theoretically feel no applied force from Equation 4.3 owing to the magnetic field distribution shown in Figure 4.9. Because the motion would already be rotational, the actuator’s motion would not need to be converted from linear motion thereby reducing mechanical complexity. At worst, a transmission amplifying rotation might be needed. Furthermore, at the cost of increased mass, the system would have a higher output with two actuators and the potential for control in the future as each wing could be actuated independently.

As before, this platform had similar major components consisting of a frame, actuators, transmission and wings. With the new approach, the frame and transmission changed drastically with the wings remaining unchanged.

Transmission Designs

With the change in actuator, a new lightweight and mechanically simple transmission was desired. As a result of the scale of the components, fabrication by hand was challenging and multiple designs were attempted. Four designs are presented below. For the purposes of these descriptions, the circular top and bottom of the magnet will be referred to as the side of the magnet, and the curved portion of the surface area will be referred to as the perimeter.

The first concept considered was the simplest design. A revolute joint was fixed to a location on the perimeter of the permanent magnet and the spar connecting to the wing was
fixed to the perimeter in a position directly opposite of the revolute joint. This results in the magnet rotating about an axis that does not pass through its centre. A schematic of this design is shown in Figure 4.12. This design was conceived for its simplicity in hope of making the fabrication process easier. The other end of the flexible joint was fixed to the frame and so that the magnet would be positioned along the centre axis of the coil. There is unfortunately a number of drawbacks in this design. First, the inertia is increased about the rotation axis owing to the parallel axis theorem resulting in a decreased natural frequency. Second, as the magnet would move along a small arc, the position of the magnet will change and therefore will only spend an instant in the optimal location. Finally, the short length of the coil severely limited the size of joint that could be used, the magnet could be located on the centre axis but not the exact centre of the coil. This meant that the magnet located near the edge of the coil which was not optimal. If the frame had been modified with a cut-out allowing the joint and magnet to be placed such that the magnet was centred, the maximum stroke amplitude would be reduced as the coil would interfere with the motion of the spar.

![Figure 4.12: Schematic of transmission design featuring an off centre rotation axis](image)

The second concept was a little more complex. Two revolute joints were fixed to the perimeter of the magnet in opposing positions. Each would be fixed to the inside of the coil rather than the base. This design attempted to bring the magnet much closer to the axis of rotation. A schematic of this design is shown in Figure 4.13. This design worked in theory, but in practice was infeasible to fabricate. The spacing where the joints were to be fixed and mounted between the coil and magnet would barely allow for the smallest joint that could be fabricated. Furthermore, fixing the components to the inside of the coil in the correct orientation was nearly impossible.

A third concept was conceived and thought to be the most elegant transmission. Two long flexible beams would be fixed to each side of the magnet and mounted onto the inside of
the coil. Previous designs had the bending axis of each joint in line with one another whereas in this design they were parallel and apart. The concept here was to allow enough space for the joints to be included and for the joints to behave as a beam that was fixed at both ends. This design also caused the flexible beam to deflect in a bending mode shape. Unfortunately, this design suffered from many of the same challenges as the second design. The joint space was only improved marginally, and the joint ends were difficult to orientate perpendicular to both the magnet and coil interior.

The final design which was eventually chosen mounts to joints to the frame such that they are exterior to the coil. The other ends of the joints are connected together forming a U-shaped component. The spar runs through the “U” and holds the magnet at the centre of
the coil. By placing the magnet inside with the spar and keeping the joint mechanisms on
the outside of the coil, many of the problems with the previous designs were avoided. This
design however does increase the amount of mass of the system as well as the aerodynamic
damping.

![Figure 4.15: Schematic of transmission design featuring external joints](image)

**Fabrication of New Transmission**

Fabrication of the new transmission followed a process very similar to that used for the four-
bar transmission mentioned in Section 4.4.1. As the transmission had fewer components
it could be fabricated in a single process as opposed to multiple subassemblies. The raw
materials used were the same with 150 $\mu$m carbon fibre prepreg used for rigid links and
flexible polymide film for the joints. The most significant difference was the cutting of the
U-shaped piece of carbon fibre prepreg. As a result of the fibres being unidirectional, the
material only had high strength in one direction. This was not problematic with the four-
bar transmission as the individual links experience minimal stress. The U-shaped piece on
the other had the interior material removed to allow free motion around the coil resulting
in sharp corners that acted as stress concentrators. To protect against breaking, the two
pieces of carbon fibre that would create the part were cut such that the fibres would run
perpendicular to one another when assembled.

**Frame**

Holding everything together was a frame made from precured carbon fibre. Carbon fibre
has excellent strength to weight ratio which is ideal for the rigid frame of an MAV. A basic
rectangular frame with cross beams allowed the other components to be mounted directly to a
flat surface. Pieces of carbon fibre were cut by hand and bonded together with cyanoacrylate.
The width of the frame kept the two actuators at a distance preventing interference from one another and allowing for the addition of a nylon nut for the purpose of testing.

**Assembly**

Assembly of the final prototype followed a specific order which was refined through trial and error. Unlike a piece of furniture which has holes that match together or physical constraints that aid in alignment, each connection in the assembly needed to be delicately placed. The order of assembly was as follows: fixing the spar to the magnet, fixing the coil to the frame, fixing the spar/magnet to the transmission, fixing the transmission to the frame, and fixing the wing to the transmission. These steps were then repeated on the other side of the frame resulting in a single wing pair. All assembly was bonded with cyanoacrylate and performed by hand.

**4.4.3 Simulation Model**

For completeness, a simple quasisteady model was started simulate the flapping dynamics of the vehicle.

The wing was assumed to be a flat plate. Removing the small angle assumption results in

\[ c_l = 2\pi \alpha \rightarrow c_l = 2\pi \sin \alpha \]

(4.7)

where \( c_l \) is the coefficient of lift, \( \omega \) is the angular velocity of the transmission joint, and \( \alpha \) is the angle of attack. This author acknowledges that this is a very simple model of the lift and is only valid for attached flow. The platform's wings will pass through high angles of attack and eventually experience flow separation.
The moment equation is similarly written without the small angle assumption

\[ c_m = \frac{\pi \alpha}{2} \rightarrow c_m = \frac{\pi \sin(\alpha) \cos(\alpha)}{2} \rightarrow c_m = \frac{\pi \sin \alpha}{2} \]  

(4.8)

where \( c_m \) is the moment coefficient. The force on an infinitely thin section of the wing is assumed to be

\[ dF_a = 2\pi \sin \frac{\alpha}{2} \rho V^2 dA \]  

(4.9)

where \( dF_a \) is the aerodynamic force, \( \rho \) is the density of air, \( V \) is the velocity of air relative to the section, and \( dA \) is the area. The area and speed of the section are can be expressed as

\[ dA = cdx \quad \text{and} \quad V = \omega r = \dot{\phi} x \]

where \( c \) is the chord, \( \dot{\phi} \) is the angular velocity of the wing, and \( x \) is the position along the spanwise direction of the wing. The total moment applied to the wing can be expressed as follows.

\[ \tau_a = \int_0^l x dF_a \]  

(4.10)

Substituting the expression for \( dF_a \) gives

\[ \tau_a = \int_0^l \rho x^3 \dot{\phi}^2 c \pi \sin \alpha dx \]  

(4.11)

and integrating results in the following equation.

\[ \tau_a = \frac{\rho c l^4 \pi \dot{\phi}^2 \sin(\alpha)}{4} \]  

(4.12)

The dynamic equation of flapping can be modelled simply as

\[ J_1 \ddot{\phi} + k_1 \phi = \tau_a + \tau_d \]  

(4.13)

where \( J_1 \) is the moment of inertia of the wing about the axis of flapping, \( k_1 \) is the stiffness of the flapping joint, and \( \tau_d \) is the driving moment supplied by the actuator.

The dynamic equation of pitching was modelled as

\[ J_2 \ddot{\theta} + k_2 \theta = \tau_m \]  

(4.14)

where \( J_2 \) is the moment of inertia about the pitching axis, \( k_2 \) is the stiffness of the pitching hinge, \( \theta \) is the pitching angle. Adding the expressions for the right hand side of Equation 4.13 gives
\[ J_1 \ddot{\phi} + k_1 \phi = -\frac{1}{4} \rho cl^4 \pi \sin(\alpha) \dot{\phi}^2 + mB \sin(\phi) \cos(\omega t) \] (4.15)

Substituting the expressions for \( \tau_m \), Equation 4.14 becomes

\[ J_2 \ddot{\theta} + k_2 \theta = \frac{1}{12} \rho c^2 l^3 \pi \dot{\phi}^2 \sin(\alpha) \] (4.16)

The pitching angle and angle of attack and their derivatives can be related by

\[ \frac{\pi}{2} = \theta + \alpha \quad \text{and} \quad \dot{\theta} = -\dot{\alpha} \quad \text{and} \quad \ddot{\theta} = -\ddot{\alpha} \]

which leads Equation 4.16 to become

\[ J_2 \ddot{\alpha} = k_2 \left( \frac{\pi}{2} - \alpha \right) - \frac{1}{12} \rho c^2 l^3 \pi \dot{\phi}^2 \sin(\alpha) \] (4.17)

This model can be developed further by introducing the additional complexity based on the work of Ahmed [21].

### 4.5 Lift Measurement Apparatus

In order to test the performance of various platforms of the UTIAS Robotic Dragonfly an apparatus to measure performance was required. Many experiments pertaining to dragonfly and insect kinematics has made use of scaled up models. Such large experiments allow for off-the-shelf sensors to be placed at various locations on prototypes to give insight into performance. Such free distribution of sensors is unrealistic when working with at-scale designs as space is already limited. Any physical additions to a platform would directly affect dynamic behaviour and potentially impede the performance of the prototype [137].

In order to test at-scale flapping winged MAVs a common solution is to measure the net body forces resulting from overall lift generation. This approach allows the force generated by the wings to be measured without interfering with the behaviour of the prototype. As net lift generation was the focus of the project, overall body forces are sufficient for testing.

The flapping wings of an insect-scale flapping-winged MAV cause body forces that may be transient, complex, and small in magnitude. To capture this, a lift sensor required very low force resolution as well as high measurement bandwidth (sample rate).

To date, there are no off-the-shelf products geared towards measuring lift generation of MAVs. This is to be expected as the field is highly specialized and the requirements are not similar to other industrial or commercial applications. To solve this issue, many research groups use custom apparatuses to test their platforms. Similarly, the platforms of the UTIAS Robotic Dragonfly were tested by a custom lift sensor.
4.5.1 Design

The lift measuring apparatus was based around a bending-beam load cell and was designed by Szabo [109]. Such load cells are intended for static measurements but it was believed that the a load cell with the right properties would be capable of handling the dynamic forces of the platform. This approach was implemented because it was economical and allowed easily acquired or fabricated components.

A load cell of this type detects applied forces via beam bending. When a force is applied, the bending of the beam causes a change in strain which is measured by strain gauges. As the strain of one of these strain gauges changes, its resistance changes which can be measured as a voltage across circuit elements. The detected voltage is linearly related to the beams deflection and therefore the applied force. The system can be calibrated allowing for determination of applied forces. Although load cells are not designed for dynamic measurement, they are suitable for MAV testing as long as the natural frequency of the load cell is well above the driving frequency of the MAV platform.

For the purposes of testing insect-scale MAVs, the load cell is required to be as sensitive as possible. If a load cell is too stiff, the strain measured will be too small to generate a notable voltage change. However, if the load cell is too flexible, the apparatus may become excited due to the dynamics of the prototype being tested. The particular load cell used for testing the UTIAS Robotic Dragonfly was the double cantilever S215 (SMDS2551-002 by Strain Measurement Devices, Inc.). The characteristics of the load cell are shown in Table 4.6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Load</td>
<td>±8.9 N</td>
</tr>
<tr>
<td>Deflection at Maximum Load</td>
<td>0.11 mm</td>
</tr>
<tr>
<td>Rated Output</td>
<td>2 mV/V</td>
</tr>
<tr>
<td>Bridge Resistance</td>
<td>1000 Ω</td>
</tr>
<tr>
<td>Max. Excitation Voltage</td>
<td>20 V</td>
</tr>
<tr>
<td>Material</td>
<td>Stainless Steel</td>
</tr>
</tbody>
</table>

The load cell was mounted onto a custom base platform which also contained a separate mounting location for circuitry. The platform was fabricated with wood and standard fasteners and was designed such that the load cell was raised above the base to give any prototype design sufficient space to flap its wings.

Data was measured with a data acquisition device (DAQ). The DAQ used was the USB-1608G (Measurement computing Corp.). Specifications for the DAQ can be found in Table 4.7. Owing to the minimum input resolution of the DAQ, an amplifying circuit was required to boost the signal coming from the load cell. An amplifying circuit with an
amplification gain of 10000 was used based on the Szabo’s design [109]. A brief summary of the performance of the overall testing apparatus can be found in Table 4.8.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Output</td>
<td>2 mV/V</td>
</tr>
<tr>
<td>Rated Force</td>
<td>8.9 N</td>
</tr>
<tr>
<td>Excitation Voltage</td>
<td>121 V</td>
</tr>
<tr>
<td>Gain</td>
<td>10000</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.27 mV</td>
</tr>
<tr>
<td>Maximum Load</td>
<td>2.7 V</td>
</tr>
</tbody>
</table>

### 4.5.2 Static Calibration

As the apparatus gave an output voltage, this information needed to be transformed into useful units to study prototype performance. A static calibration was performed to quantify the relationship between output voltage and applied force by weighing a set of precision masses on the load cell. The set of precision masses contained 3 masses ranging from 1 - 10 g. The masses were characterized with a small jewellery scale as listed in Table 4.9.

<table>
<thead>
<tr>
<th>Label</th>
<th>1</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Mass</td>
<td>1.001</td>
<td>2.00</td>
<td>4.993</td>
</tr>
<tr>
<td>Accuracy</td>
<td>99.99</td>
<td>100</td>
<td>99.7</td>
</tr>
</tbody>
</table>

To calibrate, the precision masses were placed methodically on the load cell tip allowing the DAQ to record the voltage. The result was a linear relationship between the weight of the masses and the voltage. Overall the calibration test was performed many times and was found to be very consistent. The mean transformation between applied force and output voltage was 24.9 V/N. The mean coefficient of determination was $r^2 = 0.999145$. Select calibration trials are shown in Figure 4.17. It should also be noted, that due to the high gain of the amplifying circuitry, post processing in MATLAB was used to filter the data.
Dynamic Testing

To ensure the static calibration could be maintained during dynamic loading, a test was done to confirm that the dynamic measurements could be assumed to be quasistatic. An oscillating force was applied to the load cell to test the dynamic properties of the apparatus. This was achieved with a small vibrating disc motor of known eccentricity. The motor was driven at different frequencies resulting in a sinusoidal force on the load cell. The results were compared to theoretical force due to an eccentric rotor and showed that there was no significant difference between the predicted force and measured force in the operating frequency range of the Idealised Dragonfly.

4.5.3 Power Supply

The task of providing power to MAVs poses significant long-term challenge. With lift-off being an enormous challenge to many groups, having an on-board power supply is taken to be a future challenge to address. Prototypes were driven using a function generator and power supply. Each coil was driven with a square wave function at an amplitude of $\pm 4.5 \text{ V}$.

4.6 Summary of 2EM Series

Over the course of the project a number of different 2EM platforms were designed and fabricated. The methodology slowly evolved through trial and error and experimental results. To demonstrate the performance of the platform, the physical parameters of select platform
iterations of interest are shown in Table 4.10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>2EM14</th>
<th>2EM15</th>
<th>2EM18</th>
<th>2EM19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>( l_w )</td>
<td>30</td>
<td>30</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Mean Chord</td>
<td>( l_{ch,mean} )</td>
<td>6</td>
<td>6</td>
<td>4.6</td>
<td>4.6</td>
</tr>
<tr>
<td>Maximum Chord</td>
<td>( l_{ch,max} )</td>
<td>30</td>
<td>30</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Membrane Thickness</td>
<td>( t_c )</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Planform Area</td>
<td>( A_w )</td>
<td>182.6</td>
<td>182.6</td>
<td>110.9</td>
<td>110.9</td>
</tr>
<tr>
<td>Wing (only) Mass</td>
<td>( m_w )</td>
<td>2.7</td>
<td>2.7</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Actuator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drive Configuration</td>
<td>( d_a )</td>
<td>Rot.</td>
<td>Rot.</td>
<td>Rot.</td>
<td>Rot.</td>
</tr>
<tr>
<td>Diameter</td>
<td>( h_a )</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>Height</td>
<td>( m_a )</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Elastic Joints</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission Joint</td>
<td>-</td>
<td>2N×1</td>
<td>1N×3</td>
<td>2N×1</td>
<td>1N×3</td>
</tr>
<tr>
<td>Transmission Stiffness</td>
<td>( k_t )</td>
<td>109.2</td>
<td>40.9</td>
<td>109.2</td>
<td>40.9</td>
</tr>
<tr>
<td>Pitching Joint</td>
<td>-</td>
<td>0.5N×4</td>
<td>0.5N×2</td>
<td>0.5N×4</td>
<td>0.5N×2</td>
</tr>
<tr>
<td>Pitching Stiffness</td>
<td>( k_t )</td>
<td>3.41</td>
<td>2.56</td>
<td>3.4</td>
<td>2.56</td>
</tr>
<tr>
<td>Frame</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height</td>
<td>( h_f )</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Width</td>
<td>( w_f )</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Thickness</td>
<td>( t_f )</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wingspan</td>
<td>-</td>
<td>87</td>
<td>83</td>
<td>75</td>
<td>71</td>
</tr>
<tr>
<td>Mass (actual)</td>
<td>-</td>
<td>225</td>
<td>222</td>
<td>222</td>
<td>240</td>
</tr>
</tbody>
</table>

4.7 Lift Testing

To test the lift generated by the prototypes, the load cell based apparatus outlined in Section 4.5 was used. A nylon nut was bonded to the frame of a prototype and then mounted to the S215 load cell with a matching bolt (4-40 nylon bolt, 4613A109 and 94812A112 by McMaster-Carr Supply Company). The prototypes were mounted in line with the point where calibration was performed. The experiments would begin with the prototype at rest. As the signal from the load cell was being recorded each actuator would be driven with a \( \pm 4.5 \) V square wave signal for a number of seconds and then turned off. This procedure allowed for each data set to account for the specific weight of each prototype during analysis. A high-speed camera (Exilim EX-FL by Casio) was used to record some of the tests in an attempt to record overall kinematics. As a result of the low resolution of the camera, only qualitative information slightly better than manual observation could be obtained.
Throughout the attempts to test lift generation in prototypes, a number of challenges were encountered. The first, related to fabrication, was that a number of the early prototypes would become damaged when driven near resonance for an extend period of time. Second, was the high levels of noise present in the building as well as the circuitry. In some cases, a portion of the buildings ventilation was turned off to minimise noise. Finally, a persistent drift was present in the output signal making it impossible to calculate lift as there was no fixed reference signal for when the prototype was at rest. After much investigation, it was discovered that the electromagnetic actuators were interacting with the strain gauges in the load cell and causing the signal to drift. A simple solution to this problem involved mounting the prototypes just 20 mm higher with a longer bolt.

Early Iterations of the 2EM Series

Early prototypes were constructed with the same basic design with a large variety of transmission and pitching joint properties. The previous four-bar linkage transmission was made up of very flexible joints and the bulk of the system’s stiffness came from the natural stiffness of the piezoelectric bending-beam actuators. For the 2EM series, this stiffness had to come entirely from the flexible polymide joints. Many early iterations exhibited low stroke and pitch amplitude leading to poor performance. Another notable observation was that a large decrease in pitching stiffness would aid in increasing stroke amplitude but would still perform poorly as throughout the majority of the stroke the wing’s angle of attack was too low. In some cases, a severe decrease in pitching stiffness would cause the wing to flutter. These early iterations were vital in fine tuning later iterations and refining the fabrication process.

Iterations 2EM14, 2EM15

The iterations 2EM14 and 2EM15 were the highest performing iterations that maintained the wing dimensions of the Idealised Dragonfly. They were the product of attempts to design and fabricate a series of iterations with relatively smoothly varying properties. This was by using polymide of differing thickness and varying the width of the joint. The polymide thickness did not vary in integers but instead doubled with each thickness increase. Based on Equation 3.1, doubling the thickness of a joint while maintaining all other dimensions would result in a joint that was eight times stiffer. To allow for more delicate variation the width of the joints would vary between 0.5 - 4 mm. Any smaller was too difficult to fabricate and would tend to twist rather than bend, and any larger was too bulky and caused increased aerodynamic drag.

Both iterations functioned in very narrow frequency domains with peak performance occurring at 18 Hz. At this frequency, the 2EM14 had a stroke amplitude of $\pm 40^\circ$ and a
maximum pitch amplitude of approximately $\pm 35^\circ$ whereas the 2EM15 had a stroke amplitude closer to $\pm 45^\circ$ and a pitch amplitude of around $50^\circ$. The mean lift was calculated across 10 stroke periods and was found to be 0.71 mN and 0.78 mN respectively. Lift curves for the 2EM14 and 2EM15 can be found in Figures 4.18 and 4.19.

**Iterations 2EM18 and 2EM19**

The kinematics and lift generated by the 2EM14 and 2EM15 appeared to have a somewhat optimal configuration of joint stiffness. Further modification and refinement of the joint stiffness could potentially increase performance but was difficult to develop. Fabrication was performed by hand, and was unlikely to allow for more finely tuned transmission and pitching stiffness. Owing to the design, the physical space taken by the actuators caused the wings to actually rotate about an axis that was not directly at the wing base causing the wings to travel along a longer arc. Based on this understanding and the previous results it seemed that the aerodynamic drag was too simply too large.

In a final effort to increase performance the 2EM18 and 2EM19 were developed. These iterations were identical to the 2EM14 and 2EM15 except they had smaller wings. The same wing planform based on *Sympetrum sanguineum* was scaled down from a length of 30 mm to 24 mm. The resulting wings had a 40% decrease in planform area. Experimental tests with these new iterations showed significant changes in performance. The decrease in wing size led to a higher natural frequencies and increased stroke amplitudes. The 2EM18 was found to perform the best at 20 Hz where it was observed to have a stroke amplitude of $\pm 60^\circ$ and a pitching amplitude of $\pm 60^\circ$ resulting in a mean lift of 1.34 mN. The 2EM19 had
even more drastic kinematics with a stroke amplitude of ±65° and a pitching amplitude of nearly 75°. This iteration appeared to pitch too much resulting in a mean lift of only 1.07 mN. It appears that the tradeoffs of a smaller wing were surpassed by the increased pitching and stroke amplitude as both cases produced superior lift results when compared to their full wing counterparts.
Chapter 4. UTIAS Robotic Dragonfly and the Search for a New Actuator

Figure 4.20: Experimental results for 2EM18 while driven at 20 Hz

Figure 4.21: Experimental results for 2EM19 while driven at 23 Hz
Chapter 5

Conclusion

The hope represented by this project is to one day have autonomous flying robots that not only resembles dragonflies but also mimic their flight performance. Based on the large body of data on the species *Sympetrum sanguineum* a piezoelectric based platform was developed and in this work an alternative electromagnetic based platform was designed, fabricated, and tested.

As much of the inspiration behind this project came from the Harvard RoboBee project, an appreciable amount of time has been spent pondering why the RoboBee was able to lift-off but the UTIAS Robotic Dragonfly could not. At the end of his dissertation Szabo speculated that the issue might stem from the choice of insect being reproduced. He theorizes that the aerodynamic interactions encountered by the dragonfly are much greater than the honeybee’s short wings causing the wing tips to travel faster and encounter much greater aerodynamic damping. Among other things, this work has been able to give some support to Szabo’s speculation and experimentally demonstrate improved performance through decreasing wing size and therefore aerodynamic damping.

5.1 Discussion

To date, although lift-off was not achieved, perhaps the groundwork for the future has been made. Fabrication of the prototypes remains challenging but a new electromagnetic actuator was successfully integrated into a platform. Measurable lift was generated by some iterations that was comparable to that of the piezoelectric based designs.

A number of observations can guide future designs. First, normal hovering generates significantly more lift than asymmetric hovering. Second, increasing natural frequency may not only come from increased joint stiffness but also by changing the wing size or the axis of wing rotation. Finally, an optimal pitch stiffness is very close to having a joint that is too compliant.

Traditionally, the major focus of insect scale flapping winged MAVs have been in finding actuators that scale down yet provide sufficient power. Based on the results of this project and the successful lift-off of other small wingspan MAVs at Harvard and Shanghai Jiao Tong University [148, 132], it appears that the solution to lift-off may actual lie in scaling down of the design. It is also worth noting that while scaling down may aid in lift-off, it will likely be a cause for increased difficulty in eventually adding all of the components required for autonomous flight. To one day attain true biomimicry actuators will have to be custom
designed and manufactured and a higher fidelity fabrication process will likely be required to allow for more precise, lightweight, and complex designs. With these progressions it seems quite possible that the project will eventually achieve lift-off.

5.2 Future Work

The longterm scope of the project requires an enormous amount of development and progress. It is this author’s belief that the most effective application of future efforts would be in simulation, fabrication, increased power density, and imaging.

5.2.1 Simulation

Much of the research on insect-scale aerodynamics in recent years has come from computational fluid dynamics (CFD) and experimental work. Taking this new knowledge into account, future work on aerodynamic simulation should not only focus on the wings but on the entire vehicle. Although a couple research groups have achieved lift-off of sub-gram platforms, these vehicle designs do not physically emulate the bodies of insects. Furthermore, researchers must pursue multiphysics simulation integrating CFD and internal vehicle dynamics. To date, researchers have only simulated vehicle dynamics with simple quasisteady aerodynamic models.

5.2.2 Fabrication

Fabrication of prototypes is still a lingering challenge. It has been very difficult to cut, layer, and assemble such small and complex components. Many groups have attempted to develop insect-scale MAVs, but the only groups to develop a flying platform that can be considered to be true biomimicry are the teams at Harvard University and Shanghai Jiao Tong University. While these teams have had more success than others with less advanced fabrication abilities, the SCM process used for the RoboBee project still produces significant variability between prototypes of identical design [64].

5.2.3 Increased Power Density

In the literature, two other MAV projects have successfully achieved lift-off with electromagnetic actuation. One was true biomimicry with a linear configuration and the other was superficially biomimicking with a rotational configuration [92][148]. These demonstrate that electromagnetic actuation of flapping wing MAVs is feasible if the right conditions are met. Custom-built actuators similar to those teams would allow for an increased power-density in the actuator as the coils were constructed with enormous amount of epoxy. Furthermore,
this would not require actuator characterisation as the coil properties would be known. As the actuator currently takes up the overwhelming majority of the mass budget, increasing the power density of the actuators should be a top priority.

5.2.4 Imaging

Finally, the lack of kinematic data must be addressed. Up to this point, only qualitative kinematic information has been collected through testing. A high resolution high-speed camera would allow for more reliable method of determining stroke amplitude and wing pitching. Ideally, a multi-camera 3D tracking could give valuable information regarding the camber of the wings. Such information in conjunction with improved fabrication technology would allow for optimization of wing stiffness to camber the way living insects do.

5.3 Contributions and Closing Remarks

Contributions of this work include an extensive literature review of the field and an investigation into possible actuator technologies for insect-scale flapping wing MAVs. The result of this was selection and characterisation of an electromagnetic actuator that could be used in both a linear and rotational manner. Eventually this actuator integrated into the design and fabrication of at-scale dragonfly inspired MAV. The platform was sub-gram and is the lightest flapping wing MAV with independently driven wings to incorporate a rotational electromagnetic-based actuator to date. In recent years, the field of flapping wing MAVs has grown significantly. Currently, commercial and industrial MAVs are thriving, and number of groups have had shared similar goals, approaches and challenges. However, when it comes to insect scale projects we still face the earliest challenges such as lift-off, stable hover, and on-board power. Despite these hurdles it is inevitable that they will one day be overcome.
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