DESIGN OF A HIGH ENDURANCE MAV

by

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Francisco Javier Diez
and approved by

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ABSTRACT OF THE DISSERTATION

Design of a high endurance MAV

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Micro Aerial Vehicles (MAVs) are increasing in popularity and are finding applications in both the civil and defense sectors. A major limitation of MAV platforms is low endurance, which greatly diminishes mission capabilities. This study was restricted to MAVs with a characteristic length of 20cm or less and a weight of less than 100 grams; although, these restrictions were relaxed in a few cases. A comprehensive approach was taken to develop a high endurance coaxial MAV. A literature review showed that hover capable organisms, such as hummingbirds and bats, also suffer from the same low aerodynamic efficiency issues that MAV designers face. Following nature’s example, the maximum possible power loading, also known as hover efficiency, was increased by minimizing vehicle disc loading. Through simulations and experiments, the classic quadcopter platform proved too inefficient to achieve maximum endurance. Higher aerodynamic efficiencies did not provide a high enough power loading to achieve high endurance. This investigation shows that the coaxial configuration, due to it’s very low disc loading,
has the highest power loading and therefore the highest possible endurance. Motor/propeller matching was also performed to maximize efficiency. A database of propellers and motors was created and all possible combinations were simulated, along with different gear ratios, to shift the motor efficiency peak closer to that of the propeller. This optimization yielded a propulsion system which had a power loading comparable to biological flyers. Finally, the entire vehicle was simulated using a battery optimization model and accurate predictions of vehicle weight, thrust and endurance were obtained. Using this approach, hundreds of vehicle and component combinations can be simulated and optimized rapidly. The developed model included simulations for the static hover case and a dynamic case, where a constant climb rate was considered. Dynamic case simulations predicted the optimal climb rate to achieve maximum altitude. Using precomputed data obtained from the simulations, a Pareto front was created and an optimal vehicle configuration was selected. This approach was used to create a coaxial micro drone with a maximum achieved endurance of 37 minutes. This endurance represents a 460% improvement over the average 8 minute flight time of the sub 100g drones examined. The simulations and models developed in this study resulted in predicted MAV endurances within 30 seconds of the experimental measurements, regardless of payload or battery size. Total flight weight ranges were between 40 and 88 grams depending on payload and the MAV version in question. The final MAV platform created was foldable into a 40mm profile and launchable via a pneumatic launching device. Basic air/water capabilities were also demonstrated giving the MAV the ability to be deployed from underwater. Future work includes adding robust autonomy and swarming capabilities.
Acknowledgements

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## Nomenclature

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<tr>
<td>$\alpha$</td>
<td>Angle of Attack</td>
</tr>
<tr>
<td>$\eta_m$</td>
<td>Motor Efficiency</td>
</tr>
<tr>
<td>$\eta_p$</td>
<td>Propeller Efficiency</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Angular Velocity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of Air</td>
</tr>
<tr>
<td>$A$</td>
<td>Effective Disc Area</td>
</tr>
<tr>
<td>$BC$</td>
<td>Battery Capacity</td>
</tr>
<tr>
<td>$c$</td>
<td>Airfoil Chord Length</td>
</tr>
<tr>
<td>$C_d$</td>
<td>Coefficient of Drag</td>
</tr>
<tr>
<td>$C_l$</td>
<td>Coefficient of Lift</td>
</tr>
<tr>
<td>$DL$</td>
<td>Disc Loading</td>
</tr>
<tr>
<td>$ED$</td>
<td>Battery Specific Energy</td>
</tr>
<tr>
<td>$ED_{LiPO}$</td>
<td>LiPo Battery Specific Energy</td>
</tr>
<tr>
<td>$FM$</td>
<td>Figure of Merit</td>
</tr>
<tr>
<td>$i$</td>
<td>Electric Current</td>
</tr>
<tr>
<td>$i_0$</td>
<td>No Load Current</td>
</tr>
</tbody>
</table>
\( I_{ESC} \) \hspace{0.5cm} \text{ESC Current}

\( I_{mot} \) \hspace{0.5cm} \text{Motor Current}

\( I_{servo} \) \hspace{0.5cm} \text{Servo Current}

\( I_{veh} \) \hspace{0.5cm} \text{Total Vehicle Current}

\( K_v \) \hspace{0.5cm} \text{Motor Constant}

\( P \) \hspace{0.5cm} \text{Power}

\( P_i \) \hspace{0.5cm} \text{Ideal Power}

\( P_{elec} \) \hspace{0.5cm} \text{Electric Power}

\( P_{shaft} \) \hspace{0.5cm} \text{Shaft Power}

\( PL \) \hspace{0.5cm} \text{Power Loading}

\( Q_m \) \hspace{0.5cm} \text{Motor Torque}

\( R \) \hspace{0.5cm} \text{Winding Resistance}

\( T \) \hspace{0.5cm} \text{Thrust}

\( t \) \hspace{0.5cm} \text{Airfoil thickness}

\( T/W \) \hspace{0.5cm} \text{Thrust to Weight Ratio}

\( v \) \hspace{0.5cm} \text{terminal Voltage}

\( V_0 \) \hspace{0.5cm} \text{Incoming Fluid Velocity}

\( V_e \) \hspace{0.5cm} \text{Exit Fluid Velocity}

\( v_m \) \hspace{0.5cm} \text{Internal Motor Electromotive Force}

\( v_{bat} \) \hspace{0.5cm} \text{Battery Voltage}
\[ v_{\text{mot}} \quad \text{Motor Voltage} \]

\[ W_{\text{bat}} \quad \text{Battery Weight} \]

\[ W_{\text{frame}} \quad \text{Frame Weight} \]

\[ W_{\text{mot}} \quad \text{Motor Weight} \]

\[ W_{\text{payload}} \quad \text{Payload Weight} \]

\[ W_{\text{veh}} \quad \text{Total Vehicle Weight} \]
Chapter 1

Introduction

This chapter presents the motivation and goals for this study; while also establishing the expectations based on the benefits and drawbacks of Micro Aerial Vehicles (MAVs). This chapter also provides a brief review of current MAV platforms, with regards to a limited set of criteria. A recurring observation is the low endurance of MAVs. We therefore present the aerodynamic factors that contribute to an almost universal poor performance of MAVs.

1.1 Motivation and Goals

Recent advances in Micro-Electromechanical System (MEMS) devices, and the rapid miniaturization of electronics, as well as improvements in battery technology, enabled researchers to create smaller and smaller unmanned aerial vehicles (UAVs) [1]. Along with this, came a demand for small UAVs capable of a vast range of missions; these include reconnaissance, search and rescue, building and environment mapping, and hazardous environment missions. Advances and miniaturization in sensor technology (such as: charged-coupled device (CCD) cameras, infrared sensors and micro hazardous compound sensors) presents a wider range of useful payload capabilities [2]. MAVs often negotiate tight spaces and need to be deployed in numbers which requires them to be small, cheap and very lightweight. The term "MAV" was defined by the Defense Advanced Research Projects Agency (DARPA) in 1997 as an aerial vehicle weighing less than 100g and having a maximum characteristic length of 15cm [3]. However,
in recent years, this definition has become quite flexible. Any aerial vehicle that loosely conforms to that criteria can still be called an MAV. While MAVs are very capable, they are also plagued by a lack aerodynamic efficiency and poor electronic performance. These factors diminish MAV maximum endurance. Flight times of less than 10 minutes are very common for small hover capable vehicles \[4\][5]. Thereby, the potential for MAVs to perform useful missions is greatly diminished. These observations show the need for a high endurance MAV platform with a practical payload capability. Our goal, when beginning this project, was to develop a low cost, high endurance MAV platform capable of a vast range of missions relating to both civilian and defense applications. The major focus of this research is improving endurance. Endurance is arguably is the most limiting factor for completing practical missions. Cost factors cannot be underestimated either; because many applications require the deployment of large numbers of MAVs as in swarms. A low cost platform prevents swarm missions from becoming prohibitively expensive.

1.2 Review of MAVs

There are many types of MAVs available for use in both research and industry. Many MAVs are commercially available for entertainment; while other are purposefully built for specific defense or civil applications. This study mainly focuses on hover capable MAV’s; however, a few quasi hover capable flapping wing flyers were included for completeness. Hover capable MAVs are divided in two categories. Rotary wing MAVs; and flapping wing MAVs. The studied MAVs need to weigh less than 100 grams and have a characteristic length of no more than 200mm. Unfortunately, hover capable flapping wing MAVs are few and found primarily in academia. In order to include some of the most representative flapping wing MAVs, the characteristic length was relaxed along with
hover capability. The studied rotorcraft strictly adhered to the above mentioned constraint. Table 1.1 shows the endurance of typical rotorcraft while Table 1.2 presents the endurance of typical flapping wing MAVs. The rotorcraft in this category have an average endurance of 10.6 minutes; while the average endurance of the flapping wing vehicles is 7.1 minutes. The average endurance for all studied MAV’s is 8 minutes. This demonstrates that MAVs have limited mission capabilities due to low endurance. A notable outlier among commercially available rotorcraft is the PD-100 Black Hornet. A helicopter based, defense MAV developed by Prox Dynamics that has an exceptional endurance of 25 minutes. However the cost of this MAV started around $190,000; but according to the Army’s budget request for the 2019 Fiscal Year, it is estimated that the cost of this MAV should be around $20,000 per unit. While this a major cost improvement, the PD-100 Black Hornet remains prohibitively expensive for swarming applications.
Table 1.1: Rotorcraft Drone Endurance

<table>
<thead>
<tr>
<th>Drone Model</th>
<th>Weight (g)</th>
<th>Endurance (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD-100 Black Hornet</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>Seiko-Epson uFR-II</td>
<td>12.3</td>
<td>3</td>
</tr>
<tr>
<td>Ladybird V2</td>
<td>35</td>
<td>6</td>
</tr>
<tr>
<td>Mini X6</td>
<td>52</td>
<td>8</td>
</tr>
<tr>
<td>QR W100s</td>
<td>89</td>
<td>10</td>
</tr>
<tr>
<td>DJI Tello</td>
<td>80</td>
<td>13</td>
</tr>
<tr>
<td>Parrot Airborne Mini</td>
<td>54</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 1.2: Flapping Wing Drone Endurance

<table>
<thead>
<tr>
<th>Drone Model</th>
<th>Weight (g)</th>
<th>Endurance (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano Hummingbird</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>DelFly Explorer</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>DelFly Micro</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>H2Bird</td>
<td>13.2</td>
<td>10</td>
</tr>
<tr>
<td>Micro Bat</td>
<td>11.5</td>
<td>6.28</td>
</tr>
<tr>
<td>Bionic Bird</td>
<td>9.35</td>
<td>6</td>
</tr>
<tr>
<td>Avitron V2.0</td>
<td>9.07</td>
<td>8</td>
</tr>
<tr>
<td>36cm Ornithopter</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>28cm Ornithopter</td>
<td>30.6</td>
<td>8</td>
</tr>
<tr>
<td>15cm Ornithopter</td>
<td>8.7</td>
<td>1</td>
</tr>
<tr>
<td>10cm Ornithopter</td>
<td>4.32</td>
<td>0.5</td>
</tr>
</tbody>
</table>
1.3 Challenges Faced by Low Reynold’s Number Flyers

Despite their endless benefits and applications, MAV’s are not as widespread as their potential allows. MAVs operating at low Reynold’s numbers exhibit low aerodynamic efficiency [11]. Reynold’s number describes the ratio of inertial forces to viscous forces. Therefore, low Reynold’s number flyers need to overcome higher viscous forces which results in higher aerodynamic losses [2]. It has been demonstrated in the literature, consistently, that, compared to larger scale flyers, micro flyers suffer from higher relative viscous losses and overall lower aerodynamic efficiency [2][12]. This loss in performance is not limited to any single type of aviation. Fixed wing flyers, ornithopters (bird-like flapping wing aircraft), and rotorcraft are all victims to this phenomenon. For fixed wing flyers reducing the Reynold’s number decreases the overall performance. This is seen experimentally in the reduction of \((L/D)_{\text{max}}\), which is associated with maximum attainable range; it is also seen in the reduction of \(C_L^{2/3}/C_D\), which is associated with maximum endurance [13]. Similar conclusions can be drawn from analysis of propeller blades as is applied to hover capable rotorcraft under investigation.

A multitude of problems arise when operating at small scales some of which are presented below. Complications arise from flow structures near the airfoil, as well as flow structures in the wake of a propeller. Inefficiencies that arise due to structures near the blade, result in high profile drag losses. The increase in profile drag at low Reynold’s numbers is mainly attributed to a thicker boundary layer and the laminar separation bubble phenomenon [14][15]. Laminar separation bubble is a phenomenon caused by a strong adverse pressure gradient along the surface of the airfoil This in turn causes the laminar boundary layer to detach from the airfoil. The separated flow quickly turns turbulent and the thickness of the turbulent region increases rapidly. This region eventually reaches the airfoil again; and where the flow reattaches is called the reattachment point. The
area enclosed by the separated laminar flow and the turbulent flow is called the laminar separation bubble [14][16]. The laminar separation bubble and a thicker boundary layer intuitively contribute to significantly larger profile drag losses. Additional losses are associated with the structure of the rotor wake; where certain phenomena occur that are unique to low Reynold’s number rotors. Wake structures have been observed in the literature by using Digital Particle Image Velocimetry (DPIV). Various distinct flow structures were observed that cause additional losses. For instance, wake sheets trailing from the rotor blades were much thicker and more turbulent than their larger scale counterparts. Losses associated with tip vortices were substantially higher; and viscous core sizes of the tip vortices were relatively large compared to the blade’s chord length [17].

The cumulative effect of the above mentioned phenomena results in lower overall performance of rotors. This manifests experimentally Figures of Merit (FM) of around 0.5 for small scale propellers versus 0.8 for their larger counterparts [17].
Where $FM=1$ accounts for the ideal case of accelerating a flow through a disc area as described by the well-established momentum theory. Therefore, it is desirable to develop propellers that can perform better in the low Reynolds number range. This is a very complex problem and it’s solution might be years away. Therefore, other routes are examined to increase the performance of hover capable vehicles. Considering the aforementioned challenges, clarifying the objectives will illuminate the course of action for this research.

1.4 Objectives

The objectives for this project are divided into two categories; a set of primary objectives and the secondary objectives. Both of these objectives are guided by our goals as well as from our sponsor. The primary objectives are strictly adhered to while the secondary objectives allow some flexibility. Constraints set forth by the secondary objectives can be relaxed if other benefits are possible. In brief the objectives are as follows:

**Primary Objectives**

- Design and build a sub 100g MAV
- Optimize for maximum endurance
- Develop a step by step process for high endurance optimization

**Secondary Objectives**

- Design and build a foldable MAV with a 40mm profile
- Launchable through a simple launching device
- Amphibious capabilities - Able to be deployed from water
Chapter 2
Theory

Momentum theory was chosen and used to analyze both biological and artificial hover capable flyers. Corrections to this theory are also presented in the case of flapping wing flyers. Momentum theory is used to analyze a variety of hover capable animals. It demonstrates how nature faces the same low efficiency problems mentioned previously, and, it provides guidance as to how nature resolves those problems.

2.1 Momentum Theory

Momentum theory, also known as Disc Actuator Theory, was used to conduct MAV vehicle performance analysis, specifically the propulsion system performance analysis. It was chosen for its fundamental nature and the information it provides relating to the figure of merit. The advantage of using a figure of merit is that the analysis can be generalized to any type of hovering flyer whether biological or artificial. From momentum theory, \( P_i \) is the minimum power required for a drone to hover as in equation [2.1] [18][19].

\[
P_i = \sqrt{T^3/2\rho A}
\]

(2.1)

Where \( T \) is thrust and \( \rho \) is the medium density. Momentum theory assumes an actuator disc of a fluid with a given diameter and swept area \( A \); and it calculates the energy required to accelerate that fluid through the actuator disc [19]. Figure [2.1] shows a graphical representation of momentum theory, where \( V_0 \) represents
velocity of the incoming fluid and $V_e$ represents exit velocity of the fluid. Across the actuator disc, there exists a pressure difference which manifests as the force of thrust shown in Figure 2.1. Therefore, by knowing the propeller diameter (i.e. actuator disc) and the thrust required to hover, the power required to hover by a flying vehicle can be calculated. To calculate hover power requirements for flying vehicles in hovering mode, whereby thrust is always equal to weight, the only two parameters needed are weight and propeller diameter.

![Figure 2.1: Disc Actuator Theory/Momentum Theory](image)

**2.2 Figure of Merit**

From momentum theory, Ideal Power, $P_i$ required to hover can be calculated. This is defined as the minimum power required to hover for a vehicle when all the assumptions and simplifications for an actuator disc are considered. Therefore, ideal power can be used to define Figure of Merit (FM) as shown by Liu and Moschetta [20].

$$FM = \frac{IdealPower}{ActualPowerUsed} = \frac{P_i}{P}$$

Any hovering vehicle or organism is not without losses, and deviates from actuator disc assumptions. This implies that any vehicle or organism will consume more
power than what is predicted by momentum theory. Any value of $FM > 1$ is impossible because it would violate momentum theory. For example a drone with a FM of 0.5 would imply that it consumes twice the ideal energy required for it to hover.

2.3 Disc Loading

Disc Loading ($DL$) is a useful parameter when evaluating disc actuator theory. DL has a fundamental role and it’s use will become more apparent later. For now it is sufficient to say that an accurate representation of Disc Loading for different types of hovering flyers, will aid in rewriting momentum theory in a way that relates to vehicle endurance. DL is defined as the thrust divided by the total effective disc area \[ DL = \frac{Thrust}{EffectiveDiscArea} = \frac{T}{A} \] (2.3)

This presents a problem when trying to define DL for biological and mechanical flapping wing flyers. For rotary wings, i.e. propellers, the Actuator disc area is simply the total area swept by the propeller. For flapping wing, the actuator “disc” is defined differently and the total effective disc area needs to be found. For biological flyers and artificial flapping wing flyers, some parameters need to be known like the wing span, flap angle and the angle of the flapping plane in order to find the effective disc area. The flap angle and the wing span are used to find the area affected by wing flapping. That area is then projected from the flapping plane to the horizontal plane to obtain the actuator disc area \[21\][22]. Figure 2.3 illustrates this point where $S'_d$ is the area affected by the flapping, and $S_{d,proj}$ is the actuator disc area. The actuator disc is defined differently in the case of flapping wing flyers; because, only the area through which the flow gets accelerated needs to be considered. In other words, in the case of flapping wings, the air is only accelerated through a portion of the disc circle. It is then easy to
see how a flapping wing flyer with a very small flapping angle uses a much lower area as an actuator versus a flyer with a very wide flapping angle. The $DL$ would then be defined as the thrust divided by the total effective disc area.

**Disc Area for Rotary Wing**

![Disc Area Diagram](image)

**Figure 2.2:** A graphical representation of the effective disc area for a rotary wing. The effective disc area in this case is simply the total area swept by the propeller.
Figure 2.3: A graphical representation of the effective disc area for a flapping wing. The effective disc area in this case is the area swept by the flapping wing, projected onto the horizontal plane. [22]
2.4 Power Loading

It was mentioned in the previous section that momentum theory would be rewritten in a way that relates to vehicle endurance. We begin by defining Power Loading ($PL$) as used by Leishman et al [17].

\[ PL = \frac{\text{Thrust}}{\text{Power}} = \frac{T}{P} \]  

Equation (2.4)

PL is directly related to vehicle endurance. Power loading is defined as thrust (where thrust generated is equal to hovering vehicle weight), divided by the power required to produce that thrust. The less power required to hover a vehicle with a fixed weight, the longer it will fly given the same energy source. All things equal, a vehicle with a higher $PL$ will always have a longer endurance than one with a lower $PL$. Therefore, it is desirable to use PL as a primary parameter so that any analysis done is directly related to endurance. Power Loading is also known in the Vertical Take-Off and Landing (VTOL) community as Hover Efficiency [23]. Although not a true efficiency it is still the most useful parameter relating to hover endurance.

From momentum theory, power loading and disc loading are relatable quantities. The relationship between PL and DL provides the basis on which to analyze hovering flyers. The ideal power required to hover, $P_i$, can be written in terms of Eq. 2.1. Considering the thrust at hover, $T$ is equivalent to the vehicle weight. The ideal power is then given by,

\[ P_i = T \sqrt{\frac{T}{A}} \frac{1}{2\rho} \]  

Equation (2.5)

where $A$ is the effective disc area and $\rho$ is the density of air. The terms are rearranged to obtain the following relation.

\[ \frac{T}{P_i} = \sqrt{\frac{T}{A}} \frac{1}{2\rho} \]  

Equation (2.6)
Finally, a relation between Power Loading and Disc Loading is obtained.

\[ PL = \frac{1}{\sqrt{DL^{\frac{1}{2p}}}} \]  

(2.7)

Where \( PL = T/P_i \) and \( DL = T/A \).

This shows that for each \( DL \) there is a maximum power loading that can be achieved. Therefore, for any \( DL \) there is a maximum endurance that can be achieved for a given battery size. By plotting \( PL \) as a function of \( DL \) we notice a 1/2 power relationship between the two. As disc loading decreases, \( PL \) increases rapidly. This implies that vehicles with a large actuator disc area, and therefore lower disc loading, can hover for much longer periods of time than those with a smaller actuator disc area. Figure 2.4 shows the relationship between \( PL \) and \( DL \). It is easy to see how a helicopter, which has a very large disc actuator and low disc loading, has larger \( PL \) and hovers longer than any of its counterparts. On the other side of the spectrum, direct lift aircraft like the Harrier, hovers for a very short amount of time and consumes a large amount of fuel doing so \[40]\.

This inverse relationship is attributed to the \( DL \) which is orders of magnitude larger for the Harrier compared to a helicopter. It is important to note that there is a limit to how much \( DL \) can be reduced before adverse effects are observed. For example, a decrease in disc loading reduces the aircraft’s wind gust resistance \[48]\.

If disc loading is reduced too much an aircraft can become difficult to fly even in mildly windy environments.
Figure 2.4: This figure shows how disc loading effects power loading. We can see that a reduction in disc loading causes a dramatic increase in power loading. This also implies that a reduction in disc loading has a dramatic effect on hover endurance [23].
2.5 Clues From Nature

Earlier the challenges faced by low Re flyers were presented. To overcome this problem, we decided to get some inspiration from nature. Nature is filled with successful hovering organisms of small sizes which are also faced with the challenges of low Reynold’s number flight. So how does nature solve the problem of low efficiency? That question was answered by selecting suitable biological candidates and comparing them to artificial flyers on a PL and DL basis.

Nature has always provided clues and inspiration to engineers and helped them solve many of today’s problems. The practice is called biomimicry and it has led to many innovations in almost every field of engineering [41]. For this application, the performance of hover capable biological flyers was examined. Review of the literature offered three biological flyers worth investigating. The first biological flyer investigated was the hummingbird. This tiny bird is of great interest since it operates in low Reynold’s numbers and is one of the very few birds capable of sustained hover. There are extensive studies devoted to hummingbird hovering and ample data for analysis [24] [25] [26]. The second biological flyer investigated is a nectar feeding bat. These bats also hover while feeding and have been investigated for their hover performance [22]. It is worth noting that certain creatures might be able to hover momentarily but very few are capable of sustained hover. This study will only focus on biological flyers capable of sustained hover. To complete the investigation some hovering insects were briefly considered.

The methodology described here can be applied widely across both artificial and biological flyers. Since propellers are commonly described based on their FM, biological flyers were also described in terms of their FM. A plot that shows the FM visually is the PL in terms of DL. For hovering flyers the thrust is equal to weight. Therefore, PL reduces simply to weight divided by power. This metric
will be used in units of $g/W$ (Grams/Watt). The DL is defined as thrust, or in this case weight, divided by the area swept by the rotor, given by Eq. 2.3. Previously described, for rotors it is simple to obtain DL. But for biological fliers obtaining DL and PL is slightly more complicated. Most data obtained from biological flyer literature describes muscle mass specific power consumption, which estimates metabolic rates during hovering flight. The complete process, used to calculate the consumed power of hovering biological flyers goes beyond the scope of this research. It is worth noting however, that published parameters include muscle mass specific power consumption, total animal weight, total muscle mass and flight muscle percentage \[24\] \[25\] \[26\] \[22\]. The calculated consumed power provides the PL value; and using the methods described in the previous section, DL was also obtained.

To see how biological flyers compare to their man-made counterparts, data was plotted in terms of power loading and disc loading on a logarithmic scale in Figure 2.5. A logarithmic scale helps explore a wider range of data and makes the data easier to read. Included in Figure 2.5 is the maximum theoretical power loading as given by momentum theory, represented by the solid black line. Dashed lines represent figure of merit. Artificial drone data was obtained by simple static thrust-stand measurements performed in the lab. When it comes to biological fliers, it was expected for them to have very high FM. After all, they had million of years of evolution working to perfect their design. Efficient movement, in terms of energy consumption, is seen often in nature \[42\] \[43\], but it is not seen in hovering flight. The lack of efficiency in hovering flight is a possible indication that high FM is hard to achieve at these scales. The exception being some entomological flyers which can reportedly achieve figures of merit as high as 0.9 \[38\] \[39\]. The caveat is that these insects take advantage of unsteady aerodynamic effects and vortical flows to produce lift which might increase the FM \[27\]. However, these effects cannot increase performance over the limit provided by Momentum
Figure 2.5: In this figure artificial and biological flyers are compared on the basis of power loading and disc loading. Biological flyers also suffer from lower efficiency but can still achieve high power loading through the reduction of disc loading.

Theory. It is also worth noting that at the scale of entomological flyers, metabolic energy rates are difficult to obtain and certain assumptions must be made. Given the large uncertainty, entomological measurements were omitted from the graph, but the following discussion still applies. Along with the relatively low FM of avian flyers in Figure 2.5, it is noticeable that biological flyers also have very low disc loading. This effectively increases the Power Loading without the need to increase aerodynamic efficiency. This observation is advantageous because it is much easier to decrease disc loading than it is to increase aerodynamic efficiency and thereby the FM. As seen earlier, increasing aerodynamic efficiency would involve dealing with complex aerodynamic structures that increase losses at low Reynold’s numbers. The low FM of biological flyers also indicates that high FM is a desirable but not a necessary attribute for high endurance flying. An argument has been made that Power loading is the most objective way of comparing hover capable devices [28]. After all, endurance of a hover capable vehicle is directly
related to its power loading. It is no accident that in the VTOL community power loading is called Hover Efficiency. Therefore, FM should only be used as a relative metric when DL is held constant or approximately constant. Figure 2.5 also shows how a vehicle with low FM and very low disc loading can outperform another with very high disc loading even at the unobtainable FM of 1. Therefore, the design goal is to decrease disc loading as much as possible to move a hover-capable vehicles in a region of maximum possible power loading. This can be done in two ways: The weight of the vehicle can be decreased, which is notoriously difficult. Alternatively the propeller diameter can be increased, and in so doing the rotor swept area is increased; and assuming the weight remains constant, disc loading is effectively decreased.
Chapter 3  
Propulsion and Platform Selection

This chapter explores the various options for propulsion type and vehicle platform. The two most common propulsion types used today are flapping wing and rotary wing. We concluded that at the time of this research rotorcraft is a superior propulsion method when designing for maximum endurance. Different rotorcraft platforms were analyzed and it was shown that the coaxial platform was superior. Other characteristics of these propulsion methods and platforms are also discussed, which could be of value when designing a hover capable vehicle.

3.1 Flapping Wing vs Rotorcraft

In order to design the MAV, a propulsion method needed to be selected. It was argued in a previous section that the most objective way to compare different flyers is Power Loading, since it is directly related to high endurance. Therefore, FM was used as a relative metric for vehicles with similar disc loading. The added benefit in using these metrics is that they can be applied to any type of platform no matter how simple or complex. Assuming all things equal, a vehicle with a certain power loading will have the same endurance as any other vehicle type with that same power loading. It is so universal in fact, that it can be used for comparing artificial to biological flyers. Even though the study is focused on Power loading, a thorough investigation into different propulsion methods will be conducted. After all, endurance alone cannot account for all circumstances; other propulsion methods might offer alternative solutions preferable over increases in
endurance.

**Flapping Wing**

![Flapping Wing](image)

**Rotorcraft**

![Rotorcraft](image)

Figure 3.1: An example of a flapping wing flyer (left) and a rotary wing flyer (right) [54] [56]

### 3.1.1 Flapping Wing

The study of flapping wings is in its infancy; but the potential benefits and applications of such designs cannot be understated. For thousands of years man has been fascinated with bird flight. However, for the majority of human history, man has struggled to reproduce such means of propulsion [29]. Nature’s success in using flapping wing propulsion is a strong argument for its potential benefits. It would be impossible for million years of evolution to converge on flapping wings if it were not an exceptional means of propulsion. For example, many insects that can hover for extended periods of time and have remarkable range despite their tiny size. Until recently, technology was ill suited to reproduce biomorphic; but recently, due to advances in the fields of Computational Fluid Dynamics (CFD), microelectronics, and composites are shedding new light into flapping wing flight as a means of propulsion [29]. Further advances in aerodynamics also contribute heavily for understanding the mechanisms with which
flapping wings produce lift [1]. Since the discovery of stable Leading Edge Vortices (LEV) in insect flight, flapping wings have become an increasingly common propulsion choice for low Reynolds number applications. The literature has revealed many unsteady aerodynamic effects that help explain the production of lift in flapping wings. Based on those effects, many researchers consider flapping wings a superior form of propulsion at low Reynold’s numbers [20] [27] [30]. Quasi-steady aerodynamic models, were traditionally used to predict fixed wing and propeller performance. But those models fail dramatically at predicting the lift generation of flapping wings [21]. The actual mechanisms that produce lift in flapping wings are described later in this chapter.

While flapping wings have been observed in nature for a long time, they present obvious advantages and challenges. Some advantages are, high maneuverability, the ability to hover, the ability to mimic animals, and perhaps stability [20] [27]. In fact, many flying insects are observed taking off backwards and perform incredible maneuvers while maintaining exceptional stability. Yet it is unclear how the efficiency of flapping wings compares to that of the well-established rotating wing counterpart. Furthermore, flapping wings represent another leap in complexity because the wings are constantly accelerating and decelerating. Variations in acceleration leads to highly unsteady non-linear flows and complex kinematics which are notable hurdles in flapping wing implementation [1]. The challenges associated with flapping wings cannot be underestimated, as they produce complex, three dimensional, highly unsteady, viscous dominated vortical flows. All of which is very difficult to predict and measure. Merely, tracking vorticity for long periods of time in the wake of a flapping wing is also very challenging [17]. Regardless, these challenges have not deterred researchers who still seek to model and measure these flows. Another major drawback of flapping wings is the high mechanical complexity and subsequent high mechanical losses. The complexity in both the design and manufacture of such mechanisms, as well...
as high mechanical losses should be of the utmost consideration for any MAV design. Several hypotheses claim that flapping wings are superior to traditional rotating wings, in terms of efficiency when operated at extremely low Reynolds numbers [17][30]. It has been proposed that complex vortical flows appear to explain efficient lift production at low Reynolds numbers [27].

Normal quasi-steady aerodynamics are well established for predicting rotating wing performance; yet they fail at predicting the performance of flapping wings [21]. Several proposed mechanisms may explain the complex mechanisms of lift production in flapping wing flyers. Insect wings often undergo rapid wing reversal and pitching motions; in such transition states from pronated to supinated positions and vice versa, whereby unsteady forces are created as well as vortex shedding [27]. The literature shows that there exists multiple mechanisms from which lift is produced during every stage of wing motion. During the upstroke and the downstroke, lift is produced by LEV on the wing [1]. Additionally, the Kramer effect produces lift during pronation and supination of the wing [31]. Wake capture is another mechanism of producing lift which manifests as the wing passes through its own wake. A notable mention is Weis-Fogh’s clap-fling hypothesis although this applies to a limited species of insects [1][31][32]. Deeper analysis into these mechanisms goes beyond the scope of this study. However, it is sufficient to mention that additional processes are also at play and can be referenced if needed. It is important to note that these mechanisms have the potential to further improve aerodynamic efficiency as compared to the quasi-steady aerodynamics of rotating wings [27]. It is therefore prudent to investigate flapping wing as a viable propulsion method option for MAVs.

3.1.2 Rotorcraft

Rotors are the most common engineering solution for hovering flight. They are incredibly simple to manufacture and implement and the theory behind them
is mature and established. Multiple models exist that can predict rotor performance. Furthermore, the aerodynamic phenomena responsible for lift production are well understood. The discussion about rotorcraft will be brief as it is highly documented and widely accepted.

Due to their simple mechanical design, rotorcraft do not suffer from large mechanical losses. Mechanical losses are limited to bearings and in some cases gear losses. (If selected) Flapping wings on the other hand have complex mechanisms that undergo rapid accelerations and decelerations and almost always include gears. Therefore, it terms of mechanics, rotating wings are more efficient. On the other hand, rotors at MAV scales suffer from poor aerodynamic performance. As discussed previously, a thicker boundary layer and laminar separation bubbles are a problem for smaller rotors. This leads to increased drag and lower aerodynamic efficiency compared to their larger counterparts [14][15]. As far as aerodynamics are concerned flapping wings might have the upper hand since several hypotheses suggest that flapping wings perform better at low Reynold’s numbers. In order to settle this dispute, experimental results from literature were examined. The main focus was on experimental results because they provide the most objective comparison basis. Given that power loading is the chosen method for comparing different vehicles, FM should be used for comparing vehicles at similar DL. As such cases were reviewed over a large range of DLs and compared primarily based on the PL.

3.2 Experimental Results

Experimental results were examined which compared artificial flapping wings and rotorcrafts. Only mechanical power was considered in order to ignore any motor/system coupling, electrical losses, and/or gear train losses associated with the design. For the rotorcraft case, only shaft power was considered; and for
the flapping wing case only mechanical power was considered. Figure 3.2

![Figure 3.2](image)

Figure 3.2: A comparison of artificial flapping wing and rotary wing propulsion systems in terms of power loading and disc loading.

shows that flapping wings significantly underperform compared to rotary wings both in terms of PL and FM. Literature shows that flapping wing designs can outperform rotary wings only at extremely low Reynolds number \((Re < 500)\). This range is below the area of interest at the moment. Figure 3.2 shows that rotary wings have drastically better performance over flapping wings. This level of performance is the main driving force for selecting rotary wing as our propulsion method. Rotary wings are also less mechanically complex and easier to manufacture; This implies they should be lighter and have less mechanical losses due simpler gear trains. For all of the above, the decision was made to use the rotary wing as the MAV propulsion method.
3.3 Comparing Different Platforms

Figure 3.3: Representative rotorcraft for each of the three platforms selected for investigation [53][54][55]

When it comes to hovering rotorcraft there are multiple platforms to choose. Certain parameters were chosen as fixed, based on common design constraints. Since the goal is to maximize endurance, the most common platforms were investigated in terms of PL and DL. The three most common platforms used in hovering rotorcraft are the coaxial, the single rotor and the quadcopter/multirotor, which is currently the most favored hovering MAV design. In order to compare the three platforms some parameters were held constant across all vehicle types. The fixed parameters are the characteristic length of the rotorcraft and weight. We chose to fix the characteristic length because, effective design starts with a design envelope for the vehicle. The general size of the vehicle is one of the first parameters to be decided and it usually depends on the application of the vehicle. Identical vehicle weights were considered to make the comparison fair. Other components were ignored, or assumed identical across all platforms. By limiting parameters of length and weight, the only parameter remaining is the platform configuration itself. For the coaxial and the single rotor, the characteristic length was represented by the propeller diameter since most often that is the single largest component of the vehicle. For the quadcopter, the characteristic length will be the diagonal measurement spanning two arms including the propellers as shown in Figure 3.4.
The analysis begins with simple geometric analyses to see which of the proposed platforms offers the lowest DL. As mentioned earlier, reducing the disc loading is the easiest way to increase maximum allowable PL and therefore endurance. The propeller diameter chosen for the single rotor and the coaxial are equal to the design envelope. The idea behind this choice was to increase the maximum propeller swept area. For the quadcopter, the propeller size was chosen such that it represents the largest possible propeller that can be accommodated within the design envelope, L. This way the analysis represents the best case scenario for each platform with respect to DL. Direct observation of Figure 3.5 shows that the coaxial configuration has the largest effective actuator disc for a given design envelope. This indicates that a coaxial with a larger disc actuator implies a lower DL and, therefore, a larger maximum allowable PL. From geometric analysis we see that the quadcopter represents a 45.7% increase in DL over the single rotor, and 91.4% increase in DL over the coaxial. It can be concluded that the coaxial is superior in terms of DL; however, the FM should then also be considered to make the analysis complete.
It was mentioned earlier that FM is also an important parameter when trying to maximize the PL of a system. This brings up a caveat for coaxial platforms. The coaxial platform suffers from coaxial losses which arise from the bottom propeller operating in the wake of the top propeller. The other two platforms don’t suffer from this problem; so it is safe to assume that the single rotor will outperform the quadcopter due to the smaller DL. A question then arises: will coaxial losses overpower the benefits obtained from a reduction in disc loading? Studies showed that coaxial losses for a pair of propellers is around 22-28% compared to two independently operated propellers \[35\]. In order to complete the analysis, three platforms were simulated using Xfoil and Qprop \[34\][46]. Only mechanical power was used to avoid any complications introduced by motor/propeller coupling. Additionally, all platforms were simulated with the same propeller but scaled to fit the desired diameter. Xfoil and Qprop were validated through experimental results in a later chapter. As expected Figure 3.6 shows that coaxial rotor design has the lowest FM. This is attributed to the 28% loss imposed on the system. However, for the same weight vehicle, the hover point is at a different location on the x-axis. The hover point for the quadcopter is located so far to the right (DL>0.25), that it is not visible on the plot. Paying attention to the hover
points illustrates that a coaxial rotor design has a higher PL compared to both the quadcopter and the single rotor. This can be seen better by plotting power loading in terms of vehicle weight. Figure 3.7 shows that the coaxial outperforms all platforms in terms of PL at any thrust (i.e. vehicle weight). For completeness the consumed power plotted against thrust is also presented. Finally, Figure 3.8 shows that the coaxial platform consumes the least amount of power at any thrust level. Therefore, it is concluded that for a high endurance vehicle, optimal performance is achieved with a coaxial design.

![Figure 3.6: Comparison of the different platforms with respect to PL (Hover Efficiency) and DL. The lines plot the entire throttle range for each platform and the hover point is shown as a point. At hover, the coaxial outperforms all other platforms in terms of PL but has the lowest FM everywhere.](image-url)
Figure 3.7: Performance comparison of the different platforms with respect to PL (Hover Efficiency) and Thrust/Vehicle Weight.

Figure 3.8: Comparison of the different platforms with respect to consumed mechanical power and produced thrust. The coaxial requires the least amount of power and the quadcopter requires the most power for any thrust.
3.4 Stability

Coaxial aircraft have unique requirements in terms of control which makes a traditional Proportional Integral Derivative (PID) controller more challenging to implement compared to a quadcopter [44]. Nevertheless, it was adequate for this application and stable flight was achieved. Quadcopters are naturally very unstable flyers and therefore rely solely on the controller to remain upright [50]. They take advantage of their high maneuverability and a fast reacting embedded controller which makes thousands of adjustments per second to control attitude.

It is worth noting that maneuverability stems from the lateral distance of the propellers with respect to the center of mass (COM). This allows them to apply large moments on the vehicle. On the other hand the coaxial’s propellers are perfectly in line with the COM which implies low maneuverability compared to a quadcopter. Moments around the COM of the coaxial are produced by the cyclic control of the swash plate and the passive dampening effect of the stabilizer bar, but the moments are limited in magnitude. The coaxial stability can be compared to that of the common helicopter, which is a stable hovering vehicle. This implies that after a disturbance it always tends to return to its original vertical orientation [51]. Stability is mainly caused by the location of the center of pressure (COP) with respect to the COM. The COM is naturally lower than the COP which produces a restoring moment that tends to rotate the vehicle any time it deviates from level [52]. An empirical comparison of the three platforms in terms of stability and maneuverability is presented in Table 3.1.

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<th>Stability</th>
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<td>Quadrotor</td>
<td>Unstable</td>
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<td>Helicopter/Single Rotor</td>
<td>Stable</td>
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<td>Coaxial</td>
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For simplicity, a common quadcopter based PID controller was used for our coaxial drones. Minor adjustments were needed to adapt the controller for the coaxial. It was found that, for the PID loop to be effective for a coaxial, the distance between the COM and the COP must also be considered. This was demonstrated as in Figure 3.9. It shows the most general example and illustrates that something different should be expected when trying to control a coaxial. In a quadcopter the center of mass is located very close, if not aligned with, the center of pressure. Also, as the aircraft rotates, the weight of the motors and propellers on the arms impart equal and opposite restoring moments which cancel each other out. Therefore a quadcopter has no significant restoring moment trying to bring it back to level flight, and the controller has full authority over attitude. On the other hand, a coaxial has COM and COP spaced out considerably; and when displaced from level forces resembles a pendulum. The restoring moment increases as the angle increases. The effect is more pronounced as the distance between the COP and the COM increases or as the angle $\theta$ increases, such as in fast forward flight. In simple terms the coaxial needs constant input to maintain a desired angle; whereas an ideal quadcopter does not. This difference in the dynamics of the two vehicles proved beneficial for the intended application, because the vehicle would easily self stabilize. It is expected that a properly designed controller will perform even better on a coaxial MAV. However, designing a controller for the coaxial MAV would be too time consuming and goes beyond the scope of this research. Controller improvements were left for subsequent development; meanwhile, a well tuned, simple PID rate controller was used. To mitigate oscillations we simply reduced the distance between the coaxial MAV’s COM and COP. This approach achieved the desired hover stability with minor instabilities arising in rapid forward flight.
Figure 3.9: It is shown that a coaxial has large restoring moments when pitched or rolled. These moments are ill suited for controller designed for a quadcopter and contribute to large oscillations.
Chapter 4
Optimization

In this chapter, the various optimizations derived to achieve high endurance for the MAV are discussed. The propulsion system was first optimized and the discussion steers towards propeller parameter selection and motor propeller matching. It is shown how gearing can help match a propeller and motor which are not ideal for each other. The vehicle is then optimized as a whole and two distinct cases are considered: A static case that examines the vehicle in hover operation and optimizes battery size; and a dynamic case that investigates the effect of constant speed in axial flight. Finally, all data obtained from the models were used to create a Pareto front of optimal designs.

4.1 General Design

To briefly review the design requirements for the MAV we revisit our primary and secondary objectives: The first goal is to design and fabricate a sub-100g MAV for maximum endurance; and the second goal is to design and fabricate a foldable MAV with a 40mm profile that can be launched through a simple launching device while also maintaining air water capabilities. In the last chapter, coaxial MAVs were shown to be superior platforms in terms of PL. This vehicle profile is also beneficial for the secondary objectives because the coaxial configuration is the easiest of the three platforms to fold into a tubular profile. In addition, two propellers makes this a suitable candidate for amphibious operation since we can employ a dual plane water transition strategy as demonstrated through previous
work in this lab [15]. The ability to launch the vehicle stems from a sturdy frame design and ballistic testing, that will be performed later. Figure 4.1 shows the general design for the high endurance MAV. It is a coaxial rotorcraft implementing a small flight controller and geared DC motors. The top propeller is connected to a stabilizer bar which uses angular momentum to passively and cyclically alter the pitch of the top propeller thereby improving stability [19]; this method for passive stabilization is well established. The bottom propeller is connected to a set of servos through a swashplate which provides pitch and roll control. Each propeller is connected to their own motor through a set of gears. The independent motors are required to provide yaw control by differentially varying the torque/rpm of each propeller. Propellers are hinged, and spring loaded which allows the whole vehicle to be folded in to a 40mm profile. This form factor includes room for batteries and a payload.

![Figure 4.1: A graphical representation of the general design of our MAV. The illustration shows the deployed configuration (left) and the folded configuration (right)](image)
4.2 Propulsion Component Optimization

In order to obtain the highest endurance possible, the vehicle’s power loading needed to be maximized. It was already shown that a MAV primarily needs low disc loading; and secondarily it needs a high figure of merit. When examining the propulsion system as a whole, FM can be directly associated with propulsive efficiency. Holistically the propulsion system in its entirety implies the need to consider both the motors and the propellers and how they couple together.

4.2.1 Propeller Optimization

Previous analysis on PL and DL pertained only to propellers. Therefore, the propeller was selected first based on that criteria; and the motor was selected second based on the selected propeller. The first parameter that needed to be determined for the propeller was diameter. As discussed earlier, the diameter should be maximized within the overall design envelope. The design constraint, was that the vehicle should have a folded length of no more that 130mm. However, this does not necessarily translate to a diameter. Taking into account the need to have folding propellers and adequate propeller spacing, a maximum propeller diameter of...
diameter of 190mm was derived. Therefore, in maximizing propeller size, 190mm propellers were used. The next parameters needed for propeller design were airfoil section and propeller pitch. To select the airfoil, XFOil was used to analyze as many low Reynolds number airfoils as possible and thereby chose the one with the best performance. An estimate was first made for the $Re$ of the MAV. That value was then selected as the basis to perform all analysis. It was estimated that the vehicle would operate at a $Re$ of approximately 15000. Many airfoils were then analyzed in terms of $C_l/C_d$ vs angle of attack (alpha). The airfoil with the highest $C_l/C_d$ at that Reynolds number was chosen. The angle of attack at the peak provided the pitch of the propeller. Rigorous analysis showed that airfoils with a low thickness to chord ratio ($t/c$) performed best. In other words the airfoils with the thinnest profiles were superior at these low Re numbers. This is also consistent with findings in the literature [37]. As such, the Eppler 376 airfoil was an excellent candidate for the vehicle as shown in Figure 4.4. Unfortunately, finding a propeller with a very specific airfoil is extremely difficult and manufacturing our own propeller was prohibitively time consuming. We therefore set out to find a propeller that had an airfoil which resembled the most favorable selection. We were able to find a 190mm propeller with a manufacture’s undisclosed proprietary airfoil, as shown in Figure 4.5. This airfoil shares the low $t/c$ ratio and performed similarly to the Eppler 376. The performance of various selected airfoils, including the undisclosed airfoil used, is shown in Figure 4.3.
Figure 4.3: A graph of the Xfoil data comparing multiple low Reynolds number airfoils in terms of $C_l/C_d$ and their angle of attack. The highest peak gives us the best performing airfoil and the location of the peak on the x-axis gives us the pitch of the propeller blade.

Figure 4.4: The Eppler 376 airfoil exhibited the best performance out of all airfoils tested. The airfoil has a very low thickness to chord ratio which is associated with high performance at low Re in the literature.

Figure 4.5: This undefined airfoil was available on a 190mm propeller with similar performance to the Eppler 376
4.2.2 Motor Model

With a propeller selected, a suitable motor to drive it was examined. In order to do that it was necessary to first model and understand motor behavior. The behavior of an electric motor was modeled by the equivalent circuit shown in Figure 4.6.

![Equivalent Circuit for a brushed DC Electric Motor](image)

In Figure 4.6, \( Q_m \) represents Motor Torque and \( \Omega \) represents the motors angular velocity. \( R \) represents the motor’s Winding Resistance, \( v_m \) represents the internal back-EMF (Electromotive Force), and \( K_v \) represents the Motor Constant. Finally, \( v \) represents the terminal voltage and \( i \) represents consumed Current. It is worth noting that the motor model depicted in Figure 4.6 also accounts for losses. Frictional losses are accounted for through the \( i_0 \) term and resistive losses are accounted through the \( R \) term. Applying the typical circuit equations, as well as energy conservation, we form the following relations:

\[
Q_m(i) = (i - i_0)/K_V \quad (4.1)
\]

\[
\Omega(i, v) = (v - iR)K_V \quad (4.2)
\]

\[
P_{shaft}(i, v) = Q_m\Omega = (i - i_0)(v - iR) \quad (4.3)
\]

\[
P_{elec}(i, v) = vi \quad (4.4)
\]

\[
\eta_m(i, v) = P_{shaft}/P_{elec} = (1 - i_0/i)(1 - iR/v) \quad (4.5)
\]
Where $P_{shaft}$ is Shaft Power, $P_{elec}$ represents electric power and $\eta_m$ represents the motor’s Efficiency. To fully characterize a motor the following three parameters are needed:

- $i_0 = \text{No Load Current}$
- $R = \text{Winding Resistance}$
- $K_V = \text{RPM/Volt at no load}$

The equations presented above are all in terms of voltage and current, but it is prudent to rewrite them in terms of voltage and RPM. Having the equations in terms of RPM is useful for comparing both a motor and a propeller; because at any given time, there is direct known relationship between the two. Both RPM are equal in the case of a direct drive system; Motor and propeller RPM will be different by a constant factor for a geared system. Recognizing the differences between direct drive and geared systems aids in later analysis. To characterize a motor we focus on three parameters: torque, shaft power and motor efficiency. After rewriting the equations the following motor model equations are obtained:

$$Q_m(\Omega, v) = \left[v - \frac{\Omega}{K_V}\right]\frac{1}{R} - i_0\frac{1}{K_V}$$  (4.6)

$$P_{shaft}(\Omega, v) = \left[v - \frac{\Omega}{K_V}\right]\frac{1}{R} - i_0\frac{\Omega}{K_V}$$  (4.7)

$$\eta_m(\Omega, v) = \left[1 - \frac{i_0R}{v - \Omega/K_V}\right]\frac{\Omega}{vK_V}$$  (4.8)

Theoretical plots were obtained using the above equations for $Q_m$, $P_{shaft}$ and $\eta_m$ respectively as shown in Figure 4.7. These graphs fully describe a motor at any RPM and voltage; the most important thing to note is that the motor is most efficient in a specific range. Therefore, in order to have an efficient propulsion
system, the motor needs to operate in its most efficient range. Maximum power is observed to occur in the middle of the RPM range regardless of applied voltage. Another noteworthy observation is that maximum torque is observed at the lowest RPM while maximum efficiency is observed near the highest RPM. This implies that both high torque and high efficiency cannot be achieved directly using a DC brushed motor. In the next section, a method to overcome this issue is presented. Lastly, the motor model is verified experimentally in Chapter 6.
Figure 4.7: Motor output variables as a function of motor speed and applied voltage. Maximum power output is observed at the middle of the RPM range while maximum torque is observed at the lowest RPM. Location of highest efficiency is observed near the high end of the RPM range and is voltage dependent.
4.2.3 Motor/Propeller Matching

Propellers and motors have a region where they are most efficient. It is therefore necessary to properly match a motor to a propeller to increase the total efficiency of the system. In a well-matched system, the motor and the propeller both operate near peak efficiency at hover. In a poorly matched system either the motor, the propeller, or both, operate outside of their peak efficiency. By multiplying motor efficiency with propeller efficiency an estimate of propulsion system efficiency is obtained. Figure 4.8 illustrates how a well-matched pairs and poorly-matched pairs function. For example, assuming both motor and propeller operate at 90% efficiency the total system efficiency would be 81%. In contrast, if both motor and propeller operate at 50% efficiency, then the total system efficiency would be 25%. Once an efficient propeller design is established, efficient motor design ensures that the propulsion system operates with simultaneous motor and propeller efficiencies.
propeller peak efficiencies.

Such is the case when examining the motor efficiency map. For example, the efficiency map of the candidate MAV motor, a 8.5mm 15000Kv micro DC motor is presented. Alongside, the propeller efficiency is presented as chosen in the previous section. Figure 4.9 shows that peak motor efficiency is achieved between 30000-55000RPM and 0.5-1.5mNm of torque. At these small scales, micro motors operate most efficiently in the high RPM range. This was also observed in Figure 4.7 as $\eta_m$ for the respective RPM values. A discrepancy between motor and propeller efficiency range results in low performance when trying to match a motor with a propeller. Propellers at the scales that are being investigated usually operate at rotational speeds that are around an order of magnitude less that what is ideal for this motor. The propeller’s highest efficiency occurs in the least efficient area in the motor efficiency spectrum. If that propeller was paired with said motor directly, then 90% of the electrical energy imparted to the motor would be lost.

Figure 4.9: Propeller efficiency range (left) and motor efficiency range (right) in terms of RPM and torque. Motor and propeller efficiency peaks do not match which indicates poor performance for our propulsion system.
The next section presents a method whereby peak motor efficiency can be shifted to the propeller such that both systems can maximize their optimal performance respectively. Choosing a different motor is not always an option at these scales. Quite often there simply are not enough choices on the market in order to find an optimal motor. Figure 4.9 shows that the given motor operates well at low torque/high RPM region; while the propeller operates well in a high torque/low RPM region. This indicates that using mechanical gears, motor torque could be increased while decreasing the RPM. Gearing would result in a more optimum vehicle propulsion design. It should be noted that gearing effectively changes the $K_v$ value of the motor without much sacrifice other than a small gearing loss. Equation 4.8 shows that a change in $K_v$ would change the location of the efficiency peak; therefore, gearing can be used to match our propeller and motor.
4.2.4 Gearing

To decide whether gearing was a viable option for this application, the behavior of a geared motor needs to be understood. Gearing, effectively changes the $K_v$ value of the motor; and therefore, the model described earlier can be used to predict motor behavior. It is important to note that after the $K_v$ is changed, motor parameters calculated will now apply only to the output shaft after gearing. When gearing is applied, the $K_v$ value is divided by the gear ratio to give the new $K_v$ value of the motor. An example of gearing for the 8.5mm, 15000$K_v$ motor is shown in Figure 4.10 The motor is geared at a ratio of 4:1. It shows that the gearing essentially scales both the RPM and the Torque axes. In effect gearing moves the efficiency peak to a lower RPM and a higher torque region. This is exactly the set of conditions needed to match the selected propeller to the motor. Also the motor’s voltage limit also constrains the area covered by the efficiency map. This limit is shown as the solid black line in both graphs. Any area beyond that limit is not safely obtained without damaging the motor.

![Graph showing the effect of gearing on motor performance](image)

**Figure 4.10**: It is shown how gearing effectively moves the location of the peak efficiency by scaling the x and y-axes.

In order to select an optimal gearing, the motor gear ratio was incrementally increased until the motor and propeller peak efficiencies were aligned. After analyzing different gear ratios it was found that a gear ratio of 12:1 was ideal for
this motor/propeller combination. After gearing, the maximum efficiency of the propeller matched the maximum efficiency of the motor, as shown in Figure 4.11. The FM of our system was successfully maximized which directly increased the PL. Previously, disc loading was minimized to give the best possible chance at maximizing PL values. The effect of these two optimizations combined maximizes the overall MAV endurance. It is important to note that not every motor can be geared to perfectly match a propeller; to do so, each motor was examined through its gearing range.

Figure 4.11: It is shown how a 12:1 gear ratio achieves the optimal match between the propeller and motor in terms of efficiency.
4.3 Endurance Optimization

Endurance optimization considers the vehicle and the ancillary influential components. Models were developed to account for vehicle weight and battery capacity. Examining the total vehicle current consumption at the battery was necessary for accurate endurance calculations. A static case was investigated first as this directly reflects vehicle hovering, and represents the best case scenario for maximum endurance. A dynamic case was also investigated which represents a constant speed for axial flight; this analysis also provides information for optimal climb rate and maximum achievable altitude.

4.3.1 Static Case

Battery optimization is a crucial step in optimizing a vehicle for high endurance; but the solution may not be the most intuitive. As batteries are added to the vehicle, flight time is increased due to greater available energy; conversely, as batteries are added, vehicle weight is increased, which in turn increases the power required to keep it in the air. At some point the vehicle can become too heavy to lift itself off the ground. It is therefore imperative to select a battery size appropriate to its application.

Figure 4.12: This plot shows simulation data for the increase in RPM as it correlates to an increase in simulated vehicle weight. The static case implies the vehicle is hovering during the entire RPM range.
Static experiments and simulations were performed to simulate the hover case. In general, because the vehicle is static, the throttle increase actually increases the simulated weight of the vehicle. This is shown in Figure 4.12. This is a very useful observation; because it can then be used to calculate battery weight. With the motor and propeller selected, frame weight can be assumed to be known. For a given motor and propeller size, the frame can be designed and weight can be obtained from the CAD model. In this case, a base frame was designed for the given propeller which can be modified for each motor examined. In the CAD drawing, the frame weight remained approximately constant so it can be assumed that the frame weight is known in the model. Motor weight is known as well as the propeller weight and other components from manufacturer data. Finally, the payload weight is dictated and known by the designer. Therefore, the only unknown remaining is the battery weight, given by Eq. 4.9.

$$W_{bat} = W_{Veh} - W_{mot} - W_{frame} - W_{payload} \tag{4.9}$$

In order to find the battery capacity, Xfoil and Qprop were used to simulate power consumption of the propulsion system at every throttle level. Current draw values were obtained at every throttle level. Using the current draw and the battery capacity allows the calculation of MAV endurance. Battery capacity was calculated using battery weight and battery specific energy. In this case Lithium Polymer (LiPo) batteries were used for their high specific energy and their ability to deliver large amounts of current. Further advantages of LiPo batteries are that they come in all shapes and sizes and can be custom ordered from manufacturers at any desired capacity level. The battery capacity is then given by Eq. 4.10.

$$BC = ED \times \frac{W_{bat}}{v_{bat}} \tag{4.10}$$

where:
\[ BC = \text{BatteryCapacity}(Ah) \]
\[ ED = \text{BatterySpecificEnergy}(Wh/g) \]
\[ ED_{LiPo} = 130(mWh/g) = 0.130(Wh/g) \]

From the literature and experiments, it was found that the specific energy of LiPo batteries is around 0.130Wh/g \[49\]. Battery capacity, in units of \(Ah\), was obtained by multiplying the specific energy by the weight of the battery and dividing by the battery operating voltage. In static scenarios, thrust represents vehicle weight, and battery weight is the only variable in the weight calculation; this means that every propeller RPM level corresponds a battery weight. Battery capacity is proportional to battery weight; therefore, each propeller rpm level corresponds to a battery capacity.

To calculate vehicle endurance, one more parameter needs to be calculated, i.e. the total current for the entire vehicle. This includes the current consumption of the servos, the ESCs, and the energy losses due to the coaxial interaction described earlier. Total vehicle current consumption is given by Eq. 4.11

\[ I_{veh} = (I_{mot} \times \frac{v_{mot}}{v_{bat}} + I_{ESC}) \times 0.72 + I_{servo} \]  \hspace{1cm} (4.11)

Plotting equation 4.11 against thrust produces Figure 4.13. This figure shows how much current is drawn from the batteries for the given propulsion system at any vehicle weight. Assuming a constant battery voltage, Figure 4.13 can also be used to calculate the total power consumption at any vehicle weight. Once the current is calculated, endurance was obtained and plotted against battery capacity. Figure 4.14 shows how, as batteries are added, endurance increases. There is a complication which makes it difficult to select a battery size; The problem is that the graph lacks information on vehicle feasibility. It simply shows how long motors can operate before the battery would be depleted. It is entirely possible that the configurations at high battery capacities could indicate vehicles that are too heavy to take off or operate effectively. This is resolved by plotting endurance...
Figure 4.13: This plot shows the total current draw of the vehicle including current consumption for servos and correction for coaxial losses, as a function of Thrust to Weight Ratio ($T/W$) which results in Figure 4.15. $T/W$ ratio, the maximum predicted thrust divided by the weight of the vehicle, gives direct knowledge of the feasibility of the vehicle. Maximum predicted thrust is taken as the thrust of the propulsion system at battery voltage. Vehicles with high battery capacities correspond to vehicles with a thrust to weight ratio below one. A vehicle with $T/W < 1$, means the vehicle weighs more than the maximum thrust and therefore cannot take off. This region is shown as the red shaded area in Figure 4.15. Also, any vehicle with $1 < T/W < 1.5$ can theoretically take off, but it would be very unstable and hard to fly; this is shown as the yellow shaded region. Any vehicle with a $T/W > 1.5$ can take off and is maneuverable enough to be stable. This is shown as the green shaded region. Of note, as the $T/W$ is increased, the vehicle’s maneuverability also increases [47]. There is a trade off between maneuverability and endurance. Every point on the graph represents a different battery size. When endurance alone is considered, Figure 4.15 shows that endurance is maximized when battery size is maximized within the fly-ability
Figure 4.14: This plot shows the Vehicle endurance as a function of battery capacity. As we add battery the vehicle endurance increases. However, no information is given about vehicle feasibility.

limits provided by the T/W ratio. This figure enables a designer to select a point on the graph based on endurance and maneuverability; then a designer can select the battery size that corresponds to that point.
Figure 4.15: This plot shows the vehicle endurance as a function of thrust to weight ratio. This plot provides information about vehicle feasibility and practicality. Based on this graph alone a designer can make a decision on battery size to be used.
4.3.2 Dynamic Case

The case in which the vehicle is moving axially at a constant velocity was also investigated. Here the vehicle's airspeed is non zero which represents a constant rate of climb. The propulsion system was simulated using Xfoil and QPROP programs for various vehicle airspeeds. The vehicle was modeled as described in previous sections. The effect of airspeed on vehicle endurance is shown in Figure 4.16. The data in Figure 4.16 was filtered to only include vehicles with a thrust to weight ratio of at least 1.3. Vehicle velocities from 0 to 5m/s were modeled. A decrease in endurance as airspeed increases for any thrust to weight ratio was observed. Therefore, the scenario where the MAV is hovering stationary corresponds to the highest endurance. The effect of the decrease in endurance with airspeed is more pronounced at lower $T/W$ ratios. As the $T/W$ ratio increases and approaches 3.5, the reduction in endurance is much less pronounced. This

![Dynamic Endurance Vs T/W](image)

Figure 4.16: Effect of airspeed on endurance plot for best performer motor/propeller in Fig. 4.15. An increase in airspeed results in a decrease in endurance regardless of $T/W$ ratio. Highest endurance is achieved during hover.

is represented by the tighter spacing between the lines near the 3.5 $T/W$ as
compared to the spacing near the 1.3 $T/W$. One final observation is that for airspeeds of $4m/s$ and above, the lines never reach a $T/W$ ratio of 1.3. There are two factors that contribute to this. First, as the weight of batteries increase, and $T/W$ ratio decreases, the voltage required by the motor to produce that thrust also increases. And second, as the airspeed increases, the load on the motor increases which also results in higher voltage requirements. Therefore, parts of the lines in Figure 4.16 that do not reach a $T/W$ ratio of 1.3 correspond to vehicles that would require a voltage higher than the motor voltage limit. These points are omitted such that every point on the graph represents realistic MAV configurations.

For the hover case, the MAV is static and corresponds to no change in altitude. For the dynamic case, the airspeed and endurance can be used to calculate MAV maximum altitude. Figure 4.17 shows the effect of airspeed on maximum altitude. For a given thrust to weight ratio, as airspeed increases, endurance decreases and maximum altitude increases until it reaches a maximum value; after which, both endurance and altitude decrease. This shows that there is a compromise between max endurance and max altitude when selecting an airspeed for the MAV. There also exists a maximum airspeed after which both endurance and altitude suffer considerably. An MAV should not generally operate at airspeeds higher than what provides maximum altitude due to the sharp decrease in performance. Of course, there are cases where speed is more important, but when maximum altitude is of concern, optimal airspeed must be selected to maximize that value. It is worth noting that, in Figure 4.17 any vehicle configurations lying on the thrust to weight line are identical. For example, a vehicle that has a 35 minute endurance at a thrust to weight ratio of 1.6, is the same vehicle that has a maximum altitude of 5.4Km. This implies that as the $T/W$ ratio decreases, both endurance and altitude increase. It was mentioned in a previous section that as $T/W$ ratio increases, vehicle maneuverability also increases. Therefore, Figure 4.17 shows
that maneuverability must be sacrificed to attain higher values of endurance and altitude.

Figure 4.17: Effect of airspeed on endurance and maximum altitude. Maximum altitude increases with increase in airspeed until a maximum value is achieved, after which both endurance and altitude decrease sharply.
To complete the optimization analysis, a multi-objective optimization model (Pareto Optimization) is proposed. The multi-objectives to be optimized, include endurance, range and payload. A large number of data points were pre-computed for this optimization. All possible combinations of gear ratios, battery size, airspeed and thrust to weight ratio were computed using the methods and models described earlier. Payload was also simulated by simply adding weight to the total vehicle weight equation. The isolated effect of payload on the MAVs is presented in a later section. Operational limits of all components including voltage and current limits of all electronic components were also considered. This ensures that every data point presented represents a realistic vehicle. This brute

Figure 4.18: Precomputed data representing complete operational spectrum of a vehicle.
force approach provides the complete operational envelope of the vehicle. Figure 4.18 shows all the precomputed theoretical vehicle performance variables including endurance as a function of payload and maximum altitude. Each data point in the figure represents a unique battery, payload airspeed and gear ratio combination. As expected, the vast majority of the vehicle configurations are sub-optimal. Figure 4.18 shows a clear upper limit on performance; this limit is represented by the yellow points in Figure 4.18 as is the Pareto front.

When selecting vehicles on the Pareto front, no improvement can be made on any of the optimized parameters without sacrificing performance in another. This implies that any design that is not Pareto optimal can have at least one parameter improved without sacrificing another of the optimized parameters. Designers should, as much as possible, only select vehicle designs that lie on the Pareto front. Figure 4.19 shows only the Pareto results which form a surface. Any point on this figure represents a realistic simulated MAV. Based on the application of the MAV a designer can quickly choose a design from the Pareto front. Figures 4.18 and 4.19 can also include multiple motor and propeller combinations. This would vastly expand the investigated area and provides a designer with optimized designs that encompasses all components available at the time of design. In fact, more motor and propellers were considered in this way when designing the MAV. However, a single propulsion system was presented to avoid having figures cluttered with very large amounts of data. The process is identical to what was described already and more data points would simply add to the Pareto optimization.
Figure 4.19: Pareto front surface representing optimal design spectrum for thr MAV.
4.4 Other Component Selection

So far, the optimization problem for endurance of a coaxial vehicle has been presented with emphasis on the propulsion system (i.e. motor, propeller selection) for both static and dynamic operating cases. Motor/propeller matching for a given design objective is arguably the most important aspect when designing for maximum endurance. It is however important for the rest of the vehicle components to work well together and to be small enough and light enough for the application. For completeness, some of the important components will be presented but not analyzed in detail. The swash plate is actuated using linear servo actuators to control pitch and roll. The servo pictured in Figure 4.20 weighs only 1.5g; and the vehicle requires two servos to operate. One servo controls pitch and the other controls roll. Yaw control is provided by the torque difference between the two main motors which are each controlled by a 5A brushed motor Electronic Speed Controller (ESC), and weighs 0.4g. Control of the entire aircraft is provided by a TinyFish flight controller, which weighs 1.75g, and runs a modified version of Betaflight firmware. All the components were primarily chosen for their weight and ability to work with multiple propulsion systems.
Figure 4.20: Some of the other components used on our MAV are shown. Servo actuator (left), brushed motor ESC (middle) and flight controller (right).
Chapter 5

Design

This chapter presents the different design elements that make up the final MAV. The frame design is presented first and the component configuration used to achieve a compact MAV. The drivetrain design is then presented followed by the folding propeller design. The electronic component diagram is also shown which was simplified as much as possible to minimize weight. And finally, the final vehicle design is shown.

5.1 Frame Design

With most of the components selected the next step was to design the entire vehicle. It was mentioned earlier that one of our objectives was foldability into a 40mm profile. Therefore, our design should be as compact as possible and able to accommodate all of the components. The first thing that needs to be designed is the frame or the chassis. It needs to be small, lightweight and easy to manufacture. The frame was designed on a commercial CAD software and all the components were modeled to ensure they all fit. Multiple versions of the frame were created to accommodate different motors and other components but minimal differences exist between frames. The frame along with component placement is shown in Figure 5.1.

The frame was then manufactured by PLA plastic using additive manufacturing which resulted in a precise frame weighing only 1.8g.
Figure 5.1: Shown is the design of the frame, or chassis, of the MAV. Multiple versions of this frame were made to accommodate different motors for testing but they are all based on the same design.

5.2 Drivetrain Design

Since the design includes a coaxial set of propellers which are both located on top of the main body and electronics; a hollow shaft system was designed to independently rotate both propellers. Figure 5.2 shows a section view of the frame with the drivetrain installed. The outer shaft is shown in red while the inner shaft is shown in green. The blue component is a collar that holds the mechanism in place and is allowed to spin along with the outer shaft. Two bearings are used on the outer shaft to align it with the frame and reduce friction on the drivetrain. The lower gear is fixed to the inner shaft while the upper gear is fixed to the outer shaft. In Figure 5.2 the 6mm motors are shown to drive the mechanism; however, other variations of the frame were made to accommodate other motor sizes as well.
Figure 5.2: Shown is a section view of the drivetrain of the MAV. The inner shaft is shown in green while the outer shaft is shown in red. The gears and how they mesh with our motors are also shown.
5.3 Folding Prop Design

Since the foldability of the MAV was a secondary objective, a simple folding mechanism was opted for the propellers. Each blade is hinged at the root and held in place with a 1mm steel pin. The pin not only acts as the folding axis, but also provides a simple mount for a torsion spring which applies a constant force holding the blade extended and deployed. Figure 5.3 shows a section view of the mechanism. It shows a deployed propeller blade on the right and a folded propeller blade on the left. The torsion springs are also shown in red. This design achieves an immediate deployment of the propeller once the vehicle exits its 40mm enclosure. This would allow the vehicle to be compactly stowed and deployed upon release. A passive system without torsion springs was also considered. This utilized only centripetal force to deploy the propellers; however, in experiments, this system lacked reliability.

Figure 5.3: Shown is a section view of the simple folding propeller mechanism. It operates with torsion springs shown in red.
5.4 Electronics Design

At the scale at which the MAV is operating, electronics can take up a significant portion of its weight. At larger scales this is not always a concern because not all electronics scale with vehicle size. For example, the same flight controller that can control a 50g recreational MAV can in theory, control a 100kg agricultural drone. Other electronics, like ESCs, need to scale with size because as the vehicle increases in size, it needs a higher current to fly. It would then need larger components, such as MOSFETs, to handle increases in current. When designing for an MAV it is extremely important to have a minimalist mindset when it comes to electronics. In this case the standard UAV electronics were distilled down to their most essential components. We chose a flight controller and receiver combo that encompasses all the sensors required for flight in a small 1.75g package. Additionally, two motors were needed to produce lift and provide yaw control. Two servos were needed to provide pitch and roll control. All electronics used the same voltage to eliminate unnecessary voltage regulators which add weight and complexity to the MAV. Any other electronics used in further testing, such as cameras, were considered payload. The electronics diagram is shown in Figure 5.4.
Figure 5.4: Diagram of the electronics used in our MAV.
5.5 Final Design

The final design resulted in a compact and elegant mechanical form; it can fold to conform within the 40mm design envelope. Spacing was also maintained between the two propellers to allow for water-to-air transition, which will be covered later. The first generation MAV had a total flight weight of 39g; and the second generation had a flight weight of between 40g - 90g, all below the predefined threshold of 100g. The heaviest version tested had a weight of 90g but had some stability issues. Figures 5.5, 5.6, 5.7 and 5.8 show the final design of our MAV which we named the GadFly.

Figure 5.5: Final Design Front View
Figure 5.6: Final Design Back View
Figure 5.7: Final Design Bottom View
Figure 5.8: Final Design Folded Configuration
Chapter 6

Results

This chapter begins by experimentally verifying the simulation results obtained by Xfoil and Qprop. It also outlines the experimental setup used to make measurements. A few different versions of the completed MAVs are presented. Their performance is compared experimentally to the theoretical predictions as well as with other existing MAVs. A successful launch and subsequent flight of the MAV is also presented followed by a demonstration of its water/air capabilities.

6.1 Experimental Results

So far the analysis presented was based on theoretical models. This section presents how those models were verified with experimental results. Xfoil and Qprop were primarily used for simulating the propulsion system. In order to verify the obtained results, an experimental setup was constructed to measure the parameters of interest. We constructed the thrust stand shown in Figure 6.1 to measure thrust, torque, voltage and current at the motor. RPM was also measured using a LASER beam which was interrupted by the spinning propeller; the frequency of the interruption was measured through a photodiode. A voltage sensor was connected in parallel to the motor and a current sensor was connected in series to the motor. Both were connected to a custom built Arduino based DAQ. A load cell was mounted behind the motor to measure thrust and was also connected to the DAQ. A torque sensor was mounted axially to the motor as shown in Figure 6.1. Data was collected simultaneously to ensure no variations
Figure 6.1: Experimental setup used to measure Thrust, Torque, Voltage, Current and RPM.

between runs which would manifest as errors in the data. In the case where ESC losses needed measurement, a voltage and current sensor were connected before and after the ESC. This gave electric power readings in and out of the ESC and power losses were thus calculated. The frame itself was constructed from steel to increase rigidity and minimize vibrations.

When testing the propulsion system, 200 samples were taken at each datapoint and the average was used in Figures 6.2, 6.3, 6.4 and 6.5. Agreement of thrust and torque with theoretical values indicates a valid aerodynamic model of the simulation; while agreement of voltage and current with theoretical values, indicates a valid motor model. First, Thrust as a function of RPM is presented in Figure 6.2 and Torque as a function of RPM is presented in Figure 6.3. The plots represent results for the previously selected 190mm propeller and the 8.5mm 15000Kv motor. Experimental thrust values match theoretical predictions with an average error of 2.58%; while torque measurements deviate from the theoretical with an average error of 16.7%. When examining Figures 6.4 and 6.5 it was concluded that this disagreement had a negligible effect on the final result. A
possible source of error for the torque measurements might be the sensor itself. Unfortunately, the sensor available was not rated for such small measurements. In order to collect torque data, a large number of data was collected and averaged for each data point. The hope was that, with enough data points the mean value would converge to the actual value. However, final simulation results for endurance are based on the voltage and current predictions; therefore, more weight was given in validating voltage and current.

In order to determine how well the simulation models performed, the motor was examined for voltage and current, both plotted against thrust. This might be an unconventional way to plot these variables; but there is merit in doing so, for example the application shows how much current is consumed at a given thrust level/vehicle weight. Experimental voltage values match theoretical predictions with an average error of 3.07%; experimental electric current measurements match theoretical measurements with an average error of 4.36%. This agreement validates the performance predictions of the propulsion system since power consumption predictions are accurate. This also indicates that the simulation predicts motor performance. Electric current predictions in Figure 6.5 includes the current consumption by the motor ESC. It is worth noting that the losses associated with the ESC are due to the switching of a MOSFET used to regulate voltage. At full throttle and zero throttle the MOSFET is constantly on and constantly off respectively, which implies no switching and therefore no losses. That is why the first and last data points for electric current do not match the prediction. This could have been added to the model; however, there would be no impact on the final endurance prediction since no vehicle ever operates at full throttle at hover. For this reason error calculations ignored the first and last experimental measurements.
Figure 6.2: Experimental Thrust as a function of propeller RPM. Agreement of thrust to the theoretical results indicates a valid aerodynamic model.

Figure 6.3: Experimental Torque as a function of propeller RPM. Some disagreement of Torque to the theoretical results is observed. This could be attributed to the use of an improper torque sensor.
Figure 6.4: Experimental Voltage as a function of Thrust. Agreement of voltage to theoretical results indicates a valid motor model.

Figure 6.5: Experimental Current as a function of Thrust. Good agreement of electric current to theoretical results indicates a valid motor model.
6.2 Optimized Propulsion System Performance

After verifying the predicted results with experimental data the performance of the optimized propulsion system was presented. The performance of the propulsion system, as exhibited in Figure 6.6, presents the entire operational map of the propulsion system as compared to the biological and artificial flyers presented previously. As the weight of the MAV increases the DL and PL change as well. This is shown by the solid orange line in Figure 6.6. The line represents the full operational map of the given motor/propeller combination. Figure 6.6 also shows that the performance of the propulsion system is comparable to biological, hover capable flyers of similar scale. While at higher DL the performance of the propulsion system is comparable to that of larger drones with an FM of approximately 0.6. This represents significant improvement over the propulsion systems used in most MAV’s of similar scale that only reach an FM of less than 0.2. The optimized propulsion system outperforms other MAV’s in both PL and FM. Vehicle performance on the given spectrum is a factor of total vehicle weight. The highest PL does not correspond to the highest FM. This again indicates that high efficiency is a desirable, but not necessary, factor for high endurance flying. Ideally, to achieve maximum endurance, the vehicle should operate at maximum PL, where the peak of the orange line occurs. This is not always possible since the weight of the fixed components could force operation in the higher DL region.
Figure 6.6: Optimized propulsion system performance compared to biological hover capable flyers and artificial drones. PL is comparable to biological flyers and larger drones at higher DL.
6.3 Primary Objective Results

![Image: First Generation GadFLy in deployed configuration (left) and in hovering flight (right).]

Multiple motors were examined to determine the best choices for the GadFLy MAV. The first-generation GadFLy used a 6mm 14000Kv motor which was selected based solely on size and geometric constraints. This motor is very popular in MAVs and is used extensively in both commercially available micro drones and in research. The second-generation GadFLy used a 8.5mm 15000Kv motor which was selected according to the motor optimization discussion in Chapter 4 and matched to the optimal propeller. The first-generation GadFLy performed admirably with a maximum endurance of 13 minutes, compared to the average of 8 minutes for MAVs. It used a 190mm propeller and weighed 39 grams and has a thrust to weight ratio of 1.6. The thrust to weight ratio indicates there is little room for improvement for this motor/propeller combination. It is worth mentioning that the only optimization performed on the first generation GadFLy was related to the propeller alone and focused on simply minimizing DL. An improvement in endurance of 62.5% compared to the 8 minute average is testament to the importance of minimizing DL. The second-generation GadFLy used the optimally selected motor, gear ratio, and battery combinations to achieve a very impressive maximum endurance of 37 minutes. This is over four times longer than
Figure 6.8: Second Generation GadFLy

The average MAV endurance. Different versions of the second generation GadFly were created and their performance can be seen in Table 6.1. At its heaviest the second generation GadFly was unstable; but it was able to remain airborne for the duration of the test. This is common as a drone Thrust to Weight ratio falls below 1.5 and demonstrates that the dynamics of the vehicle changes as weight was added and the controller had difficulty stabilizing the vehicle. It also shows that there is a limit to how much the thrust to weight ratio can be reduced before

Table 6.1: Second Generation GadFly Performance

<table>
<thead>
<tr>
<th>Battery Size (mAh)</th>
<th>Weight (g)</th>
<th>Endurance (min)</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
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<td>41.2</td>
<td>9.4</td>
<td>Stable</td>
</tr>
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<td>14.6</td>
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<td>1350</td>
<td>72.8</td>
<td>30.8</td>
<td>minor instabilities</td>
</tr>
<tr>
<td>1800</td>
<td>88.2</td>
<td>36.7</td>
<td>major instabilities</td>
</tr>
</tbody>
</table>
major stability issues arise. The manufacture and experimental testing of these vehicles allowed verification of the theoretical model developed which is based on momentum theory.

Figure 6.9: Theoretical and experimental endurance results for a micro coaxial drone showing how increasing battery capacity increases endurance and reduces thrust to weight ratio.

Endurance for each MAV configuration was measured by fully charging the batteries and performing a simple hovering flight without any translational motion. The flight was timed and the experiment ended when the vehicle could not produce enough thrust to stabilize itself and remain airborne. The experimental results along with the predictions made by the MAV model is presented in Figure 6.9. It shows the improvements in endurance that can be achieved with proper optimization of an MAV. Theoretical predictions are presented for four different motors, all paired with the same propeller. As mentioned previously, only vehicles with a $T/W$ ratio above 1.5 should be considered. Figure 6.9 provides complete information about hover vehicle performance when no payload is considered. Maneuverability is represented by the $T/W$ ratio and endurance is given directly. Each point in the theoretical line represents a different battery size which means that, when maximum endurance is desired, a complete vehicle
can be selected based on this figure alone. The significance of this figure cannot be underestimated. Endurance measurements represented in Figure 6.9 were observed to be within 30 seconds of the theoretical predictions, which validates our complete theoretical MAV model. Vehicles with different combinations of motors, propellers, gearing and other components can be represented in this graph and the selection process becomes apparent. The graphs in Figure 6.9 represent vehicles with no added payload. The effect of payload on the optimized MAV was also investigated. Figure 6.10 shows how the performance of the optimized

![Effect of Payload on Endurance](image)

Figure 6.10: Effect of payload on endurance plot for best performer motor/propeller in Fig. 6.9. Endurance is reduced with the addition of payload at all $T/W$ ratios.

MAV changes with payload increase. Reduction in endurance of a vehicle with the addition of payload is more pronounced at higher $T/W$ ratios and less pronounced at lower $T/W$ ratios. This is seen as the wider spacing between the lines at higher $T/W$ ratios and the tighter spacing at lower $T/W$ ratios. Using this graph, a designer can select the optimal battery configuration for a UAV at any given payload and thrust to weight ratio. Thus, this graph fully represents the performance of a UAV for any payload and battery configuration.
It is often desirable for a designer to know the performance of a system with a fixed thrust to weight ratio and for different payloads. To maintain a constant thrust to weight ratio, the addition of payload has to be counteracted by a removal of the same weight of battery. Thus, the total weight of the vehicle remains the same as the payload increases. This is especially useful when operating at a very low thrust to weight ratio. For example, if the vehicle operates at a thrust to weight ratio of 1.5, more payload cannot be added and keep the vehicle flyable based on the limits mentioned earlier. Therefore, as we add payload we should remove battery weight to maintain the ratio of 1.5. Plotting the endurance vs payload for a fixed 1.5 thrust to weight ratio, represents the best case scenario when it comes to endurance for any payload. The graph therefore represents a limit of performance for the selected thrust to weight ratio. Figure 6.11 represents the endurance plotted against payload for an arbitrary thrust to weight ratio of 2.2. This thrust to weight ratio was selected because it provided exceptional stability in testing. The relationship obtained is linear since battery capacity is removed without adding weight. And therefore for the same power consumption, a given battery capacity will be depleted at a constant rate; that would imply a linear relationship. Experimental results are also shown to verify our model.
Figure 6.11: Effect of payload on endurance for a constant thrust to weight ratio of 2.2.
The MAVs presented in Tables 1.1 and 1.2 are revisited and plotted in terms of endurance and weight in Figure 6.12. The purpose is to compare the performance of the GadFly to already existing vehicles that fall within the parameters dictated in the first chapter. Figure 6.12 shows that the GadFly outperforms all MAVs which were selected for this study in terms for endurance. The GadFly can remain airborne for 12 minutes longer than the next best performer; and the GadFLy can fly 24 minutes longer than rotorcraft of the same weight. It is worth noting that the next best performer is the PD-100 Black Hornet, a vehicle significantly higher in cost as compared to the GadFly. The cost of the GadFly was kept low to allow for future applications such as swarming and large scale operations. The performance of the GadFly is further proof that an optimization approach which aims at reducing DL and maximizing PL, is extremely effective at maximizing hover endurance of an MAV. The results obtained from this optimization approach are not limited to MAVs. The theories and methods used to develop these models apply to any size hovering vehicle; which implies that, improvements in endurance can be achieved in larger hovering vehicles. Although we expect the effect to be less pronounced for their larger counterparts.
Figure 6.12: Final Performance Comparison of the GadFly MAV.
6.4 Secondary Objective Results

The three secondary objectives described in Chapter 1 are addressed next. The first objective mentioned was the desire to have a foldable MAV in a 40mm profile. Figure 6.13 shows the GadFly folded and nested in a 40mm tube. The propellers have some compliance which allows them to bend slightly and conform around the MAV components. This compliance allows for flexibility in the design which implies that precision in the folding mechanism is not a primary concern. Of course, the use of stiffer propellers would require a slightly more precise folding mechanism. It is worth noting that multiple versions of the GadFly were constructed and not all conform to the 40mm profile.

A 40mm tube was also used to construct a pneumatic launcher capable of launching the vehicle at different velocities. The launcher design was kept simple and consisted of a pressure chamber, a 40mm diameter barrel, and a solenoid valve to release pressure and send the vehicle out of the barrel, shown in Figure 6.14. To ensure the MAV would survive launch, the vehicle was designed such that the force from the launch would apply to the lower gears which in turn applies the force to the frame itself. In this manner, no sensitive components are directly impacted by the launch; although they are still subject to the same abrupt acceleration forces. A sabot with a foam pad was constructed; it was placed behind the GadGly to protect it during launch and seal the escaping
Figure 6.14: Pneumatic MAV Launcher

Figure 6.15: Successful GadFly Launch
pressurized air. Multiple tests were conducted with launches performed outdoor at higher velocities, and indoors at much lower velocities. During the outdoor tests, wind gusts were an important factor; and for strong wind gusts, the vehicle was immediately landed after launch. Future work should quantify the wind gust operational limits of the vehicle. A successful launch is shown in Figure 6.15. Indoor launches went flawlessly with the MAV stabilizing instantly after the launch and full control was regained.

Amphibious operation was achieved with this vehicle; although it is limited to simple deployment from water and not dedicated water operation. To achieve water-to-air transition, the dual plane transition strategy was implemented. This strategy was demonstrated in previous lab publications [45]. This strategy consists of two independent propellers or rotors that provide thrust on two different parallel planes that are adequately spaced apart from each other. Each propeller has the ability to switch between a water mode, which is a low rpm/high torque setting, and air mode, which is the normal motor operation setting. The idea behind this is that any propeller which is submerged underwater operates in water mode; and when out of water, the propeller operates in air mode. By this logic, the transition process breaks down to five stages that are illustrated in Figure 6.16. In stage one, both propellers are submerged and therefore both operate in water mode. They are both applying an upwards force to bring the vehicle to the surface. In stage two, the top propeller reaches the air/water interface and is turned off while the lower propeller keeps lifting the vehicle up. In stage

![Figure 6.16: Dual Plane Transition Strategy](image-url)
three, the top propeller is out of water and begins to spin in normal air operation and pulls the vehicle out of the water. The bottom propeller, being submerged, continues to thrust in water mode to assist with vehicle exit. In stage four, the bottom propeller is at the water/air interface and is turned off, while the top propeller continues to lift the aircraft out of the water. Finally in stage five, all propellers are out of water and engage in normal air operation; then a mission can commence as normal. From experiments it is known that propellers work reliably both in water and in air but have difficulty at the interface. That is one reason why propellers stop at the interface; it also gives time for the motors and ESCs to transition from mode to mode. One more reason the propellers are stopped is to avoid disturbances that can contribute to instabilities for the vehicle. Figure 6.17 shows a successful water to air transition of the GadFly.
Figure 6.17: Successful Water to Air Transition
Chapter 7
Conclusion

The ultimate goal of this study was to develop a high endurance MAV platform capable of a vast range of applications. A review of the literature revealed that MAVs suffer from low aerodynamic performance, which is common for all low Reynolds number flyers. The mechanisms contributing to poor performance at small scales were identified and presented. Most notable was the laminar separation bubble which is known to increase profile drag in propellers and wings operating at low Reynolds numbers. Several solutions have been proposed in the literature; however, no proposed solutions were able to effectively be utilized at the scale and weight of interest. Biological hovering flyers were explored and analyzed, based on momentum theory, to gain some insight as to how nature addresses such issues. It was found that biological hovering flyers such as the hummingbird, the nectar feeding bat, and various insects also suffer from similar aerodynamic phenomena. At hover they exhibit a relatively low FM of approximately 0.5. Their success at hovering is attributed to their low DL which results in higher PL. Following nature’s example, it was decided it would be best to circumvent the problem of low aerodynamic efficiency instead of solving it. This resulted in optimizations and analysis that focused primarily in the reducing of DL and the maximizing of PL. Such an approach is also supported by Momentum Theory.

The two most popular propulsion methods, the rotary wing and the flapping wing, were examined and their potential benefits and drawbacks were presented. Experimental results from the literature were compared and analyzed in
terms of PL and FM, based on Momentum Theory. It was found that the traditional rotary wing outperforms the flapping wing both in terms of power loading and FM; and therefore, it was selected for this application. The most popular hovering vehicle platforms were examined. The quadrotor, the single rotor, and the coaxial were analyzed in terms of DL. The coaxial proved to have the lowest disc loading and the lowest FM. To make the selection different platforms were simulated while keeping the weight and the characteristic length identical. Despite the low FM, the coaxial platform proved to be the best performer in terms of PL.

The airfoil for the propeller used in the coaxial MAV was selected based on $C_l/C_d$; and its diameter was maximized within the design envelope to minimize DL. Different motors were examined and matched to the propeller. The effect of gearing on the efficiency peak of the motor was presented and used to select the motor and gear ratio. By selecting the correct motor and gear ratio, the performance of the propulsion system was optimized. In a matched motor/propeller pair, both the propeller and motor operate in their respective regions of highest efficiency. A 8.5mm, 15000Kv, DC motor with a gear ratio of 12:1 was selected for this application. The performance of the optimized propulsion system was compared to biological flyers, based on Momentum Theory; and the optimized propulsion system was found to be comparable to biological flyers at similar DL. At higher disc loading the performance of the propulsion system was comparable to that of larger drones. A model was created to simulate the entire MAV including battery, servos, ESC losses, and other components. Using that model, an endurance optimization was performed for both the static and dynamic cases. For the static case the thrust of the propulsion system equals the weight of the vehicle. In this case, the battery size was optimized to provide the highest endurance MAV; however, a sacrifice in maneuverability was observed at lower $T/W$ ratios which corresponded to the highest endurance. The dynamic case, where
the vehicle climbs axially at a constant rate, was also simulated. As airspeed was increased, a decrease in endurance was observed. By simulating the dynamic case, optimal airspeed was selected to achieve maximum altitude. Values beyond optimal resulted in a sharp decrease in both endurance and maximum altitude. Using both the static and dynamic cases, a multi-objective Pareto optimization was performed. All possible vehicle configurations were precomputed and used to create a Pareto front attempting to maximize endurance, altitude and payload. As a result the Pareto front defines the MAV’s entire operational limits.

To verify the theoretical models used in the simulations, a thrust stand was created to measure thrust, torque, voltage, electric current, and RPM. Multiple MAVs were then constructed and tested to verify the predictions made by the theoretical models; these MAVs were named GadFlys. The first generation GadFly was optimized only in terms of DL by careful selection of a propeller and demonstrated a maximum endurance of 13 minutes which represents a 62.5% increase over the 8 minute average for this scale. The second generation GadFly achieved a maximum endurance of 37 minutes which is over four times the average. The endurance measurements from these MAVs were used to verify the model developed for simulating the entire vehicle. The experimental measurements for endurance were within 30 seconds of the theoretical predictions. This result validates the models used, both for the propulsion system and for the entire vehicle. Finally, the effects of payload on the MAV were demonstrated, i.e. for the endurance curve as a whole and on the fixed $T/W$ ratio.

A set of secondary objectives was also achieved. The GadFLy MAV can be folded into a compact 40mm profile and then launched from a pneumatic launcher. This simple launcher was developed specifically for this project; it was able to launch the MAV both for both indoor and outdoor tests. Water/air capabilities were also demonstrated. The tests were limited to simple deployment from an underwater environment followed by transition to normal air operation. The
capabilities of the GadFly cannot be underestimated. Together they contribute to a robust platform capable of a vast range of missions. Virtually any sensor can be integrated, and along with the high endurance and multimodal locomotion abilities, forms an almost universal platform with applications in defense and civil sectors. The cost of this unit was also kept very low. (under 350 dollars in hardware to be exact.) This allows the GadFly platform to be used in swarming applications where hundreds of MAVs can be deployed cheaply.

7.1 Future Work

This prototype MAV shows promise for further development, research, flight controls, as well as mission applications and operations. Preliminary tests were performed to integrate autonomous capabilities on the GadFly. The goal is to continue this research and integrate micro GPS and compass technology. Micro electronics for this application were already selected and fall well within our payload capabilities. Future applications of a working autonomous GPS enabled system will include waypoint navigation, target tracking, and various swarming missions. Future work would also focus on developing a dedicated controller for improved stability. Finally, larger versions of the GadFly will be developed using the principles outlined in this document. Larger versions might offer even higher endurance and greater payload capabilities which would further expand the operational spectrum of this platform.
References


