Feasibility Study of a Solar Powered Hybrid Micro-Aerial Vehicle

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ABSTRACT

Micro aerial vehicles (MAVs) are finding new applications every day, from surveillance to civil structure health monitoring and exciting photography. Parallel advancements in ultra-thin, high power-to-weight ratio (PWR) solar panels are paving the way for sustained flight, especially for MAVs that are heavily dependent on the limited energy density of batteries. There is renewed interest in solar-powered MAVs, which can offer unprecedented flight times on sunny days. In this context, we propose a solar-powered hybrid MAV configuration, named 'Solar Swifter' that combines the performance of a quadcopter, allowing vertical take-off and landing (VTOL), with the capabilities of a fixed-wing aircraft for conventional cruise flight. Preliminary analysis has shown that with just 1.9 W from ultra-high PWR air-stable solar panels (Organic Photovoltaic, OPV), an MAV with a mass of $51g$ can achieve vertical take-off and fly at $8m/s$. This performance can be further enhanced by using a lower aspect ratio wing, resulting in a square-shaped wing. The next step in developing the Solar Swifter is to investigate the aerodynamic effects of a fan-in-wing configuration at low Reynolds numbers, which has not been studied in the past.

1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are rapidly becoming integral to various aspects of everyday life. Among these, Micro Aerial Vehicles (MAVs) have garnered significant attention, particularly for their potential in autonomous applications [1, 2]. A major challenge in achieving full autonomy for MAVs lies in the incomplete understanding of how performance, power, and computational limitations impact their functionality. MAVs must operate within stringent power budgets, severely limiting their flight endurance.

One promising solution to this limitation is the use of solar power. It has been shown that it is feasible to have solar powered micro aerial vehicles [3, 4], albeit, requiring further performance improvements.The performance and application of MAVs are limited by their mode of flight. They are typically either rotary-wing, which allows vertical take-off and landing (VTOL) and hover capability, or fixed-wing, which enables relatively higher payload, range, and endurance capabilities. This paper investigates the performance of a hybrid MAV that combines both rotary and fixed-wing capabilities, aiming to leverage the performance advantages of each. The recent advancements in flexible solar panels [3, 5, 6] which offer high PWRs, provide additional motivation for this approach. By integrating these technologies, the hybrid MAV could potentially enhance both the flight endurance and operational flexibility, making it more suitable for a wide range of applications.

2 AERODYNAMIC CHARACTERISTICS AT LOW REYNOLDS NUMBER

MAVs are classified based on their mass, up to 100 grams, and size, up to 0.1524 m (or six inches). This classification places them in the Reynolds number range between 10^4 and 10^5. This relatively low Reynolds number implies that the aerodynamic efficiency, specifically the lift-to-drag (L/D) ratio, of their wings is much lower compared to larger aircraft, as illustrated in Figure1.

The low L/D ratio at low Reynolds numbers is primarily due to the dominance of viscous forces, early laminar flow separation, inefficient pressure recovery, thicker boundary layers, and reduced lift generation. Understanding these factors is crucial for designing efficient aerofoils and aircraft operating in this regime. The low L/D ratio imposes higher power demands, which is particularly challenging for MAVs, where the power budget is already stringent. Therefore, aerodynamic design requires extra care to mitigate these effects.

The Reynolds number range of 10^4 to 10^5 lies at a transition point where the L/D ratio can vary significantly, potentially changing by an order of magnitude depending on the aerofoil design. Appropriate surface roughness can help maintain linearity in the L/D ratio within this Reynolds number range. However, achieving favourable surface roughness is challenging at the MAV scale.

The Reynolds number has a significant impact on the lift-to-drag (L/D) ratio of a cambered aerofoil, whereas a symmetrical aerofoil experiences relatively minor changes, as shown in Figure 2. For a symmetrical aerofoil, such as the NACA 0003, a five fold increase in Reynolds number ($1x10^5$)

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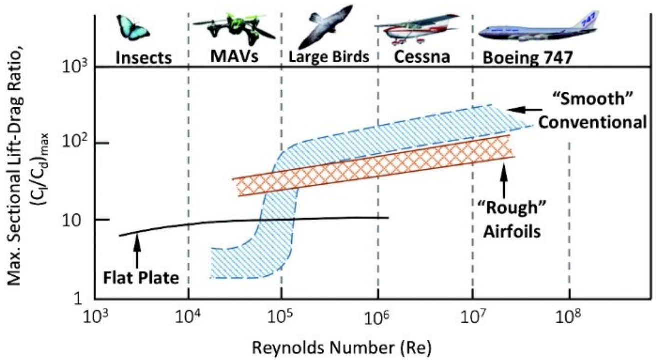

Figure 1: Aerodynamic efficiency of wing-section versus Reynolds number for different regimes of aircraft (taken from [7]).

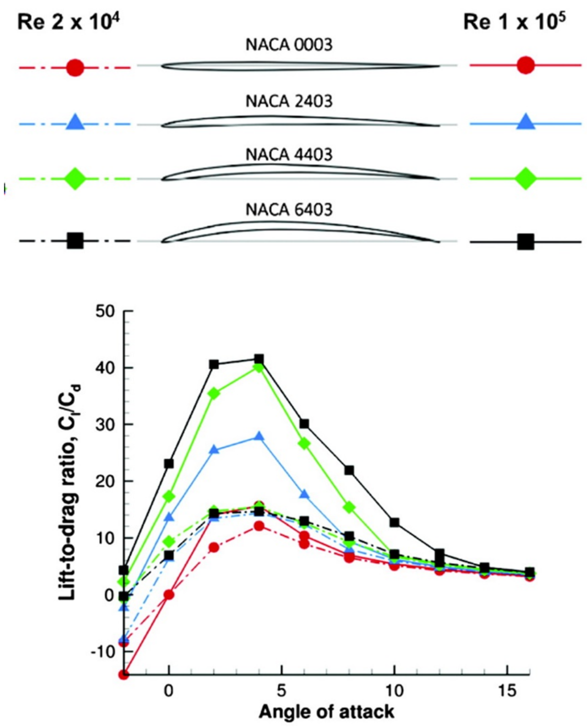

Figure 2: The effect of Reynolds number on different aerofoils used for MAVs (adapted from [7]).

results in 1.4 times increase in the maximum section lift to drag ratio (C_l/C_d). In contrast, for a cambered aerofoil, like the NACA 6403, the increase in section lift to drag ratio is approximately threefold. Additionally, higher camber aerofoils such as the NACA 6403 offer significantly higher aerodynamic efficiency compared to lower camber aerofoils such as the NACA 4403 and NACA 2403.

3 Performance Analysis of MAVs

Micro Aerial Vehicles (MAVs) primarily utilise three configurations: fixed-wing, rotary-wing, and flapping-wing. Each configuration has distinct characteristics that influence performance and application.

Flapping-wing MAVs are typically very lightweight and offer a few minutes of endurance, making them suitable for specific short-duration tasks [8]. Rotary-wing MAVs, such as the DJI Mavic 3, which weighs 963 grams and can fly for up to 43 minutes [9], are highly maneuverable, providing useful range and endurance. Fixed-wing MAVs, on the other hand, offer the best endurance and range for a given mass. For instance, the Black Widow, weighing 80 grams, can fly for 30 minutes [10], whereas a comparable rotary-wing MAV, such as the QRW100S, weighs 90 grams but only offers 10 minutes of endurance.

Figure 3 summarises the performance of MAVs across these configurations. On average, fixed-wing MAVs provide approximately 2.5 times higher performance compared to rotary-wing MAVs. Flapping-wing MAVs exhibit the best performance for MAVs weighing less than 50 grams, overlapping with the category of Nano Aerial Vehicles (NAVs). This comparison highlights the trade-offs between maneuverability, endurance, and weight among different MAV configurations.

4 Solar Powered Aircraft

The quest for a solar powered aircraft began in 1974, the very first aircraft was named Sunrise which had a span of 9.75 meters and an empty mass of 12.25 kg [12]. To date over hundred different solar powered aircraft have been built and flown [13], out of those the most prominent aircraft considered to be be milestones of solar flight have been collected in [14] along with their performance data.

Micro Aerial Vehicles (MAVs) have garnered significant attention for their potential in various applications, including surveillance, environmental monitoring, and disaster management. Enhancing their endurance and operational efficiency through the integration of solar panel technology has emerged as a fruitful avenue. Initial research into solar-powered MAVs primarily focused on feasibility studies and conceptual designs. Early efforts were hampered by the limited efficiency of photovoltaic cells and the high weight of available solar panels. Researchers experimented with various MAV designs to optimise the surface area for maximum solar exposure while maintaining aerodynamic efficiency [6].

Silicon-based solar cells, representing the first generation of solar technology, are primarily divided into two types: monocrystalline and polycrystalline silicon. Monocrystalline silicon cells are renowned for their high efficiency, typically ranging from 20% to 25%. However, they are costly to produce and rigid, limiting their applications where flexibility is required. In contrast, polycrystalline silicon cells offer moderate efficiency, between 15% and 20% [15], at a

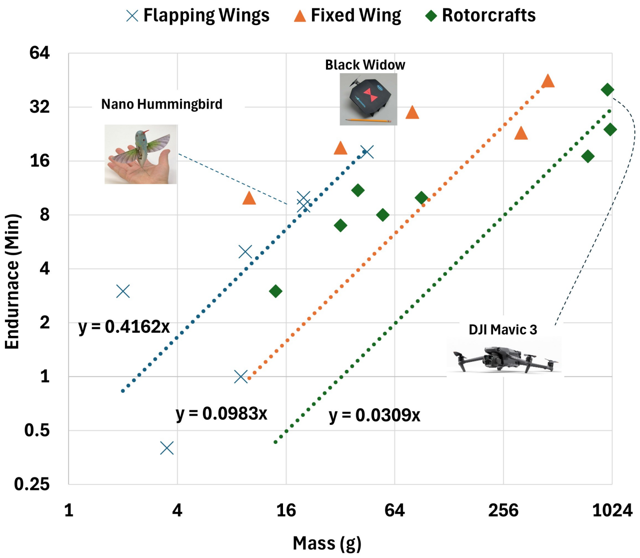

Figure 3: The Endurance performance of MAVs with different configurations (data sources [10, 11, 9]).

lower cost, making them more affordable but less efficient compared to their monocrystalline counterparts.

Thin-film solar cells, considered the second generation of solar technology, include materials such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). CdTe cells provide moderate efficiency (10-16%) [16] and perform better in low-light conditions, making them suitable for diverse environmental settings. CIGS cells offer higher efficiency (12-20%) than CdTe and have the added advantage of being flexible, which broadens their application range. However, their production process is more complex. The advent of ultrathin perovskite solar cells marks a significant advancement in solar technology. These cells exhibit rapidly improving efficiencies, with laboratory results exceeding 25%, thus rivaling and potentially surpassing traditional silicon cells. Perovskite solar cells benefit from high absorption coefficients and tunable bandgaps, allowing for tailored applications and the potential for higher efficiencies through tandem structures.

Organic photovoltaics (OPVs) are another emerging technology with current efficiencies lower than silicon and Perovskite cells, typically in the range of 10-15% [17]. Despite this, OPVs offer significant advantages, including their lightweight and flexible nature. They can be manufactured using low-cost, roll-to-roll processes, making them attractive for applications where flexibility and lightweight are crucial, such as in portable and wearable electronics.

Figure 4 highlights 'typical' losses along the route from the sunbeam to the thrust force, including battery charging and discharging, which amounts to a net loss of 85% to 89%. This substantial figure clearly indicates the need for optimising each sub-system to achieve good overall performance. Theoretical values for maximum efficiency for solar cells range between 15% and 25%, [3] depending on material characteristics, as highlighted above, but these values are not typically achieved in practical production cells.

Most solar cells are mechanically cut silicon slices, and the material is often too thick to be lightweight. To protect these cells from mechanical damage, humidity, and temperature, they must be embedded in a foil or fiberglass. New manufacturing processes have been developed to deposit a thin silicon layer onto a foil, resulting in very lightweight and flexible cells. The efficiency of thin solar cells has considerably improved in recent years, thanks to advancements in material science and fabrication techniques.

Despite these improvements, optimising the entire energy conversion and storage system is crucial to enhancing overall efficiency. This includes improving solar cell efficiency, minimising losses in battery charging and discharging, and enhancing the aerodynamics and weight distribution of MAVs. By addressing these areas, we can significantly reduce energy losses and improve the performance and endurance of solar-powered MAVs.

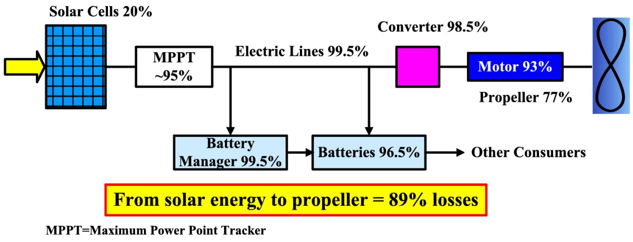

Figure 4: Typical energy losses in a solar powered propulsion system (adapted from [18]).

For the application of solar technologies in MAVs, the most fundamental performance attribute is the power-to-weight ratio (PWR). The PWR of solar panels has evolved rapidly over the past decade. The PWR of different technologies, as illustrated in Figure 5, suggests that OPVs are the highest performers with a PWR as high as 33.8 W/g. The ultrahin Perovskite comes second with a PWR of 30 W/g. However, due to higher solar energy conversion efficiency, the Perovskite solar cells are particularly suitable for applications where weight, efficiency and flexibility are critical factors and that is the MAVs.

5 CONCEPTUAL DESIGN - HYBRID MAV

Having discussed the solar technologies above, it is useful to study successful electric MAVs when designing a solar MAV. Lockheed Martin's MicroSTAR4 has a mass of 85 g, a 23 cm wingspan, and a cruise speed of 11 m/s. The Black Widow, another notable MAV, has a mass of 80 g, a wingspan of 15 cm, and a flight time of 30 minutes. The Black Widow

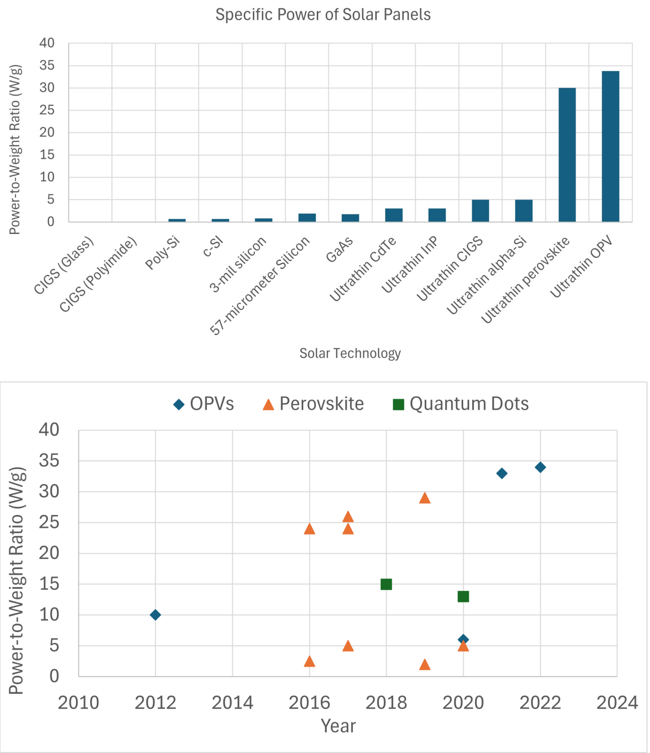

Figure 5: The Power-to-Weight ratio of different solar technologies (data source [7]).

utilises 4.35 W of power from its batteries [10].
It has been shown that propeller efficiencies of 80 percent or greater are achievable at the MAV scale, and motor efficiencies of 70 percent [4, 10] are also possible . Additionally, an aerofoil with a maximum linear dimension of 0.1524 cm can fly at the low Reynolds numbers associated with small aerofoils and low speeds, achieving a lift-to-drag ratio of 10. For the Black Widow, the 80 grams of total mass are divided into approximately 50 grams for propulsion, 10 grams for payload, 7 grams for controls, and 14 grams for the structure. In summary, compiling basic design parameters for solar and electric MAVs is beneficial. 6 lists the wing loading and PWR of different solar-powered aircraft and MAVs. It is clear that the relatively low wing loading, i.e., an ultra-lightweight body, is crucial for the flight capabilities of MAVs.

Solar-powered MAVs are feasible in either rotorcraft or fixed-wing configurations [4, 13, 19]. Combining these two configurations can offer performance benefits, including improved range, endurance, payload capacity, and maneuverability. Figure 7 presents a sketch of the proposed configuration, named 'Solar Swifter SS1'. The main features include solar panels covering the top surface, a propeller attached to the nose of the aircraft providing forward thrust, and triple propellers providing vertical thrust or lift. The triple propellers are attached to the wing tips and the tail, enabling pitch and lateral stability and control by positioning the center of gravity aft of the aerodynamic center. Furthermore, the propellers are ducted or embedded in the wing, which may offer up to 100 percent lift enhancement with a drag penalty [20].

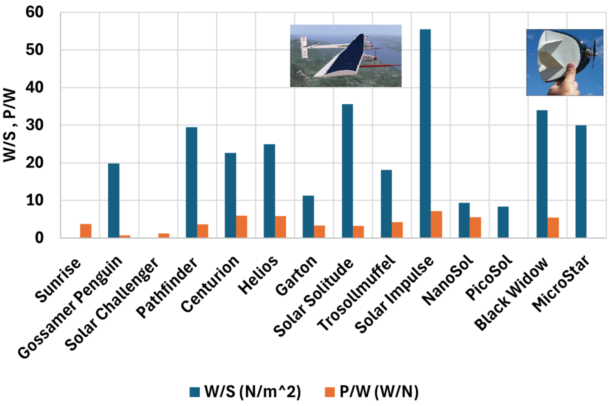

Figure 6: Comparing wing loading and power loading of solar powered aircraft and MAVs (data source [13, 4])

5.1 *The Sizing Approach*

The MAV class of aircraft lies at the critical Reynolds number regime where lift to drag ratio can jump ten folds which can negatively impact the performance as highlighted above in Figure 1. The sizing can begin by locking the span dimension to 0.1524 m, to comply with the widely endorsed maximum size of MAVs [1, 11, 21]. The relationship of Reynolds number with aspect ratio of wing for different air speeds is plotted in Figure 8, a low aspect ratio, $AR < 2$, for the range of flight speeds considered, $6 < V < 20$ m/s, enables Reynolds number above 1×10^5 to utilise the significant aerodynamic benefits highlighted in the previous section.

In level flight the required thrust depends on the overall drag of the aircraft, the standard drag equation is given below

$$C_D = C_{D_0} + \frac{1}{\pi A R e} {C_L}^2 \tag{1}$$

where C_{D_0} is the zero-lift drag. A conservative estimate of the zero-lift drag coefficient is made, estimating it to be 0.05. This value is derived from considering the friction coefficient for laminar and turbulent flow over a flat plate at a Reynolds number of 1×10^5, which is approximately $0.04 < C_{D_0} < 0.06$ [22]. The lift dependent drag is a function of Oswald efficiency factor e (a factor that represents the change in drag with lift for a three-dimensional wing or aircraft) which is significantly different at the low Reynolds number regime considered herein [23]. At the Reynolds number of 1×10^5 the Oswald efficiency can significantly change with the aspect ratio and the taper ratio λ of the wing, see Figure 9. An AR value of 5 can reduce the Oswald efficiency by

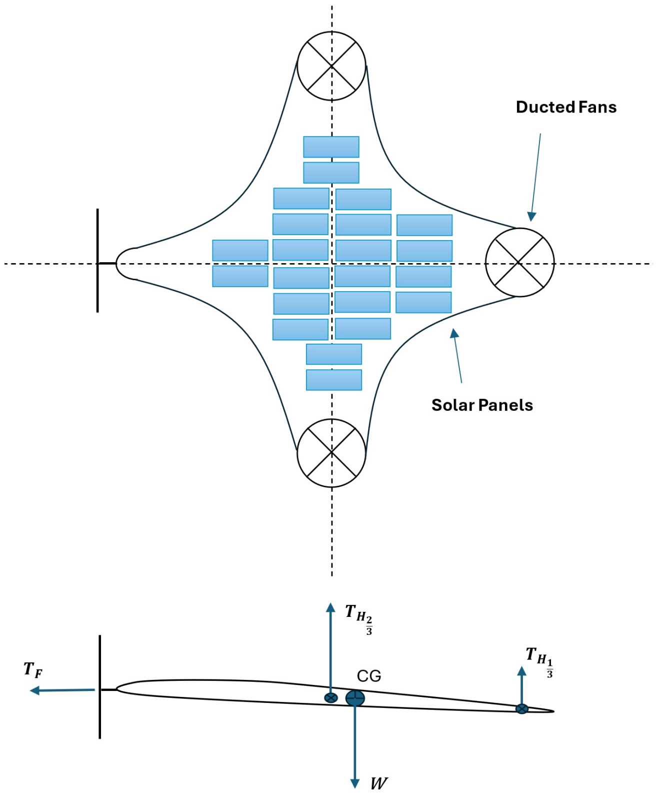

Figure 7: A sketch of the proposed configuration.

50% compared to an AR value of 2. This further consolidates the design point to be around AR of 2.

6 FLIGHT PERFORMANCE OF SOLAR SWIFTER SS1

An estimation of Solar Swifter's performance can begin by evaluating the available power, which depends on the efficiency and power loading of the solar panels used. In this context, we employ the recently developed ultra-thin organic photovoltaic (OPV) panels [6], known for their high power-to-weight ratio (PWR) of 33.8 W/g, weight-to-area ratio of 0.0458 N/m$\hat{2}$, and efficiency of 15.8% under a solar irradiance of 1000 W/m$\hat{2}$. Therefore, the available power is directly proportional to the wing's plan area, calculated as $P_{ava} = 0.0458S$ W.

The available power must be sufficient to support both vertical take-off and landing (VTOL) as well as forward flight modes. During vertical flight, the aircraft must overcome gravity and air resistance. Consequently, the required thrust can be determined using the following equation:

$$T_{VTOL} = (W_{pp}+W_{St}+W_{Sys}+W_{Sol})+\frac{1}{2}\rho V_c^2 S C_{D_P} \quad (2)$$

where W_{pp} is the weight of powerplant, W_{St} is the structural weight, W_{Sys} is the systems weight, W_{Sol} is the solar panels weight, V_c is the vertical or climb velocity and C_{D_P} is the profile drag coefficient. To evaluate the air drag in vertical flight mode, we assume the aircraft behaves like a flat plate with airflow perpendicular to the plan area. The profile drag coefficient of a flat plate is 1.28 [24].

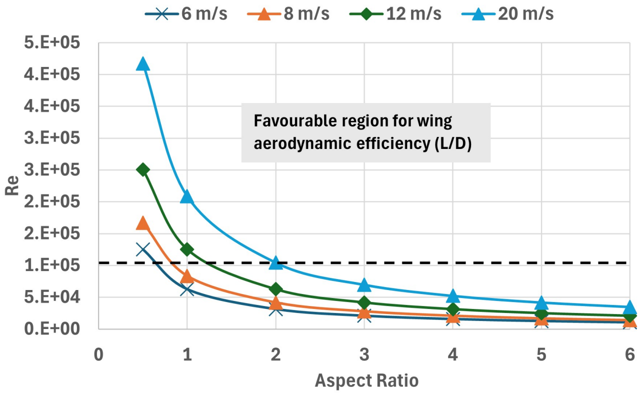

Figure 8: Reynolds number versus aspect ratio of the wing.

The weights of the powerplant, structures, and systems can be approximated based on the weight of MAVs in its class, excluding the weight of the batteries, as the Solar Swifter is designed to be entirely solar-powered at this stage. For MAVs in this class, the weight of batteries and/or solar panels can constitute up to 40% of the maximum take-off weight [10, 25, 4]. For instance, a solar-powered quadcopter described in [19] weighs 70 g, with the weight excluding batteries and solar panels being 50 g. This information enables a preliminary power budget estimation. The power required for vertical flight can be evaluated using the following equation.

$$P_{VTOL} = \frac{1}{\eta_p} V_c(50\times10^{-3}\times9.81+0.0458S+\frac{1}{2}\rho V_c^2 S C_{D_P}) \quad (3)$$

η_p is the propulsive efficiency taken to be 80% and the profile drag coefficient is taken to be 1.28.

Similarly for the forward flight mode the power required is given by

$$P_{FF} = \frac{1}{\eta_p}\frac{1}{2}\rho V^3 S(C_{D_0} + \frac{1}{\pi ARe}{C_L}^2) \quad (4)$$

The 10 illustrates the flight capabilities of the conceptual design. For an aspect ratio of 2, which corresponds to a rectangular wing, the available power is 1.9 W. This configuration supports a cruise velocity of $8m/s$ and a maximum vertical climb velocity of $2.5m/s$. In contrast, an aspect ratio of 1, corresponding to a square-shaped wing, significantly enhances performance. With this configuration, the available power increases to 3.7 W, enabling a cruise velocity of 9 m/s and a vertical climb velocity of 4.2 m/s.

Furthermore, for the given surface area the addition of ultra

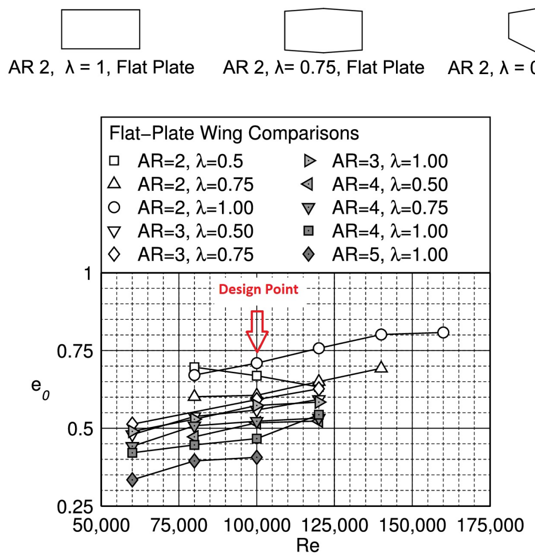

Figure 9: The effect of aspect ratio (AR) and taper ratio (λ) on Oswald's efficiency for different Reynolds number (derived from [23].

thin OPV solar panels add less than a gram of weight which is less than two percent of the take-off weight. This extraordinary power to weight ratio may allow open up the possibility of increasing the payload performance.

7 CONCLUSION AND FUTURE WORK

The preliminary analysis have shown that with the recent development of ultrahin OPV solar panels a solar powered flight of the proposed configuration is possible. The performance is predominantly dependent upon the aspect ratio, a lower aspect ratio $AR < 2$ implies high surface area and Oswald efficiency factor. At the scale of six inch span a maximum cruise velocity of 9 m/s and a vertical climb velocity of 4.4 m/s is possible.

The preliminary performance analysis of the Solar Swifter serves as a foundation for the future development of renewable energy-powered hybrid MAVs. Further exploration is needed to investigate the potential for integrating vertical and forward thrusters, which could reduce stall velocity and expand the range of operational velocities. This will involve examining the impact of fan-in-wing configurations on the MAV's aerodynamic performance during forward flight. While the effects of fan-in-wing designs have been studied at higher Reynolds numbers [20], no studies currently exist for low Reynolds numbers (i.e. $Re < 1 \times 10^5$).

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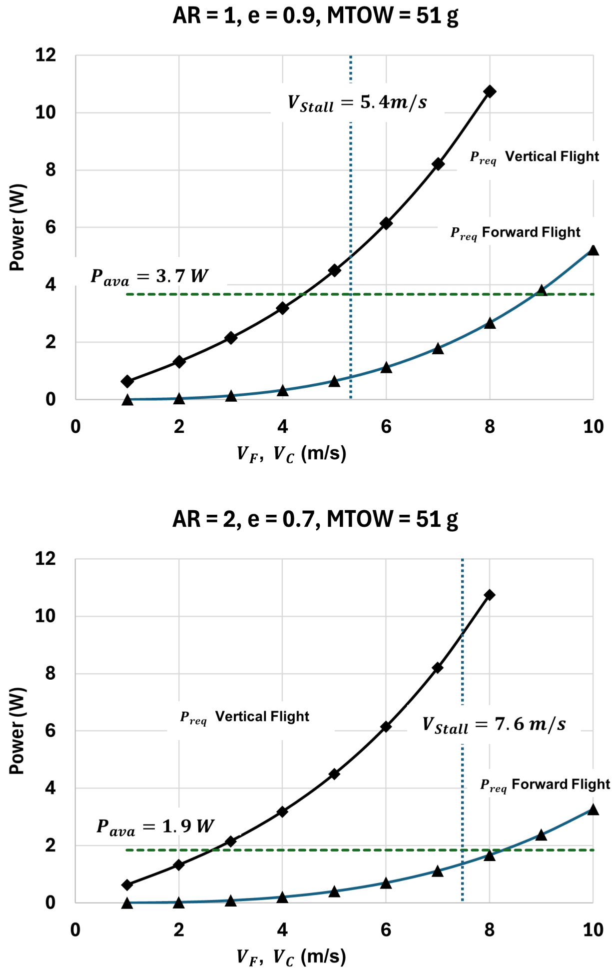

Figure 10: Preliminary power budgeting for forward and vertical flight.

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