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A Parametric Study on Design Variables for Solar Powered Long Endurance Unmanned Aerial Vehicle

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ABSTRACT

Solar-powered long-endurance unmanned aerial vehicles (UAVs) offer significant potential for various applications due to their extended flight endurance. However, optimizing the design of solar-powered UAVs to achieve maximum efficiency and performance remains a complex challenge. The main objective of this research is to explore the sensitivity of solar-powered UAV mass to different design variables and technological constraints. The study employs a conceptual design methodology, iterating through various design configurations while specific design variables within bounds of historical data. Key parameters, including aspect ratio, wing span, payload mass, power consumption, cruise altitude, and technological constraints such as solar panel efficiency and battery energy density, are systematically varied to analyze their impact on UAV mass. The study also considers the influence cloud cover on solar power generation. This parametric study's results divulge solar-powered UAV mass's sensitivity to these design variables and technological constraints. By identifying key factors influencing UAV mass, the study offers actionable insights for designers and engineers in aerospace industry. The findings contribute to advancing the understanding of solar-powered UAV technology and lay the groundwork for future research and development initiatives to enhance UAV performance and efficiency.

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1. Introduction

1.1 Application of Solar Powered UAVs

Solar-powered long-endurance UAVs, have potential application in fields of communication(Mohsan et al., 2023), surveillance(Sharma et al., 2020), disaster management, and crop monitoring(Velusamy et al., 2021). Regenerative nature of solar energy enables extended flight endurance for these UAVs (C. Zhang et al., 2021). Solar power uses overcome the limitations of traditional battery-powered UAVs, which often have short flight duration(Townsend et al., 2020). By harnessing solar energy, UAVs can power onboard equipment for these applications involving continuous surveillance.

1.2 Geometric Configuration and Mission Requirements

Mission specific requirements dictates overall configuration of solar powered UAV. (L. Zhang et al., 2021). Shape and size of wings are critical elements of UAV configuration. Mission requirements, such as weight and power consumption of onboard equipment add to the complexity of the design(İlhan & Çalık, 2024). Cruise altitude and environmental conditions also influence the area of solar panels (Turk et al., 2022).

1.3 Onboard Power Systems and Structural Constraints

Power consumption of onboard equipment is key design determinant of solar powered UAV. (Chen, 2022). As power consumption of equipment increases, large wing area is required for solar panel installation. As weight of the UAV increases, power requirement for sustained flight increases, which in turn requires additional solar panel. This cycle continues until a new convergence is achieved at which power consumption of sustained flight and onboard equipment is balanced by available solar power. (Al Dhafari et al., 2024). Overcoming these practical challenges is essential for broader application of solar-powered UAVs(Mukhachev et al., 2022).

1.4 Impact of Design Variables on UAV Mass

The research posits that variations in design variables, such as Aspect Ratio (AR), span (b), cruise altitude, solar panel efficiency, and battery energy density, significantly impact mass of a solar-powered long-endurance UAV (Gao et al., 2023). Specifically, it is suggested that optimizing these design variables through an iterative design cycle will lead to a demonstrable reduction in UAV mass while meeting mission requirements with extended flight endurance (Zhang et al., 2020).

1.5 Challenges in UAV Mass Optimization

This research examines interplay of various design factors and how they affect overall weight of a solar-powered UAV(Zhang et al., 2022). The aim is to minimize UAV weight while meeting specific design needs, critical for efficient and prolonged flight. This approach is essential for developing lightweight, high-performance solar-powered UAVs, particularly for missions that require them to stay in the air for extended periods(Moelyadi et al., 2021).

1.6 Significance and Implications

The significance of this research lies in its examination of the growth sensitivity of UAV mass to key factors, including geometry parameters, mission requirements, environmental conditions, and technology constraints. This study provides an influence of these design variables on the overall mass of UAVs. These insights can help designers and engineers make better choices to improve performance of solar powered UAVs. The study also shows how to customize UAVs for different missions and environmental conditions. The study further elaborates on the weight sensitivity of UAVs to advancements in technology. The findings have broader implications for optimizing and using renewable energy in aviation.

2. Literature Review

2.1 Historical Evolution of Solar-Powered UAV

The design methods for solar-powered UAVs have evolved significantly over time, combining aeronautical engineering, renewable energy, and innovative design methodologies. To date, 93 solar powered UAV have been designed. These UAVs range from small remote-controlled models to high-altitude and long-endurance (HALE) platforms, showing the flexibility and scalability of solar-powered UAV technology across different sizes and applications(Elmeseiry et al., 2021).

2.2 Early Development and Proof-of-Concept Studies

In the early stages of developing solar-powered UAVs, the main goal has been basic feasibility through proof-of-concept studies (Shehu et al., 2021). Researchers looked into placing solar cells on the surfaces of UAVs to produce electricity for propulsion and onboard systems. The focus was on making the solar panels as efficient as possible while balancing the amount of energy generated with the energy used by UAV(Wu et al., 2023).

2.3 Aerodynamic Optimization

As technology advanced, the focus shifted to optimizing aerodynamic design of solar-powered UAVs(Bhutta, 2023). This involved refining wing shapes, aspect ratios, and structural designs to meet power and weight growth of onboard systems. More sophisticated methods, such as computer modeling, wind tunnel tests, and simulations, have been used to boost the aerodynamic performance of these UAVs(Lakshmanan et al., 2023).

2.4 Use of Advanced Materials and Energy Storage Solutions

Modern composites and lightweight alloys are now essential to designing solar powered UAVs (Prakash et al., 2023) . This change is done to reduce structural weight without significantly compromising the strength and stiffness of airframe. At the same time, a shift from conventional batteries to high energy density storage systems is observed(Kidd et al., 2020). This transition allowed for storage of excess solar energy during day time to provide propulsive power for night operation.

2.5 Mission-Specific Design Considerations

As the next central theme, researchers evolved the design of solar powered UAVs for mission specific requirement's such as surveillance and monitoring missions (Molina et al., 2023). Design methodologies emerged to satisfy mission needs such as payload, altitude and operational characteristics (F. Khoshnoud et al., 2020).

2.6 Research Gap in UAV Mass Sensitivity

Despite these advancements, a significant literature gap exists whereby, sensitivity of UAV mass to various design variables including Aspect Ratio (AR) and span (b) remains unexplored(Dang et al., 2023). Additionally. no investigation delves into the impact of mass and power consumption of payload, cruise altitude, weather conditions, solar panel efficiency, and battery energy density on the overall mass of solar powered UAV (Yudan et al., 2020).

2.7 Proposed Research

To address this gap, presented study explores the effects of design variables, mission requirements and technology constraints on mass of solar powered UAVs. The research also meets the challenge of optimizing UAV configuration. This research opens future development avenues in UAV technology by enhancing knowledge on weight sensitivity to design variables.

3. Aim of Research

This research aims to present sensitivity of UAV weight to geometry variables, design requirements and technology constraints. By identifying the critical parameters which affect weight growth of solar powered UAVs, this sensitivity analysis can identify critical parameters which affect weight growth of solar powered UAV. By addressing these variables, weight of solar powered UAV can be reduced.

4. Method Section

Conceptual design methodology for solar-powered UAVs, presented by Hwang(Hwang et al., 2019), serves as the foundation for mass estimation. The weight growth of UAVs is influenced by eight parameters outlined in Tables 2, 3, and 4. Employing conceptual design methodology, each design iteration is converged while adjusting the aspect ratio and an additional variable within predetermined bounds. Built-in iteration tool of Microsoft Excel ® is used for design cycle. The remaining design parameters are kept fixed at baseline values during each iteration. UAV weight is then plotted against aspect ratio and another design variable to demonstrate weight sensitivity to these parameters. Datafit ® software is used for plotting weight of solar-powered UAV versus design variables.

Figure 1 presents the mass of a solar-powered UAV (m_{tot}) as a sum of individual components while the mass of each component is a fraction of the total mass of UAV (m_{tot}). Based upon heuristics(George & Jacob, 2024), the mass of individual components is projected as:

i. The mass of control servos (m_{servos}) is assumed as 1 % of total mass (m_{tot}).

ii. The power consumption of these servos(P_{servos}) is taken as 1.2 % of total power consumption(P_{tot}).

iii. Mass ($m_{payload}$) and power consumption ($P_{payload}$) of payload depend upon mission requirement.

iv. The mass of solar panels (m_{cell}) depends upon total power consumption (P_{tot}) and efficiency of the solar cell (η_{cell}).

v. Wing reference area(S_{ref}) is the projected area of wing and span(b) is the distance between the two wing tips. Eq. (1) expresses the mass of airframe in terms of aspect ratio(AR) and wing span(b)(Farbod Khoshnoud et al., 2020).

$$m_{struct} = 0.44b^{3.1}AR^{-0.25} = 044b^{3.1}(\frac{b^2}{S_{ref}})^{-0.25} \quad (1)$$

vi. Maximum power point tracker (MPPT) is a device that adjust voltage of solar panels to maximize power output. Eq. (2) gives its mass(m_{MPPT}) which is directly proportional to the total power consumption(P_{tot}) of UAV. (Farbod Khoshnoud et al., 2020)

$$m_{mppt} = k_{mppt}P_{tot} \quad (2)$$

vii. Eq. (3) presents the mass of propulsion system (m_{prop}) which is directly proportional to power required for flight (P_{req}) (George & Jacob, 2024)

$$m_{prop} = 0.005P_{req} \quad (3)$$

viii. Mass of battery (m_{batt}) depends on its energy density (k_{batt}) and energy required to be stored on board.

ix. Mass of UAV (m_{tot}) equals the sum of masses of individual components. Eq. (4) presents total mass of UAV as sum of masses of individual components(Farbod Khoshnoud et al., 2020).

$$m_{tot} = m_{cntrl} + m_{payload} + m_{cell} + m_{sytuct} + m_{mppt} + m_{prop} + m_{batt} \tag{4}$$

A meaningful information can be extracted from this methodology when these 30 parameters are classified in following 4 types;

i. The first group includes parameters that can be assumed constant for specialized applications because current state of mature technology does not warrant any significant improvement in these constants. For example, propeller efficiency can be considered 85 % for a perfect design. These design constants are given in Table 1.

ii. The second group has 2 variables, namely, Aspect Ratio (AR) and wing span (b), which define the wing planform of a UAV. Table 3 presents these 2 geometry variables that affect structural UAV weight.

iii. The third group includes 4 variables that depend upon mission requirements. Table 4 provides these mission requirements for solar-powered UAV.

iv. Two (2) technology constraints, battery energy density ($kbatt$) and solar cell efficiency $\eta cell$, present the current state of mature technology and challenge scientists to fill the gap between theoretical and achievable efficiencies(Dang et al., 2023).

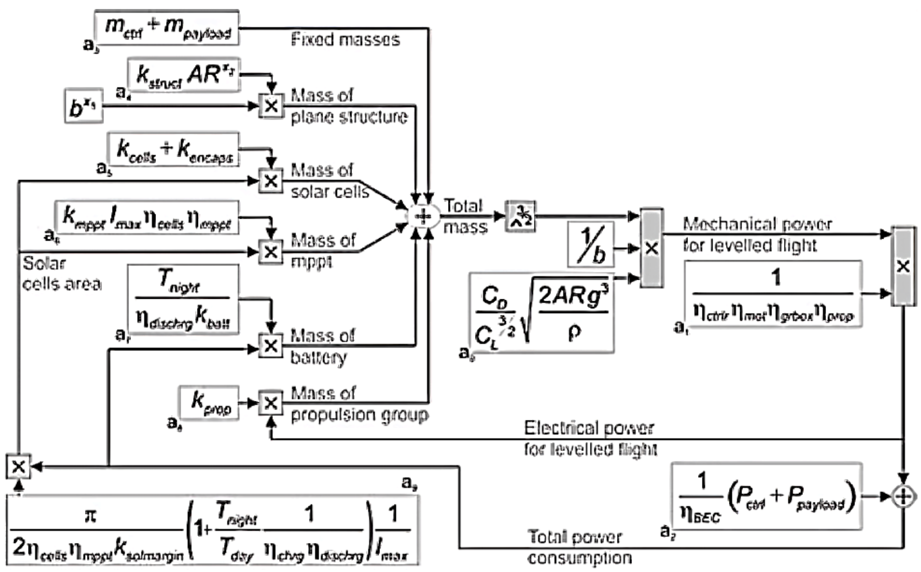

Figure 1: Conceptual Design Methodology

Changes in wing span (b) and aspect ratio (AR) directly impact UAV's structural weight, affecting total weight and energy balance. Design requirements such as mass and power consumption of payload, cruise altitude (i.e., air density), and presence of clouds (i.e., available solar energy) influence power requirements. Improvement in solar cell efficiency and battery energy density lead to reduced wing size required for solar panel installation and decreased battery weight. Consequently, any modifications in mission requirements, geometric variables, or technological constraints necessitate another design iteration for updated configuration. Baseline values and ranges for each design variable are determined based on a historical review of solar-powered UAVs (Molina et al., 2023).

Table 1(a). Design constants

Parameter	Value	Unit	Description
C_L	0.85	--	Lift coefficient
C_D	0.02	--	Drag coefficient
e	0.9		Oswald's Efficiency
I_{max}	900	W/m^2	Maximum Irradiance
K_{cell}	0.3	kg/m^2	Area density of solar cells
K_{encaps}	0.20	kg/m^2	Area density of encapsulation
K_{mmpt}	0.0005	kg/W	Mass to power ratio for MPPT
K_{prop}	0.005	kg/W	Mass to power ratio for motors

Table 1(b). Design constants

Parameter	Value	Unit	Description
K_{Struct}	0.44	--	Structural constant
η_{BEC}	0.8	--	Efficiency of converter
η_{Charge}	0.9	--	Charge efficiency of battery
$\eta_{discharge}$	0.9	--	Discharge efficiency of battery
$\eta_{control}$	0.95	--	Efficiency of control servos
$\eta_{gear\ box}$	0.9	--	Efficiency of gearbox
η_{mppt}	0.9	--	Efficiency of MPPT
η_{prop}	0.85	--	Efficiency of motors
X_1	3.1	--	Area Exponent
X_2	0.25	--	Aspect Ratio Exponent

Table 2. Geometry Variables

Parameter	Range	Unit	Description
B	19-35	m	Wingspan
AR	6-26	--	Aspect Ratio

Table 3. Mission Requirements

Parameter	Baseline	Range	Unit	Description
$m_{payload}$	18	12-24	kg	Mass of Payload
P_{Power}	250	150-350	Watts	Payload Power
Altitude	2000	1000-3000	m	--
$K_{Sol\ margin}$	0.8	0.7-1.0	--	Solar Margin

Table 4. Technology Constraints

Parameter	Baseline	Range	Unit	Description
n_{cell}	30	20-40	%	Solar Panel Efficiency
K_{batt}	300	200-400	Watt/kg.hr	Battery Energy Density

Figure 2 present the baseline configuration. this baseline configuration has been used for subsequent weight sensitivity analysis.

5. Results And Discussion

5.1 Wing Geometry

The aspect ratio (AR) and span (b) define the wing planform. For solar-powered UAVs, AR and span (b) vary between 6 to 26 and 18 to 30 meters, respectively. Within these ranges, design iterations are carried out to converge 100 configurations. In Figure 3, the mass of each configuration is plotted for the corresponding AR and span. The mass of the UAV decreases as AR increases up to 18. However, further increase in AR beyond 18 causes an increase in UAV weight.

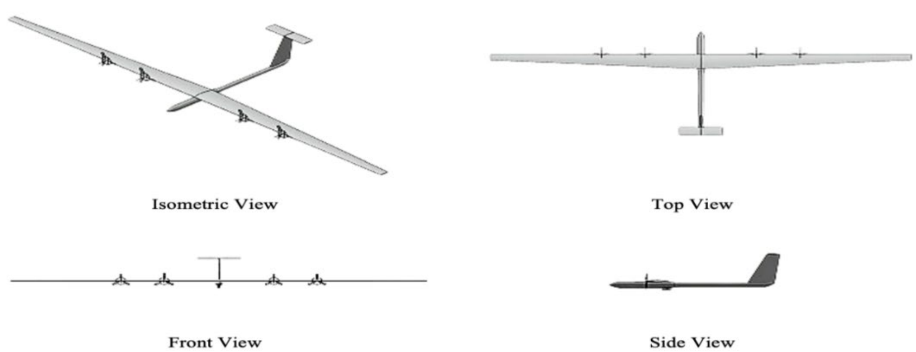

Figure 2: Baseline configuration

As wing span increases, UAV weight also increases. This increase in UAV weight is conceivable due to the strength and stiffness requirement of the wing, which supports a large bending moment of lift force. Conclusively, the smallest wing span with AR 18 results in a UAV with minimum weight.

5.2 Payload Mass ($m_{Payload}$)

Weight of onboard avionics payload is varied from 12 kg to 24 kg. Design iterations are carried out within these ranges to converge 25 configurations with different payload weights and AR. Figure 4 shows variation in UAV weight with payload weight and AR. It is observed as payload weight increases; UAV weight also increases. While it comes intuitively that UAV weight can be reduced by reducing payload weight. Figure 4 substantiates that 1 kg increase in payload weight leads to 8 kg increase in UAV weight. Therefore, weight of payload should be minimized to reduce total UAV weight.

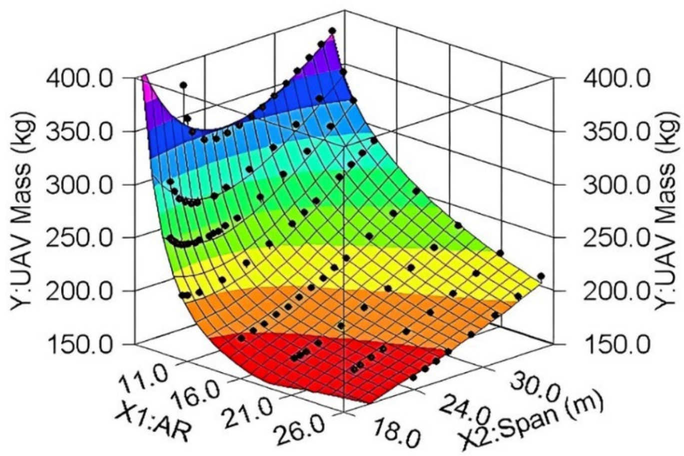

Figure 3: Influence of Wing Geometry

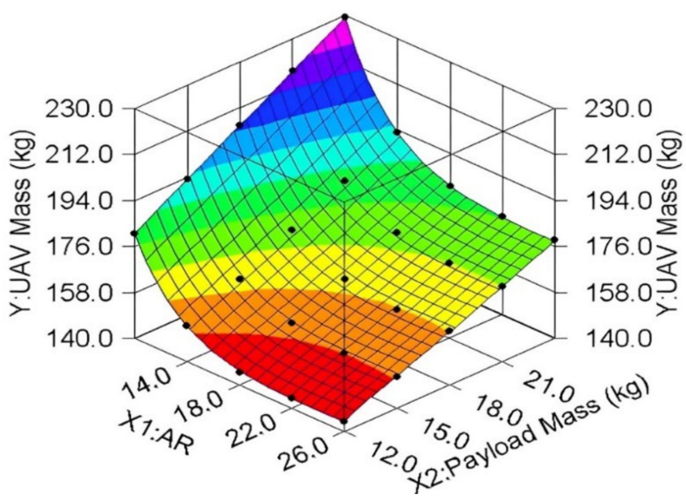

Figure 4: Influence of Payload Mass

5.3 Payload Power ($P_{Payload}$)

The onboard payload's power consumption ranges from 200 watts (W) to 400 watts (W). The AR ranges from 6 to 26. Design iterations are carried out within these ranges to converge 25 configurations with different payload power consumption and AR. Figure 5 shows variation in UAV weight with payload power consumption and AR. It is observed as power consumption of payload increases; UAV weight also increases. Increase in payload power consumption requires an increase in solar panel area. As wing area is increased for installation of additional solar panel, UAV weight also increase, leading to further increase in power requirement. This loop continues till design converges to a new configuration. 100 watts increase in payload power consumption leads to a 64 kg increase in UAV weight. Therefore, power consumption of payload should be minimized to reduce total UAV weight. Again, AR 18 stands out as an ideal AR which results in minimum UAV weight irrespective of payload power consumption.

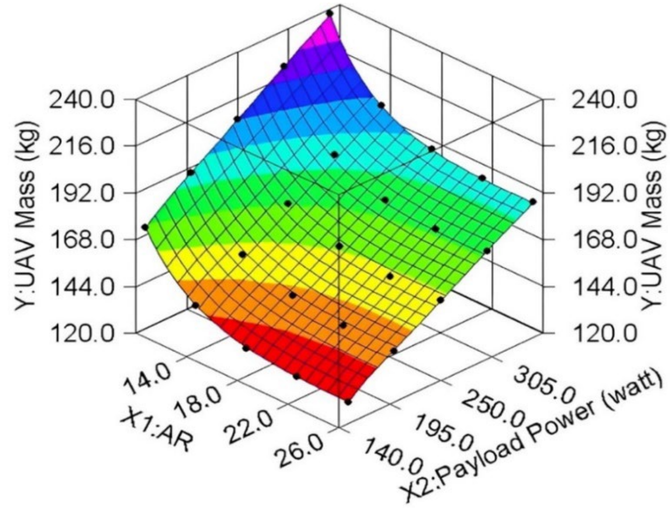

Figure 5: Influence of Payload Power

5.4 Cruise Altitude

The power required for flight depends upon cruise altitude (i.e., air density ρ). A decrease in air density experienced with cruise altitude increases the power requirement for flight. Cruise altitude for UAVs is varied from 1000 m to 3000 m. Design iterations are carried out within these ranges to converge 25 configurations at 5 different altitudes. Figure 6 shows variation in UAV weight with cruise altitude and AR. It is observed that as cruise altitude increases; UAV weight also increases. For smaller AR, increase in UAV weight with increasing altitude is quite significant. However, for AR higher than 18, a linear increase in UAV weight is observed with increasing altitude. Within cruise altitude range of 1000 m to 3000 m, AR 18 is desirable due to minimum UAV weight.

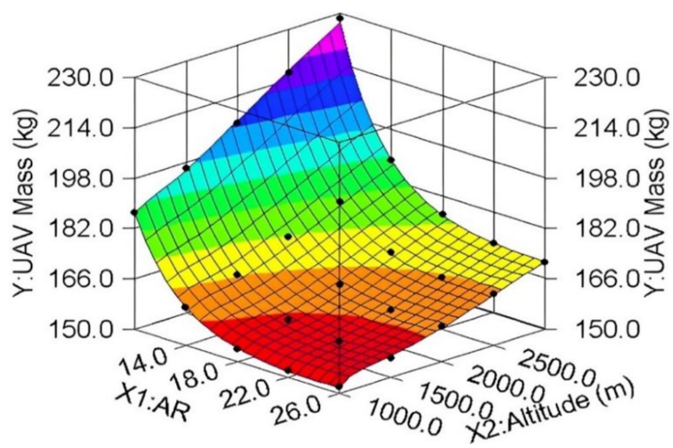

Figure 6: Influence of Cruise Altitude

5.5 Cloudy Overcast

If clouds overcast then solar radiation incident on panels decreases leading reduced power output. This seriously affects energy balance and UAV will not be able to perform 24 hours' flight. Therefore, Solar margin ($K_{sol\,margin}$), is introduced in as a safety factor in design iteration. A value of solar margin as 1.0 means that 100 % solar irradiation is available whereas a solar margin of 0.8 means that 80% of irradiation is available due to clouds. Solar margin ($K_{sol\,margin}$) is varied from 0.7 to 1.0 within AR range of 6 to 26.

Within these ranges, design iterations are carried out to converge 25 configurations. Figure 7 shows variation in UAV weight with solar margin and AR. It is observed that decrease in solar margin increases UAV weight. Effect of solar margin on UAV weight gradually diminishes for AR higher than 18. Again, AR 18 is an ideal AR with minimum

UAV weight.

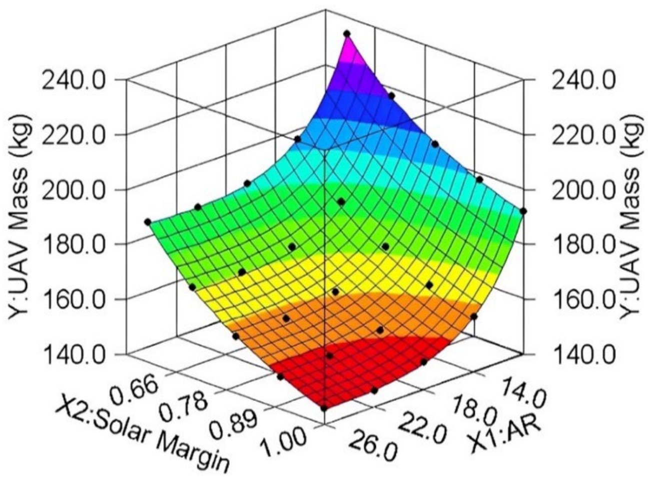

Figure 7: Influence of Clouds

5.6 Efficiency of Solar Panel (η_{cell})

The efficiency of solar panels is a critical technology constraint that dictates the weight growth of solar-powered UAVs. Presently, production solar panels have an efficiency of 30 %. To ascertain the influence of panel efficiency on weight growth, solar panels' efficiency varies from 20% to 40 %. Within these ranges, design iterations are carried out to converge 25 configurations. Figure 8 shows variation in UAV weight with solar panel efficiency. It is observed that as solar panel efficiency increases, UAV weight decreases. An increase in solar panel efficiency from 20% to 40 % results in a 23 % decrease in UAV weight. Again, AR 18 stands out as an ideal AR, which results in minimum UAV weight for solar panels with different efficiencies.

5.7 Energy Density of Battery (K_{batt})

Energy density of batteries is an important technology constraint that affects the weight growth of solar-powered UAVs. To reduce UAV weight, high-energy-density batteries like Lithium Polymer (Li-Po) and Lithium-Ion (Li-Ion) batteries are used. Commercially available models of these batteries have an energy density of 250 watts/kg/hr. Design space exploration is carried out by varying the energy density of 200 to 400 watts/kg/hr batteries. Figure 9 shows the weight of 25 UAV configurations as a function of battery energy density and AR. It is observed that UAV weight decreases with an increase in battery energy density. An increase in battery energy density from 200 watts/hr/kg to 400 watts/hr/kg results in a 34 % decrease in UAV weight. Therefore, a battery with maximum energy density should be used to minimize total UAV weight. Again, AR 18 stands out as an ideal AR with minimum UAV weight for batteries with different energy density (Zhang et al., 2022).

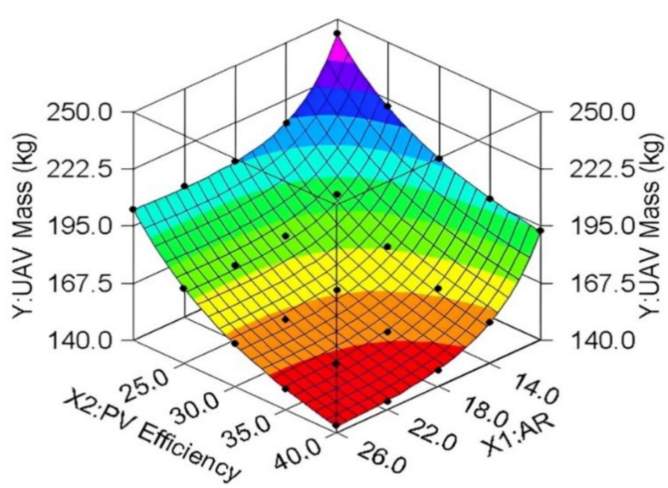

Figure 8: Influence of Solar Panel Efficiency

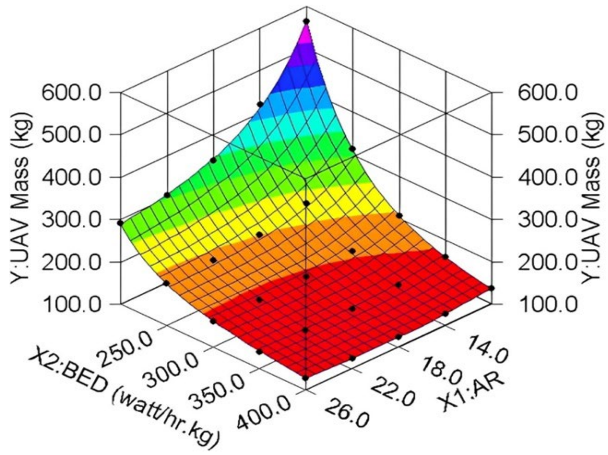

Figure 9: Influence of Battery Energy Density

5.8 Validation

Several scientists have studied the correlations between gross weight, wingspan, wing area and speed of flying machines, from the hang glider to big airliners. One of the best contributors in this field is Henk Tennekes who presented a fascinating correlation in a log-log diagram named "Great Flight Diagram". Concept of geometric similarity is the basis of this model. Eq. (5) presents weight (W), directly proportional to cube of wing loading (W/S).

$$\frac{W}{S} = 47W^{\frac{1}{3}} \tag{5}$$

Another model which estimates wing loading of aircraft is proposed by B W McCormick. Eq. (6) present McCormick boundaries (Stamm & Woods, 2024).

$$\begin{aligned} \frac{W}{S} &= 85.5\left(W^{\frac{1}{3}} - 9.9\right) \\ \frac{W}{S} &= 44.8\left(W^{\frac{1}{3}} - 9.9\right) \end{aligned} \tag{6}$$

A. Noth et al have presented a model for solar powered UAVs based on the data of sail planes. (İlhan & Çalık, 2024). Eq. (7) presents wing loading of solar powered as a function of weight and aspect ratio (AR).

$$\frac{W}{S} = 0.59W^{0.35}AR^{0.84} \tag{7}$$

Figure 10 presents the proposed UAV in a Great Flight Diagram against previously designed solar-powered UAVs and weight-size estimation models. The blue marker indicates the current design. The proposed UAV follows the trend of high-altitude, long-endurance solar-powered UAVs, which validates the design and optimization scheme of the presented solar-powered UAV.

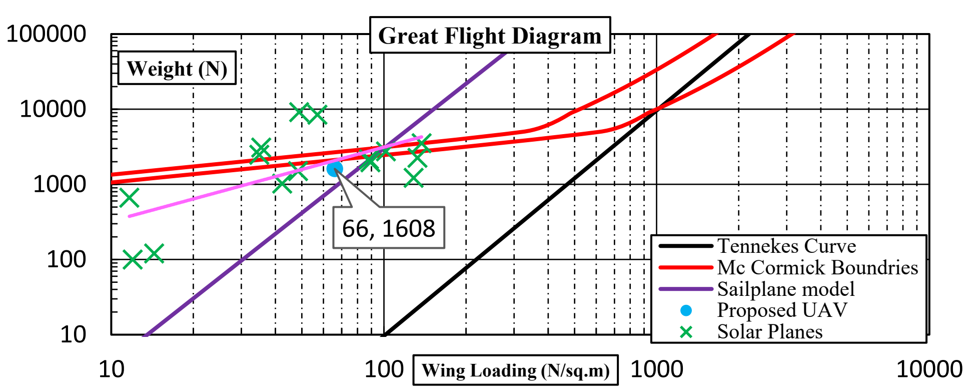

Figure 10: Proposed UAV in Great Flight Diagram

6. Conclusions And Recommendations

This research presents a comprehensive optimization scheme for solar-powered UAVs, offering nuanced insights and actionable recommendations for future advancements in UAV technology.

6.1 Key Design Variables and Their Impact

Mass optimization of solar-powered UAVs is a complex interplay of two-wing geometrical parameters, namely, aspect ratio (AR) and span (b). A careful selection of these design variables is required to achieve an optimal UAV mass. Noticeably, aspect ratio 18 appears to be a determining factor towards the minimum UAV mass. Meanwhile, the wing span should be kept minimum for a given AR to have the lightest UAV configuration.

6.2 Payload and Power Management

Mass and power consumption of the payload are critical influences on overall UAV mass. Both payload and power consumption should be minimized to reduce UAV mass effectively, thereby enhancing operational efficiency and endurance. This calls for a holistic approach in the design and power management of onboard the payload during UAV development.

6.3 Cruise Altitude Considerations

Cruise altitude is another critical parameter affecting UAV mass. This study highlights that higher operational altitude is associated with increased UAV mass. Therefore, lowest permissible cruise altitude to meet mission requirements is recommended to achieve lightest configuration.

6.4 Environmental Factors

Cloudy overcast reduces available solar power and negatively impact delicate energy balance of UAV. Solar Margin is proposed as safety factor in design iteration. However, a reasonable approach in selection of solar margin is required to optimize UAV design for real world scenarios without being overconservative.

6.5 Technological Constraints

Solar panel efficiency and battery energy density are key technological constraints influencing UAV mass. A substantial decrease in UAV mass can be achieved with improvements in solar panel efficiency and battery energy density. As technology continues to evolve in these areas, further reduction in mass is projected which will improve the performance of solar powered UAVs.

6.6 Significance of study

The study provides a comprehensive understanding of factors which influence mass of solar-powered UAVs. This research provides a methodology to parametrically analyze and optimize UAV configurations. The study further provides actionable recommendations to aerospace engineers to optimize solar powered UAVs. The awareness provided by this study on efficiency of solar panel and energy density of batteries serves as an impetus for further development in these fields.

6.7 Limitations

This study relies on dependency of UAV mass on variables in conceptual design methodology. Assumptions in these design variables can potentially introduce discrepancies between theoretical models and real-world scenarios. Moreover, these assumptions may oversimply the interaction between design variables, potentially influencing weight optimization scheme. Composite materials are ideal for lightweight but strong airframes that minimize overall weight while accommodating onboard storage batteries and solar panels. However, the initial design and development cost of composite airframes shadows the commercial viability of solar-powered UAVs. An efficient power management system is required to convert and distribute energy with minimal losses to propulsion and control systems. Improving this system efficiency is essential for the reliability and scalability of solar-powered UAVs.

6.8 Implications

The research on solar-powered long-endurance UAVs has potential to transform aerospace industry with aerial platforms for surveillance, disaster management, environmental monitoring, precision agriculture, communication, and military operations.

Novelty Statement

This paper has identified critical parameters affecting the weight growth of solar-powered UAVs. By addressing these variables, the weight of solar-powered UAVs can be reduced. Reducing the weight of solar-powered UAVs can reduce cost and improve mission performance.

Author Contributions

100 % contribution by Author 1.

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