SUSTAINABLE AUTONOMOUS SOLAR UAV WITH DISTRIBUTED PROPULSION SYSTEM

by

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Dedicated to my parents, mentors, and this fragile world.

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LIST OF ABBREVIATIONS

- AI - Artificial Intelligence
- ANOVA - Analysis of Variance
- BEC - Battery Eliminator Circuit
- GIS - Geographical Information System
- GPS - Global Positioning System
- RPM - Revolutions per Minute
- UAV - Unmanned Aerial Vehicle
- VTOL - Vertical Take-Off and Landing

GLOSSARY

- Airfoil: The airfoil defines the lift and drag characteristics of the wing and should be designed or selected such that level flight power is minimized (Morton, D’Sa, & Papanikolopoulos, 2015).

- Angle of Incidence: Angle between the axis of an impinging light beam and the perpendicular to the object surface (Gooch, 2011).

- Drag coefficient: The drag coefficient is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment (Clancy, 1996, p. 57).

- Lift coefficient: The lift coefficient is a dimensionless coefficient that relates the lift generated by a lifting body to the fluid density around the body, the fluid velocity and an associated reference area (Clancy, 1996, p. 57).

- Thrust: Thrust is the force which moves an aircraft through the air (NASA, 2015).

- Wi-Fi: Wi-Fi is a wireless local access network technology defined by the IEEE 802.11 standard (Gorshe, Raghavan, Starr, & Galli, 2014).

EXECUTIVE SUMMARY

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Solar-powered Unmanned Aerial Vehicles (UAVs) solve the problem of loiter time as aircrafts can fly as long as sufficient illumination and reserve battery power is available. However, Solar-powered UAVs still face the problem of excessive wingspan to increase solar capture area, which detracts from maneuverability and portability. As a result, a feature of merit for solar UAVs has emerged that strives to reduce the wingspan of such UAVs. The purpose of this project is to improve energy use efficiency by applying a distributed propulsion system to reduce the wingspan of solar-powered UAVs and increase payload. The research focuses on optimizing a new design analysis method applied to the distributed propulsion system and further employs the novel application of solar arrays on both top and bottom of the wings. The design methodology will result in a 2.1-meter wingspan, which is the shortest at 2020, for a 24-hour duration solar-powered UAV.

SECTION 1. INTRODUCTION

1.1 Introduction

Over the past decade, interest in UAVs has grown rapidly in a number of areas, including commercial, industrial and government affairs (Morton et al., 2015). According to Markets and Markets (2019), "Unmanned Aerial Vehicles (UAVs) market is estimated to grow at a Compound Annual Growth Rate (CAGR) of 15.5% from 2019 to 2025. The main growth contribution came from monitoring, surveying & mapping, precision agriculture, aerial remote sensing, and product delivery". Limited endurance limits the type and range of work that can be done by multi-axis rotorcraft. Solar-powered UAVs with self-charging capabilities are beginning to be noticed and studied by researchers. Benefiting from improved battery density and solar panel efficiency, researchers and hobbyists are able to build compact solar UAVs. "The application of alternative energy sources in UAVs has established one of the broader challenges in its design and implementation", as specified by Ramanathan et al., (2007), promoting ideas through the use of solar cells (Lubkowski, Jones, Rojas, & Morris, 2010), lithium-polymer (LiPo) batteries (Song & Evans, 2000), among others (Pedraza Betancourth, Parra Villamarin, Vaca Rios, Bravo-Mosquera, & Cerón-Muñoz, 2016). The world has seen the emergence of solar-powered UAVs that can fly for more than 12 hours without light, theoretically achieving a permanent endurance.

Previous analyzes and preliminary experiments have indicated that hybrid propulsion systems powered by solar energy can provide excellent autonomy, due to their energy storage capacity and continuous charging capability (Pedraza Betancourth et al., 2016). On the other hand, developments in battery technology have not met the increased demand for drone functionality. The most energy-intensive part of the flight is the propulsion system. Therefore, the more efficient propulsion system is particularly important in the case of the same energy consumption.

Lift of an aircraft is mainly caused by the pressure difference between the upper and lower surfaces of the wings. Conventional jets, on the other hand, usually have extra pods suspended beneath the wings because their propulsion systems require compressed air. By pressing the air backward and providing the initial velocity to make the air flow which creates a pressure difference between the upper and lower surface of the wings, the plane was able to take off and maintain its altitude. But in the process, the pods create extra drag by rubbing against the air, and a lot of the high-velocity air is wasted instead of being used to generate lift. To address this problem, NASA has designed a new propulsion system that greatly improves air efficiency and minimizes air drag by placing propellers at the edges of the wings and using electric motor drives. According to Borer, “Distributed propulsion is a class of integrated aerodynamic-propulsion concepts that do not have a formal definition, but generally involves the distribution of the propulsion system beyond what may otherwise be most efficient from a traditional decoupled design standpoint, for the purpose of enhanced aircraft performance” (Borer et al., 2017). NASA's X-57 "Maxwell" aircraft has significant reduction of energy consumption in cruise flight by incorporating distributed electric propulsion technology into its design (Borer et al., 2017). The distributed propulsion system is also a great way to spread out the weight of the fuselage, leaving plenty of room for other electronic devices, such as cameras, by distributing heavy objects such as batteries over the wings. By combining a long-endurance solar UAV with an efficient distributed propulsion system, the newly designed UAV has the potential to increase both range and payload.

1.2 Statement of Problem

The purpose of this study is to reduce the energy consumption during UAV cruise by optimizing the design method of the distributed propulsion system to reduce the weight of the battery and increase the UAV's cruise time.

1.3 Research Question

Can the design process be optimized to include distributed propulsion systems and distributed power scavenging to reduce the energy consumption of the UAV while cruising relative to non-distributed UAVs?

1.4 Significance of the Problem

The research helps reduce the wingspan of fixed-wing UAVs for maneuverability and portability, without sacrificing cruise capability. Meanwhile, a distributed propulsion system gains more lift for the same power consumption compared to a single-motor system, which allows researcher to reduce the battery weight of UAV. The weight savings could be used to carry more scientific observations or communications equipment. The shrunken battery pack will also reduce charging time and improve the UAVs' ability to cope with rainy weather.

1.5 Scope of the Study

During the study, distributed propulsion systems with different configuration has been evaluated and compared with conventional single-motor propulsion systems. At the beginning of the experiment, researcher selected the Astra 2.15E F5J glider as the test platform and tested its airfoil performance after modeling. After obtained the lift and drag coefficients, calculated the performance of different distribution propulsion system configurations with a different number, size, power and turning speed of motors to compare the thrust-weight ratio and cruise power consumption. To determine the best layout and motor combination. According to this design, the UAV is assembled. Finally, the actual performance is tested and compared with the theoretical value.

1.6 Assumptions

1. During the flight of the UAV, the air density is assumed to be uniform and constant at different altitude. This will affect whether the wing gains a constant lift.
2. All calculations of the output power of solar cells assume that the angle of incidence is 90 degrees. Lighting conditions can vary depending on weather and time of day.
3. The rated voltage of the battery is assumed to be maintained after discharge.
4. Airflow speeds are assumed to be constant regardless of the presence of wind speed in the environment.

1.7 Limitations

1. The airfoil of the glider has been identified as MH 32. Different airfoils will bring different lift and drag coefficients, which could influence the experimental results.
2. The experiment only tested the final configuration design in the field.

3. The efficiency of the motors in the selection process is calculated rather than experimental, and the parameters are sourced from the manufacturer and may differ from actual performance.

1.8 Delimitations

1. The study does not consider the effect of the roughness of the fuselage and the wing surface.
2. The current research only considers the impact of the propulsion system on energy consumption and does not consider the energy consumption of computing units and image system.
3. The research focus on the design of the system rather than the design and performance of the UAV's shape.

SECTION 2. REVIEW OF LITERATURE

2.1 Solar UAV Design

The energy density of lithium batteries is a critical problem in UAV design. “The commercial use of lithium metal batteries was delayed because of dendrite formation on the surface of the lithium electrode, and the difficulty finding a suitable electrolyte that has both the mechanical strength and ionic conductivity required for solid electrolytes” (Mauger, Armand, Julien, & Zaghib, 2017). Although several research institutes and companies are trying to improve energy density with different methods and materials, the energy density of batteries that can be mass produced is still lower than 250Wh/kg at present.

Rigorous calculations were required to arrive at the solar cell configuration on the aircraft and the suitable arrangement for the electrical system requirements. (Pedraza Betancourth et al., 2016). The larger the battery capacity also means the larger the solar panel area required for the same charging time, the larger the motor thrust required for flight, and the relationship between them is almost linear. The relationship results in almost all the power redundancy being consumed by the extra battery weight, making it difficult to allocate the excess power to the payload.

Other than the aircraft itself, as claimed by Cestino, “Although the wind does not affect the aircraft’s power generation, it has a significant effect on its drag and power consumption” (Cestino, 2006). High wind speeds can cause the lightweight wings to vibrate and tilt, requiring the motors to use extra power to balance the fuselage. Therefore, the wind information of different time periods in the flight area also needs to be considered in the design to ensure that the UAV can have enough thrust to resist strong winds in future use.

As claimed by Arai, the design of solar-powered UAVs is derived from an extensive parametric study on the characteristics of UAVs at the same category, aiming to interpret and analyze the main design features (geometric, aerodynamic and performance) that make up an aircraft with solar panels(Arai et al., 2014; Marta and Gamboa, 2014). At the beginning of the design process, the wing is the first factor to be considered. The wing determines the number of solar cells the UAV can carry, and the lift can provide. The length and area of the wing determines the number of solar cells the UAV can carry, as well as the battery mass. At the same time, the Charge Margin has a positive linear correlation with battery mass. The area of the solar cell directly determines the amount of electricity it can provide, so a larger wing area is positively correlated with the amount of electricity that can be generated (Pedraza Betancourth et al., 2016). Additionally, the impact on power generation, excessively long wings will also cause difficulties in transportation and take off process, so it is particularly important to choose the right length according to actual needs. The smallest 24 hours solar-powered UAV has 3.2 meters wingspan made by A. Noth (2006). Which can fly up to 27 hours. However, in order to achieve this goal, the UAV does not carry any observation equipment to reduce the total weight to 2.5 kg. The Noth's research proves the possibility of UAV with unlimited range ability, but the UAV assembled in the experiments do not have practical value. The AtlantikSolar, a 24-hour solar-powered UAV designed by ETH Zurich, has a wingspan of 5.6 meters with two cameras that the total weigh is more than 7.22 kg. Based on pervious study, this study will further reduce the wingspan to 2.1 meters and carry at least one camera to provide basic observation capability.

Extensive aerodynamic studies were required to select the best airfoil and the best wing structure to meet the aircraft requirements (Pedraza Betancourth et al., 2016). As mentioned above, most aircraft lift comes from the pressure difference between the upper and lower surfaces of the wings, so the airfoil is an important indicator affecting the speed, endurance and power consumption of the aircraft. Thousands of types of airfoil design have been developed, each with its own unique application, and the size will directly affect its actual performance. Therefore, only when the UAV's functions and design parameters are fully understood at the design time, can the most suitable airfoil be selected according to the results of the aerodynamic simulation. For longer wings, additional cylindrical carbon fiber rods are usually added to the center of the wing to strengthen the structure.

The propeller is determined according to the power and dimension of the motor. The propeller efficiency is the ratio of propulsive power out to shaft power in. It can also be expressed as the ratio of the product of thrust and shaft speed to the product of resistance torque and speed. "Good efficiency can be obtained through proper design of the electric brushless motor (95%) and of the propellers (85%) which have a high diameter and a speed of about a thousand revolutions per minute" (Cestino, 2006). Therefore, it is necessary to determine the thrust, speed, and torque of the motor before a propeller is selected. The greater the thrust, the greater the energy consumption. The total power of the motor should not exceed the maximum power provided by the solar panel, given the wingspan and the power of the solar panel carried. Energy efficiency and loss should also be considered.

Battery management is the most important part of the aircraft circuit design. The energy density of the battery determines the weight and volume of the battery pack. Charging and discharging efficiency affects energy loss, charging time and maximum discharge power. According to Ohm's law, parallel batteries will increase the capacity of the battery pack, and series batteries will increase the voltage of the battery pack (Millikan, R. A., & Bishop, E. S., 1917). With the same motor power, higher voltages require less energy capacity, while greater capacity provides longer battery life. Therefore, the battery configuration often mixes series and parallel based on required capacity and motor operating voltage. Until now, lithium-ion batteries with liquid electrolytes have dominated for more than two decades. Now, there is a growing need to further increase energy density using lithium metal as an alternative to graphite/copper current collector components. Lithium metal/polymer batteries are once again the choice for many applications (Mauger et al., 2017).

As claimed by Cestino, “Ordinary existing solar cells are between 10% and 15% energy efficient while heavily affecting the development rate of solar-powered platforms. High efficiency (16–17%) thick (200–300 microns) single crystal silicon cells are available today at a low price (about 800 $/m2). More efficient (up to 22%) very thin (50–70 microns) single crystal silicon cells are also available, although at a higher price (about 30000 $/m2)” (Cestino, 2006). A few solar panels can achieve a 35% energy conversion rate under ideal conditions, but as mentioned earlier, the power of the solar panel is not the decisive factor in the weight of the aircraft, since greater power generation means more battery capacity is needed to store electricity. Like the array of batteries, solar panels follow ohm's law and can be considered low-power sources. Solar panels are connected in parallel to increase generation power, and in series to increase generation voltage.

The main factor hindering the utilization of PV power remains the low energy conversion efficiency of PV systems, which is crucial to be able to accurately achieve maximum power point tracking (MPPT) (Seyedmahmoudian et al., 2016). “A number of valuable studies have been conducted to review the performance of MPPT methods” (Seyedmahmoudian et al., 2016). To make the solar panels most efficient at generating electricity under arbitrary lighting conditions, MPPT is required in all solar-powered system. MPPT also needs to match the corresponding circuit according to the different output voltage and input voltage.

2.2 Double-sided solar array

Understand the principles of how solar panels generate electricity is necessary to maximize the absorption efficiency of solar array. “The fundamentals how the solar works include two phenomena, i.e.: (1) Photonics electron excitation effect to generate electron-hole pairs in materials and (2) diode rectifying” (Priambodo, Hartanto, & Poespawati, 2011). “The excitation process generates electron-hole pairs which each own quantum momentum corresponds to the absorbed energy. Naturally, the separated electron and hole will be recombined with other electron-holes in the bulk material. When the recombination is occurred, it means there is no conversion energy from photonics energy to electrical energy, because there is no external electrical load can utilize this natural recombination energy. To utilize the energy conversion from photonic to electric, the energy conversion process should not be conducted in a bulk material, however, it must be conducted in a device which has rectifying function. The device with rectifying function in electronics is called diode” (Priambodo, Hartanto, & Poespawati, 2011). Increasing the number of photons that cause the excitation effect is the only way to increase the converted energy of a solar cell without changing the structure and density of the diode.

As measured by Martin Green et al.(2019), under the same light conditions, the light area is still the largest factor affecting solar panel output. To increase the light exposure of solar panels, researchers have tried different approaches. “Monofacial panels are the most commonly used panel configuration in today’s photovoltaic (PV) industry. Recent trends, however, show a steady increase in the share of bifacial panels in the PV market, and ITRPV also predicts further increase in market share of bifacial PV over the next decade” (Khan et al., 2019). “Bifacial solar modules offer many advantages over traditional solar panels. Power can be produced from both sides of a bifacial module, increasing total energy generation” (Pickerel, 2019). “Some bifacial module manufacturers claim up to a 30% increase in production just from the extra power generated from the rear” (Pickerel, 2019).

Ground sculpting is also been considers improving the efficiency of solar array. “A standalone, optimally-tilted bifacial panel placed over a flat ground (with 50% albedo) is expected to produce a bifacial energy gain of 30% (per module area). In contrast, for a panel array in a solar farm, self and mutual shading reduce the bifacial gain at the same tilt to 10-15% (per farm area)" (Khan et al., 2019). With appropriate arrangement, "bifacial gain can approach 50% … The enhanced output, along with reduced soiling loss and lower cleaning cost of the ground sculpted vertical bifacial (GvBF) solar farm could be of significant technological interest" (Khan et al., 2019).

To increase the intensity of the light shining on the solar panels, a study was conducted on the flight attitude and path planning of the UAV. As claimed by Huang and Chen, "how to deal with the coupling between UAV motion, mission constraints, energy production, and the energy consumption is the key to 3D path planning for solar-powered UAVs to continuously monitor fixed targets" (Huang, Chen, Wang, & Su, 2019). "Based on the motion trajectory characteristics in relation to the force balance, the state variables at each waypoint of the UAV are parameterized in the form of the variables to be optimized and their first and second derivatives, and a spline interpolation function is introduced three times to obtain the first and second derivatives of the solution variables", "the horizontal plane component of the UAV flight speed is set to the minimum power level flight speed, while the yaw rate is solidified and the sun position is assumed to be unchanged for a short period of time to simplify the optimization process and thus obtain the final optimal solution" (Huang, Chen, Wang, & Su, 2019).

The study entails measuring the different efficiencies of solar panels on different terrains, reflectivity, and textured surfaces, and combining them with UAV attitude and path planning algorithms to determine the ability to maximize energy output when completing a given task.

2.3 Triplane

The complexity of the task in reality includes time, place, content and operators. Single multi-rotor UAVs and fixed-wing UAVs sometimes do not meet the complex requirements of field missions. This complex requirement from reality has also given rise to the need for a vertical take-off and landing (VTOL) aircraft. "In recent years, improvements in battery technology, computing power, and sensor availability have spurred the development of multi-rotors. However, a standard multi-rotor lacks the efficiency for long range flight. Married with the trend in small-scale electric drones, the class of "hybrid" VTOL aircraft with both a fixed-wing and rotors has recently risen in popularity. They use lifting surfaces to enable longer range and endurance flights and keep VTOL capabilities, eliminating the need for a substantial runway” (Shi, Tang, Lupu, & Tokumaru, 2020).

There are several fixed-wing VTOL aircraft exist, which “can be categorized as tilt-rotor, tail-sitter, or copter-plane” including the famous Boeing V-22 Osprey. The V-22 Osprey is a tilt-rotor aircraft, capable of vertical or short take-off and landing, with forward flight like a conventional fixed-wing aircraft (Bolkcom, 2005). “The V-22 tilt-rotor design combines the helicopter's operational flexibility of vertical take-off and landing with the greater speed, range, and fuel efficiency of a turboprop aircraft” (Bolkcom, 2005).

In addition to fix-wing tiltrotors VTOL aircraft such as the V-22, copter-plane class also has the advantages of a fixed wing. Lockheed Martin introduced X2 technology (2013) which the vertical tail of the helicopter was replaced with a pusher propeller to provide horizontal thrust. The attitude is controlled by counter-rotating blades added to the coaxial main rotors. “X2 Technology, with its counter-rotating coaxial main rotors, pusher propeller, and advanced fly-by-wire system, will deliver efficient 230-knot cruise airspeed, improved hover efficiency, and weight-optimized design in an affordable package” (John, 2010). A similar concept was used in Purdue I-Boomcopter (Mcarthur, Chowdhury, & Cappelleri, 2018). “The I-BoomCopter’s front boom is equipped with a horizontally mounted propeller, which can provide forward and reverse thrust with zero roll and pitch angles” (Mcarthur, Chowdhury, & Cappelleri, 2018).

The triplane takes advantage of the distributed propulsion system to maximize the area exposed to sun light, in order to retain the ease of operation of the multi-rotor UAV while integrating the high efficiency advantages of the fixed wing. Unlike simply adding solar panels to a conventional VTOL aircraft, the structure of the triplane is optimized specifically for solar panels. The triplane, like NASA's Helios, by designing a complex flight control program to compensate for the disadvantages of structure. The attitude of the aircraft is adjusted by individually controlling the speed of the motors in different positions.

2.4 Summary

Chapter Two reviewed the design processes of a solar-powered UAV. It also clarifies the main difficulties and considerations to be weighed during the design process. Among them, the battery and power system are the most important factors and solving the trade-off between them is the most critical problem in the whole research. The introduction of the distributed propulsion system is an attempt to solve this problem from the dynamic system. Incorporate a double layer of solar panels and path planning algorithms to increase the power output of the solar array during the aircraft design process. After the success of the conventional fixed wing in achieving its design goals, the Triplane will be designed further to verify the possibilities of this novel aircraft type.

SECTION 3. RESEARCH METHODOLOGY

3.1 Research Typology

The research is a quantitative experiment. By collecting and comparing the effects of different distribution combinations on lift performance, the fitting curve will be obtained, and the percentage of lift improvement of distributed propulsion system compared with traditional layout has been calculated.

3.2 Framework

Over the past decade, interest in unmanned aerial vehicles (UAVs) has rapidly expanded with research efforts spanning commercial, industrial, and governmental domains (Morton et al., 2015). Pedraza Betancourth claimed that “hybrid propulsion systems with solar energy offer excellent autonomy due to their energy storage capacity and continuous recharge” (Pedraza Betancourth et al., 2016). However, large size and a small weight is still their common problem.

The purpose of this study is to improve the efficiency of energy use by designing a new distributed propulsion system, to reduce the wingspan of UAV and increase the payload. To understand the specific performance improvement of a distributed system, we need to compare and verify the theoretical performance of a distributed system with a different configuration.

3.3 Sampling Approach

Stratified sampling has used in this study. Botev states, “stratified sampling is a method of variance reduction when Monte Carlo methods are used to estimate population statistics from a known population” (Botev & Ridder, 2017). Using stratified sampling ensures that the results consider the full range of samples. The results will not be affected by excessively concentrated samples so that there are not enough results in some sections. The samples will be grouped according to different independent variables.

3.4 Variables

The dependent variable is Power Consumed for Flight (Wh), and the independent variables are the airspeed, propeller radius, number of motor and efficiency of motor-propeller combo.

1. Airspeed (m/s). Airspeed will be measured by the airspeed gauge.
2. Propeller Radius (m). Measured by caliper.
3. Efficiency of Motor-Propeller Combo. Calculated from the parameters of the motor and propeller.

3.5 Proposed Analysis

MATLAB has been used to analyze the data. The data collected and calculated has been made by Excel and input into MATLAB. The fitting curve was drawn according to the scatter plots and the performance difference between different configuration has been calculated.

3.6 Sequence of Activities

The CAD model was established based on the selected glider airfoil shape and been imported into Fluent ANSYS to calculate the lift and drag coefficients at different freestream speeds which will be used as the calculation benchmark afterward. Different configurations of distributed propulsion systems have been listed, and the cruise energy consumption required to maintain the same speed and payload has been calculated based on the coefficients obtained. The best configuration obtained by comparing the results. Purchasing components and assemble the designed UAV to test its performance in the field under ideal conditions. Comparison between the calculation results and the actual test results have been made to get the conclusion.

3.7 Assessment instruments

The researchers constructed a table with different independent variables and corresponding power. The results have been presented as scatter plots.

Scatter Plot. “A scatter plot is a type of plot or mathematical diagram using Cartesian coordinates to display values for typically two variables for a set of data” (Friendly & Denis, 2005). “The data are displayed as a collection of points, each having the value of one variable determining the position on the horizontal axis and the value of the other variable determining the position on the vertical axis" (Utts, 2005).

3.8 Data Collection

During the flight, the airspeed been recorded and listed as an independent variable. Corresponding to the energy consumption at that time, in order to collect the accuracy of the results, researcher maintained a specific speed for a period and record all the energy fluctuations during that period, and finally calculate the average energy consumption at this speed. The energy consumption at different speeds have been recorded in the final chart and the scatter plot been fitted.

3.9 Conclusion

Limited by funding and time constraints, researchers will not verify the performance of each propulsion system. However, based on accurate simulations and calculations, the researcher can still obtain the approximate performance of different combinations of propulsion systems and choose design solutions from them. By comparing simulation and computational results, researchers can adjust design parameters using the optimized design methodology derived from this project, determine whether distributed propulsion systems help decreasing UAVs' wingspan and increasing payloads. If the experimental results are consistent with the simulated and calculated results, then it can be demonstrated that the optimization approach of this project is effective.

Having solved the efficiency problem for conventional fixed-wing solar aircraft, the same research approach can be applied to triplane. The novel aircraft type will provide more energy supply for the solar-powered VTOL aircraft.

SECTION 4. RESULTS

4.1 Optimized Design Flow Diagram of UAVs with Distributed Propulsion System

The loop shown in *Figure 4.1* is the optimized design diagram for this project. Unlike conventional solar UAV designs, the wing area covered behind the propeller, the combined efficiency of the propeller and motor, and the weight change produced by the multiple motors are taken into account. Allows the designer to take into account the interaction of several different motors and propeller combinations, with a holistic derivation of the lift-to-weight ratio. Helps the designer push the aircraft's wingspan size to the limit.

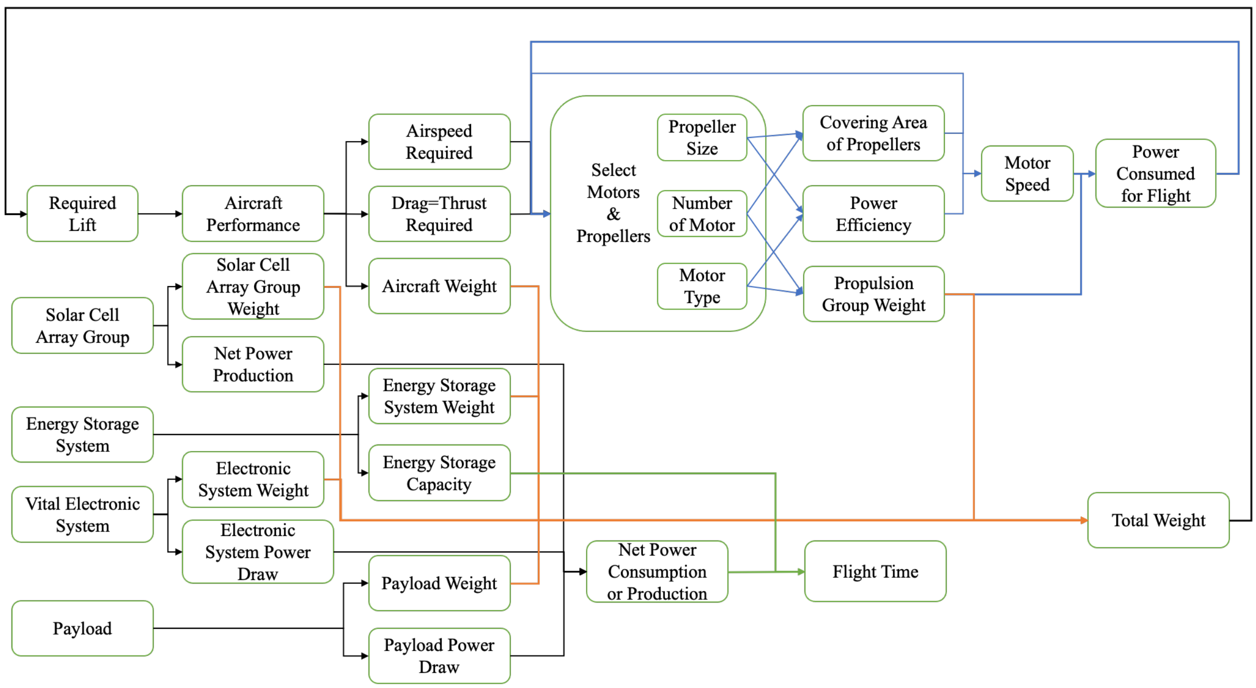

Figure 4.1. The figure depicted above is a double-loop iterative design relationship of solar-powered UAVs with distributed propulsion system.

Figure 4.2 shows a calculation procedure to determine the minimum speed and energy consumption required to maintain flight at different weights. In this process, the total weight of the components other than the battery system is considered constant, and the corresponding flight speed and endurance is calculated by varying the weight of the battery pack.

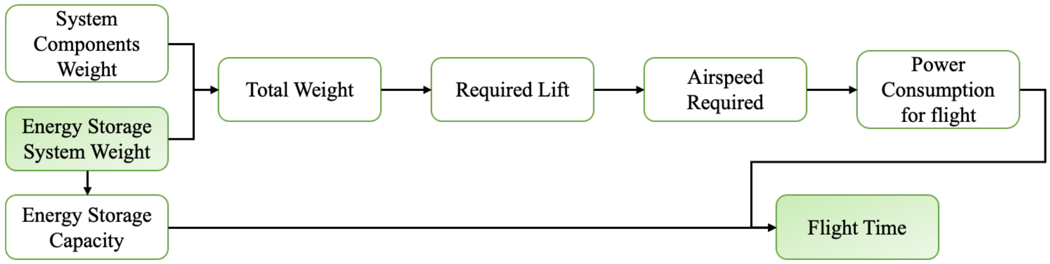

Figure 4.2. The figure depicted above is the design process of determining minimum airspeed for flying and corresponding power consumption.

To quantify the relationship and effects on lift and drag caused by different motors type, number, and propeller type and size, the detailed optimization logic is shown in *Figure 4.3* and implemented in MATLAB.

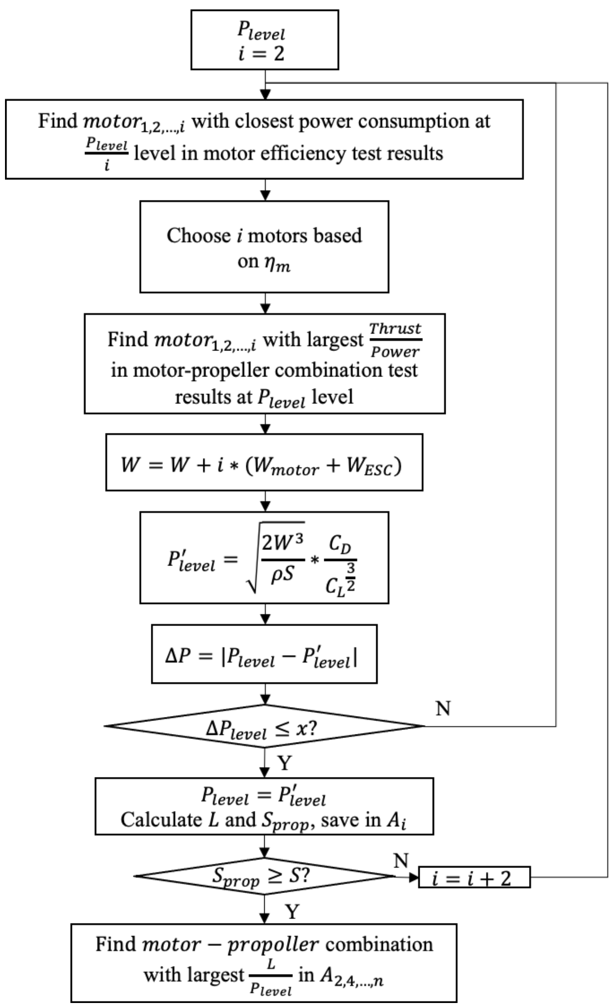

Figure 4.3. The figure depicted above is the motor and layout calculation process of the distributed propulsion system.

P_{level} are the datasets calculated from *Figure 4.2*, represented power consumption during level flight with chosen battery pack. i is the number of motors will be using in distributed propulsion system, η_m represent efficiency of motor. In this research, 85 motors from market have been evaluated on efficiency and thrust performance with different type and size of propellers from seven inches to fourteen inches. The motor thrust performance are provided by motor manufactures and verified on force sensor ATI Gamma. Motor efficiency calculation results and thrust data are represented in Section 4.2. w_{motor} is the weight of single motor, in the case that $i > 2$, motors could be different and W_{motor} represents the sum of the motor weights on one side of the wing. $W_{ESC}$is the weight of single Electronic Speed Control (ESC). x is defined by aircraft designer which represents the difference between energy consumption considered weight of motors and ESCs and the ideal energy consumption. S_{prop} is the area of the propeller covering the wings, limiting the number of motors increasing to countless. A_i store all the layout results and finds the ones from these arrays that matches the design requirements.

4.2 Calculation Results

Figure 4.4(a) shows the minimum speed and corresponding minimum power required to maintain flight for different battery capacities, i.e., weights, of the aircraft. The result is fully idealized and does not include the energy loss of the motor and propeller. *Figure 4.4*(b) shows the corresponding flight times for different battery capacities and energy consumption. The maximum flight time obtained by keeping the aircraft near three kilograms with the platform chosen for this project.

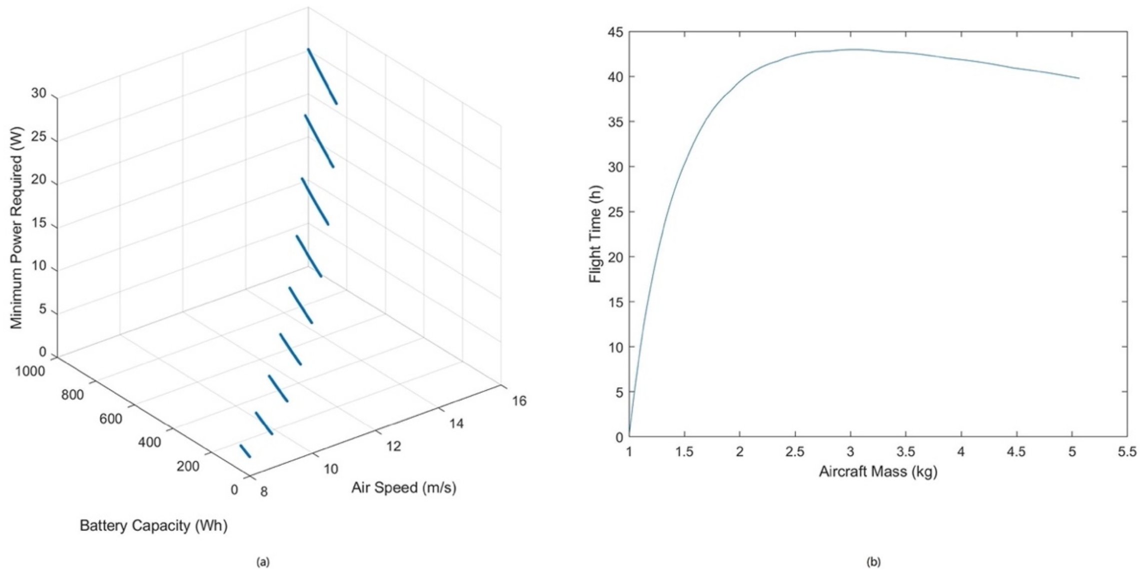

Figure 4.4. This figure represents depicts the different energy storage system capacities correspond to flight speed, energy consumption and flight time. (a) Minimum airspeed required for level flight. (b) Flight time varying based on aircraft mass.

Figure 4.5 shows the maximum efficiency of each motor-propeller combination and the thrust-to-power ratio with different propeller sizes.

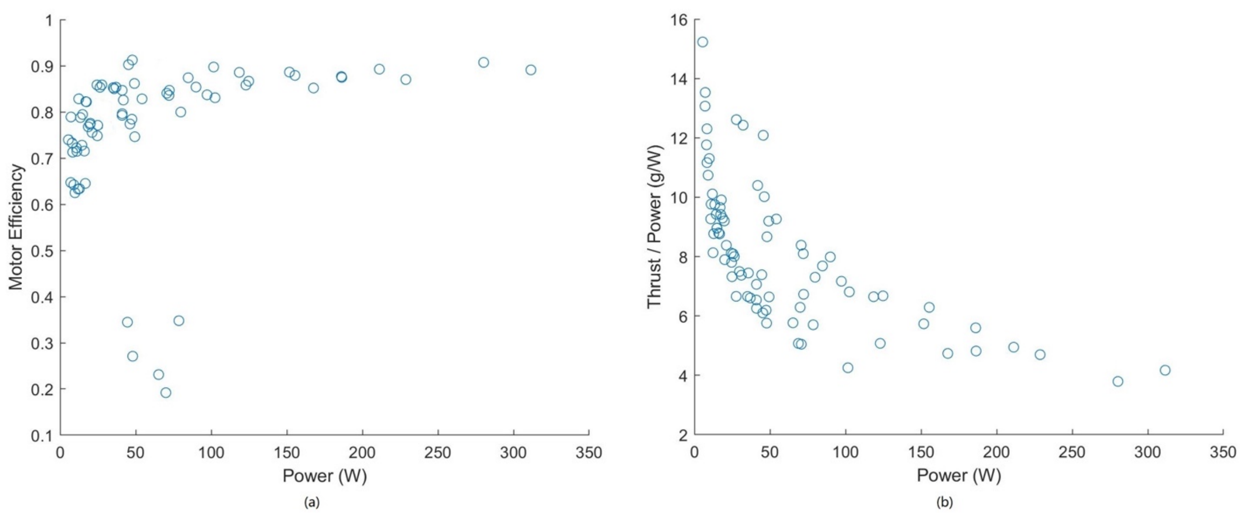

Figure 4.5. This figure represents depicts Motor-Propeller efficiency and corresponding thrust-power ratio. (a) Calculated Motor-Propeller efficiency. (b) Measured thrust-power ratio.

4.3 Assembly Diagrams

Avionics System consists of flight control, power management, and payloads shown in *Figure 4.6*. Battery Eliminator Circuit (BEC) is used to convert the battery voltage and provide constant power to the motors and flight control. Flight control is responsible for receiving ground commands and controlling the output performance of the motor. Global Positioning System (GPS) information and flight status information are provided to both the ground station and the payloads. The advantage of the independent power supply of each motor is that when a certain motor has problems, the motors will not affect each other, and the flight control can adjust the output according to the actual situation to balance the aircraft. The payloads consist of an on-board computing unit, camera(s), airspeed meter, and so on. Depending on the property of the mission, the designer can decide on devices to carry.

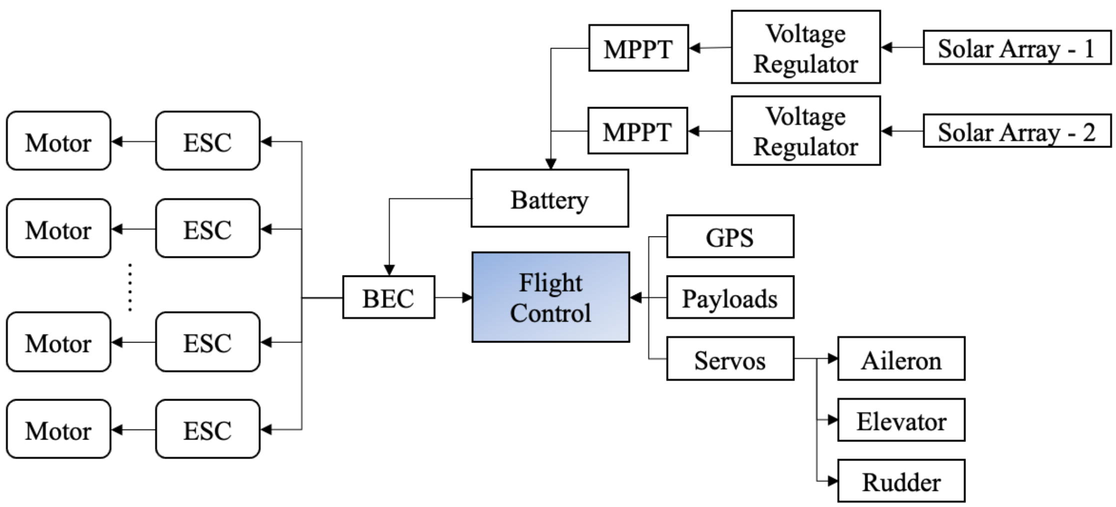

Figure 4.6. This figure represents depicts the electrical topology concept of avionics system.

The output power of a solar panel depends on the product of voltage and current, the Maximum Power Point Tracking (MPPT) circuit is designed to maximize the output power of the solar array in different light environments. Two sets of solar arrays were designed in this research, the solar panels on the upper wing will be directly exposed to the sun. Solar panels on the underwing receive direct light only in rare cases, such as forest fires, but most of the time receive diffuse light from the environment and the ground. M. R. Khan (2019) confirms that solar panels, especially bifacial solar panels, can absorb energy from the ground. The different ground shapes and materials reflect sunlight differently, which affects the efficiency of solar panels. This leads the researcher to consider supplying energy to some of the low energy circuits of the aircraft, such as the flight control module, by adding solar panels to the lower surface of the wing. Two separate MPPT circuits are necessary to maximize two sets of solar arrays since arrays will have different voltage-current curves.

The wing structure is made of laser-cut basswood, supported and attached with carbon fiber tubes as shown in *Figure 4.7*. 3D printed Polylactic Acid motor mounts are fixed on basswood and carbon fiber tubes.

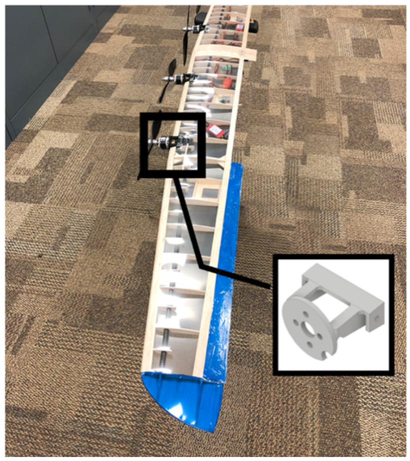

Figure 4.7. This figure represents depicts CAD model of motor mounts and basswood wing structure.

The assembled UAV and the corresponding component systems are shown in *Figure 4.8*. The Energy Storage System, Flight Control and Vital Electronic System are integrated into the fuselage. The UAV receives ground signals and makes attitude adjustments via transmitter and receiver.

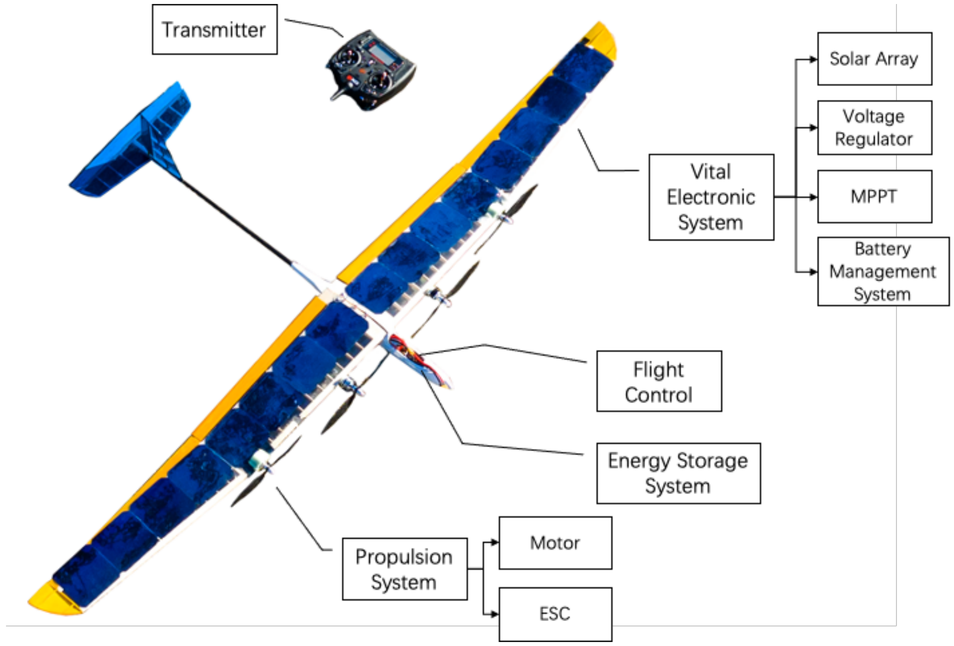

Figure 4.8. This figure represents depicts fully assembled UAV and component systems.

4.4 Experimental Data

Figure 4.9 shows a comparison between the calculated lift and the actual lift measured by the ATI Gamma force sensor and La Crosse Anemometer. The lift data in *Figure 4.9* at low speed (less than six m/s) provides a good match with predicted values. At airspeed higher than six m/s, the actual speeds diverge from the predicted values which are probably due to imperfections on the airfoil surface that cause drag and the motors mounts and their impact on airflow.

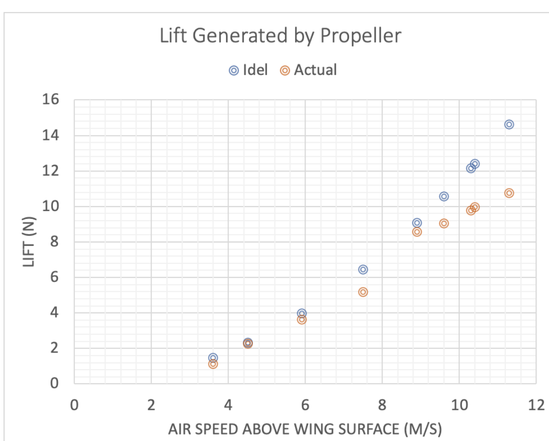

Figure 4.9. This figure represents depicts test results from force sensor compared with calculated results of lift.

Figure 4.10 shows the power performance of five solar panels when it is one meter above the concrete ground with different angles of incidence. Each solar panel weighs 7 grams, which means that adding about 105 grams of weight to the lower wing surface will gain 6W additional energy. The additional weight will consume around 0.0017W of energy in flight. The additional net energy input warrants more in-depth future research, such as by changing the aircraft's attitude to capture more energy, or by reading geo-information data to allow the aircraft to plan its route through a surface with sufficient reflectivity.

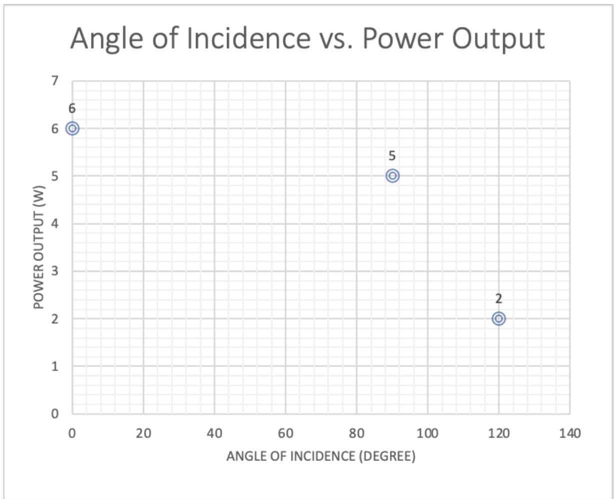

Figure 4.10. This figure represents depicts test results of solar panels with different angles of incidence.

Figure 4.11 shows the distributed propulsion system consumes less electrical energy than the monolithic propulsion system to provide the same lift before lift reaches 9 N.

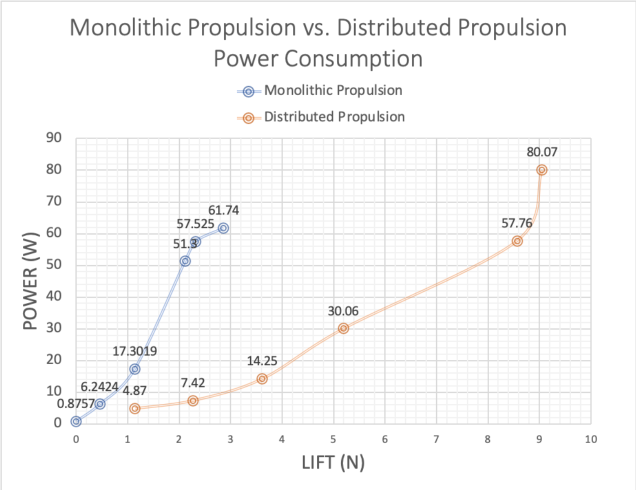

Figure 4.11. This figure represents depicts the comparison of power consumption of monolithic propulsion system and distributed propulsion system for providing the same lift.

After lift greater than 9 N, the energy consumption of the propulsion system starts to climb due to the number of motors. This reflects the fact that the distributed propulsion system may consume more energy during the takeoff phase of the aircraft because the motors are working at full power, but once the aircraft start level flight, the energy consumption of the system decreases rapidly. Compared to the monolithic propulsion system, the difference in energy consumption of the distributed propulsion system can be up to about 154.3%. For solar-powered UAVs whose goal is endurance, energy consumption during level flight is more important than energy consumption during climbing.

4.5 In-Flight Photos

The flight tests were conducted twice in the field, launched by hand. The UAV's flight status is stable and can complete the process of climbing, steering, horizontal cruise, and landing as shown in *Figure 4.12*. Because no landing gear is designed, the landing is accomplished by operating the aircraft fly into an arresting net or manual catching.

Figure 4.12. This figure represents depicts flight status during outdoor testing.

SECTION 5. SUMMARY, CONCLUSIONS, AND RECOMENDATIONS

The project proposes a design optimization method for a solar-powered UAV to reduce the energy consumption of the UAV in flight by applying a distributed propulsion system. CFD software was used to simulate and obtain the drag coefficient of lift of the aircraft wing. Mathematical models are used to calculate motor and propeller efficiency. An iterative algorithm is programed in MATLAB to determine the aircraft gross weight, motor, and propeller combination. Design and build UAV platforms using CAD and 3D printing. Designed and built the avionics system. Proposed a design method to increase the energy input without adding drag through double-sided solar panels. Finally, the reliability and performance of the entire system was tested outdoors.

There are still some issues in the project that deserve further improvement. For reliability and complexity reasons, the choice of motors in the prototype is still singular, which limits further improvements in system efficiency. From the optimization calculations, it is entirely possible that a combination of different motors and propellers could provide better efficiency performance, but this would further increase the complexity of the system. Meanwhile, the performance of ground-facing solar panels can also be tested at different ground surfaces, where different reflections and terrain may come up with different results.

The application of distributed propulsion systems makes it possible to decrease the size solar-powered UAVs without sacrificing endurance. The energy consumption of a distributed propulsion system can be reduced by up to 154.3% compared to a monolithic propulsion system for the same amount of lift. The application of a distributed propulsion system allows not only homogeneous control of the UAV's propulsion system, but also heterogeneous control, which helps improve maneuverability. Meanwhile, double-sided solar panels can also provide additional net power input to the system. By utilizing the area on the lower surface of the wing, a net energy input of about 5.99W can be obtained after adding 105 grams of weight.

In conclusion, the experimental data and flight results achieved the design purpose and confirmed the feasibility of the optimization method.

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