Energy System Optimization and Simulation for Low-altitude Solar-powered UAVs

Ke Li,[1] Jingyi Liu,[1] W.J. Eerland [1] and Dongsheng Wen [1]
Beihang University, Beijing, 100191, China

For a solar-powered flight vehicle that is flying at low altitudes for a long time, it is very important to accurately calculate the demand for the energy storage equipment. In this paper, an energy system optimization management method is proposed for the low altitude long endurance unmanned aerial vehicle (UAV). This method takes into account the influence of the light intensity, the number of hours during the day, the climate conditions at that time. The criteria for optimizing and extending the method are described to improve the stability and robustness of the aircraft's continuous multi-day flight performance. In order to meet the day and night demand of small wingspan aircraft, considering the impact of local environmental conditions on the aircraft, a surplus time was designed to meet the long-term flight stability. The battery capacity was calculated by optimizing the expansion criteria. The simulation presented in this paper details the state of the aircraft taking off from 7 o'clock on the first day, thus verifying in the aircraft's complete daytime and nighttime flight capabilities, achieving the goal of long time flight. It provides a reliable design method for the improvement and full utilization of the energy system of low-altitude long endurance solar aircraft.

I. Nomenclature

A	=	*altitude*
E..	=	*energy*
P..	=	*power*
θ	=	*incidence angle of sun*
η .	=	*efficiency*
m.	=	*mass*
ρ	=	*density of air*
S	=	*wing area*

1 ⋆Associate professor, School of Aeronautical Science and Engineering. like@buaa.edu.cn

Postgraduate Student, School of Aeronautical Science and Engineering. sy1805512@buaa.edu.cn

†Assistant professor, School of Aeronautical Science and Engineering. willem@buaa.edu.cn

Professor, School of Aeronautical Science and Engineering. d.wen@buaa.edu.cn

g	=	*gravitational acceleration, m/s2*
G	=	*radiation density, W/m2*
τ	=	*atmospheric turbulence*
t	=	*time*
φ	=	*latitude of local position*
T	=	*engine thrust of UAVs*
V	=	velocity of flight
H	=	height
SOC	=	state of charge
k_{ccf}	=	cloud layer or fog thickness factor

II. Introduction

Solar-powered unmanned aerial vehicles (UAVs) can significantly increase the flying endurance of electric vehicles [1]. Under suitable environmental conditions, a solar powered UAV collects excess solar energy during the day and stores it in the battery so that the aircraft can fly at night and use it in the following day and night cycle. This long-time capability of UAVs, especially the ability to fly for multi-days or to fly permanently can be used in missions such as large-scale surveying, observation, or telecom relaying. These functions can be applied to a range of missions, such as search and rescue, industrial or agricultural inspections, meteorological investigations, and border patrols. [2 to 4].

At present, after many years of development, solar aircraft have formed two major categories: high-altitude large aspect ratio, long-endurance aircraft and low-altitude small aspect ratio, long-endurance aircraft. The former is represented by the Zephyr [5] and the Solara [6]. Low-altitude solar aircraft are rarely developed because of more meteorological challenges. Most studies have focused on conceptual design without extensive flight experience. Noth presents the conceptual design method, realization and experimental flight results of the 3.2-meter wingspan SkySailor [7]. In 2008, the solar-powered flight was completed for 27 hours' continuous flight without using thermals. SoLong [8] took advantage of solar energy and at the same time searched for and used the upwelling heat flow for a continuous flight of 48 hours. However, the deliberate search for heat flow restricted the freedom of the aircraft's track and weakened the practicability.

The flight of solar UAVs can be extended with the improvement of the performance of solar , however, it needs to fly across day and night, it also depends on the design of energy management system [9]. Hitherto, the most researches focused on solar photovoltaic and solar thermal conversion, and the influence of environmental conditions on the energy conversion efficiency, etc., the lack of in-depth analysis and optimization of energy system management module. For example, literature [10] predicted the performance of solar cells when operating conditions such as flight time, speed and height changed by simulating the hourly changes of solar radiation and solar cell temperature. [11] put forward a method of energy management is in the daytime the solar part into gravitational potential energy storage, in the night by gravity gliding release of stored energy, this method converts the potential energy is limited, and does not apply to low solar energy plane. Because solar energy can't use the whole day in a row, so need to design effective energy management system to manage, collection, storage and consumption of energy, in order to make a low-altitude solar –powered plane in day and night task sustainable or permanent flight [12]. Therefore, the proper energy management method is an effective method to solve the conflict between the battery quality required by aircraft and the energy demand at night [13].

Therefore, the main work of this article. First, an energy system management method was proposed for low-altitude long-endurance unmanned aerial vehicles. This method considers the light intensity, day-and-night duration of the flight date, and the climatic conditions at that time, such as early morning and evening clouds and nighttime- environmental disturbances factors affect the energy consumption of solar aircraft. Secondly, optimize the system design and flight Simulink of the UAV's energy system, verify the ability and stability of the aircraft's continuous or permanent flight, and provide a reliable design method for the improvement and full utilization of low-altitude solar-powered energy systems.

III. Solar UAV's Energy System Composition

Figure 1 shows the composition of the energy system. The solar cells are connected in a fixed structure, covering the given surface of the wing, or other parts of the aircraft, such as tail or fuselage. During the day, solar cells convert light energy into electricity. The Maximum Power Point Tracker (MPPT) ensures that the solar cell operates at the maximum power point [14]. The generated energy is first used to power the motor and on-board electronics, and the second is to use the remaining energy to charge the battery. At night, solar panels cannot provide energy. The energy consumed by each component is provided by the battery. Until the next day, the solar cells work again to provide energy to the system, that is a new cycle begins.

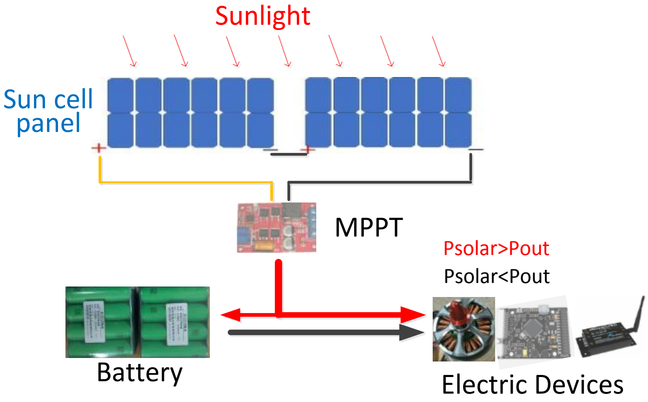


Fig.1. Solar UAV Energy System Composition

Solar arrays are a key component in UAV energy systems. At the maximum power point, the available solar power is the largest, equal to $P_{max} = V_{MPPT}I_{MPPT}$. Solar cells should work exactly at this point, when the ratio between P_{max} and light intensity exactly represents the efficiency of solar cells [15]. The current of a solar cell is proportional to its area, and it is almost linear with the change in light intensity [16]. Temperature also affects the characteristics of solar cells. In general, considering the same irradiation conditions, solar cells can provide higher power at low temperatures [17].

One of the equipment in the energy system is MPPT (Maximum Power Point Tracking), which is an upgraded new product of traditional solar charge and discharge control. By adjusting the working status (voltage, current) of the solar panel, the solar panel is always operated at the maximum power point of the V-A characteristic curve, and more solar power is output to obtain greater efficiency [14,18]. A considerable amount of research has been devoted to the development of more efficient and easy-to-use MPPT devices [19 to 21]. For example, studies in the literature [22] show that the MPPT efficiency can reach 0.97. Therefore, for the use of MPPT in solar-powered UAVs, the technical foundation is very mature.

Energy storage equipment is extremely important for solar aircraft that achieve long-endurance or permanent flight. The energy in the energy storage device is used to supply the aircraft with low solar power or sustained flight at night. Therefore, there are several important features of the equipment, stable charge-and-discharge performance, and greater energy density to minimize battery quality.

IV. Energy System Management Method

A. Solar radiation power of UAV

The solar power P_{solar}, which the main influencing factors include solar cell efficiency, MPPT efficiency, solar cell array area, beam radiation intensity, and beam incident angle. Cell efficiency is closely related to the materials used. Due to production costs and processes [23,24], silicon cells are generally used. The efficiency of industrial monocrystalline silicon cells exceeds 20%, and the efficiency of polycrystalline silicon cells is also close to 20%. MPPT efficiency is a definite parameter whose main function is to obtain the maximum output power of a solar cell [22,25]. The area of the array is an important design parameter, which has a great influence on the output power and is basically a linear relationship. The larger the array area, the greater the output power. The intensity of the beam and the angle of incidence of the beam depend on the time of day and the date of the day, and has an important effect on the output power. The impact of the above factors on the solar output power will be specifically analyzed.

Beam radiation is a parameter that changes with time, environmental conditions, according to the literature [26] can get the expression:

$$G_H = G_{se}\tau_b \cos\theta \tag{1}$$

First, the parameter G_{se} is the extraterrestrial radiation intensity, and its expression is shown in (2):

$$G_{se} = G_{sc}(1.00011 + 0.034221\cos B + 0.00128\sin B + 0.000719\cos 2B + 0.000077\sin 2B) \tag{2}$$

$G_{sc} = 1367\ W/m^2$ is the radiation constant.

Above of them, $B = (n-1)\dfrac{360}{365}$ (°), n is the n-th day of the year, $1 \le n \le 365$. Therefore, the time-varying extraterrestrial radiation is shown in Figure 2.

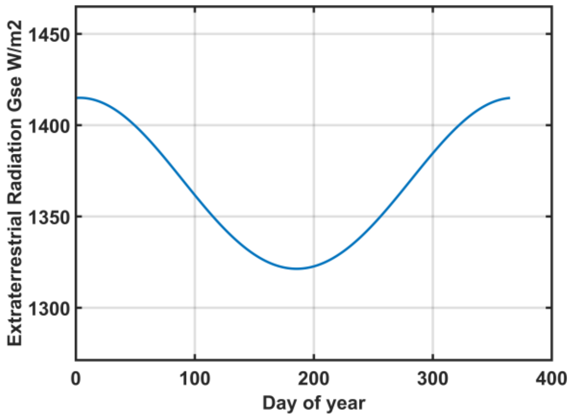


Fig.2. Curve of radiation outside the ground as a function of time

Second, the parameter τ_b indicates atmospheric turbidity. This paper uses the "transparent" atmosphere as an example. Its expression is [27]:

$$\tau_b = a_0 + a_1 \exp(-k \cdot m) \tag{3}$$

Atmospheric mass: $m = \frac{1}{\cos\theta}$, related to the angle of incidence of the solar beam. Flight height A = 0.2 Km, and flight environmental conditions are shown in Table 1.

Table 1 Flight Environmental Parameters

Parameter	Value
latitude	40 °(N)
Altitude	200m
Visibility	23Km "transparent" sky
Weather	Sunny (almost no clouds)
Wind	Level 3 (below)
Precipitation	No

Therefore, the formula for calculating the coefficient of "transparent" atmospheric turbidity:

$$\begin{aligned} a_0 &= 0.4237 - 0.00821(6-\mathrm{A})^2 \\ a_1 &= 0.5055 + 0.00595(6.5-\mathrm{A})^2 \\ k &= 0.2711 + 0.01858(2.5-\mathrm{A})^2 \end{aligned} \tag{4}$$

The angle of incidence θ of the solar beam is a parameter that varies with latitude, time, and date. The solution of its expression is described in detail in [26]. Here's a simple expression:

$$\begin{aligned} \cos\theta = {} & \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ & + \cos\delta\sin\beta\sin\gamma\sin\omega \end{aligned} \tag{5}$$

In this paper, the aircraft model is assumed to be reduced to a certain height of the horizontal plate, and the impact caused by the change of the flying attitude angle is a small amount, and the impact on the incident angle of the solar array as a whole is small. Therefore, the angle β=0 and angle of incidence are:

$$\cos\theta = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \tag{6}$$

According to the expression, the influencing factors can be analyzed. This paper selects a latitude of 40 ° (N), where δ is the sun's direct incident angle (using an exact approximation equation) [27]:

$$\begin{aligned} \delta = {} & (180/\pi)(0.006918 - 0.399912\cos B + 0.070257\sin B - 0.006758\cos 2B \\ & + 0.000907\sin 2B - 0.002697\cos 3B + 0.00148\sin 3B) \end{aligned} \tag{7}$$

As a result, there are many factors that affect the incident angle of the solar beam. Now we can solve the fixed latitude and fixed beam incident angle. After the above analysis and discussion, the corresponding radiation turbidity τ_b and beam radiant intensity G_H at the desired date and time can be calculated.

The input solar power P_{solar} calculation expression and determine the influence parameters one by one, which can describe in detail the power that the solar cell can generate and the energy that can be obtained in a day. Solar power expressions from the literature [28]:

$$P_{solar} = \eta_{sm}\eta_{mppt}S_{sm}G_H \cos\theta \tag{8}$$

Here, solar cell efficiency η_{sm}, MPPT efficiency η_{mppt}, array area S_{sm} (m^2), beam radiation intensity G_H (W/m^2), solar beam incident angle θ (rad). The solar array power can be calculated based on the solar beam radiation intensity and beam incident angle calculated in the previous section.

B. UAV energy output

The analysis of energy input and output balance of solar aircraft is the key to flying UAVs during long flights. By analyzing the solar power, the plane needs to use power, and the change trend of battery storage energy to determine the flight status of UAV. For low-altitude long time solar-powered aircraft, the basic method to maintain their long-time flight is to maintain a low-altitude level flight for maximum energy efficiency, and at the same time use solar cells to obtain energy from sunlight to charge the storage battery. Insufficient light intensity or continuous flight at night.

For energy input/output balance performance analysis, it is assumed that the aircraft is setting minimum altitude to maintain the minimum power required for level flight and maintain horizontal flight. Total required power:

$$P_{out}^{nom} = \frac{P_{level}}{\eta_{prop}} + P_{av} + P_{pld} \tag{9}$$

Among them, P_{level} level-flight needs to use the power to calculate the expression [29]:

$$\begin{cases} T = D = 1/2 \cdot \rho V^2 S \cdot C_d \\ m_{tot} g = L = 1/2 \cdot \rho V^2 S \cdot C_l \end{cases} \tag{10}$$

$$P_{level} = TV = \left(\frac{C_d}{C_l^{\frac{3}{2}}}\right)\sqrt{\frac{2(m_{tot} g)^3}{\rho S}} \tag{11}$$

Table 2 Aircraft aerodynamic parameters

Parameter	Value
η_{prop}	0.70
Pav	10 W
Ppld	0 W
Cl	0.8830
Cd	0.041
A	200 m

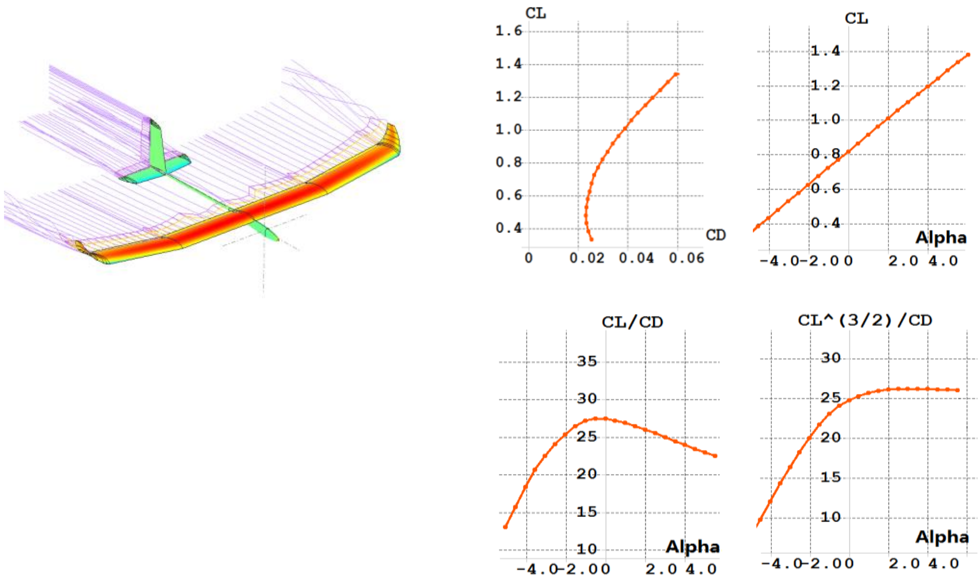


Fig.3. Aircraft flow field and aerodynamic parameters

The aerodynamic parameters of the aircraft model are shown in Table 2. Among them, Cl and Cd are lift coefficient and drag coefficient, respectively. The above aerodynamic coefficients can be obtained through the simulation software Xfoil [30]. For example, the simulation results of the aircraft model calculated in this paper are shown in Figure 3. The detailed design parameters are shown in Table 3 in Section V.

The battery power is an important parameter for the balance of energy input and output of the aircraft. During the daytime, solar power is provided to power the propulsion assembly and the onboard equipment. When the solar array power is greater than the output power, the solar array begins to charge the storage battery until the sunset solar power is less than the output power. When the solar power is less than the output power or at night, the required energy output of the aircraft is entirely derived from the battery. Therefore, the state of charge of the storage battery can be used as the parameters to evaluate of the energy balance of the system. Battery energy expression:

$$E_{batt}(t)=\int_t (P_{solar}-P_{prop}-P_{av}-P_{pld})d_t \tag{11}$$

Define the state of charge (SOC) of the battery, the ratio of the current battery capacity to the rated capacity of the battery [31], and its expression [32]:

$$\mathrm{SOC}=\frac{\mathrm{P_{solar}}-\mathrm{P_{flight}}}{\mathrm{E_{battery}}} \tag{12}$$

Here, $E_{battery}$ are the battery rated capacity. According to the design of the battery self-protection circuit, the SOC of the battery is required to be maintained within a certain safety range, that is $0.2 \le SOC \le 1$, the SOC minimum limit threshold $SOC_{\lim} \ge 0.15$ [33]. When the battery is over discharged, the SOC state is too low to cause irreversible damage to the battery, making the battery usable capacity rapidly attenuate. Thus, considering the long battery life design, keep the SOC value above the minimum threshold.

C. Criteria of method extended

In order for the aircraft to be able to fly permanently and have better multi-day flight stability, it is necessary to expand the energy balance design method. In general, a necessary and sufficient condition for an aircraft to perform long-distance flight over the day and night is its surplus time $t_{exc} > 0$. The surplus excess time is defined as [34]:

$$t_{exc}=\frac{Ebatt(t=t_{eq})}{P_{out}^{nom}}\Big|_{Psolar(t>t_{st})=0} \tag{13}$$

Here, $t=t_{eq}$ is the time when the solar power are equal to the output power at the next morning, t_{st} is the sunrise time. The significance of surplus excess time is, when $t=t_{eq}$ due to the influence of clouds and other factors $Psolar=0$, how long the remaining battery capacity can continue to maintain the flight. One of the design methods given in [8], [35] is to maximize surplus time, i.e. $\max(t_{exc})$. However, due to cloud cover and other factors, the design method cannot give an intuitive long-time flight stability analysis for the battery charging process. This paper will provide an intuitive and detailed design method of surplus time, as an extension criteria of the long-time aircraft energy system management design method.

For the demand of aircraft across the day-and-night, the impact of local environmental conditions on the aircraft should be considered, and a surplus excess time t_{exc} that meets the stability of long-term flight stability should be designed. The specific expansion criteria are as follows:

1) Determine the local geographical latitude φ, the date $Date$ of the aircraft flight, and the date window $Date[min,max]$ for continuous flight.

2) Calculate the length of the night $t_{night}^{\min}, t_{night}^{\max}$, according to the date window $Date[min,max]$ of the flight.

3) Earnings time calculation:

a. Change in night time caused by date change:

$$t_{exc}^{Date}=t_{night}^{\max}-t_{night}^{\min} \tag{14}$$

b. Estimate the influence of meteorological factors such as clouds and water fog in the early morning and evening $t_{exc}^{Weather}$. The impact of rainfall is fatal for solar-powered aircraft, thus the selection date of flight should be as far as possible to avoid local rainy days.

c. The addition time t_{exc}^{Plevel} because of the night flight environment effects on the aircraft, such as gusts, vertical turbulence, etc., cause additional power consumption of the aircraft.

Thus, the total demand surplus time:

$$t^{req}{}_{exc}=SUM(t_{exc}^{Date},t_{exc}^{Weather},t_{exc}^{Plevel}) \tag{15}$$

Furthermore, the installed battery capacity is a crucial parameter for the aircraft, which affects the ability of the aircraft to store and release electrical energy. The battery capacity is too small, and the stored energy is insufficient to support the aircraft flying at night long-endurance; the battery capacity is too large to be fully charged during the day, and the excess battery quality is the burden of the aircraft, which additionally increases power consumption. Therefore, the battery capacity required for flight needs to be calculated. The method for determining the battery capacity is as follows:

1) The battery capacity required for the surplus period:

$$E_{exc} = P_{out}^{nom} \cdot t_{exc} \tag{16}$$

2) Maximum battery capacity required for night flight:

$$E_{night}^{\max} = P_{out}^{nom} \cdot t_{night}^{\max} \tag{17}$$

3) Battery design minimum state value $SOC_{\min}$.

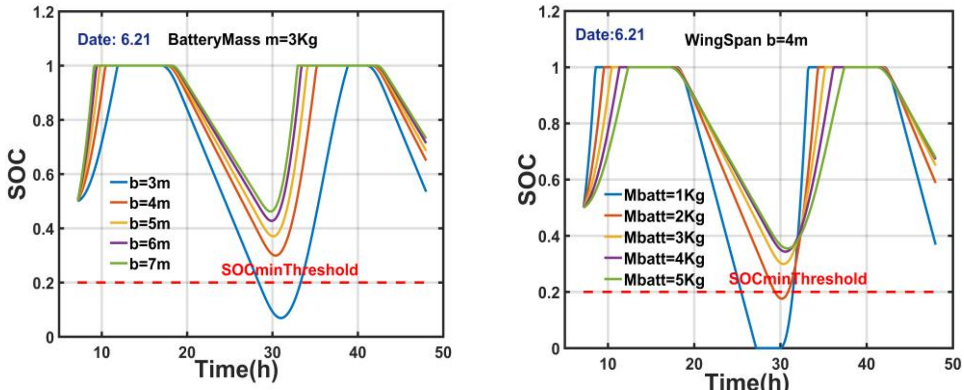
4) The required minimum battery capacity:

$$E_{batt,\min}^{req} = P_{out}^{nom} \cdot (t_{exc}^{req} + t_{night}^{\max}) / SOC_{\min} \tag{18}$$

The above process optimizes design of the surplus time at the required flight date window $Date[min, max]$ to meet the mission requirements of the solar UAV continuous flight on the selection date. Follow section will verify validation of the method.

V. UAV platform parameter design method

The third part gives a detailed description of the energy system management method of solar aircraft. However, according to the expressions (8) (9) and (11), it can be understood that the design parameters of the aircraft are different, which will greatly affect its long-term or permanent flight performance. As shown in Figure 4. The wingspan of an aircraft influences the solar power obtained, and the quality of the carried battery determines the energy that can be stored.

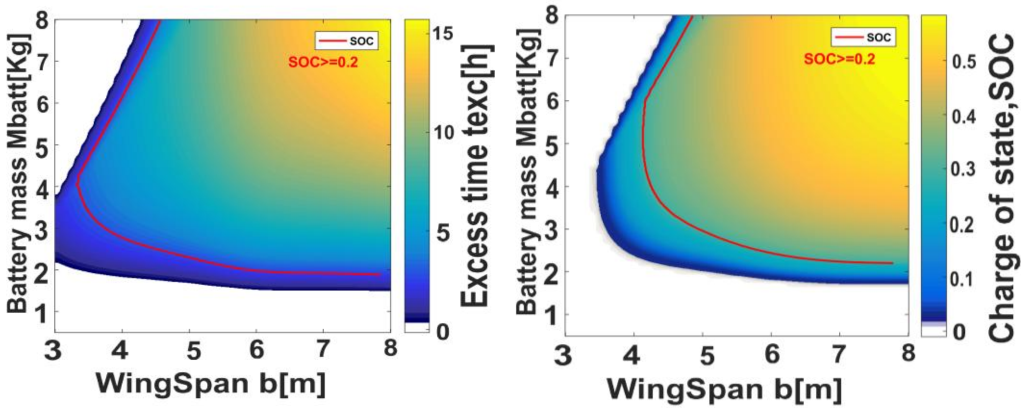


(a) (b)

Fig.4. Effect of aircraft wingspan (a) and battery mass (b) changes vs. SOC (Date June 22nd)

According to Fig. 4. (a), when the battery quality is fixed, the wing span of the aircraft changes, the charging time of the aircraft battery, the battery full time, the flight duration, and the SOC status value will change. The specific performance is that when the wing span of the aircraft increases, the battery charging speed gradually increases, and the time for full battery charging increases. At this point the aircraft will have the remaining power for the aircraft to climb, convert the energy into potential energy storage, and when the solar power is low, it can be used for low power gliding of the aircraft, increasing the flight time of the aircraft. At lower solar power or at night, the larger wingspan allows the aircraft to fly at lower power, so it takes longer to continue flying and the minimum SOC of the battery state of charge increases accordingly. Fig.4. (b) shows the effect of the battery quality carried by the aircraft on the permanent flight performance of the aircraft when the aircraft wingspan is fixed. The quality of the battery carried is too small, although the charging speed is faster, the stored energy is less, and it is impossible to maintain the continuous flight of the aircraft across the day and night. Therefore, it is necessary to increase the quality of the carried battery. However, as the battery quality increases, the speed of charging will also be reduced. To avoid overloading the battery, led to battery will not be fully charged, and the remaining uncharged battery will become an additional burden on the aircraft and increase the power consumption of the aircraft. Therefore, the optimization of the wingspan and battery quality of the aircraft must be carefully optimized.

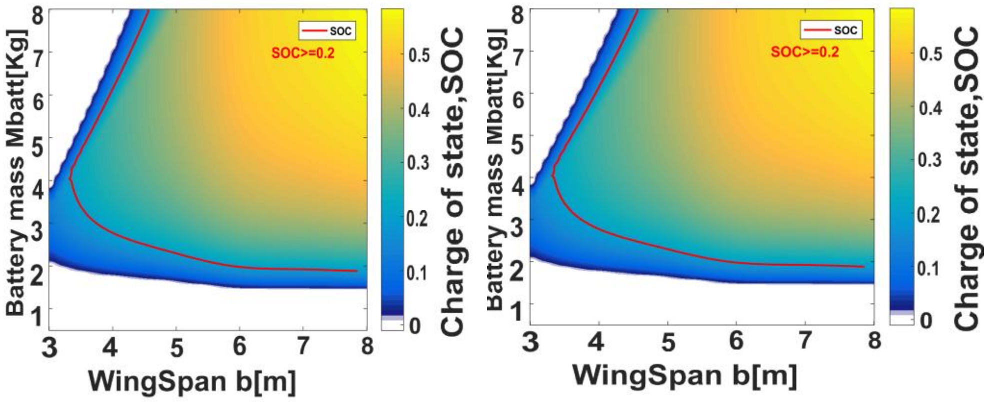
The energy system management method of the third Section is used to analyze the effects of wingspan and battery quality on the surplus time and battery state of charge (Date, June 22nd), as shown in Figure 5. The aircraft wingspan and battery quality optimization design domain is determined based on the SOC threshold.



(a) (b)

Fig.5. Surplus excess time t_{exc} (a) and SOC (b) vs. wing span and battery mass (Date, June 22nd)

Fig.5. shows the optimal relationship between wing span and mass versus aircraft surplus time and SOC. However, according to the expressions (5)(6)(7)(8), the solar power follows the date, so there should be some difference in the results of the optimization on different dates. For example, the date window designed by this article is the 6.21 ± 2 month, as shown in Figure 6. It is the optimization result of Date, April 21st. Compared to Date, there is a significant difference in June 22nd. Therefore, to achieve a permanent flight of the aircraft, the parameters of the aircraft need to be designed and selected using the boundary optimization results of the flight date of the aircraft. Later in the simulation test will be introduced according to the boundary date optimization results, select the aircraft design parameters for permanent flight performance verification.



(a) (b)

Fig.6. Relationship between surplus time t_{exc} (a) and SOC (b) vs. wing span b and battery mass M_{batt} with time change (Date, April 21st)

VI. The method simulation results

According to the expansion criteria, the nominal latitude determined in this paper is 40°(N), and the test flight date is June 21. The aircraft's life time window is required to be relative to the flight date, that is, April 21st to August 21st. The battery used in this article is a high energy density lithium-ion battery, model SONY18650VTC6, 6S configuration (21V), energy density $k_{batt}=243Wh/Kg$ [36].

Then, according to the literature [26], calculate the night time of the date window, Date.June 22nd, the minimum night time $t_{night}^{\min}=9.2h$, Date.April 21st, and the maximum night time $t_{night}^{\max}=10.7h$. Thus $t_{exc}^{Date}=1.5h$. the influence of factors such as cumulus clouds in the early morning and evening on the charging process of the aircraft is selected $t_{exc}^{Weather}=t_{night}^{\max}\cdot k_{ccf}=2.1h, k_{ccf}=0.2$, among which k_{ccf} is the cloud layer or fog thickness factor [37]. For nighttime flight, the ambient air flow disturbances and the additional power loss caused by the model correction are chosen $t_{exc}^{P_{Level}}=0.1\cdot t_{night}^{\max}=1.1h$. Therefore, the minimum surplus time $t_{exc}^{req}=4.7h$ required to ensure that the aircraft flies during a long flight in the date window. According to expression (18), the aircraft carries the battery quality $E_{batt,\min}^{req}/k_{batt}\approx3.0Kg$.

This article uses SunPower E60 solar cells, the efficiency up to 23.7%, taking into account the actual test deviation, calculation and simulation testing using 22% [23,38]. The simulation test will analyze the aircraft model's solar power input and nominal demand power output curve characteristics, as well as verify the performance of the model's continuous permanent flight on different days within the design date window.

A. UAV input/output power

Validate the performance of the energy system design method stated in the second part of the method. Keeping the model flying at a fixed altitude during the simulation can obtain the required power for the aircraft's level flight, from which the nominal output power of the aircraft can be calculated. The nominal output power can be used to calculate the battery capacity required for day-night flight on the corresponding date. Combined with the surplus time of the date, the capacity of the battery needed for the date window to maintain a stable and continuous flight can be obtained. Simulation test aircraft model parameters, as shown in Table 3. The optimum design point of the aircraft is shown in Figure 9.

Table 3 Aircraft model parameters

Parameter	Value
Wingspan	5m
Aspect ratio	13.3
Length	1.6m
Height	0.4m
Wing area	1.875m^2
Total mass	6.8Kg
Battery mass	3Kg
Level velocity	8m/s

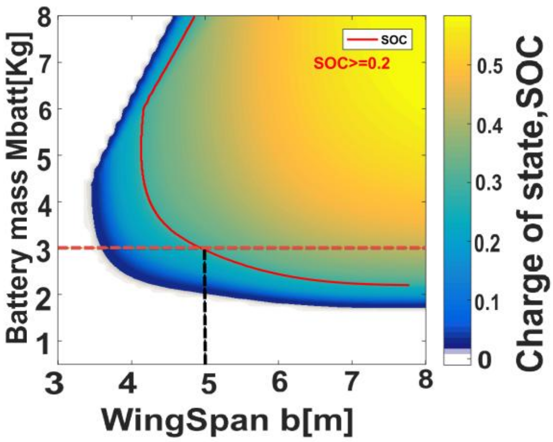


Fig.7. Aircraft Optimization Design Point (Date, April 21st)

As shown in Figure 10, (a) is the aircraft's leveling power at H=200m. The nominal output power is illustrated. The design requires a power of 35W-50W. The main factor is to consider the effect of gusts, vertical air currents on the model, and to correct the model. (b) is the solar power curve of the aircraft on the date of June 22nd. In the figure, the maximum solar power, solar power changes over time.

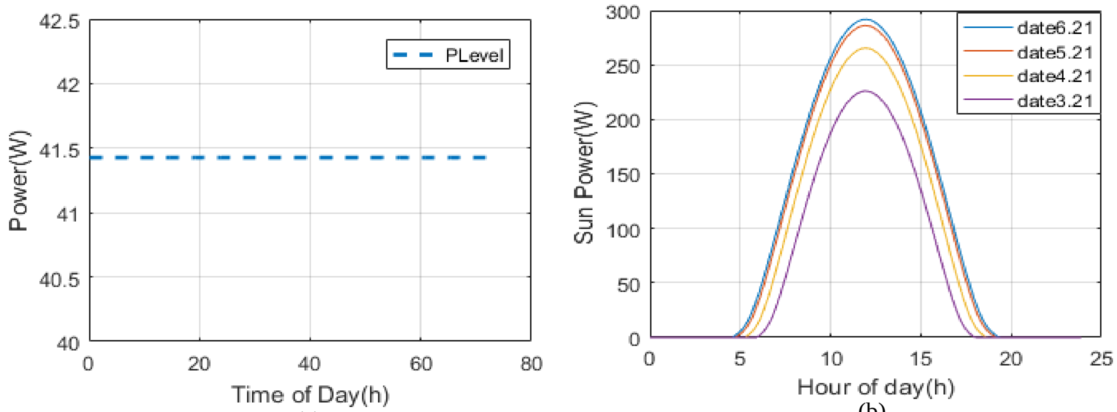


Fig.8. Level flying power (a) and solar power (b) curves

B. Power balance simulation test of system

The first step for a solar-powered aircraft to achieve a multi-day flight is to complete a single day-night flight. Therefore, first describe the state of the aircraft on the first day of launch. As shown in Figure 11, it is the energy power curve of date June 22nd. The solar-powered aircraft took off at 7 o'clock and the battery power status was 0.5. At this time $P_{solar} > P_{Level}$, when maintaining the aircraft's level flight, while charging the battery, the SOC curve can be observed. After less than 3 hours, the battery is full. The aircraft can climb the height to convert energy into potential energy storage.

After 6:00 pm, it began to consume battery power to keep the aircraft flying in the evening. After the sunrise the next day, the second cycle begins.

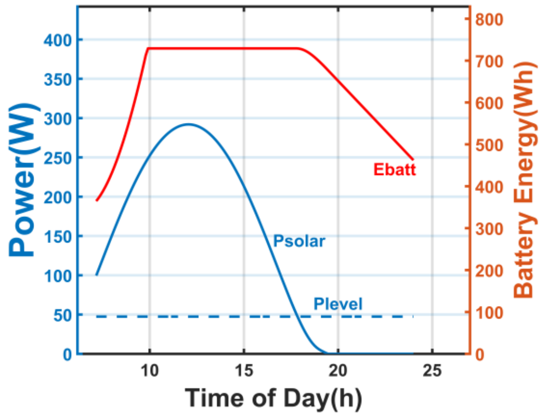


Fig.9. Energy Power Curve of June 22nd (Flight Simulation)

Second, the performance of the aircraft continued to fly for several days. Figure 12 shows the flight simulation of the aircraft for three days, using the SOC status level to evaluate the ability of the aircraft to continue flying during the day and night. The SOC shown in the figure is at a minimum value of 0.3. That is, when the solar input power is equal to the output power on the second day, about 30% of the battery remains. The solar power is then greater than the output power, which can gradually charge the storage battery. The surplus time of the remaining battery power and the full battery time of the battery meet the basic requirements for day and night flight.

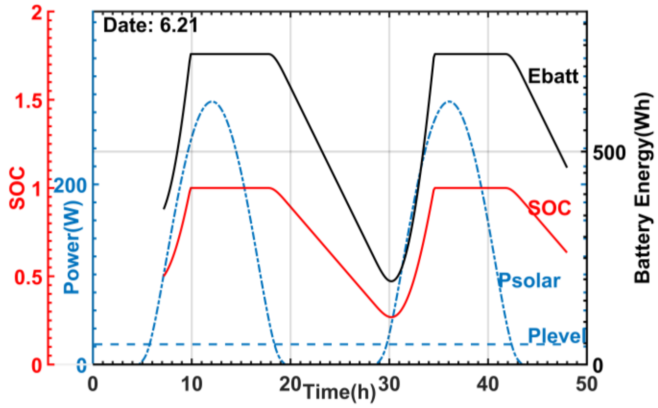


Fig.10. Energy Power Curve of date June 22nd simulated continuous flight

Finally, the energy input and output energy performance curves for different days are analyzed, as shown in Fig. 11, which is the energy curve of date April 21st. The flight environment conditions are the same as the date June 22nd. Due to the influence of the date change on the radiation intensity of the light beam, the solar output power is significantly reduced, so that the time for charging the battery is longer and the full battery time of the battery is reduced. At the same time, due to the change of the date, the time of the day becomes shorter and the time of the night increases. The discharge time of the battery is also greatly increased, and the residual value of the battery's power decreases, and the surplus time. The lowest value of the state of charge parameter SOC is 0.21, which also decreases synchronously and approaches the SOC design threshold. Therefore, the date change has a significant influence on the parameters of the solar aircraft.

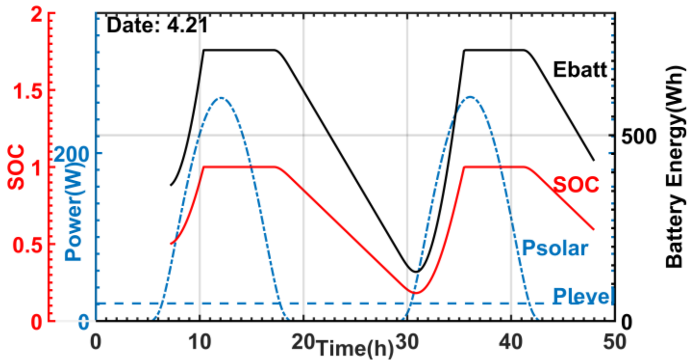


Fig.11. Energy Power Curve of April 21st simulated continuous flight

VII. Conclusion

This paper proves that the solar-powered spacecraft energy system management methods and the criteria for the expansion of the method can improve the stability and robustness of the aircraft's multi-day flight performance. In the part of UAV platform design, the influence of the parameters of the solar-powered vehicle on the continuous flight performance is analyzed, and the design reference method of the solar UAV platform is given. In the simulation test, the aircraft was taking off from 7 o'clock on the first day to verify the flight capability of the aircraft throughout the day and night and achieve the long-time flight of aircraft on the June 22nd to meet the mission requirements for multi-day flights. In addition, it also analyzes and verifies the ability of the aircraft continuous flight on April 21st, the edge of the time window selected in this paper. The feasibility of this method is verified in this paper. Future research work will focus on the development of actual flight equipment to verify the effectiveness of the practical application of this theoretical method and to apply the solar-powered flight platform.

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