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Energy management strategy for solar-powered high-altitude long-endurance aircraft

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ABSTRACT

Development of solar-powered High-Altitude Long-Endurance (HALE) aircraft has a great impact on both military and civil aviation industries since its features in high-altitude and energy source can be considered inexhaustible. Owing to the development constraints of rechargeable batteries, the solar-powered HALE aircraft must take amount of rechargeable batteries to fulfill the energy requirement in night, which greatly limits the operation altitude of aircraft. In order to solve this problem, a new Energy Management Strategy (EMS) is proposed based on the idea that the solar energy can be partly stored in gravitational potential in daytime. The flight path of HALE aircraft is divided into three stages. During the stage 1, the solar energy is stored in both lithium–sulfur battery and gravitational potential. The gravitational potential is released in stage 2 by gravitational gliding and the required power in stage 3 is supplied by lithium–sulfur battery. Correspondingly, the EMS is designed for each stage. The simulation results show that the aircraft can always keep the altitude above 16 km with the proposed EMS, and the power consumed during night can be also alleviated. Comparing with the current EMS, about 23.5% energy is remained in batteries with the proposed EMS during one day–night cycle. The sensitivities of the improvement of crucial technologies to the performance of aircraft are also analyzed. The results show that the enhancement of control and structural system, lithium–sulfur battery, and solar cell are ranked in descending order for the performance improvement of solar-powered HALE aircraft.

1. Introduction

In recent decades, many research groups all around world have paid great attentions to the development of the solar-powered High-Altitude Long-Endurance (HALE) aircrafts [1–3] for the reason that HALE aircrafts can always travel at high altitude, low speed, circle specific areas of interest and energy source can be considered inexhaustible [4]. They are ideally suited to provide potential applications especially for communications, wide area surveillance, telecoms relay, remote sensing, observation and target identification, battlefield management, crop and forest assessments and so on [5]. In many situations, HALE aircrafts can replace or complement the role of satellites but much cheaper [6]. Furthermore, since the atmosphere of Mars and Venus are similar with the high-altitude atmosphere on earth, solar-powered HALE aircraft is also considered by many groups to explore Mars and Venus [7].

The solar-powered HALE aircrafts are the typical representatives of all electrical aircrafts. Extensive research progresses made for the HALE aircraft category have placed the solar-powered aircraft concepts into practice [8]. Almost all of solar-powered HALE aircrafts employed electric motors, driven by rechargeable batteries and solar cells. The solar cell converts solar energy to electrical power and rechargeable batteries are used for storing the possible excess energy production [9]. There are two series of HALE aircraft projects which basically achieve the aim of high-altitude long-endurance flight: ERAST and Zephyr [10,11]. But, due to the problems on structure and rechargeable battery, none of aircraft realizes long endurance flight in real sense. After these pioneering experiments, researchers gradually realize that the crucial factor limiting the development of solar-powered HALE aircrafts is the problem how to fulfill the power requirements under weight constraint of rechargeable batteries [12–14]. current technological level, the weight of the batteries occupy around 50% of the total mass of solar-powered HALE aircrafts, therefore, for a renewable energy aircraft, regenerative power technologies such as solar cell, rechargeable batteries, and energy management systems, are the keys to achieve long-endurance [15,16].

Comparing to fuel cell [17] and hydrogen [18], Lithium–sulfur is one of the most promising rechargeable batteries for its high theoretical specific energy of 2600 W h/kg [19] base on the lithium–sulfur redox couple. Furthermore, as kind of cathode material, elemental sulfur shows other advantages such as its abundance in nature, low cost and environmental friendliness [20]. There is immense interest to adopt lithium–sulfur battery for electric

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Nomenclature

α	attack angle
α_{day}	day angle
α^*	the control command of attack angle
δ	the solar declination angle
ε	eccentricity ratio of earth
ϕ	the latitude of the location
μ	pitch angle
η_A	efficiency of airscrew
η_B	efficiency of battery
η_{BM}	efficiency of battery Manager
η_{MPPT}	efficiency of MPPT
η_{PC}	efficiency of power conversion
η_{SC}	efficiency of solar cell panel
ρ	the air density
τ	the transmittance factors
θ	the zenith angle
ω	the hour angle
AR	aspect ratio
C_D	drag coefficients
C_L	lift coefficients
D	drag force
H	altitude of the aircraft
I_{0n}	the intensity of the extraterrestrial normal solar radiation
I_{SC}	the extraterrestrial normal solar radiation constant
L	lift force
L_{span}	span length
P_{BM}	the output power of battery manager
P_{csm}	the consumed power
P_{level}	the power consumed during level flight
P_{prop}	the required power of propulsion system
P_S	solar power per square
Q_B	the quantity of electricity energy in battery
S_C	area of solar cells
S_W	the wing area
T_h	thrust force
V	airspeed
d_n	the day number of the year
h_{lowest}	the lowest altitude
m	the mass of aircraft
m_b	the mass of battery
$\bar{m}_b$	the energy density of battery
m_{struct}	the mass of structure
q	the rate of charge
q_{max}	the maximum rate of charge
r	sun–earth distance
r_0	the mean sun–earth distance
t	the local apparent time
x	horizontal ordinate of the aircraft

Abbreviations

ECE	Energy Conversion Efficiency
EMS	Energy Management Strategy
HALE	High-Altitude Long-Endurance
MSPS	Mean Solar Power per Square
MPPT	Maximum Power Point Tracking
SPS	Solar Power per Square
TSES	Total Solar Energy per Square

vehicle applications and stationary storage of renewable energies such as solar and wind energy [21]. But the development of lithium–sulfur battery using a liquid electrolyte has a number of problems to overcome, such as low-active material utilization due to the insulating nature of sulfur, a poor cycle performance with agglomeration, and poor electrical contact between the sulfur and conductive carbon after the charge–discharge process [22–25]. Nowadays, the energy density of electric batteries in application is around 350 W h/kg [26], and this value is expected to be doubled within next decade [27,28]. Although more battery can provide more energy during night, the weight of additional batteries needs more energy to sustain continuous flight at the same time [13]. So it is really hard to develop a solar-power HALE UAV under current technological level.

The ultimate aim of solar-powered HALE aircraft is to achieve a high-altitude long-endurance flight. Therefore, it is also important to research on alternative method to enhance flight endurance except waiting for the great technological progress made in ultra-lightweight structure or lithium–sulfur battery. Many researchers have realized the importance of Energy Management Strategy (EMS) to improve the power efficiency of systems, including wind farm [29], hybrid vehicle [30–35], commercial buildings [36], light electric bus [37–39], air conditioning [40] and so on. Moreover, since the sun is not available throughout the whole day, effective designs of EMS for managing, collecting, storing and consuming energy are needed to make the solar-powered HALE aircraft do as a real alternative to satellite in both day and night missions [41]. Thus, an appropriate EMS is considered as an efficient method to solve the conflict between the mass of batteries and the energy requirement during night [42].

The EMS proposed in this paper is based on the idea that the solar energy can be partly stored in gravitational potential in daytime. The flight path of HALE aircraft is divided into three stages. During the stage1, the solar energy is stored in both lithium–sulfur battery and gravitational potential. The gravitational potential is released in stage 2 by gravitational gliding and the required energy during stage 3 is supplied by lithium–sulfur battery. According to this divide, the corresponding EMS is designed for each stage. The remainder of this paper is organized as follows: The modeling of solar-powered HALE aircraft and the solar energy assessment model are introduced in Sections 2 and 3, respectively. Next, the current EMS and the proposed EMS are presented in Section 4. The implementation and simulation about proposed EMS is demonstrated in Section 5. The crucial technologies such as Energy Conversion Efficiency (ECE) of solar cell, energy density of lithium–sulfur battery, control and structure system for the development of solar-powered HALE aircraft are discussed in Section 6. Finally, the conclusions are presented in Section 7.

2. Modeling of solar-powered HALE aircraft

For describing the motion of the aircraft, a mathematical model based on point mass dynamics is supposed to be applicable [42], as shown in Fig. 1, solar-powered aircraft is assumed to fly in still air, the velocity axes [43] is used for the aircraft, thus, the assumption of vertical plane flight induces an assumption of zero yaw angle.

The dynamic model of aircraft can be formulated as follows:

$$\begin{cases} m\dot{V} = T_h \cos\alpha - D - mg\sin\mu \\ mV\dot{\mu} = T_h \sin\alpha + L - mg\cos\mu \\ \dot{H} = V\sin\mu \\ \dot{x} = V\cos\mu \end{cases} \tag{1}$$

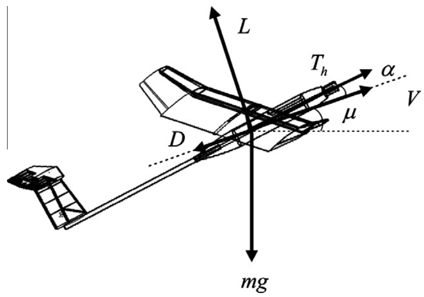

Fig. 1. Scheme of forces acted on aircraft.

Table 1
The basic parameters of studied solar-powered UAV.

Parameter	Value	Unit	Description
m_{struct}	37	kg	Mass of structure
m_b	16	kg	Mass of battery
L_{span}	22.5	m	Span length
AR	25	–	Aspect ratio
S_W	20.25	m^2	Wing area
S_C	16.2	m^2	Area of solar cells

where V is the speed, T_h is thrust force generated by motor and screw propeller, α is attack angle, L and D are lift force and drag force respectively, m is mass of aircraft, μ is pitch angle, x and H are the Cartesian coordinates of the aircraft.

The aerodynamic forces L and D are defined in Eqs. (2) and (3), where C_L and C_D are respectively the lift and drag coefficients, ρ is air density, S_W is wing area.

$$L = C_L S_W \left(\frac{1}{2}\rho V^2\right) \tag{2}$$

$$D = C_D S_W \left(\frac{1}{2}\rho V^2\right) \tag{3}$$

The lift coefficient is dependent on the drag coefficient, as shown in Eq. (4). They can be obtained by interpolation from a table defined by attack angle, altitude and velocity:

$$C_D = C_D(C_L) \tag{4}$$

The basic parameters of studied solar-powered UAV are listed in Table 1, which is mainly referred from Zephyr (more detailed information can be found in www.QinetiQ.com).

3. Solar energy assessment model

For the studied aircraft, its operating altitude is always very high, so the influences of temperature, humidity and albedo to solar radiation can be neglected. As a matter of fact, the orientation and the tilt of a solar panel strongly affect the amount of the collected solar energy yield [44], for the sake of simplicity, the collected solar energy is estimated with the assumption that the aircraft is always flying with zero pitch and roll angle. Thus, based on Ref. [45], the Solar Power per Square (SPS) can be estimated by the following equations, the significations of symbols in equations are listed in Table 2.

$$P_S = I_{0n}\tau \sin(\theta) \tag{5}$$

$$I_{0n} = I_{SC}(r_0/r)^2 \tag{6}$$

$$r = r_0(1-\varepsilon^2)/(1+\varepsilon\cos\alpha) \tag{7}$$

$$\alpha_{day} = 2\pi(d_n - 4)/365 \tag{8}$$

$$\theta = \frac{\pi}{2} - \cos^{-1}[\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega(t)] \tag{9}$$

$$\delta = \frac{23.45\pi}{180}\sin\left(360\frac{284+d_n}{365}\right) \tag{10}$$

$$\omega(t) = \pi - \pi t/12 \tag{11}$$

The SPS of most districts around the world can be estimated by Eqs. (5)–(11). Taking the location of ChangSha (28.2°N, 112.6°E) in 15th July as an example, the SPS P_s is depicted as dash–dot line in Fig. 2. The Total Solar Energy per Square (TSES) can be calculated by Eq. (12), where $t \in [0, T]$, T = 24 h. TSES E_s is depicted as the solid line in Fig. 2. The Mean Solar Power per Square (MSPS) P_{ms} during a day is calculated by Eq. (13), which is depicted as double dash line in Fig. 2.

$$E_S = \int_0^t P_S d\tau \tag{12}$$

$$P_{ms} = \frac{\int_0^T P_S dt}{T} \tag{13}$$

The MSPS throughout a year on the earth can be graphically presented in Fig. 3 (the reference altitude in Figs. 2 and 3 is 0 km). The places where the maximal solar power is available are specially marked, showing that these are at tropic of Cancer in summer solstice and tropic of Capricorn in winter solstice respectively. It is clearly can be seen that mean power distribution on earth is not left–right symmetric, reason of that is the distances between sun and earth are different in vernal equinox and autumnal equinox, we can find the same phenomenon in the figure of energy distribution in Ref. [42].

4. Energy management strategy

4.1. Energy management system

The function of energy management system can be described as follows: its main energy comes from solar panels which are composed of silicon cells covered on the surface of the wing. During daytime, it converts solar energy into electrical energy, which is divided into two parts by a system named Maximum Power Point Tracking (MPPT): one part supplies power to the motor and other electronics, the other part charges to battery with surplus energy [46], as shown in Fig. 4.

The efficiencies of all the components in Fig. 4 are listed in Table 3. The charging efficiency and discharging efficiency of batteries are not distinguished in this paper. Instead, the efficiency of batteries η_B is used to describe how much energy can be discharged when the charging energy is 100.

Generally speaking, the propulsion system of aircraft consists of an electric motor and a propeller, which are denoted by an airscrew in Fig. 4. So, the airscrew efficiency in Table 3 is both the propeller efficiency and motor efficiency. As everyone known that the propeller efficiency is changed with altitude for the variation of Reynolds numbers, in order to conquer this problem, the adjustable blade is always adopted in the propeller of HALE aircraft. Thus, it is reasonable to assume the aircrew efficiency is constant in basic conceptual analysis. Thus, the thrust provided by propulsion system can be calculated by the following equation:

$$T_h = \eta_A \frac{P_{prop}}{V} \tag{14}$$

where P_{prop} is the required power of propulsion system.

According to Refs. [26,47], the demonstrated specific energy levels at cell level are 350 W h/kg for lithium–sulfur batteries. Here

Table 2
The significations of symbols in Eqs. (5)–(11).

Symbol	Signification	Value/unit
P_S	Solar power per square	W/m^2/day
I_{0n}	The intensity of the extraterrestrial normal solar radiation	W/m^2
τ	The transmittance factor	0.85
θ	The zenith angle	Deg.
I_{SC}	The extraterrestrial normal solar radiation constant	1367 W/m^2
r_0	The mean sun–earth distance	149,597,890 km
r	Sun–earth distance	km
ε	Eccentricity ratio of earth	–
α_{day}	Day angle	Deg.
d_n	The day number of the year, ranging from 1 on 1st January to 365 on 31st December	–
ϕ	The latitude of the location	Deg.
δ	The solar declination angle	Deg.
ω	The hour angle	Deg.
t	The local apparent time	h

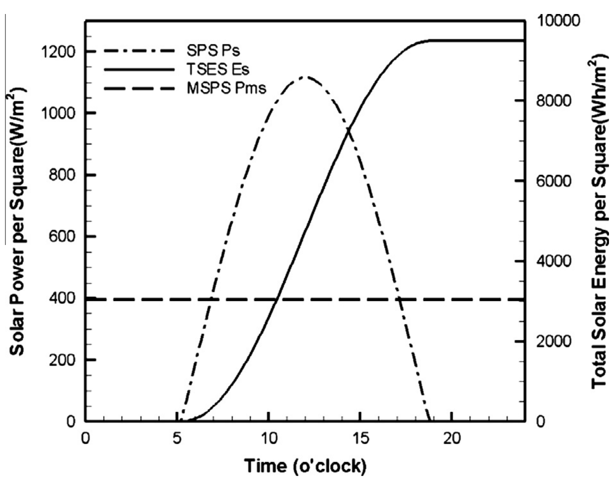

Fig. 2. The SPS, TSES and MSPS in ChangSha in 15th July.

the energy density of battery is supposed to be $\bar{m}_b = 350$ W h/kg. Battery charging and discharging can be performed at a rate up to a maximum value, thus the following model for lithium–sulfur battery is applied:

$$\dot{Q}_B = q \tag{15}$$

Q_B is the quantity of electricity energy in battery, q is rate of charge, positive is charging, negative is discharging.

4.2. Current energy management strategy

The main aim of Energy Management Strategy (EMS) is to keep solar-powered HALE aircraft aloft for long-endurance missions without energy replenishment. Taking Zephyer 7 as the example, its EMS for the long-endurance missions is elaborated as follows: The aircraft keep the balance between lift force and weight with the minimal power factor in level flight. If the output power of battery manager P_{BM} is greater than the required power of propulsion system $\eta_{PC}P_{prop}$, then the surplus power is used to charge the lithium–sulfur batteries. On the other hand, if P_{BM} is less than $\eta_{PC}P_{prop}$, the insufficient part of required power will be supplied by discharging the lithium–sulfur batteries, where P_{BM} is defined by the following equation:

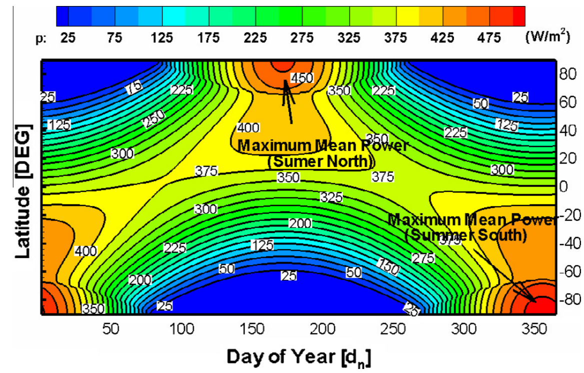

Fig. 3. Regions of Mean Solar Power Per Square (MSPS) distribution (W/m^2).

$$P_{BM} = P_S S_C \eta_{SC} \eta_{MPPT} \eta_{BM} \tag{16}$$

During level flight the pitch angle $\mu = 0$, $D = T_h \cos\alpha$, $L = mg - T_h \sin\alpha$, so the power consumed during level flight P_{level} can be calculated as follows:

$$\begin{aligned} P_{level} &= T_h V = \frac{DV}{\cos\alpha} = \frac{1}{C_L/C_D}\frac{L}{\cos\alpha}\sqrt{\frac{2L}{\rho C_L S_w}} \\ &= \frac{C_D}{C_L^{3/2}}\left(\frac{mg - T_h \sin\alpha}{\cos\alpha}\right)\sqrt{\frac{2(mg - T_h\sin\alpha)}{\rho S_w}} \end{aligned} \tag{17}$$

Thus, the current energy management strategy can be expressed as follows:

$$\dot{Q}_B = \begin{cases} q_{\max}, & P_{BM} - \eta_{PC}P_{prop} > q_{\max} \\ P_{BM} - \eta_{PC}P_{prop}, & -P_{level} < P_{BM} - \eta_{PC}P_{prop} < q_{\max} \\ -\eta_A \eta_{PC} P_{level}, & P_{BM} - \eta_{PC}P_{prop} < -P_{level} \\ 0, & Q_B > m_b \cdot \bar{m}_b \text{ or } Q_B < m_b \cdot \bar{m}_b(1-\eta_B) \end{cases} \tag{18}$$

where q_{max} is the maximum rate of charge, which usually is determined by the properties of lithium–sulfur batteries [48].

According to Eq. (17), the control command of attack angle α^* in Eq. (1) can be expressed as follows:

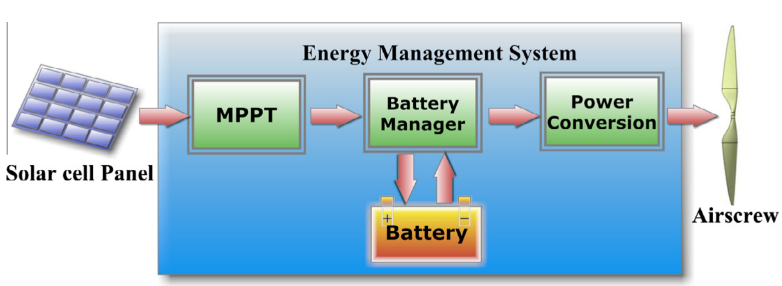

Fig. 4. Energy management system.