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Optimal Sizing and Cruise Speed Determination for a Solar-Powered Airplane

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This paper presents the use of a genetic algorithm to optimize the size and cruise speed of a solar-powered unmanned aerial vehicle named Xihe. A conceptual aerodynamic configuration design is conducted first to obtain the initial size of the aircraft and the performance parameters. The optimization process then searches for optimal solutions for minimum energy operation. To minimize the number of decision variables, the aspect ratio of the wing and the fuselage design are fixed during optimization. The mass of the Xihe aircraft is then parameterized as a function of two performance parameters: wing reference area and cruise speed. With the parameterization results, a fitness function that links the optimization problem and the genetic algorithm is then established. The genetic algorithm searches for the optimal results for minimum energy operation. This optimization process reduces the referenced wing area of the Xihe aircraft from 5.63 m^2 in the conceptual design to 4.91 m^2, which allows the reduction of the solar cell panel by 12.79%, reducing the costs. Optimization reduces the mass of the aircraft from 24.96 to 22.47 kg: a 9.98% reduction. The cost of the complex materials used would be less than originally required, and the cruise speed would increase from 10.93 to 11.23 m/s (the cruise speed for minimum power consumption).

Nomenclature

AR	=	aspect ratio
C_D	=	drag coefficient
$C_{D,0}$	=	zero-lift drag coefficient
C_L	=	lift coefficient
D	=	drag force, kg · W
E_{battery}	=	required battery energy, W · h
E_{sun}	=	average irradiance of solar radiation energy, W/m^2
e	=	wing span efficiency
f_{DOD}	=	depth of discharge of the battery
f_{safety}	=	safety factor
K	=	induced drag factor
L	=	lift force, kg · W
M_{battery}	=	mass of the battery, kg
M_{panel}	=	mass of the solar cell panel, kg
M_{payload}	=	mass of the payload, kg
$M_{\mathrm{structure}}$	=	mass of the structure, kg
M_{thrust}	=	mass of the propulsion system, kg
M_{total}	=	total mass of the Xihe airplane, kg
P_{charge}	=	power required to charge the battery, W
P_{others}	=	power required for other systems, W
$P_{\mathrm{propulsion}}$	=	power consumption of the propulsion, W
P_{required}	=	total required power to support airplane operation, W
P_{supplied}	=	power supplied from the solar power panel, W
S_{panel}	=	solar cell panel area, m^2
S_{ref}	=	referenced wing area, m^2
T_{daytime}	=	duration of daytime, h
T_{dusk}	=	duration of dusk time, h
T_{night}	=	duration for flight without sunlight, h
T_r	=	thrust force, kg · W
V_{opt}	=	cruise speed under minimum energy condition, m/s
v	=	cruise velocity, m/s
W	=	weight of the airplane, kg · W
w_1, w_2, w_3	=	weight factors for the optimization problem
η_{charge}	=	charge efficiency of the battery
$\eta_{\mathrm{converter}}$	=	efficiency of the power converters
$\eta_{\mathrm{discharge}}$	=	discharge efficiency of the battery
η_{motor}	=	motor efficiency
η_{panel}	=	efficiency of the energy conversion of the solar cells
$\eta_{\mathrm{propeller}}$	=	efficiency of the propeller
ρ_{battery}	=	energy density of the battery, W · h/kg
ρ_∞	=	air density at the designated altitude, kg/m^3

I. Introduction

DEVELOPMENT of unmanned aerial vehicles (UAVs) has been an important stream in both the military and civil aviation industries for decades and will continue to draw great attention in the future [1,2]. Applications of UAVs include remote sensing, transport, scientific search, search and rescue, and damage assessment. Design considerations for UAV development mainly include degree of autonomy and endurance capabilities. Technologies that provide autonomy involve sensor fusion, communication, navigation, guidance, and control. The achieved degree of autonomy has a significant influence on the overall value and specific applications of the UAV market, and it is desirable to keep the aircraft aloft (without any maintenance) for a long period of time. The maximum flight duration depends on the fuel available onboard. The solar-powered UAV has the potential of reaching the ultimate goal of continuous flight, because the energy source (sunlight) is considered inexhaustible. Development of solar-powered aircraft has attracted the attention of several research and design centers over the decades, since the successful flight of Sunrise (the first solar-powered aircraft), which was developed by Astroflight, Inc. [3,4]. Gossamer Penguin, Solar

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Challenger, Pathfinder, Centurion, and Helios are some notable solar-powered aircraft [5,6]. A methodology for the conceptual design of solar-powered aircraft is presented in [7]. It provides a simple means for defining, evaluating, and sizing conceptual designs for high-altitude long-endurance solar-powered aircraft. The methodology is developed from conventional aircraft design and analysis techniques [8,9] but incorporates the special characteristics and constraints for solar-powered aircraft into the design process. The results of the conceptual design may not provide optimal aerodynamic performance.

To improve UAV aerodynamic performance, certain design factors (such as the airfoil profile, the aspect ratio of the airfoil, and the wing taper ratio) must be determined with some sense of optimization. Techniques used to solve complex optimization problems, such as aerodynamic configuration designs, can be classified into two categories: gradient-based optimization techniques and stochastic search algorithms. Aerodynamic designs using computational fluid dynamics (CFD) and Navier–Stokes equations combined with gradient-based optimal control theory are popular and have been successfully used to optimize aircraft configuration designs [10–12]. The drawback of conventional gradient-based optimization techniques is the tendency to get trapped in local minima, or the difficulty in gradient calculation. Search-based algorithms, which require no gradient information for solution searching and can achieve a global optimum, offer considerable advantages for solving the complex optimization problems. Genetic algorithms, inspired by Darwin's theory of evolution and natural selection, belong to the category of stochastic search methods and are popular for solving complex optimization problems. Using genetic algorithms, solutions to the problems are evolved. Unlike other solution search methods, genetic algorithms operate on a population of solutions rather than a single solution. Solutions with favorable features are selected from the population and modified to generate a new population for evolution. The search algorithm is separated from the representation of the problem to be solved. The only link between the search algorithm and the practical problem is the fitness function defined for the particular problem. Thus, the algorithms can be used for a broad class of complex systems [13,14]. Recently, genetic algorithms have been widely studied and applied to the optimization of aerodynamic configuration designs [15–19]. Most research focuses on the optimization of the aerodynamic configurations and efficiencies of the evolutionary computation algorithms. The design of a solar-powered airplane is more complicated [7,20–22]. Not only must the characteristics and constraints of solar power be integrated into the design, but the tradeoff between the wing aspect ratio and the bracing method (which results in a compromise of the parasite drag, the induced drag, and the wing mass) must also be considered.

In this present study, the intent is to optimize a solar-powered UAV, named Xihe, with minimal energy requirements. The UAV Xihe, which is an in-house design project of the Department of Aerospace Engineering at Tamkang University, is intended to develop the skills of designing and building regeneratively powered aircraft. The goal is flight with an endurance of 8 h under sunlight and 1 h after sunset. The initial aerodynamic configuration is obtained through traditional design methods, incorporating solar power requirements based on the past UAV design experience. After the initial conceptual design, the referenced wing area of the Xihe airplane is 5.63 m^2, the mass of the airplane is 24.96 kg, and the cruise speed is 10.93 m/s at a cruise altitude of 100 m (chosen to maintain visual contact with the pilot on the ground). Note that the wind effect is not considered in the design. The initial conceptual design is optimized for the minimum energy required for straight and level flight, using a mass parameterization approach. The aircraft mass (the mass of the propulsion system, the solar cells, and the structure) is parameterized as a function of other aircraft design parameters (wing area and cruise speed). The mass parameterization results are linked with the lift requirement, energy provisions, energy consumption, and optimal cruise speed to establish a parameter search formulation that finds the optimal solution using genetic search algorithms. This study focuses on the mass parameterization of the solar-powered airplane and the formulation of the optimal sizing and cruise speed, rather than the study of computational search algorithms. The solutions are obtained using the MATLAB® Genetic Algorithm and Direct Search Toolbox [23].

II. Xihe Aircraft Configuration Design

The aerodynamic configuration design of a solar-powered aircraft is more complicated than the design of a traditional aircraft. In

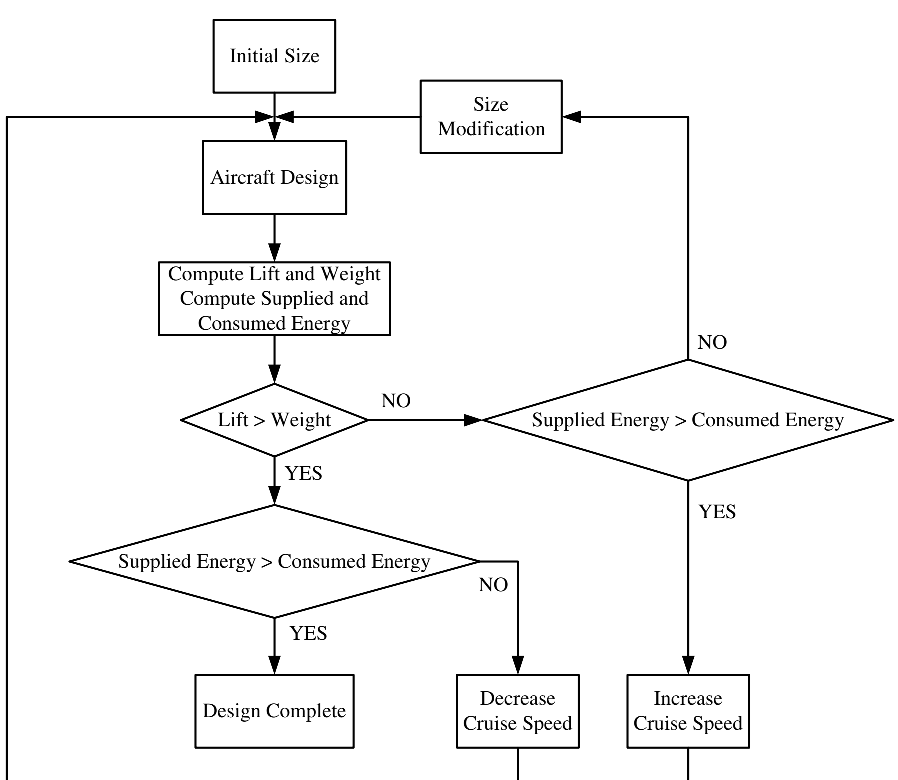

Fig. 1 Aerodynamic configuration design process for a solar-powered aircraft.

solar-powered aircraft, the power obtained from wing-mounted (upper surface) solar cell panels is directly proportional to the wing area, which, in turn, affects most of the aircraft performance parameters, such as lift, drag, weight, and cruise speed. In addition, most of the design parameters are interrelated. Adjusting one parameter usually requires reevaluation or recomputation of all other parameters. Traditionally, iteration of certain design procedures is used to obtain a compromise solution. The design procedures are usually tedious.

The process for the initial aerodynamic configuration design of the Xihe aircraft is shown in Fig. 1. This process begins with an initial wing size and cruise speed, then the lift and weight of the aircraft are computed, and the amount of power supplied by the solar cell panel and the total required power for aircraft operation are evaluated. If the lift is greater than the weight and the supplied power is higher than the consumed power, the aircraft design is complete. If the lift is less than the weight and the supplied power is less than the consumed power, the size of the aircraft has to be modified and the design process repeated. If the lift is less than the weight and the supplied power is higher than the consumed power, the cruise speed is increased and the design process repeated, but if the lift is greater than the weight and the supplied power is less than the consumed power, the cruise speed is decreased and the design process repeated.

The primary goal of the Xihe airplane is to fly for 8 h during sunlight and 1 h after sunset. Following the proposed design procedure, the preliminary aerodynamic configuration is reached, with a wing reference area of $5.63\ \mathrm{m}^2$ and a cruise speed of $10.93\ \mathrm{m/s}$. To avoid the construction difficulties, the chosen aspect ratio is a moderate value of 7, which is unchanged during the optimization process. With this design, the mass of the aircraft is 24.96 kg and its span is 6.28 m. Figure 2 shows three views of the Xihe airplane. The tail surface is to ensure that the wing lift supports the weight of the aircraft. The cruise speed obtained from the design is not likely to be the solution for the minimum power required.

Given the limitations of solar cell efficiency, battery energy density, and the weight of the structural materials, the critical challenge in reducing production costs and reaching the ultimate design goal of cruising overnight is to optimize the efficient use of the available solar energy. Because of the interaction between the lift and drag forces, a cruise speed exists that will minimize the power required for a particular cruise altitude. Assume that the power required can be reduced by 10% through optimal design. A 10% decrease in required power implies a 10% reduction in the solar cells. Thus, the battery capacity and weight can be reduced, which decreases the weight of the aircraft. The lift required for cruising can be adjusted downward. This provides an opportunity to reduce the wing reference area. In other words, the optimal design can effectively reduce the costs of the solar cells, the batteries, and the structural materials. The limited ability to acquire energy and the structural intensity requirements make optimal design necessary.

As mentioned previously, an optimal cruise speed exists that requires minimum energy at a particular cruise altitude. For aircraft design, most design parameters are interrelated. Reevaluation of the aircraft performance and recomputation of all other parameters are required to adjust a particular design parameter. To minimize the number of decision variables, the aspect ratio of the wing and the fuselage design are fixed during optimization. The mass of the Xihe aircraft is parameterized as a function of two performance parameters: wing reference area and cruising speed. Details of the parameterization will be discussed later. After the parameterization, the optimization process (shown in Fig. 3) can be initiated to search for the optimum solution. The object is to search for the optimal aircraft cruise speed and referenced wing area that satisfy the performance requirements and design objectives. That is, the aircraft lift must equal the weight of the aircraft, the power supplied by the solar cell panel must exceed the total power required for aircraft operation, and the cruise speed must equal the optimum cruise speed for minimum power consumption. Computation of the optimum cruise speed is presented in the next section. Note that airplane stability and control are not taken into consideration during the optimization process.

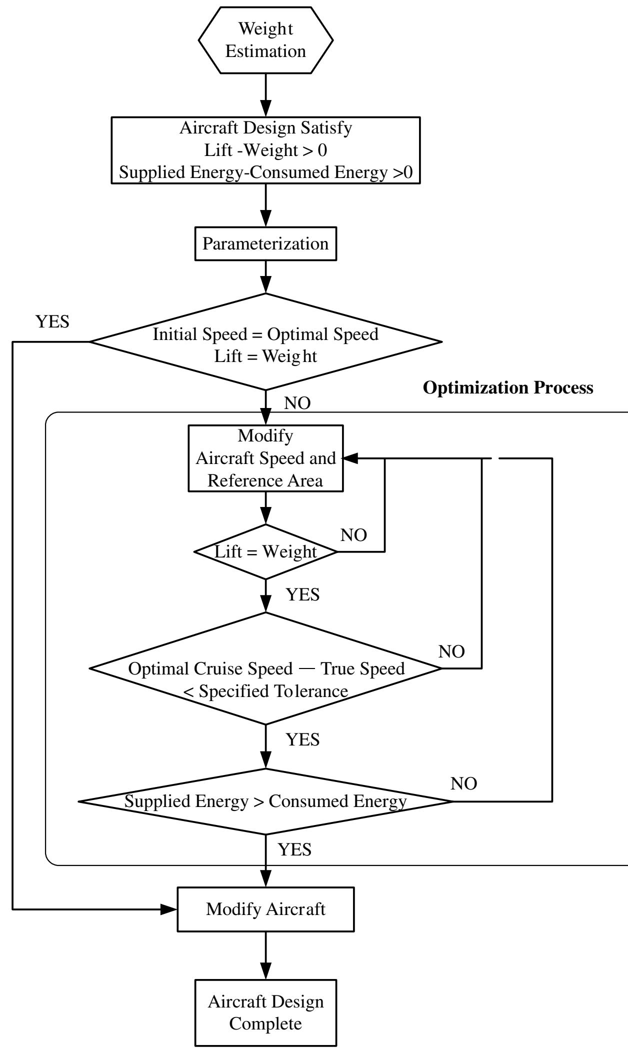

Fig. 3 The optimization process for the aerodynamic configuration design.

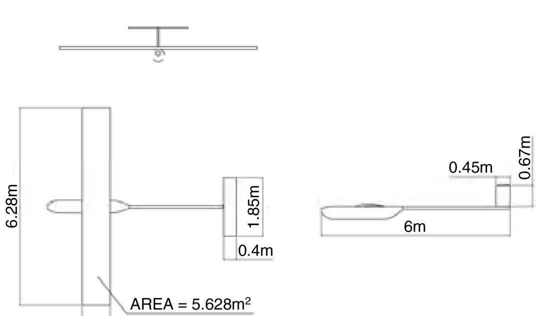

Fig. 2 Three views of the Xihe airplane.

III. Minimum Power Cruising Speed

Because of the interaction between lift and drag forces, a cruise speed exists that minimizes the energy consumption for a particular cruise altitude. The condition and the computation of the cruise speed for minimum energy operation are presented in this section. The aircraft drag force D and the lift force L can be obtained from the air vehicle configuration and the aerodynamic design for a particular flight condition. The propulsion system needs to provide a thrust force T_r to overcome the drag force. The relationship between the power required P_r in flight and the vehicle speed v is

$$P_r = T_r \times v \tag{1}$$

The lift L is equal to the vehicle weight W in straight and level flight. Thus, the thrust T_r can be expressed as

$$T_r = D = \frac{D}{W} W = \frac{D}{L} W = \frac{W}{L/D} \tag{2}$$

The drag D and the lift L are computed from

$$D = \frac{1}{2} \rho_\infty v^2 S_{\mathrm{ref}} C_D \tag{3}$$

$$L = \frac{1}{2} \rho_\infty v^2 S_{\mathrm{ref}} C_L \tag{4}$$

where C_D and C_L are coefficients for drag and lift, respectively, ρ_∞ is the air density at the designated altitude, and S_{ref} is the referenced wing area of the Xihe airplane. Thus, the thrust T_r can be rewritten as

$$T_r = \frac{W}{L/D} = \frac{W}{C_L/C_D} \tag{5}$$

Therefore, the power required P_r to overcome the drag force becomes

$$P_r = T_r \times v = \frac{W}{C_L/C_D} \times v \tag{6}$$

Because lift equals weight in straight and level flight, the weight W and the cruise speed v can be expressed as

$$W = \frac{1}{2} \rho_\infty v^2 S_{\mathrm{ref}} C_L \tag{7}$$

$$v = \sqrt{\frac{2W}{\rho_\infty S_{\mathrm{ref}} C_L}} \tag{8}$$

Finally, the power required P_r is obtained as

$$P_r = \frac{W}{C_L/C_D} \times \sqrt{\frac{2W}{\rho_\infty S_{\mathrm{ref}} C_L}} = \sqrt{\frac{2W^3 C_D^2}{\rho_\infty S_{\mathrm{ref}} C_L^3}} \tag{9}$$

From these derivations, it is clear that the required power to overcome the drag force is proportional to $(\sqrt{C_L^{3/2}/C_D})^{-1}$. Minimizing the power consumption requires maximizing $(\sqrt{C_L^{3/2}/C_D})$. The drag coefficient C_D can be expressed as $C_D = C_{D,0} + K C_L^2$ [24], where $C_{D,0}$ is the zero-lift drag coefficient. The factor K is the combination of proportional constants of the parasite, and the induced drag and is equal to

$$\frac{4}{3} \frac{1}{\pi e AR}$$

for Xihe aircraft. The variable e is the wing span efficiency, and AR is the aspect ratio. Thus,

$$\frac{C_L^{3/2}}{C_D} = \frac{C_L^{3/2}}{C_{D,0} + K C_L^2} \tag{10}$$

Taking the derivative of Eq. (10) with respect to C_L obtains the lift coefficient C_L under the minimum energy condition as

$$C_L = \sqrt{\frac{3C_{D,0}}{K}} \tag{11}$$

If the cruise speed under the minimum energy condition is V_{opt}, the vehicle weight under the minimum energy condition is

$$W = \frac{1}{2} \rho_\infty V_{\mathrm{opt}}^2 S_{\mathrm{ref}} \sqrt{\frac{3C_{D,0}}{K}} \tag{12}$$

Thus, the cruise speed v for minimum energy operation can be computed as

$$V_{\mathrm{optl}} = \left(\frac{2}{\rho_\infty} \sqrt{\frac{K}{3C_{D,0}}} \frac{W}{S_{\mathrm{ref}}} \right)^{1/2} \tag{13}$$

Equation (13) shows that the cruise speed for the minimum energy operation depends on the wing area, the total weight of the aircraft, and the air density (altitude). Changes in any variables in Eq. (13) will require recalculation of the cruise speed.

IV. Parameterization of the Mass of the Xihe Airplane

As discussed in the previous section, the optimal cruise velocity V_{opt} varies with the wing area or the weight of the airplane. The weight of the airplane can be calculated by adding up the weight of all subsystems, including the structure, the propulsion system, the solar cell panel, the batteries, and the payloads. To reach an optimal aerodynamic configuration of the Xihe airplane, the mass of the aircraft is represented in terms of other aircraft design parameters, such as cruise speed and reference wing areas. This section presents the detail of the parameterization of the mass of the Xihe airplane. During the parameterization, the platform and the aspect ratio of the wing are not changed. Therefore, the coefficients $C_{D,0}$ and K can be considered constants.

The energy from solar cells, mounted atop the wing, is delivered through a solar power management system to the motor to drive the propeller. The power management system, shown in Fig. 4, consists of maximum power point tracking, battery management, and power conversion functions. The maximum power point tracking attempts to obtain the maximum power available from the solar cell panels. Battery management monitors and controls the charge and discharge processes of the li–ion polymer battery modules. Power conversion generates the required voltage for the motor and avionics systems. Details of the design and consideration of the solar power manage-

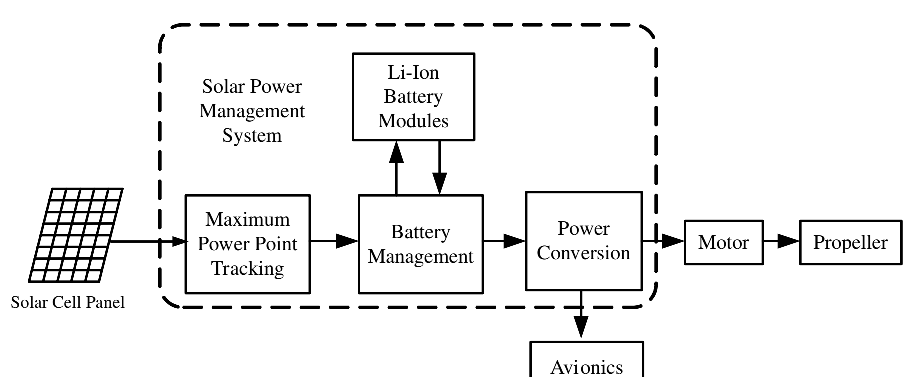

Fig. 4 The propulsion system.

ment system are presented in [25]. In this analysis, the mass of the propulsion system includes the masses of the gearbox, the motor, and the propeller. The mass of the solar power management system, excluding the li–ion battery modules, and the avionics subsystems are treated as the payload. The mass of the battery modules is considered separately.

Assuming that the solar cells will cover 85% of the wing areas, the required solar cell panel area is

$$S_{\text{panel}} = 0.85 \times S_{\text{ref}} \tag{14}$$

The mass for the unit area of the selected solar cell panel is $1.1\ \text{kg/m}^2$ in this design. Thus, the mass of the solar cell panel is

$$M_{\text{panel}} = S_{\text{panel}} \times 1.1 = 0.9350 \times S_{\text{ref}} \tag{15}$$

The mass of the structure $M_{\text{structure}}$ is computed from the wet area and the unit mass of the structure. The unit mass of the structure is $0.45\ \text{kg/m}^2$ for this particular design. Then,

$$M_{\text{structure}} = 0.9 \times S_{\text{ref}} + 4.05216 \tag{16}$$

where 4.05216 is the mass of the fuselage. In this design, the fuselage design is fixed to minimize the number of decision variables during optimization. The mass of the propulsion system is proportional to the referenced wing area. The corresponding unit mass of the propulsion system is $0.48533\ \text{kg/m}^2$ [26] in this design. Thus, the mass of the propulsion system is

$$M_{\text{thrust}} = S_{\text{ref}} \times 0.48533\ \text{kg/m}^2 \tag{17}$$

The mass of the battery M_{battery} is

$$M_{\text{battery}} = \frac{E_{\text{battery}}}{\rho_{\text{battery}}} \tag{18}$$

The energy density of the battery, selected in this design, ρ_{battery} is $196\ \text{W} \cdot \text{h/kg}$. The required battery energy is

$$E_{\text{battery}} = \frac{(0.5T_{\text{dusk}} + T_{\text{night}})(P_{\text{propulsion}} + P_{\text{others}})}{f_{\text{DOD}}\eta_{\text{discharge}}} \tag{19}$$

where T_{dusk} and T_{night} represent the duration the battery must power the aircraft, $P_{\text{propulsion}}$ represents the power consumption required for the propulsion system, P_{others} represents the power required for other systems (such as avionics and onboard circuitry), and f_{DOD} and $\eta_{\text{discharge}}$ are the depth of discharge and the discharge efficiency of the battery, respectively. In this consideration, $T_{\text{dusk}} = 3$ h and $T_{\text{night}} = 1$ h are assumed. The required power for systems other than propulsion P_{others} is 30 W. The depth of discharge $f_{\text{DOD}} = 0.8$ and the efficiency of the battery discharge $\eta_{\text{discharge}} = 0.95$ are also assumed. The power consumption for the propulsion system is

$$P_{\text{propulsion}} = \frac{T_r v}{\eta_{\text{motor}}\eta_{\text{propeller}}} \tag{20}$$

with

$$T_r = \frac{1}{2} f_{\text{safety}} C_D \rho_\infty v^2 S_{\text{ref}} \tag{21}$$

where η_{motor} is the motor efficiency, $\eta_{\text{propeller}}$ is the efficiency of the propeller, and f_{safety} is the safety factor, which is assumed to be 1.2. The efficiency of the motor is assumed to be 80%, whereas 85% is assumed for the propeller. Thus, the required battery can be expressed as

$$E_{\text{battery}} = 0.1077 S_{\text{ref}} v^3 + 98.6842 \tag{22}$$

The mass of the battery is

$$M_{\text{battery}} = 0.000549 \times S_{\text{ref}} \times v^3 + 0.5035 \tag{23}$$

The mass of the payload is $M_{\text{payload}} = 2.7$ kg for this design. Therefore, the total mass of the airplane, $M_{\text{total}} = M_{\text{structure}} + M_{\text{battery}} + M_{\text{thrust}} + M_{\text{panel}} + M_{\text{payload}}$ is

$$M_{\text{total}} = 2.32 S_{\text{ref}} + 0.000549 S_{\text{ref}} v^3 + 7.2557\ \text{kg} \tag{24}$$

In Eq. (24), the total mass of the airplane is expressed as a function of the wing reference area S_{ref} and the cruise speed v. For minimum energy operation, the constraint on Eq. (13) must be satisfied. With the total mass of the airplane being parameterized, as in Eq. (24), the optimization process searches for an optimal solution pair $(S_{\text{ref}}, V_{\text{opt}})$ that satisfies Eqs. (13) and (24), for which the lift force equals the weight of the airplane, and the power supplied from the solar cell panel exceeds the total consumed power.

V. Optimization Formulation

As discussed in the previous sections, the optimal aerodynamic configuration design is to search for optimal solutions of the referenced wing area S_{ref} and the cruise speed v, such that certain aerodynamic performance and power requirement conditions are satisfied. The constraint conditions include 1) the aircraft lift force being equal to the total weight of the airplane; 2) the cruise speed being equal to the optimal cruise speed; and 3) the power supplied from the solar cell panel exceeding the total power required for normal operation. Condition 1 is assured when $L - M_{\text{total}} \cdot g = 0$ is satisfied. That is

$$\frac{1}{2}\rho_\infty v^2 S_{\text{ref}} C_L - M_{\text{total}} \cdot g = 0 \tag{25}$$

where M_{total} is defined in Eq. (24). Condition 2 is satisfied when cruise speed $v = V_{\text{opt}}$ is achieved. For satisfying condition 3, we need to assure

$$P_{\text{supplied}} - P_{\text{required}} \geq 0 \tag{26}$$

where P_{supplied} is the power supplied from the solar cell panel and P_{required} is the total power required to support normal operation of the airplane. The power from the solar cell panel is

$$P_{\text{supplied}} = 0.85 S_{\text{ref}} E_{\text{sun}} \eta_{\text{panel}} \tag{27}$$

where E_{sun} represents the average irradiance of solar radiation energy and is assumed to be $750\ \text{W/m}^2$ (75% of air mass 1 (AM1) condition, $1000\ \text{W/m}^2$, according to IEC 60891 [27]), and η_{panel} is the energy conversion efficiency of the solar cells. Solar cell panels with $\eta_{\text{panel}} = 0.16$ are adopted in this design. Thus, the supplied power can be rewritten as

$$P_{\text{supplied}} = 102 S_{\text{ref}} \tag{28}$$

The required power includes power for the propulsion system $P_{\text{propulsion}}$, power P_{other} for subsystems other than the propulsion system, and power P_{charge} required to charge the batteries during daytime. The required charge power is

$$P_{\text{charge}} = E_{\text{battery}} / T_{\text{daytime}} \eta_{\text{charge}} \tag{29}$$

The charge time T_{daytime} is assumed to be 8 h with a battery charging efficiency of $\eta_{\text{charge}} = 0.8$. The battery charging efficiency includes the efficiencies of the maximum power point tracking and battery management. Therefore, the total required power from the solar cell panel to support normal operation will be

$$P_{\text{required}} = (P_{\text{propulsion}} + P_{\text{others}}) / \eta_{\text{converter}} + P_{\text{charge}} \tag{30}$$

where $\eta_{\mathrm{converter}}$ is the efficiency of the solar power management system, including the maximum power point tracking, the battery management, and the power conversion, and it is assumed to be 0.7. The required power in Eq. (30) is rewritten as

$$P_{\mathrm{required}} = 0.06359 S_{\mathrm{ref}} v^3 + 58.2765 \tag{31}$$

The three conditions must all be satisfied for minimum energy operation. Thus, the following optimization problem is formulated.

For the optimization problem, find a referenced wing area S_{ref} and a cruise speed v to minimize the objective function:

$$J(S_{\mathrm{ref}}, v) = w_1|L/g - M_{\mathrm{total}}| + w_2|v - V_{\mathrm{opt}}| + w_3|P_{\mathrm{supplied}} - P_{\mathrm{required}}| \tag{32}$$

subject to

$$L - M_{\mathrm{total}} \cdot g = 0 \tag{33}$$

$$v - V_{\mathrm{opt}} = 0 \tag{34}$$

$$P_{\mathrm{supplied}} - P_{\mathrm{required}} \geq 0 \tag{35}$$

with

$$\left.\begin{array}{c} L = \frac{1}{2}\rho_\infty v^2 S_{\mathrm{ref}} C_L \\ M_{\mathrm{total}} = 2.32 S_{\mathrm{ref}} + 0.000549 S_{\mathrm{ref}} v^3 + 7.2557 \\ V_{\mathrm{opt}} = \left(\frac{2}{\rho_\infty}\sqrt{\frac{K}{3C_{D,0}}}\frac{M_{\mathrm{total}}\cdot g}{S_{\mathrm{ref}}}\right)^{1/2} \\ P_{\mathrm{supplied}} = 102 S_{\mathrm{ref}} \\ P_{\mathrm{required}} = 0.06359 S_{\mathrm{ref}} v^3 + 58.2765 \end{array}\right\} \tag{36}$$

The Xihe airplane is designed to fly at a cruise altitude of 100 m. Hence, the air density ρ_∞ and the gravitational acceleration g are set to $1.225\ \mathrm{kg/m^3}$ and $9.8\ \mathrm{m/s^2}$, respectively. The equations and parameters for the optimization problem are listed in Table A1 in the Appendix. The constants and coefficients are listed in Table A2 in the Appendix. The constants w_1, w_2, and w_3 are positive weighting factors imposed to balance the numerical significance of the physical variables contributing to the objective function $J(S_{\mathrm{ref}}, v)$. In this optimization process, a difference of 1 or 2 W in the supplied or consumed power is acceptable. However, a difference of 1 or 2 m/s in the cruise speed is not acceptable, because the energy consumption is proportional to the cube of the speed. A deviation of 1 m/s from the minimum power cruise speed results in a significant difference in energy consumption. Similarly, the difference between the lift and the weight must be within an acceptable region. In this design, $w_1 = 10$, $w_2 = 60$, and $w_3 = 1$ are selected for the optimization process. The optimal value of the referenced wing area S_{ref} and the cruise speed v can be obtained by minimizing the objective function $J(S_{\mathrm{ref}}, v)$. Genetic algorithms solve the optimization problem; the objective function, Eq. (32), serves as the fitness function for the genetic algorithm and links the optimization problem to it. The decision variables (wing area and cruise speed) are mapped into binary strings that are similar to chromosomes. Genetic operators (crossover and mutation) are performed on a population of such binary strings for a series of evolutions of the solution. The MATLAB Genetic Algorithm and Direct Search Toolbox is used to find the optimal solution. The detailed search process and results are presented in the next section.

VI. Solution Search Process and Results

A genetic algorithm is initiated with a set of randomly selected solution candidates (represented by chromosomes) called a population. Some of the solution candidates from one population are selected, modified, and used to generate a new population for evolution in the hope that the new population will be better than the old one. The solutions picked to modify and generate new solutions are based on their fitness to the problem to be solved. This process is repeated until some predefined termination conditions are satisfied.

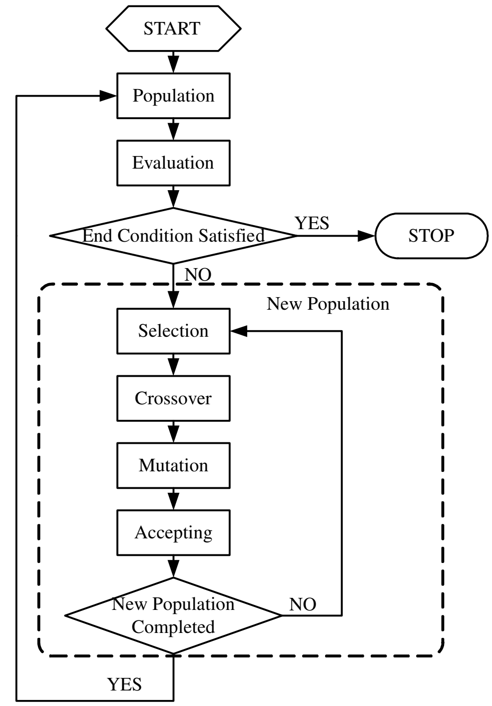

Fig. 5 The flowchart for the genetic algorithm.

The genetic algorithm flowchart is shown in Fig. 5, and the procedures are discussed next.

Step 1) To initiate the genetic algorithm, two sets of chromosomes for the initial population are randomly generated: one for the cruise speed v and another for the referenced wing area S_{ref}. Each set contains 100 chromosomes. Each chromosome is represented by a 10-bit binary string. For instance, the two sets of the chromosomes can be represented, as shown in Table 1. To retrieve the physical variable information, the chromosome represented by the binary string is decoded with the following linear function:

$$X = \underline{X} + X_d\left(\frac{\bar{X} - \underline{X}}{2^N - 1}\right) \tag{37}$$

where X represents the physical variables (S_{ref} or v), $\underline{X}$ is the lower bound of X and $\bar{X}$ is the upper bound (that is, $X \in [\underline{X}, \bar{X}]$), X_d is the decimal magnitude of the binary string, and N is the length of the binary string ($N = 10$ in this case). In this process, we set $X \in [4, 13]$ for both variables.

Step 2) In this stage, the fitness of each chromosome X in the population is determined. To evaluate the fitness of the solutions, the fitness function defined in Eq. (32) is used to score each individual chromosome for the optimization process. The fitness function is the only link between the genetic algorithm and the optimization problem. The fitness measure (scores) represents the suitability of the solutions to the optimization problem. In this aircraft configuration optimization problem, the constraints in Eqs. (33–35) must be satisfied under the minimum power cruise condition.

Step 3) If the specified end conditions are satisfied, stop the search algorithm and return the best solution in the current population.

Table 1 Chromosome sets

Reference area S_{ref}		Cruise speed v	
S_1	1001100010	V_1	1110110000
S_2	1101101010	V_2	1010110001
⋮	⋮	⋮	⋮
S_{100}	1001001010	V_{100}	0010010011

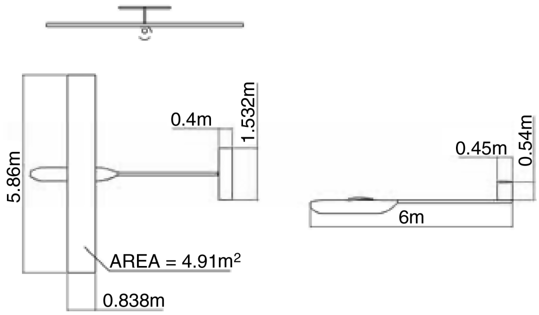

Fig. 6 Three views of the Xihe airplane after parameter optimization.

Step 4) In this step, generate a new population by repeating the following steps until the new population is complete.

Step 4.1) Select two parent chromosomes from the population for the subsequent crossover and mutation operations to generate a new offspring (children). Selection of the parents is biased toward their evaluations in the hope that better parents will produce better offspring. The optimal solutions are obtained when the fitness function $J(S_{\mathrm{ref}},\ v) = 0$ is achieved. It is assumed that the closer the fitness measure of the individual chromosome is to $J(S_{\mathrm{ref}},\ v) = 0$, the better the individual chromosome. Thus, the top 15% of those with fitness measures closest to $J(S_{\mathrm{ref}},\ v) = 0$ are selected as the parents for the next generation. It is noted that making a new population from only new offspring can lose the best solution from the last population. Therefore, some good solutions are copied directly to the new population without any changes.

Step 4.2) Crossover is a critical feature of the genetic algorithm. It can combine the subsolutions on different chromosomes and thus accelerate the search results. The scattered crossover function (provided in the MATLAB genetic algorithm toolbox) with a crossover rate 0.85 is used in this optimization process.

Step 4.3) In addition to crossover, mutation is another important operator for generating offspring. Mutation randomly changes the new offspring. It introduces a certain amount of randomness to the search that can help find solutions that crossover alone might not encounter. This can prevent all solutions in a population from falling into a local optimum point. A Gaussian mutation operator is selected in this process.

Step 4.4) The accepting action places the new offspring in a new population.

Step 5) When the generation of a new population is completed, replace the old population with the new one and start another search process.

The search process stops and returns the optimal solution when one of the following conditions is satisfied:

1) The number of generations reaches 200.
2) The fitness measure $J(S_{\mathrm{ref}},\ v) = 0$ is reached.
3) The weighted average changes in the fitness function over 100 generations are less than a specified tolerance.
4) There is no improvement in the fitness function for over 50 s.

The following results are obtained after the completion of the optimization search routine. The referenced wing area S_{ref} is 4.91 m^2, the cruise speed v is 11.23 m/s, the fitness function is $J(S_{\mathrm{ref}},\ v) = 0.2045$, the difference between the lift and the weight is $L - W = 3.4345 \times 10^{-5}\ \mathrm{kg} \cdot \mathrm{W}$, the supplied power P_{supplied} minus the consumed power P_{required} is 2.88×10^{-5} W, and the difference between the computed cruise speed and the optimal cruise speed is 0.0026 m/s. That is, the reference area $S_{\mathrm{ref}} = 4.91\ \mathrm{m}^2$ and the cruise speed $v = 11.23\ \mathrm{m/s}$ are the optimal solution for the minimum power required for the Xihe airplane. The total mass of the airplane is 22.47 after parameter optimization. Figure 6 shows three views of Xihe after parameter optimization. The span of the airplane is 5.86 m.

VII. Conclusions

Optimal airplane sizing and cruise speed determination of a solar-powered UAV are presented in this paper. An initial conceptual design using traditional methods is conducted first to obtain an initial size and the performance parameters; however, the result is not optimal in terms of minimum energy operation. To effectively use the power from the solar power panel, the aerodynamic configuration design is optimized. To minimize the number of decision variables in the optimization process, the wing aspect ratio and the fuselage design are fixed, and the mass of the Xihe airplane is parameterized by only two decision variables: the referenced wing area and the cruise speed. The optimal result is obtained with a genetic algorithm. With this result, the referenced wing area can be reduced from 5.63 m^2 in the initial design to 4.91 m^2, which provides a 12.79% savings in solar cells. The total mass of the aircraft is reduced from 24.96 to 22.47 kg: a 9.98% reduction. The cruise speed for minimum energy consumption is increased from 10.93 to 11.23 m/s. The costs for the solar cells and the compound materials for the aircraft structure are reduced accordingly.

The limitations of solar cell efficiency, battery energy density, and the weight of the structural materials make the optimization of the configuration design crucial for reducing production costs and reaching the ultimate design goal of continuous flight. This paper has demonstrated the application of the genetic algorithm to the optimization of the aircraft size and cruise speed.

Appendix

Table A1 Equations and parameters for the optimization problem

Parameters	Equations
Lift	$L = \frac{1}{2}\rho_\infty v^2 S_{\mathrm{ref}} C_L$
Power	
Solar cell panel supplied power	$P_{\mathrm{supplied}} = 0.85 S_{\mathrm{ref}} E_{\mathrm{sun}} \eta_{\mathrm{panel}}$
Power for propulsion system	$P_{\mathrm{propulsion}} = \frac{1/2 \rho_\infty v^3 S_{\mathrm{ref}} C_D f_{\mathrm{safety}}}{\eta_{\mathrm{motor}} \eta_{\mathrm{propeller}}}$
Power for other subsystems	$P_{\mathrm{others}} = 30\ \mathrm{W}$
Required charge power	$P_{\mathrm{charge}} = \frac{E_{\mathrm{battery}}}{T_{\mathrm{daytime}} \eta_{\mathrm{charge}}};\ E_{\mathrm{battery}} = \frac{(0.5 T_{\mathrm{dusk}} + T_{\mathrm{night}})(P_{\mathrm{propulsion}} + P_{\mathrm{other}})}{f_{\mathrm{DOD}} \eta_{\mathrm{discharge}}}$
Total required power	$P_{\mathrm{required}} = \frac{P_{\mathrm{propulsion}} + P_{\mathrm{others}}}{\eta_{\mathrm{converter}}} + P_{\mathrm{charge}}$
Mass	
Mass of the solar cell panel	$M_{\mathrm{panel}} = 0.9350 S_{\mathrm{ref}}$
Mass of the structure	$M_{\mathrm{structure}} = 0.9 S_{\mathrm{ref}} + 4.05216$
Mass of the propulsion system	$M_{\mathrm{thrust}} = 0.48533 S_{\mathrm{ref}}$
Mass of the battery	$M_{\mathrm{battery}} = \frac{E_{\mathrm{battery}}}{\rho_{\mathrm{battery}}}$
Mass of the payload	$M_{\mathrm{payload}} = 2.7\ \mathrm{kg}$
Total mass of the airplane	$M_{\mathrm{total}} = M_{\mathrm{structure}} + M_{\mathrm{battery}} + M_{\mathrm{thrust}} + M_{\mathrm{panel}} + M_{\mathrm{payload}}$
Optimal cruise speed	$V_{\mathrm{opt}} = \left(\frac{2}{\rho_\infty} \sqrt{\frac{K}{3 C_{D,0}}} \frac{M_{\mathrm{total}} \cdot g}{S_{\mathrm{ref}}} \right)^{1/2}$

Table A2 Constants and coefficients for the optimization problem

Parameters	Values	Parameters	Values
T_{dusk}	3 h	f_{DOD}	0.8
$\eta_{\mathrm{converter}}$	0.7	K	0.0674
T_{night}	1 h	η_{motor}	0.8
P_{others}	30 W	$C_{D,0}$	0.00758
T_{daytime}	8 h	$\eta_{\mathrm{propeller}}$	0.85
ρ_{battery}	196 W · h/kg	C_L	0.5805
$\eta_{\mathrm{discharge}}$	0.95	f_{safety}	1.2
ρ_∞	1.225	AR	7
η_{charge}	0.8	E_{sun}	750 W/m^2
η_{panel}	0.16	e	0.9

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