ANALYSIS OF PROPULSION AND ENERGY SYSTEM'S INFLUENCE ON THE PERFORMANCE OF HIGH ALTITUDE AIRSHIP

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Abstract

Performance of subsystems have profound effect on the overall performance of the High Altitude Airship (HAA). Detail analysis of subsystems needs to be carried out in order to reduce the overall length of the HAA. Optimization model is obtained with the minimum length of HAA as objective. Afterwards, aerodynamic subsystem is analyzed and the optimum envelop shape is obtained so that the volumetric drag of the HAA is minimum. In addition, working time and location of HAA are obtained regarding the energy system. And then, surrogate model of the propulsion system is established with the help of Design of Experiment (DOE) methods and Response Surface Method (RSM). Finally, optimization result is obtained by Multi-Island Genetic Algorithm (MIGA). Furthermore, sensitivity analysis of each subsystem is proceeded so as to find ways to help reduce the overall size of the traditional HAA. In addition, technical suggestions are given to improve the technical indexes of these subsystems in order to reduce the length of HAA.

1 Introduction

High Altitude Airship (HAA) plays an important role in civil and military use nowadays because its special advantages like long endurance, high time resolution and so on [1, 2]. Overall performance of HAA depends on the individual performance of its subsystems which also determines the practicability and feasibility in manufacturing of the HAA. In order to improve the overall performance of HAA and minimize the degree of difficulty in its manufacturing, subsystems of HAA need to be well designed so as to reduce the overall size of HAA.

Aerodynamic properties of HAA is determined by its envelop shape [3, 4]. Optimum shape can ensure that the volumetric drag of the HAA is minimum. Energy system and propeller propulsion system are working together to resist the wind in laminar flow and thus serve as the dynamic source for HAA [5，6]. They have a profound effect of the flight performance of HAA. Therefore, for HAA with certain payload, optimization and sensitivity analysis of its energy system and propulsion system should be taken to ensure that the size of the airship is minimized. In addition, sensitivity analysis for each performance parameters of the energy system and the propulsion system should be carried out in order to give detail instructions to minimize the length of HAA [7].

In the traditional conceptual design process, the mathematic models for the energy system and propulsion system are highly simplified. Energy system and propulsion system are replaced by power density method [8]. This is not help for analyzing the effect of the energy system and propulsion system. In addition, it's not quite appropriate in some circumstances.

In this paper, structure and aerodynamic are analyzed and optimum shape of HAA is obtained. Model of the energy system is obtained in considering of HAA's working time and location [9, 10], working time and location of HAA is obtained after analyzing the radiation intensity of flexible solar cells. Surrogate model of the propulsion system is obtained by Design of Experiment (DOE) methods and approximation models, and this will help minimize the amount of calculations.

This paper is organized in follows: First, the mission scenario of HAA and optimization objective are presented. The optimization matter is also formulated for minimum-length condition. Next, the framework for HAA conceptual design is established. And then subsystems (structural system, energy system and propulsion system) are discussed in detail. The design variables are figured out, while the system analysis is discussed. Finally, the optimization process and results for HAA are shown in detail. In addition, sensitivity analysis is carried out in order to find ways to minimize the size of traditional HAA.

2 Framework of the Conceptual Design for HAA

2.1 Mission Scenario and Optimization Objective

Energy system, which is the power source of the HAA, consists of flexible solar arrays and Lithium cells. Efficiency increase and weight reduction of the energy system helps to minimize the size of the HAA. Meanwhile, performance of solar cells is partly determined by working time and latitude of airship. Propulsion system completes the process of energy transformation with its major parts: motor, gear box and propeller. The efficiency of propulsion system needs to be improved in order to reduce the weight of the energy system. But meanwhile, because of the increased diameter, the weight of the propulsion system will correspondingly increase. However, the minimum size of the airship can be realized only when total mass of the propulsion and energy system reaches the minimum value. Therefore, an optimization scheme to solve the dilemma for propulsion and energy system needs to be proposed.

This section illustrates the framework process in the conceptual design of a non-rigid airship operated at high altitude. The mission scenario is summarized in Table 1. The optimization design objective is to design a feasible airship. It reachs minimum length and satisfies the balance constraints, which including the balance of weight and balance of energy, in the specific mission.

Table 1 Mission scenario of HAA

Design Parameters	***Values***
Altitude	*20km*
Design Speed	*20m/s*
Payload Mass	*1000kg*
Power to Payload	*10kw*
Equipment Mass	*200kg*
Power to Equipment	*3kw*
Length of HAA	*100m~200m*

The optimization model is established with the minimum length of the HAA as its objective and with six design variables: the length of airship, airship's working time, the latitude of airship's working location, slenderness ratio of airship, power of propulsion system, the number of propulsion system and the diameter of propellers. The optimization can be summarized as [11, 12]:

$$\begin{aligned} Min \quad & L_{HAA} \\ s.t. \quad & M_{total}g - F_B \le 0 \\ & Q_{req} - Q_{\sup} \le 0 \\ & P_w - P_{prout} \le 0 \end{aligned} \qquad (1)$$

where: L_{HAA} is the length of HAA, M_{total} is the total weight of the HAA, g is the standard specific gravitational force, F_B is the buoyancy of HAA, Q_{req} is the requested energy of HAA, $Q_{\sup}$ is the output energy of energy system, P_w is the needed power to resist the laminar wind and P_{prout} is the output power of propeller propulsion system.

2.2 Framework for HAA conceptual design

In this paper, mainly three subsystems are taken into consideration. They are the structure, energy system and propulsion system. The framework of HAA conceptual design is presented in Fig. 1.

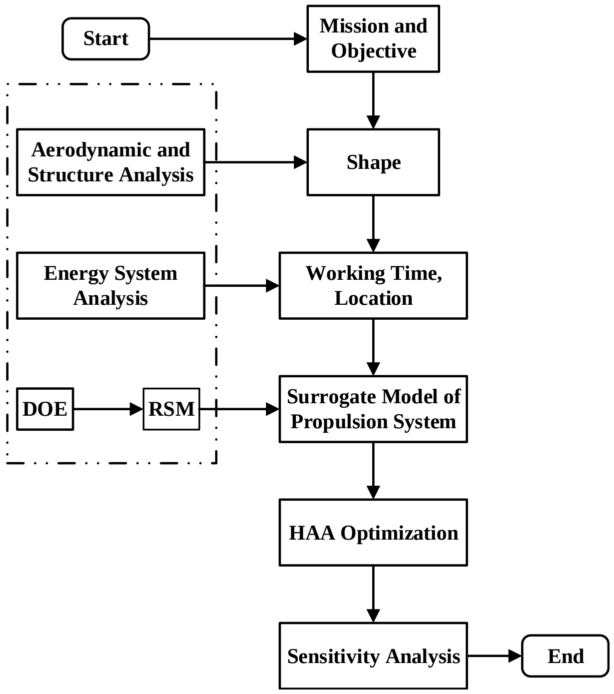

Fig.1. Framework of HAA conceptual design

The shape of HAA influences the aerodynamic properties, so at first shape of HAA is optimized, and this ensure that needed power to resist the laminar wind is minimum, so the required mass of the energy system and propulsion system will be reduced.

Energy system is optimized after the optimization of aerodynamic. After optimization, working time and location of HAA is determined in order that average light intensity will be maximum. This reduces the area of flexible solar cells and the weight of lithium cells.

Then surrogate model of propeller propulsion system is obtained. This is critical to HAA optimization. The efficiency of propeller propulsion system is very important to HAA, and a bigger power propulsion system of an airship can be divided into several the same distributed lower power propulsion system. The total efficiency of the low power propulsion system is increased, and the mass of the required energy system is decreased. But meanwhile, the number of propulsion system is increased, and the total weight of the propulsion system is increased. Hence, there should exit an optimum power, under this condition, length of HAA will be minimum.

Finally, optimization work of HAA is carried out by MIGA and sensitivity analysis of these subsystems will be proceeded.

3 Subsystem Analysis for HAA

3.1 Aerodynamic and structure analysis for HAA

The surface area of the HAA envelop can be described as [13]:

$$A = 2.33(1/\lambda)L^2_{HAA} \tag{2}$$

where: A is surface area of HAA, λ is the fineness ratio of airship envelop ($\lambda = L_{HAA}/D_{HAA}$) and D_{HAA} is the biggest diameter of the HAA envelop.

The volume of the HAA envelop is:

$$Vol = 0.465(1/\lambda)^2 L^3_{HAA} \tag{3}$$

where: Vol is the volume of HAA.

The volumetric coefficient of the envelope drag can be estimated as:

$$C_{DV} = C_F(4\lambda^{1/3} + 6\lambda^{-7/6} + 24\lambda^{-8/3}) \tag{4}$$

where: C_{DV} is the volumetric coefficient of the envelop drag and C_F is the coefficient of the skin friction of an equivalent flat plate, which is a function of the Reynolds number Re based on the same length (C_F=0.043$R\mathrm{e}^{-1/6}$).

The overall drag coefficient ($C_{DV,total}$) of the HAA can be expressed as:

$$C_{DV,total} = C_{DV}/(1-0.6\lambda^{-1}) \tag{5}$$

So the total drag of the HAA is:

$$\begin{aligned} D &= \rho_a V^2 C_{DV,total} Vol^{2/3}/2 \\ &= \rho_a V^2 C_{DV,total}(0.465(1/\lambda)^2 L^3_{HAA})^{2/3}/2 \\ &= CV^2 C_{DV,total}\lambda^{-3/4} L^2_{HAA} \\ &= CV^2 C_{Total} L^2_{HAA} \end{aligned} \tag{6}$$

where: D is the total drag of HAA, C is the constant term of equation (6), C_{Total} is the total drag coefficient of HAA, $C_{Total} = C_{DV,total}\lambda^{-3/4}$, V is the wind velocity of HAA.

The tendency of the overall drag coefficient is shown in Fig.2. When λ=4.52 , total drag coefficient of the HAA is minimum, and HAA with this shape is selected.

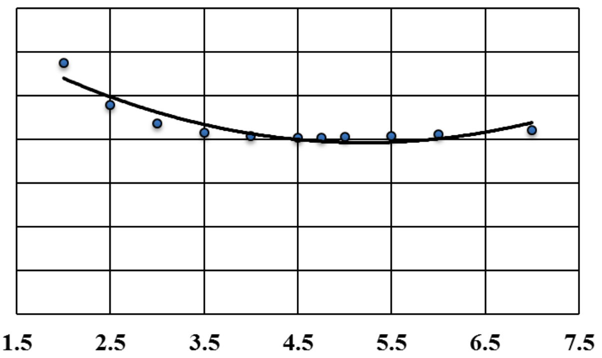

Fig.2. Tendency of the overall volumetric drag coefficient

The outer gasbag of HAA is filled with H_e so it can provide the buoyancy to make HAA float at high altitude. The buoyancy of HAA is:

$$F_B = (1-\delta_1 R_a / R_{He})\rho_a \delta_2 Vol \tag{7}$$

where: F_B is buoyancy of airship, δ_1 is the pressure ratio between inner and outer of HAA, R_{He} is the gas constant of H_e, R_a is the gas constant of the air and ρ_a is the density of the air.

The weight of the airship structure is:

$$m_{hull} = (\rho_e \cdot (A + \pi L^2_{HAA} / (2f^2)) + \rho_b A / 2)*(1 + c1) \tag{8}$$

where: m_{hull} is the weight of airship structure, ρ_e is the material surface density of the airship, ρ_b is the surface density of the gasbag and $c1$ is additional mass coefficient for other structures.

3.2 Energy system analysis for HAA

The output power of the propulsion system to resist the horizontal laminar wind is:

$$P_w = \rho_a V^3 C_{DV} Vol^{2/3} / 2 \tag{9}$$

where: P_w is the resistance power caused by the laminar wind.

So the power that energy system should provide to propulsion system is:

$$P_{prout} = P_w / \eta_{pr} \tag{10}$$

where: η_{pr} is the efficiency of the propulsion system.

The energy that supplies the airship is all from solar arrays when light intensity is enough. When light intensity is not enough or during the night, Lithium cells will provide energy to propulsion system and the airship will keep on working, the weight of the Lithium cells is:

$$m_{sb} = P_{ny} t_n / (E_{sb} \eta_{Li}) \tag{11}$$

where: m_{sb} is the weight of Lithium cells, E_{sb} is weight to power ratio of lithium cells, t_n is the total time that Lithium cells providing energy to propulsion system and η_{Li} is the efficiency of Lithium cells.

During the day, the flexible solar arrays should not only provide the energy to the propulsion system to resist the laminar wind, but also provide a part of energy to lithium cells. The energy stored in lithium cells ensures that propulsion system and other equipment keep on working during the night.

$$W_{so} = \rho_a V^3 C_d \Omega^{2/3} t_d / (2\eta_{pr}) + \rho_a V^3 C_d \Omega^{2/3} t_n / (2\eta_{pr}\eta_{tr}) \tag{12}$$

where: W_{so} is the output energy of solar cells, η_{tr} is the transition efficiency from solar arrays to Lithium cells and t_d is the working time of the solar arrays.

Hence the area of solar arrays is:

$$S_{SO} = W_{so} / (0.85 t_g E_{so} \eta_{so}) \tag{13}$$

where: S_{so} is the area of solar cells, t_g is the radiation time during the day, E_{so} is the average radiation intensity on the solar arrays and η_{so} is the efficiency of solar arrays.

E_{so} is the average radiation intensity on the solar arrays, it's value will be varied with working time and location of HAA. Reference [9] gives the detail steps of calculating the value of radiation intensity E_{so} . In this paper, only optimization work of the average radiation intensity is carried out. Fig.3 is the radiation intensity under different working time and locations.

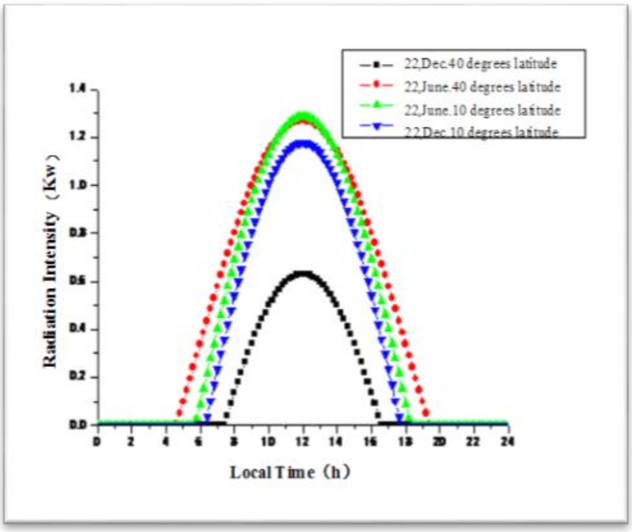

Fig.3. Radiation intensity of solar arrays

After study, based on the result in Fig.3, flight time is decided from 22*th* June to 28*th* June; working location is 10 degrees latitude, average radiation intensity is 750wh/m^2.

3.3 Propulsion system analysis for HAA

3.3.1 Surrogate model of the propulsion system

In order to have an effectiveness analysis of the propulsion system, surrogate models of propulsion system should be established precisely. In addition, in order to reduce the amount of computation and to establish an accurate surrogate model of propeller propulsion system, Uniform Design (UD) method is used to obtain the sample points with diameter and power as the design factors [14].

Then, Response Surface Method (RSM) is used to obtain the mathematics model of efficiency and weight for the propulsion system based on these sample points [15]. Detail steps are mentioned in reference [16]. Table 2 shows the coefficient of quadratic response surface model of the propulsion system.

Table 2 Coefficient of response surface model

Term	Coefficients	
	Mass(kg)	Efficient (%)
Constant	-1.2027	29.4160
p	2.7373	-0.9854
d	5.8069	6.0513
P²	-0.0092	0.0136
d²	-0.2409	-0.1209
p*d	0.0302	-0.0544

where, p is the power of single propulsion system and d is the diameter of propeller.

3.3.2 Analysis of propulsion system

Multi-objective optimization of the propulsion system is carried out to analyze the propulsion system. Minimum weight and maximum efficiency is the object. Table 3 indicates the relative effects that the various factors had on each response. Power and diameter are the main factors. To the response of the weight, power and diameter have positive effect. However, to the response of the efficiency, diameter have positive effect, and power have negative effect.

Table 3 Relative effects that the various factors had on each response

Term	Mass	Efficient
p	63.635	-35.441
d	21.474	41.707
P²	-2.9913	6.8705
d²	-8.651	-6.7987
p*d	3.2489	-9.183

In this part, multi-objective optimization for the propulsion system is carried out. The objectives are maximum power density and maximum efficiency. This job is carried out in order to make a comparison between the optimization of HAA. The optimization model of propulsion system can be summarized as follows:

$$\begin{aligned} &\text{Max} \quad \eta_{pr} \\ &\text{Max} \quad p / m_{pr} \end{aligned} \tag{14}$$

where: m_{pr} is the weight of single propulsion system, η_{pr} is the efficiency othe propulsionon system and p / m_{pr} is the power density of propulsion system, this indicates the output power of every kilogram propulsion system, it represent the.

Using NSGA-II to obtain the result. Set the value of the weight for the two objectives as $\lambda_\eta : \lambda_m = 4:1$, λ_η represents the weight value of η_{pr}, λ_m represents the weight value of p/m_{pr}, because the influence of the efficiency is far more important than the latter.

When d=11.9m, p=3.14kw, the multi-objective optimization result is:

$$\eta_{pr} = 74.61\%$$

$$p/m_{pr} = 0.0723 \text{kw/kg}$$

4 Optimization Result for HAA

4.1 Parameters setting for optimization model

To the optimization matter of this paper, design space for the number of the propulsion system is discrete, so HAA optimization design will be solved by the global optimization method.

In this paper, Multi-Island Genetic Algorithm (MIGA) is utilized to find the minimum length of HAA [17]. What's more, optimal scheme of power and propulsion systems for this HAA is obtained. Basic parameters for MIGA are given in Table 4.

Table 4 Parameters for MIGA

Parameter	***Value***
Size of Population	*100*
Number of Island	*20*
Number of Generation	*20*
Rate of Crossover	*0.9*
Rate of Mutation	*0.01*

Basic parameters of HAA are presented in Table 5.

Table 5 Parameter values for HAA

Parameter	***Value***
l	150m
λ	4
C_d	0.024
δ_1	1.05
E_{sb}	0.2kwh/kg
ρ_{so}	0.15kg/m^2
R_{He}	2077 $J/kg \cdot K$
R_a	287.0529 $J/kg \cdot K$
ρ_e	0.18kg/m^2
ρ_b	0.10kg/m^2
$c1$	0.1
η_{tr}	0.92
η_{Li}	0.90
t_n	14h
t_d	10h
E_{so}	750wh/m^2
η_{so}	0.1

4.2 Optimization results

Set initial length of HAA as 150m, Fig.4 is the optimization history of the length of HAA. The final result is:

The optimized design variables:

$$n = 3,\ p = 17kw,\ d = 12m$$

Objective:

$$L_{HAA} = 162.64m$$

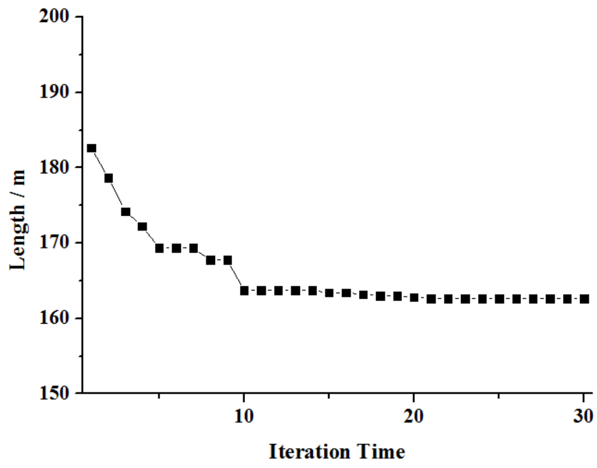

Fig.4. Optimization convergent history curves of length of HAA

5 Sensitivity Analysis for Subsystems of HAA

In this section, sensitivity effect analysis of technical indexes for the energy subsystem and propulsion subsystem on layout sizing of the airship is carried out. Technical indexes of these subsystems which will affect the layout sizing obviously is picked out and the promotional performance parameter indexes for these subsystems are set up. The tendency of the layout sizing for the airship is calculated when the aerodynamics design, flexible solar cells, propeller propulsion system, and lithium cells indexes reach the promotional ones. Which will determine the developing direction for the critical techniques of the HAA.

5.1 Sensitivity analysis of energy system

Efficiency of the energy system influences the size of HAA. Higher efficiency of energy system means less energy system, so the weight of the energy is reduced.

If the surface density of flexible solar cells reduced, the weight of the flexible solar cells is reduced accordingly. Identically, if weight to power ratio of lithium cells reduced, total mass of the energy system is reduced. This result in the reduced size of the HAA.

Efficiency of the propulsion system determines the output power of the energy system. Under the same wind power, the higher efficiency of the propulsion system, the smaller demand of the energy system, and the same for the size of the HAA.

Weight of the propulsion system affects the total weight of HAA. If the weight of the propulsion system is reduced, total weight of HAA is reduced, and this make sure that the size of the HAA is reduced.

Table 6 shows the increment value of technical indexes for each subsystem. In order to show the impact of each technical index, increment are the same. Efficiency of lithium cells is 90%, so the increment of lithium cells are 10%. The sequence of the increment values is listed in Table 6, which follows the principle that the length of HAA will gradually become smaller.

Table 6 Increment value of technical indexes for each subsystem

Subsystem	***Item***	***Increment Value (%)***				
Solar cells	η_{so}	-20	-10	0	+10	+20
	ρ_{so}	+20	+10	0	-10	-20
Lithium cells	η_{Li}	-20	-10	0	+5	+10
	E_{sb}	-20	-10	0	+10	+20
Propulsion system	η_{pr}	-20	-10	0	+10	+20
	m_{pr}	+20	+10	0	-10	-20

Running the optimization, and optimization results are obtained under each technical index. Fig.6 is the comparison between these technical indexes.

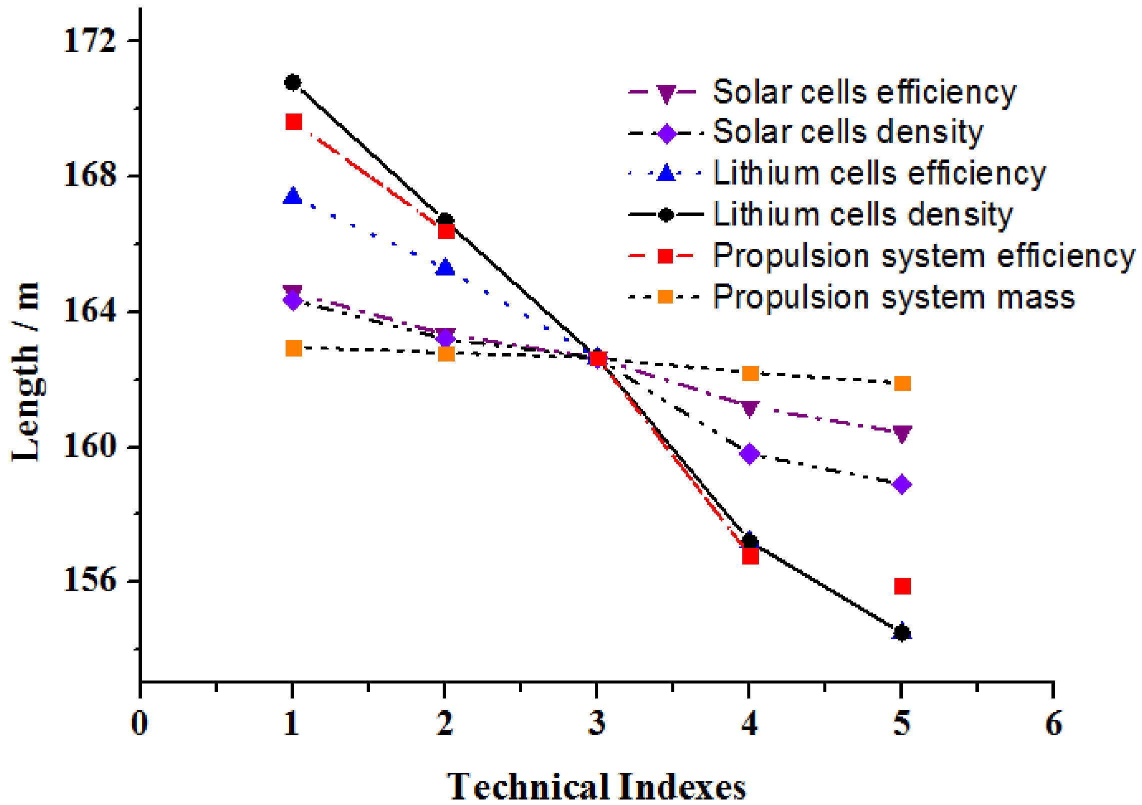

Fig .5. Optimization results comparison between each index

Fig.5 indicates the main factors of reducing the overall length of HAA:

1) Power density of lithium cells influences the size of HAA more than other factors. Efficiency of lithium cells also plays an important role in the size of HAA. It's almost as important as the efficiency of the propulsion system.

2) Efficiency of the propulsion system is the second important factors. Higher efficiency of the propulsion system, smaller size of HAA. By contrast, importance of mass for the propulsion system is much less than other factors, reduction of the mass will reduce the size of HAA, but the effect is not as much obvious as other technical indexes.

3) Efficiency and surface density of flexible solar cells will influence the overall size of HAA, but the impact is not as significant as lithium cells and the efficiency of the propulsion system. However, because the efficiency of flexible cells is in low level, if efficiency of flexible solar cells will rise dramatically, size of HAA will be reduced dramatically.

Finally, the important sequence of these technical indexes will be: power density of lithium cells, efficiency of the propulsion system, efficiency of lithium cells, surface density of flexible solar cells, efficiency of flexible cells and mass of the propulsion system.

5.2 Optimization result when subsystems are in largest increment value

Assume that all of the technical indexes of the two subsystems are in its best situations. Table 7 gives the detail value of each performance parameters.

Table 7 Value of technical indexes

Item	*Value*
η_{so}	*12%*
η_{Li}	*99%*
ρ_{so}	0.12*kg/m*^{2}
E_{sb}	0.24*kwh/kg*
η_{pr}	*+20%*
m_{pr}	*-20%*

Running the optimization, Fig.6 shows the optimization convergent curve history of the length.

The optimization result is:

The optimized design variables:

$$n = 6, p = 5kw, d = 11.8m$$

Objective:

$$L_{HAA} = 149.1m$$

Comparing with the result of Fig.4, length of HAA is reduced by 13.54m, this obviously reduces the difficulty of manufacturing at the same time.

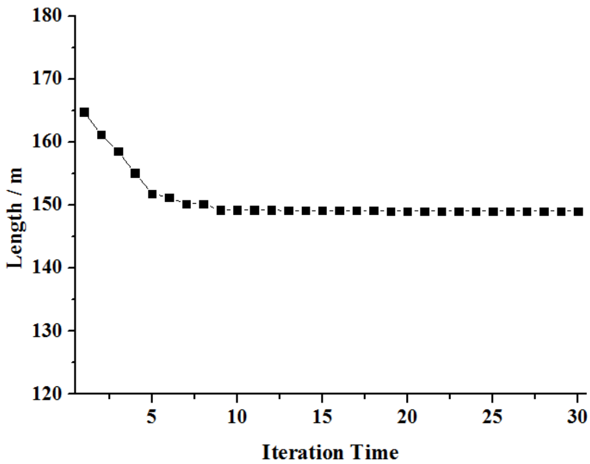

Fig.6. Optimization convergent history curves of length of HAA under largest technical indexes increment value

5.3 Technical suggestions to reduce the size of the HAA

To the optimization result and the conclusions obtained in section 5.1, improving the performance of the energy system and propulsion system reduces the size of HAA substantially. Especially improving the performance of lithium cells and propulsion system. Because efficiency of solar cells is so poor, so 20% increment is still very poor. What's more, mass of solar cells is relatively lighter than lithium cells, so its overall effect on HAA is relatively smaller than lithium cells. As to the lithium cells, the aim is trying to increase its power density. Propulsion system is the last energy transmission part of HAA, increase its efficiency will reduce the size of HAA.

6 Conclusions

This paper aims to make a sensitivity analysis of HAA in order to reduce the size of the HAA, this paper mainly includes:

1) The importance of power and propeller propulsion system of HAA is illustrated.
2) Optimization model with minimum size of HAA as its goal is established.
3) Structure analysis is carried out in order to determine the optimum shape of the HAA. In addition, accurate surrogate models of energy and propulsion systems are obtained so that a detailed analysis of their influence on HAA could be carried out.
4) The minimum size of a typical payload HAA is obtained by MIGA.
5) Sensitivity analysis of power and propulsion systems is made to help find the best scheme of subsystems for HAA.

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