DESIGN AND FLIGHT TEST OF A SOLAR-POWERED UNMANNED AIR VEHICLE FOR LONG ENDURANCE

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Abstract

A solar-powered is an airplane which is driven by electric-based propulsion systems with power supplied continuously by the endless solar energy. Conventionally, the solar plane was designed with a large wing for power generation and an extra-large aspect ratio for high aerodynamic performance. In this study, a new conceptual design was proposed in consideration of power generation, aerodynamic performance and structure strength. It was characterized by a hybrid lifting configuration, which was mainly consisted of a conventional wing and a lifting body, and a V-shaped tail to achieve the lightweight and guarantee large surface for using solar cells. The wing had a moderate aspect ratio to obtain better aerodynamic performance. The lifting body not only has a large surface for the solar cells, but also had a large volume for holding instruments. The V-shaped tail not only had less wetted surface area and lightweight, but also played a role of winglet on the lifting body to reduced drag. Parametric studies were conducted to investigate performance and capabilities of the solar plane for continuous flight. Ground experiments were carried out to measure the performance of the solar cell, motor, propeller thrust, structure, and so on. Flight tests were successful and performance was confirmed. Results show that the new concept of the solar plane was encouraged to be applied to realize a long endurance flight.

1 Introduction

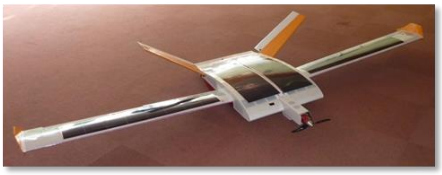
The solar-powered airplane is driven by electric-based propulsion systems with power supplied by the endless solar energy, which has the potential to eliminate fuel or electric power consumption. By replacing conventional fuel and electric power with solar energy, the solar-powered airplane is possible to be a solution to achieve a long endurance. Recently, industries are making efforts for unmanned aerial vehicles (UAV) with capabilities of high altitude and long endurance (HALE) to develop technologies, for low cost, environmentally friendly and energy efficient. The HALE UAVs are capable of wide view and communication service. The solar-powered unmanned aerial vehicle (SPUAV) may be a solution and serves as atmospheric satellites in the future [1].

The first solar plane was the Sunrise I [2], which was succeeded in 20 minutes flight by an array of solar panel with only of 10% efficiency in November, 1974. Since then, several solar planes have been designed. NASA has ever promoted unmanned solar planes, such as the Helios Prototype[3], which was driven by electric power derived from the solar energy by day and fuel-cells at night. QinetiQ's Zephy[4] successfully made a record for two weeks continuous flight by using solar cells and rechargeable high-power lithium-sulphur batteries in July 2010. Boeing has been developing the SolarEagle (Vulture II) to achieve for HALE in the near future[5]. The Solar Impulse successfully completed a cross-continental flight by 23% efficiency solar cells in the United States in June 2013[6][7]. Recently, to improve internet access around the world, both Google and Facebook started working on solar-powered drones, which are capable of flying for months and years at an altitude twice the height of passenger airlines travel. Because of the extra-large wing-span, all

No. 1, 2008

No. 2, 2009

No. 3, 2010-2011



No. 4, 2012-present

Fig. 1 Solar planes developed by the authors

Table 1. Outline of the Solar plane

	length (mm)	span (mm)	weight (kg)	Power (W)
No. 1	1060	2065	1130	28
No. 2	1446	2400	1704	40
No. 3	1469	3730	3796	80
No. 4	1050	3200	3800	136

of the conventional designs experienced control difficulties and some of them even suffered from structure failures in ground and flight tests.

The authors have worked on research of the SPUAV since 2008, and three conventional unmanned air planes (Fig. 1 and Table 1) have been design. It showed that the conventional design was difficult to achieve the long endurance, because its performance was strongly restricted by weight of structure and efficiency of the solar cells. Based on the past experiences, a new design (No.4) was recently conducted in consideration of aerodynamics, structure and the electric power supplied by the solar energy. The new solar plane was characterized by a hybrid lifting configuration, which was mainly consisted of a wing, a lifting body and a V-shaped tail to achieve sufficient power generation, better aerodynamic performance and lightweight. Overall performance of the solar-powered airplane was analyzed. This solar plane was successful in flight test driven by the solar power and results showed that this design had lightweight and better flight performance. A long endurance flight was possible to be realized by the solar power using the proposed conceptual design in this paper.

2 Design Considerations of Solar Plane

There are several technology barriers in development of a solar plane. It should be capable of flying efficiently and embedding sufficient payload. Compared with conventional airplanes, there are restrictions on the weight, structure, and other special treatments due to using the solar panel. All of them must be as light as possible to reduce the power required and guarantee payload. Additional increase of weight includes solar cells, structure to hold solar cells and power system to control solar energy. Furthermore, for 24-hour continuous flight, a number of rechargeable batteries are needed to be stored and occupy a large volume.

For an airplane, the power available (P_a), which is generated by the solar cells, should be larger than the power required (P_r). They may be estimated by using the following expressions.

$$P_r = \frac{C_D}{C_L^{3/2}} \frac{W^{3/2}}{\sqrt{\rho S_{ref}/2}} \tag{1}$$

$$P_a = \eta P_{solar} \propto S_{ref} \propto W^{2/3} \tag{2}$$

It can be seen that high aerodynamic performance, lightweight and high efficiency of the power generation P_{solar} are necessary to obtain possible solutions. In order to guarantee sufficient power generated by solar cells, the simplest way was to increase the size of the airplane so that a large area can be used to locate solar cells. The large span and high aspect ratio may reduce the lift-induced drag, improve aerodynamic performance, and increase surface area for the solar cells. Unfortunately, solar planes of this type were suffered from poor structure and stability. On the other hand, structure and systems should be as light as possible to reduce P_r and save electric power. The power generation was strongly limited by the energy conversion efficiency and the surface area available for the solar cells. High efficiency of solar cells was desirable to generate large power. The high aspect ratio also causes structure difficulties, and solar cells increase additional weight. These factors result in a challenge of design to achieve it without incurring excess weight.

Up to now, almost all of the solar planes were characterized by large surface areas to generate enough electric power, and extra-large aspect ratios (>30) for high aerodynamic performance. Unfortunately, like the Helios Prototype and Solar Impulse, which had the aspect ratio more than 30, these planes have to pay penalties of control, structure and cost. From the viewpoint of power generation, because the exposed area of surface should be used for solar cells as much possible, the flying wing or blended-wing-body plane would be good candidates. However, they do not have large aspect ratios in general, and largely curved surfaces are also inadequate for solar cells.

On the other hand, it is required that the solar cell is efficient, lighter and flexible, and inexpensive. Conversion efficiency of the solar cell is one of the most important factors, and high efficiency is desirable. However, the solar cell with high efficiency is expansive and may be broken due to bending and twisting on curved surfaces. So the solar cells, which are available and suitable for the solar plane, are rather limited. There are several kinds of solar cells which are made by various materials. At the state of the art, efficiency of the solar cell is as higher as 43%. Among these, thin-film solar cell is lighter and more easily configured for the plane, and its efficiency is going up to 15% nowadays. Single crystalline silicon cells have higher efficiency more than 20% with acceptable cost, but most of them have poor flexibility as pasted on the curved surface of the wing. In this study, a set of single crystalline silicon cells with 23% conversion efficiency were specially laminated with highly-transparent films to adapt the solar plane.

3 Unconventional Design of the Solar Plane

To maintain a large surface area used for the solar cells, and avoid structure difficulties at the meantime, a hybrid lifting configuration, which was combined by a wing with moderate aspect ratio and a lifting body, was proposed. As shown in Fig. 2, this unconventional solar plane was mainly consisted of a lifting body, a wing and a V-shaped tail. The plane was pulled by a propeller which was driven by a brushless motor, and the electric power was supplied by the solar cells put on the upper sides both of the lifting body and wing.

The size of the plane was determined by the maximum weight, electric power generated by solar cells and gliding speed. Dimensions are shown in Table 2. The design lift was defined by the weight and flight conditions. In this study, the maximum weight was 4.0kg. The projected areas of the wing and lifting body were 0.65m^2 and 0.6m^2, respectively.

3.1 Wing

The exposed part of the rectangular wing had a moderate aspect ratio 10.4 to have a better aerodynamic performance, and was easily to be constructed with lightweight and enough strength. To enhance strength of the wing structure, a thick airfoil section of NACA2414 was preliminarily adopted at the root of the wing, and gradually changed to the thin section of airfoil E374. The wing was twisted by 1 degree in spanwise. A winglet was devised on the tip of each side to reduce the lift-induced drag and improve aerodynamic performance. A pair of hinged aileron was used to control the airplane in roll.

3.2 Lifting body

The lifting body was actually a rectangular wing with a small aspect ratio. The sectional shape of the lifting wing adopted the well-known airfoil Clark-Y to make a stable flight. Unlike the

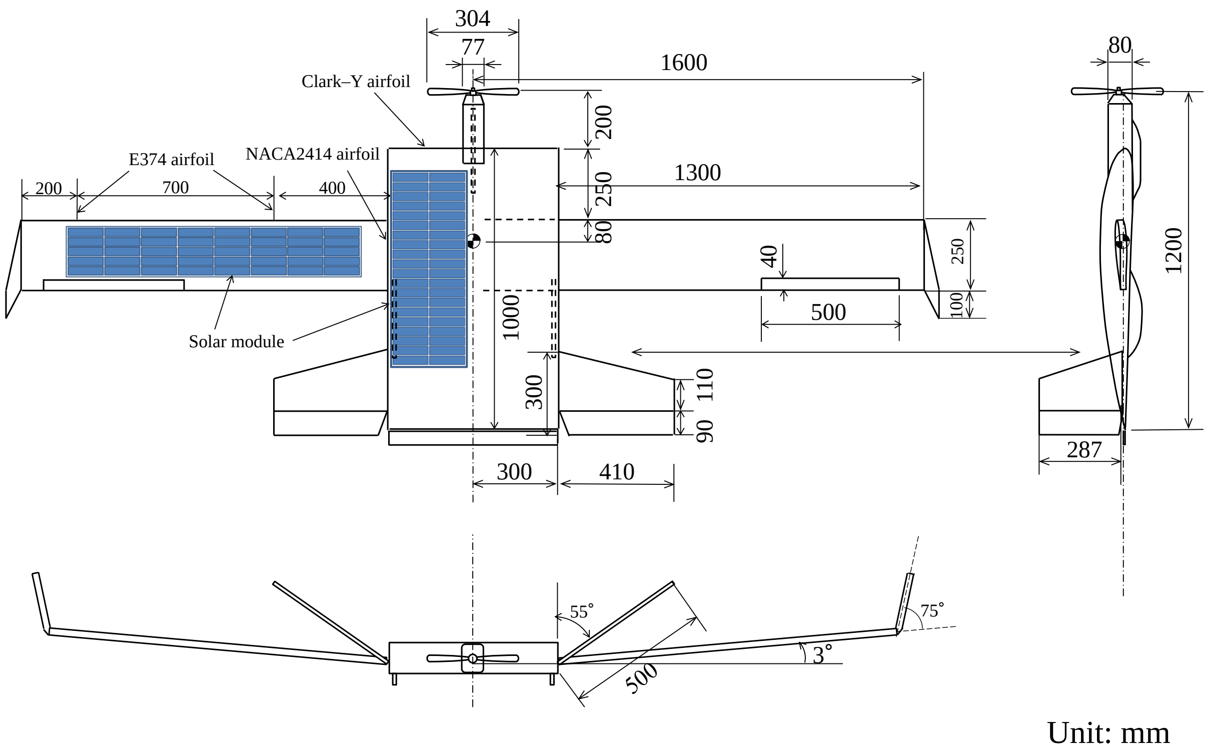


Fig 2. The designed solar plane, nicknamed Tobi which means a black kite in Japanese.

Table 2. Parameters of the designed solar plane

component	parameter	value
wing	projected area	0.650
	chord [m]	0.250
	span [m]	3.200
Lifting body	projected area	0.600
	chord [m]	1.000
	span [m]	0.600
V-tail	chord [m]	0.250
	horizontal area	0.164
	vertical area [m^2]	0.143
Solar module	area [m^2]	0.600
aerodynamics	reference area [m^2]	0.800
	design lift	0.500

conventional design, the lifting body not only had a large surface area for solar cells, but also could generate lift to obtain a better aerodynamic performance. Furthermore, because of the low aspect ratio, it might have a lightweight structure, and a large volume for storing enough rechargeable batteries with little influence on the location of weight center. Although the lifting body had a small aspect ratio, the lift was small as compared with the wing and generated a limited lift-induced drag. Suitable arrangements of the tail and fins were considered to suppress the rolled-up vortices, and thus reduce the lift-induced drag on the lifting body. As analyzed later, the lifting body was very efficient to guarantee surface area that used to generate enough electric power by solar cells, and the benefit of increase of surface area was much larger than the penalty due to drag.

3.3 V-shaped tail

A V-shaped tail was arranged to replace the conventional layout which was consisted of traditional vertical and horizontal surfaces. At the meantime, the V-shaped tail played an important role of the winglet of the lifting body to reduce the lift-induced drag generated on the lifting body. Also, the V-shaped tail was well-known to have smaller surface area than the traditional tail and has effect of decreasing the friction drag. The cant angle was 55 degree for each side of the tail, and the area was determined by satisfying both of longitudinal and lateral stabilities. The rear part of each surface of the V-shaped tail was hinged, and used as ruddervators, which combined tasks of the elevators and rudder.

3.4 Fin

A pair of fins was set under both side edges of the lifting body. They were not only used as sleds at landing, but also had effects on reducing

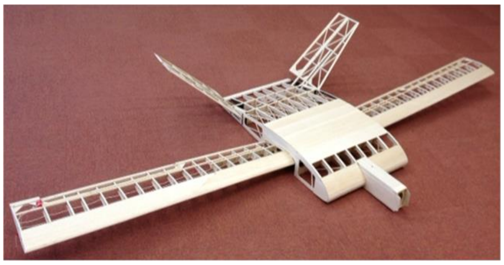
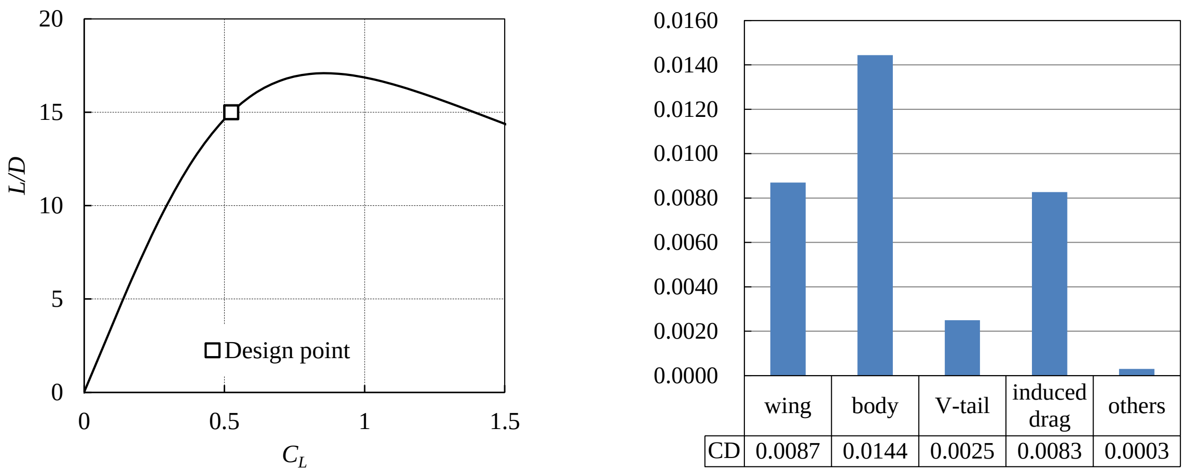


Fig. 3 Structure of the solar plane

Fig. 4 Static load test for structure

Table 3. Weight contributions

Wing weight [g]	1247
Body weight [g]	984
V-tail weight [g]	163
Solar panel weight [g]	516
apparatus [g]	778
others [g]	181
Total weight [g]	3894



a. lift/drag ratio vs lift

b. drag breakdown of component

Fig. 5 Aerodynamic performance

the lift-induced drag generated on the lifting body. The fin under each side of the lifting body could prevent air flow to be rolled up and generate tip vortices near the side of the lifting body.

4 Performance Analyses and Ground Tests

The aerodynamic performance was estimated in the design process, and then ground tests were conducted to confirm structure, propulsion system, power generation, and others.

4.1 Structure

The solar plane was mainly constructed by wood, and enhanced strength by using high quality carbon fiber. The frame is shown in Fig. 3. The final weight contributions of the solar plane are shown in Table 3, and the total mass is less than 4.0kg.

To confirm the load that the plane structure was able to support, a static load test was conducted. As shown in Fig. 4, the plane was put upside down, and a number of sand bags were distributed in the spanwise on the lower

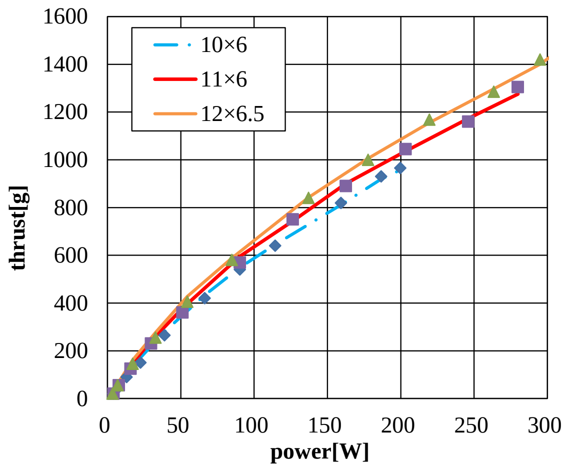


Fig. 6 Thrust of propeller

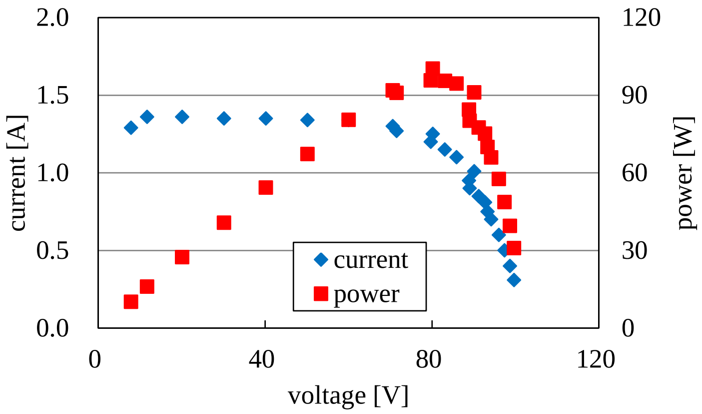


Fig. 7 Electric characteristics of the solar modules, measured at 79klux by ground test.

surface of the plane. It shows that the wing was deformed and the tip was moved by 69mm, responding 3 degree with respect to the root, under 12.8kg load. No damage was found and it indicated that the structure was satisfied for stable flight.

4.2 Aerodynamic Performance

Aerodynamic performance was estimated by a design tool which was simply combined a panel vortex method and the empirical equation [8][9]. The panel method was used to calculate aerodynamic forces due to the inviscid flow, and the empirical equations were employed to estimate the parasite drag in consideration of the viscous effect.

In Fig. 5, results of lift-to-drag ratio were given at different lift coefficients. For the current solar plane with 3.6-4.0kg weight, the design lift coefficient C_L was about 0.5, and the lift-to-drag ratio L/D was about 15. At the design condition, the lift coefficient C_L was 0.5, and the total drag C_D was about 0.0340. Although the friction drag became largely due to the lifting body, the large surface area of the lifting body could also contribute enough electric power generated by solar cells. If the flight speed is 12m/s, the friction drag due to the lifting body was estimated 1N and the power consumed was 12W. On the other hand, if single crystalline silicon cells with 23% conversion efficiency were used, the maximum electric power generated by the solar cells on the lifting body would be about 136W at the standard condition, which was much larger than the consumed power of the lifting body. It is very encouraged to use the lifting body for the solar plane.

Generally, for this design, the induced drag was only 24% of the total drag. It indicates that the friction drag was dominant and should be reduced to improve aerodynamic performance in the design of the solar plane. The solar plane of this paper was a result of the conceptual design, and will be improved in the near future.

4.3 Propeller Propulsion

The solar plane was pulled forward by thrust generated from a propeller, which was driven by electric power supplied from the solar cells. Ground tests were conducted to measure characteristics of propeller. As shown in Fig. 6, test results are shown for three propellers with different pitches and diameters. According to the estimation of aerodynamic performance, the drag was 2.61N and the cruise speed was 12.8m/s at steady level flight. Assuming the propeller efficiency to be 70~80%, the power required for motor shaft would be 40~50W. It indicates that the designed solar plane would be driven by the solar power at least for steady level flight.

4.4 Solar Power

The solar module used in this study was specially made for the designed solar plane. The conversion efficiency of the solar cell was 23%, and the module was laminated by special films with a high rate of transparence. The electric

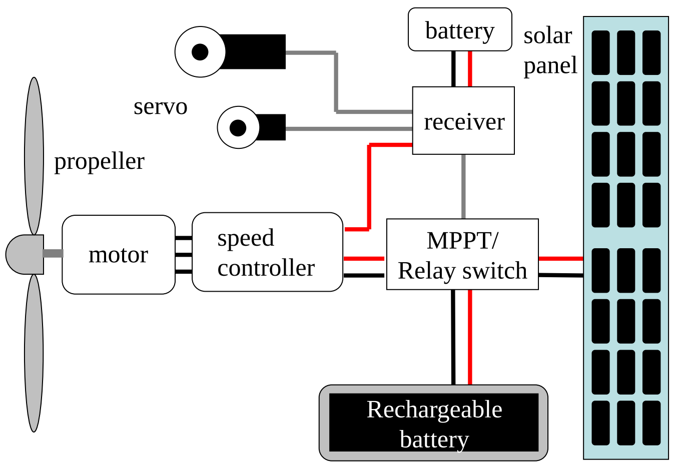


Fig. 8 Power and control systems

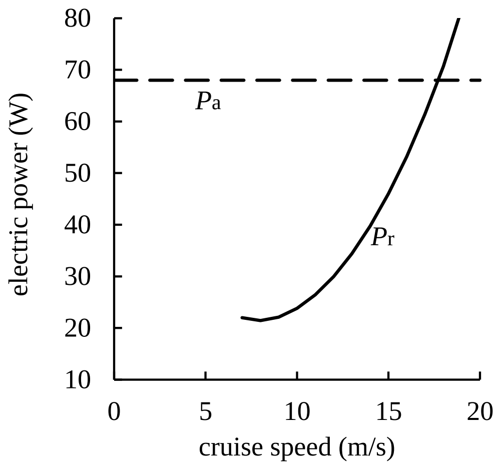


Fig. 9 Power curve of flight

power generated by solar energy is dependent on distance of the sun and earth, the angle of incidence, illuminance and curvature of the plane surface. Because of the large curvature and bad angle of incidence, the part near the leading edge of the wing was not suitable to be used for solar cells. The aileron was also excluded for solar use this time. Comparably, the lifting body was more easily used for solar cells because the chord was longer, the curvature radius was relatively larger than that of the wing. The total projected area was 1.25 m^2, and 90% part was effective to be used for solar cells. So the maximum area for power generation could be 1.125m^2, and generate the maximum power 255W.

In this study, as shown in Fig. 2, the surface area actually used for power generation was only 0.6m^2 due to high cost of the solar cells. The rating power was 132W with four solar modules at the standard test condition. The solar module could be bended at a maximum radius as large as 300mm and made it flexible to adapt to the curved surface of the plane. Ground tests were conducted to confirm characteristics of the solar module. Results are shown in Fig. 7. As can be seen, the solar modules used may generate electric power more than 95W under the condition of illuminance 79kflux.

4.5 Control System

The integral of power, control and propulsion systems were shown in Fig. 8. A special electronic device, called Maximum Power Point Tracker (MPPT) might be adopted to adapt the voltage of the solar modules so that the highest power could be possibly supplied. The electric power generated by the solar cells was either supplied to the rechargeable lithium polymer battery, or transfer directly to the propulsion system through an electric speed controller (ESC) and motor.

Generally, the MPPT had a large efficiency up to η_{mppt} ~ 95%, the efficiency of the brushless motor was η_{motor}~80%, the propeller efficiency was η_{prop}~70%, and other loss was assumed 5%, i.e., η_{mic}~95%. So, the effective electric power of the system could be calculated by the following equation.

$$P_a = \eta_{mppt}\eta_{motor}\eta_{prop}\eta_{mic}P_{solar} = \eta P_{solar} \quad (3)$$

The value was considered as the maximum P_a for propulsion. According to this equation, it can be seen that the total efficiency η was only about 50%. In flight, the P_a should be always larger than the P_r in order to maintain a constant air speed and a constant altitude. Then, the power reserved may be used to charge batteries. In this study, the P_a had the maximum of 66W, which was sufficient for steady level flight. For climbing, the electric power may be supplied additionally by the power charged and reserved in batteries.

Based on the estimation of aerodynamic performance, the power curves of the solar plane were calculated. Results are shown in Fig. 9. The solar plane may have a normal flight if the airspeed is less than 17m/s. The low speed flight was desired to save the electric power for reserving in the rechargeable batteries.

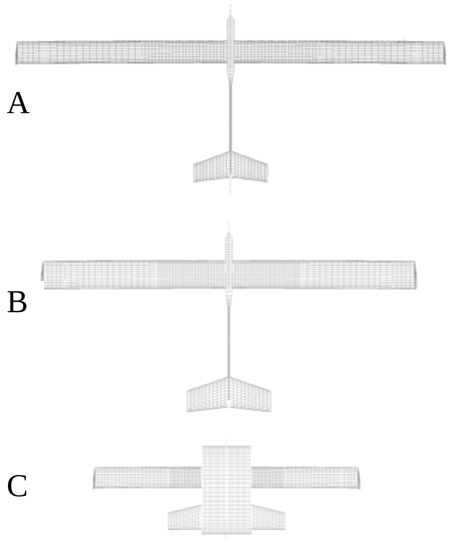


Fig. 12 Different designs

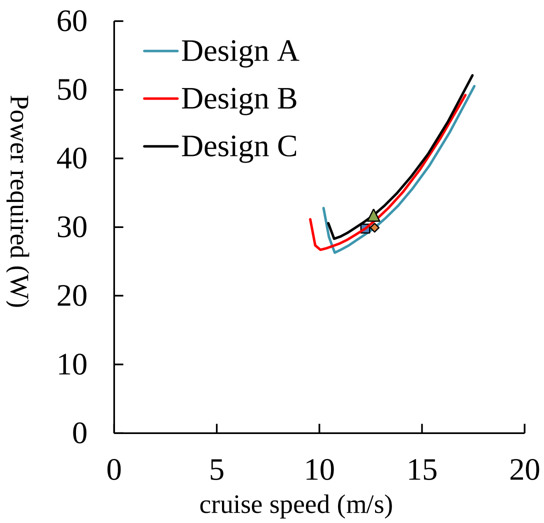


Fig. 13 Comparison of power curves

Although the power generated by the solar plane was not enough for climbing, fortunately, 50% surface area was still left and may be used for solar cells in the future.

5 Design Comparison

Here, the proposed conceptual design was compared with conventional ones.

5.1 Mass Estimation Models

The mass of all components were estimated by fitting the past data of the four solar planes constructed in the authors' research group.

Main wing: $$M_W = a S_W^{1.675} A_W^{0.825} \quad (4)$$

Lifting body: $$M_{LB} = b S_{LB}^{1.1} A_{LB}^{0.25} + M_B \quad (5)$$

Table 4 Comparison of main parameters

	A	B	C
Mass (kg)	6.957	6.032	4.803
Projected area[m^2]	1.28	1.28	1.28
Aspect ratio	19.4	13.5	12.8
$(L/D)_{max}$	28.95	24.32	18.76
Cruise speed [m/s]	12.7	12.2	12.6
P_r (W)	29.91	29.78	31.75

V-shaped tail: $$M_{tail} = c S_{tail} \quad (6)$$

Solar module: $$M_{solar} = d S_{solar} \quad (7)$$

Where *a*, *b*, *c* and *d* were coefficients depended on the materials and manufacture of the corresponding components, and M_B was the mass of the conventional body.

The total mass was a summation of all components, solar modules and payload.

$$M_{total} = M_W + M_{LB} + M_{tail} + M_{solar} + M_{mic} + M_{load} \quad (8)$$

The V-shaped tail was automatically designed by the conditions of flight stability. The payload M_{load} was specified to be 1.2kg.

5.2 Effects of Lifting body

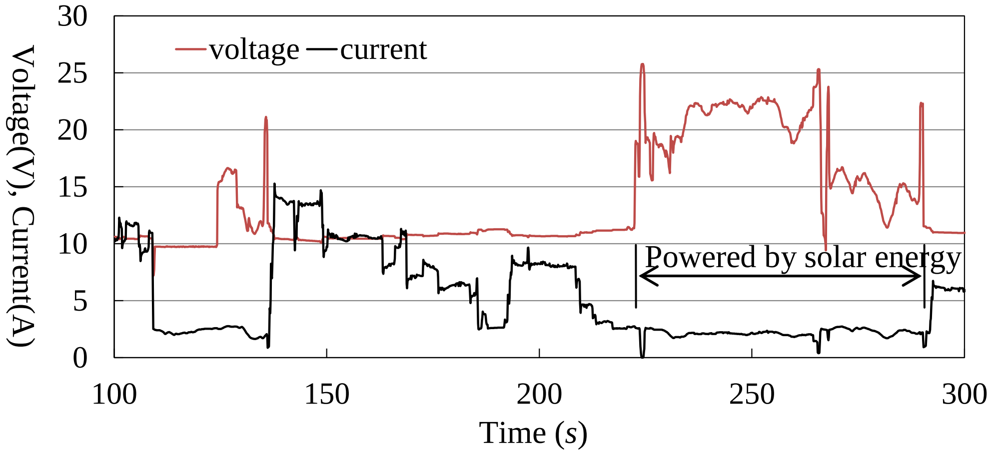
Three designs were conducted using the same process. All of them were also specified as the same projected area 1.28m^2, which corresponding to the same electric power generated by the solar modules. The power available at the thrust was 146W at the standard intensity of illumination. The design A and B were conventional configuration with large and moderate aspect ratios, respectively. The design C was the proposed solar plane No.4.

Results were compared in Fig. 12, Fig. 13 and Table 4. The mass of design A was very large because the structure weight was largely increased due to the high aspect ratio. Power curves show that all of them had very closed characteristics, and differences of power required were very small as compared with the power supplied by the solar modules. Although the aerodynamic performance of the design A was much better than those of other designs, the power consumed of them were almost the same. It indicated that the lifting body was efficient to largely reduce the mass of the plane.

a. launching

b. flying

Fig. 14 Flight test of the solar plane



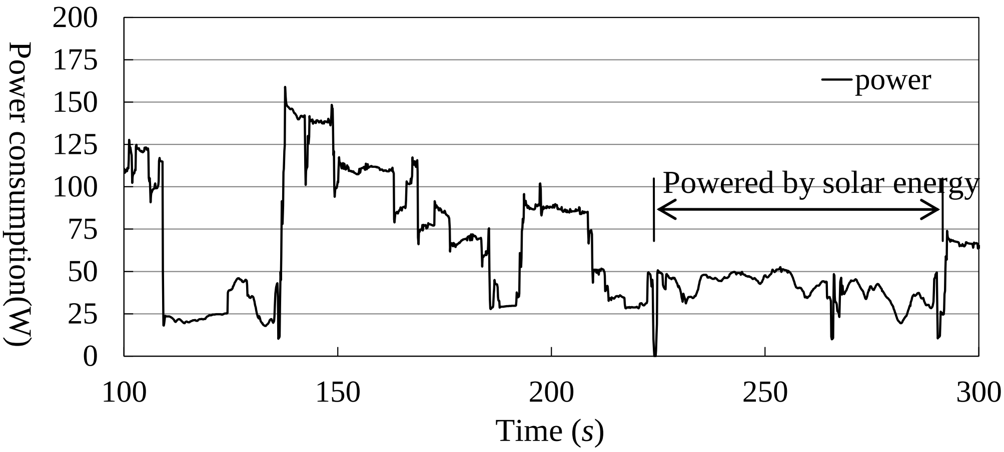


Fig. 15 Histories of electric power measured in flight

6 Flight Tests

Flight tests were conducted and succeeded in the morning of a sunny day in the end of summer of 2013 as shown in Fig. 14. The flight was controlled by a pilot on the ground using a proportional control system with the wireless remote. The maximum wind speed was recorded as 3.7m/s on the ground. The illuminance of the sunlight was 85klux, and the maximum electric power generated by the solar modules was estimated as about 100W, so the power available for propulsion was about 50W.

Firstly, a short time flight was conducted to measure various parameters of the electric system and flight conditions. The flight route of the solar plane was restricted in a small range that the radius was about 100m. According to the data recorded by an onboard GPS module, the altitude was mostly varied in a range of 15m~35m, and the speed was 9m/s ~ 18m/s, and the averaged speed was 12.9m/s. It was confirmed that the structure was satisfactory as measured in the static load test. The performance of the electric system including the solar modules was confirmed by measuring the current and voltage of the brushless motor. According to the histories of recorded current and voltage (Fig. 15), it could be seen that the solar plane was completely driven by the solar power in the time ranged in 220s ~ 290s. It indicates that electric power generated by the solar modules was sufficient to maintain a flight of the solar plane.

A 30-minute flight was finally conducted to confirm the overall performance, and test the system for the long endurance. The flight was also successful, and the solar plane was maintained to flight at the altitude ranged in 15m~35m. It shows that the solar plane is capable of conducting a long endurance.

7 Conclusions

An unconventional conceptual design was proposed for the solar plane. The hybrid lifting configuration was characterized by a hybrid lifting configuration, which was mainly consisted of a wing, a lifting body and a V-shaped tail to achieve sufficient power generation, better aerodynamic performance and lightweight. Ground tests were carried out for structure, solar modules, and aerodynamic performance was estimated by a design tool.

The flight test was conducted with using the solar energy. Overall performance of the solar-powered airplane was analyzed. It was shown that the current SPUAV was possible to achieve the long endurance.

The proper design combined the wing and lifting body was effective to be applied in the design of the solar plane to generate large electric power, maintain reasonable aerodynamic performance and reduce the weight of structure. The hybrid lifting configuration was encouraged for the solar plane to realize a long endurance flight.

According to the results of ground and flight tests, it was found that the weight of the preliminary solar plane may be further reduced and the aerodynamic performance may be also improved to obtain better flight performance.

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References

[1] Selinger, M.: Unmanned Marathoners, *Aerospace America*, Nov. 2013, pp. 36-41.

[2] Boucher, R.J.: Sunrise, the World's First Solar-Powered Airplane. *Journal of Aircraft*, Vol. 22, No. 10, 1985, pp. 840-846.

[3] Perez-Davis, M. E., Ishmael, S. D., Tiffany, G. C. and Gaier, M., *Investigation of the Helios Prototype Aircraft Mishap*, Jan. 2004, published by Createspace, 2012.

[4] http://www.qinetiq.com/Pages/default.aspx

[5] Boeing Wins DARPA Vulture II Program, Boeing News, Sept. 2010.

[6] http://www.solarimpulse.com/

[7] Ross, H., Fly around the World with a Solar Powered Airplane. ICAS 2008-10.11.1, or AIAA 2008-8954, 2008.

[8] Takeishi, S. and Lei, Z., Development of Aerodynamic Performance Analysis Tool using Panel Method, *Proceedings for 49th Aircraft Symposium*, Oct. 2011, Kanazawa, Japan. (in Japanese).

[9] Takeishi, S. and Lei, Z., Estimation of Aerodynamic Performance and Parametric Study of Unmanned Aerial Vehicle," *Proceedings for 50th Aircraft Symposium*, Nov. 2012, Niigata, Japan. (in Japanese).

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