CONCEPTUAL DESIGN OF SOLAR-WIND POWERED 'HALE' AUTONOMOUS SYSTEM WITH PRESSURIZED STRUCTURE

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ABSTRACT

Pioneering the future aerial systems and motivated by long-endurance mission requirements for defense, communication etc., this paper focuses on the aerodynamic design, airfoil selection, stability and component selection to be used for long endurance solar-wind powered unmanned aerial vehicle. The amount of fuel that is carried by unmanned aerial vehicle will severely limit the aircraft's endurance to a few days at most; the only source of energy available to very long endurance platforms is solar energy and wind energy. The design process was an interdisciplinary approach, and included a selection of high lift aerofoil, aerodynamic optimization of wing, weight balance, structural, reliability and maintainability analysis, safety improvement, cost and performance optimization. Humans have always wanted to achieve more. Thin-film flexible solar cells, high energy density batteries, miniaturized MEMS and CMOS sensors and highly efficient wind turbines have become vital for the endurance of UAVs within the past decade. Here also we can add some more features to the UAV which will help in enhancing the vehicle's performance. This added feature is the force of Buoyancy. In this project, we have designed UAV in such a way that a considerable percentage of its weight is supported by or constructed from inflatable structures containing helium gas or any other gas lighter than air.

Keywords: *Unmanned Aerial system, Solar power, Wind Power, Solar cells, Wind Turbine, High Altitude Long Endurance (HALE), Buoyancy effect.*

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I. INTRODUCTION:

The primary objective of this project is to develop a solar-wind powered unmanned aerial vehicle with pressurized body that could carry the maximum payload and to provide an initial selection of a configuration for the solar-wind powered UAV.A comparative study of similar solar-powered and wind powered UAVs will be used for preliminary configuration for this aircraft. There will also be a weight estimate for this solar-wind- powered UAV.To build a successful solar powered aircraft, a low weight design with a high aspect ratio and relatively high wingspan is necessary. Since power is one of the most critical parameters for solar-wind-powered UAVs, the fundamental equations are also considered. The concept of pressurized body will enhance the time duration of flight and reduces the weight of the UAV. Weight optimization reduces the consumption of power generated through solar and wind energy.

The design of this concept is very difficult due to availability of low solar energy and high wind energy as the altitude increases. During time of daylight, the solar energy is converted by photovoltaic cells and then distributed to the electrical motors, the payload and the battery. The energy remaining part is stored in a storage system. At night, Wind turbine and fuel cell provides energy necessary to carry out the mission. Air density at high altitude comparatively to sea level is ten times lower. Therefore, wing surface must be very large to compensate the lift and solar power. This concept requires light weight flexible structures, highly efficient Photovoltaic cells, efficient energy storage techniques, highly efficient small wind turbines and highly reliable micro-electronics. Highly efficient long endurance autonomous system at high altitudes requires very light structures, very low power (low drag at low speeds) and high cruise lift coefficients.

II. STANDARD ATMOSPHERE MODEL:

In order to compute solar cell efficiency, the cell surface temperature must be known. The cell temperature is a function of air density and ambient temperature. Also, the total power required for the UAV is a function of air density. To compute these quantities, a standard atmosphere model is necessary. The standard atmosphere model is based on geopotential altitude given by

$$h = \frac{r}{r + h_G} h_G, m \qquad (1)$$

III. UAV DESIGN:

A. Estimation of design take-off gross weight

Design takeoff gross weight is the total weight of the aircraft as it begins the mission for which it was designed. It includes crew weight, payload weight, fuel weight and the empty weight. This is given in the following equation:

$$W_0 = W_{crew} + W_{payload} + W_{battery} + W_{empty}$$

The crew weight is already given in the design requirements (W_{crew}= 0 lb). The unknowns are fuel weight and empty weight. But they are both dependent on the total weight, therefore expressing them as fractions of the total weight (W_e/W_0& W_b/W_0), W_0 can be solved as follows:

$$W_0 = \frac{W_{payload}}{1 - \left[\frac{W_b}{W_0}\right] - \left[\frac{W_e}{W_0}\right]} \qquad (2)$$

This shows that an iterative process must be used for aircraft sizing. For this purpose W_e/W_0 and W_b/W_0 must be estimated.

B. Empty Weight Fraction Estimation

(W_e / W_0):

The empty weight fraction (W_e/W_0) is estimated by taking the average values of seven W_e/W_0 ratios that belong to six competitor aircrafts founded during first study. For this the following formula is used:

$$\frac{W_e}{W_0} = \frac{\sum_{n=1}^{N}\left(\frac{W_e}{W_0}\right)}{N} \qquad (3)$$

C. Take-off Weight Analysis

UAVs with similar applications and roles were investigated. The data for (W_{TO}) and (W_E) for existing Solar Powered Unmanned Aerial Vehicle (UAV) are collected in order to develop a regression line for statistical analysis process and to gain a preliminary understanding into current design and performance specifications.

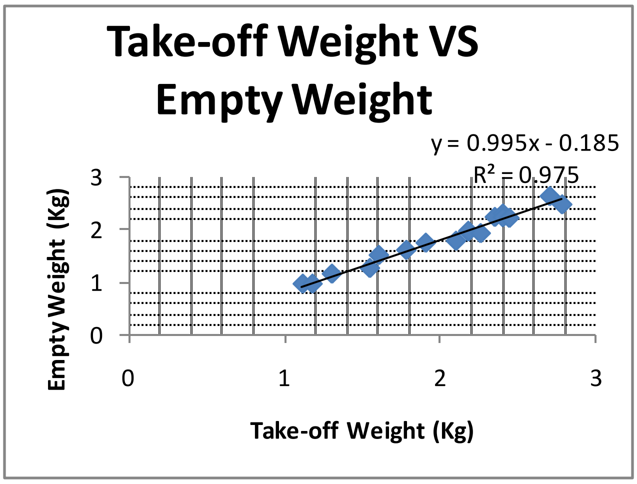


Fig.1 A logarithmic plot of empty weight against takeoff weight for a range of UAVs

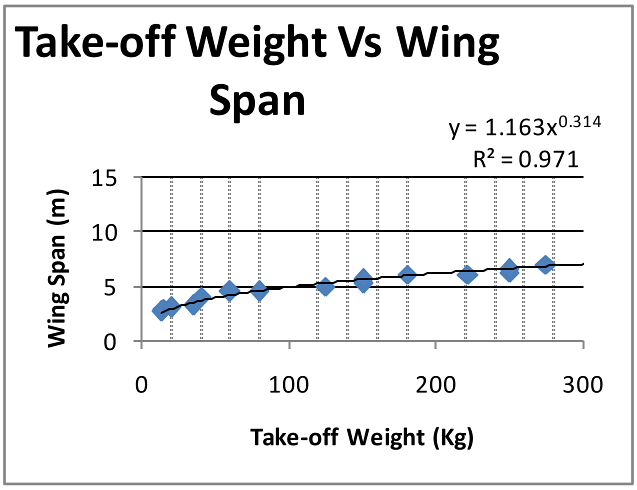


Fig.2. A plot of takeoff weight against Wing Span for UAVs

$$\text{Wing span} = 1.1631 * W_{TO}^{0.3149} \ [\text{m}]$$

D. Endurance:

For the case of electric powered flight, the endurance of the UAV is proportional to

$$\frac{W_B/W_1}{\left(1 + W_B/W_1\right)^{3/2}} \qquad (5)$$

Where WB is battery weight and W1 is aircraft weight less battery. Keeping W1 constant, and varying WB, it follows that endurance is maximized when WB = 2 x W1, that is, when battery weight is equal to twice the empty weight of the aircraft, or is 2/3 of gross weight.

IV. SIZING METHODOLOGY:

The sizing methodology for solar powered UAV is based on similar analysis for electric powered UAV. Total weight of the UAV is the main constraint for the entire performance of UAV. Total weight of the UAV is equal to the sum of the weights of payload, Airframe, battery and Motor & propeller. When total weight divided by the wing area, the equation expresses the equality between the wing loading of the aircraft and the sum of the portions of that wing loading due to each of the components. The total wing loading is usually chosen in order to allow the aircraft to meet performance requirements specified by the customer. The airframe wing loading will determine the structural performance and material requirement. The weight of the battery depends on energy density, motor efficiency and propeller efficiency and total thrust to overcome the drag and increase the endurance. From this sizing method the wing area can be estimated.

A. Sizing of Wing:

The sizing and performance estimation of the high altitude long endurance vehicle is summarized below. First, the atmospheric data related to the stratosphere viz. density, pressure, and temperature, kinematic viscosity is estimated, using standard formulae listed by Anderson. Considering variation in solar irradiance, duration of day time and wind speed throughout the year, the calculation is initiated by assuming the wing area based on statistical analysis of weight of existing UAVs, power-to-weight ratio (P/W) and wing loading (W/S). The power-to-weight ratio (P/W) and the wing loading (W/S) are the two most important parameters affecting aircraft performances like stalling speed, climb rate, takeoff and landing distances and turn performance.Optimization of these parameters forms a major part of the design activities conducted after initial weight estimation. The equations used to determine the weight-to-power ratio and wing loading as a function of stall speed, takeoff distance, and cruise speed are shown in Equations 1-3[9], respectively

$$\frac{W}{S} = \frac{1}{2}\rho V_{stall}^2 C_{L_{max}} \qquad [6]$$

$$\left(\frac{W}{P}\right)_{level} = \left[\frac{W/S(1 + 2/(\pi.e.AR.\rho.V^2))}{\frac{1}{2}.\rho.V^2.C_{d0}.V}\right] [7]$$

$$\left(\frac{W}{P}\right)_{TO} = \left[\frac{(S_{TOG}.\rho.C_{L_{max}}.g)}{1.44 * V_{landing}}\right]\left(\frac{W}{S}\right)^{-1} \qquad [8]$$

V. AERODYNAMICS OF FIXED WING VEHICLE:

The airfoil section and wing planform of the lifting surface are critically important to the performance of all flying vehicles. Unmanned Aerial Vehicle shares the ultimate goal of a stable and controllable vehicle with maximum aerodynamic efficiency. The aerodynamic efficiency is determined by the lift to drag ratio of the wing. Various airfoils were analyzed to determine which would be most beneficial.

Airfoil Aerodynamic Comparison:

Airfoil	S1223	LA2573A	Eppler 423	Dae 21
Thickness(%)	12.1	13.7	16	11.7
Camber(%)	8.7	3.2	7	6.6
Max C_L	2.425	1.183	2.00	1.7
Max C_L angle	8.0	15.0	16.0	18.0
Max L/D	71.86	18.556	40.833	48.813
Stall angle	8.0	1.0	12.0	18.0
Zero-lift angle	-13.5	-3.0	-11.5	-5.5

VI. ENERGY AND POWER:

For conventional aircraft, power available is a function of the installed engine's performance at the speeds and altitudes specified in mission requirements, for a solar powered aircraft, power available is a function of solar flux and the factors which determine its intensity. Parameters like gross weight and co-efficient of lift has strong effect on power required by the UAV.Energy required includes the power required to provide propulsive thrust for the duration of the mission. It also includes power required for running on-board systems and payload. Energy required over the duration of a mission will be balanced by collected energy, or energy available. This equality must be satisfied every day during a mission and will be a function of altitude, latitude, and time of solar year as well as airspeed, aerodynamic efficiency and aircraft weight.

Based on the daytime duration in local and wind speed at particular altitude, solar panels and wind turbine provides the energy for the avionics and payload, propulsion of the UAV and to recharge the energy storage system, which can consist out of rechargeable batteries. The power required for the propulsion system and payload are derived from solar power and wind power during the day and night time.

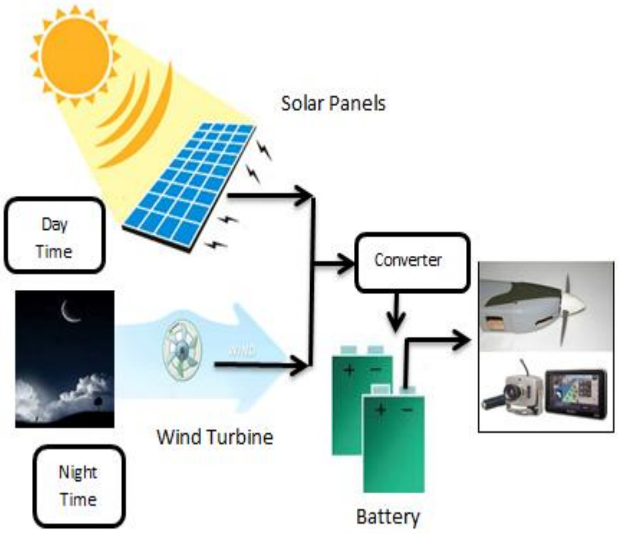


Fig.3 Conceptual Design of Energy Supply

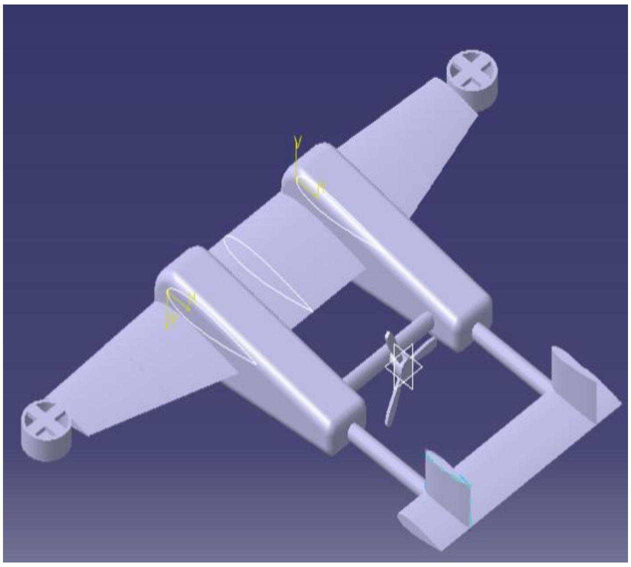


Fig.4 CAD Model

UAV requires maximum power during the climbing phase from ground to maximum altitude to maintain the level flight condition. To achieve higher thrust without sacrificing the high amounts of energy, electric motors shall be used to power the UAV. Electric motors are generally expressed in units of horsepower (hp), which is defined as

$$hp = \frac{T_0 \omega}{6{,}600} \qquad [9]$$

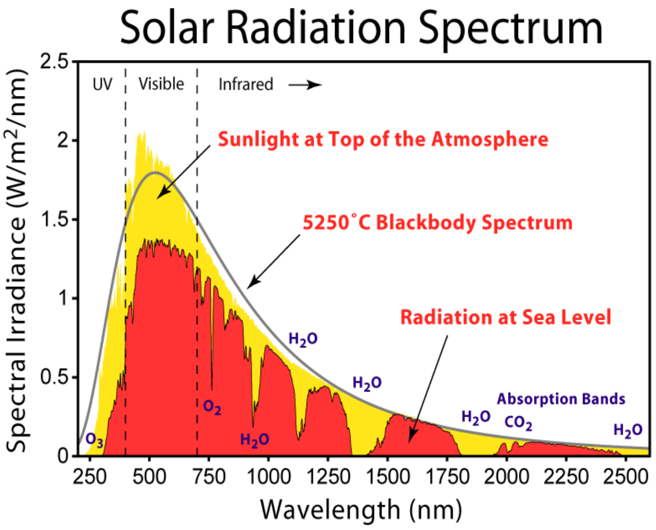
Where T_0 is the required torque and ω is the angular velocity

The mass of the electric motor depends on the power required for the mission that is given by

$$P = \frac{TV}{\eta} = \left(\frac{2}{\rho S_{ref}}\right)^{0.5} C_D \left(\frac{W}{C_L}\right)^{1.5} \qquad [10]$$

A. Solar Energy:

The amount of actual amount of solar radiation over a specific region may be reduced to approximately 50% due to our atmosphere. The actual amount of energy which reaches the surface of the earth exceeds the total energy consumption.Figure below shows the solar radiation spectrum between AM 0 (yellow curve) and AM 1.5 (red curve). The primarily cause of the loss of power across the spectrum is absorption and reflection, as well as scattering due to water vapor and carbon dioxide in our atmosphere.



At the top of the atmosphere, about 1,368 W/m2 of energy is provided by solar radiation (BGC, 1994). Due to atmospheric absorption and depending on the time of year and the geographic latitude, this amount is reduced at lower altitudes [9].

The mean monthly value of the intensity of direct solar radiation normal to the solar beam actually received at the earth's surface at noon time in India varies from 0.51 to 1.05 kW/m^2, depending on latitude, altitude of the station, and season. Average daily solar energy incident in India is 5KWh/m^2 day.

Solar Irradiance is a measure of amount of solar power at a location. This irradiance varies throughout the year depending on the seasons. It also varies throughout the day, depending on the position of the sun in the sky, and the weather.

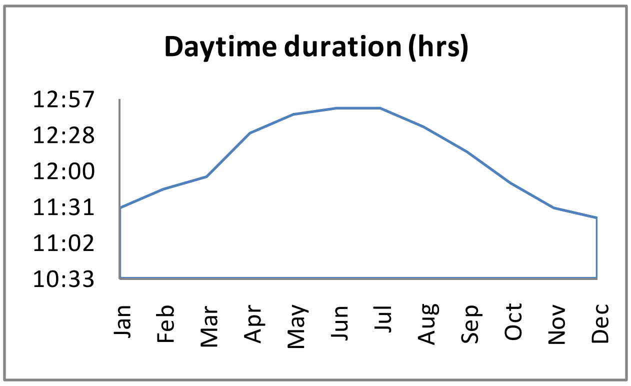


Fig.5 Average solar insolation measured in $kWh/m^2/\ day$

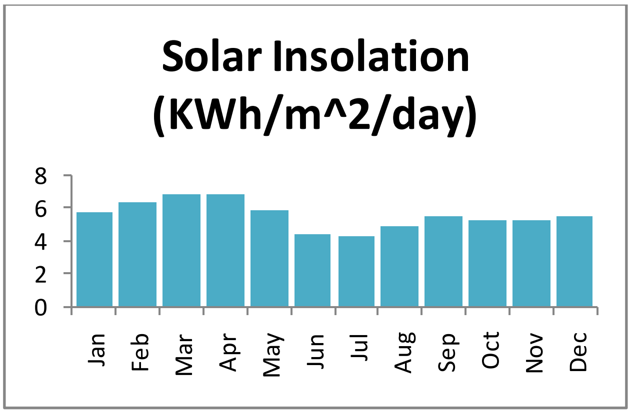


Fig.6 Solar Insolation over India during a year.

B. Photovoltaic Cell:

Multiband photovoltaic cell with three distinct light absorption regions, all integrated onto a single-layered thin film which has the efficiency exceeds 35%, because it captures a wider area of the light spectrum.

The average amount of solar radiation in India is consider to be 600W/m^2. The average day time duration is 11.30hrs. Assuming that the power required for the desired mission is 40KW.

C. Wind Energy:

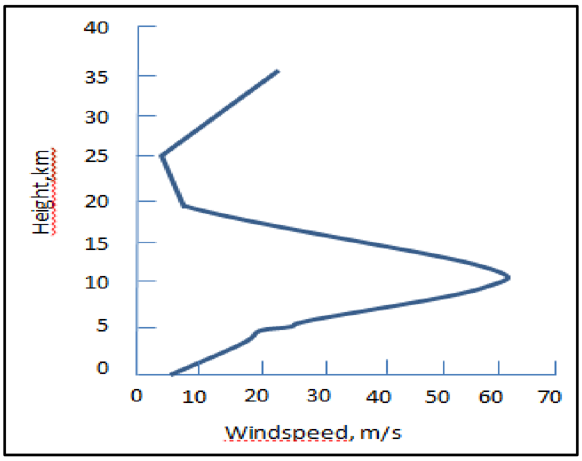


Fig.7 Wind Speed vs Altitude

An operating altitude of 16-18km is chosen, because this region consists of relatively mild wind condition with speed of 10-20m/s which suits for the generation of wind power. The power of wind turbine depends on the wind speed. Wind speed increases as the altitude increases shown by the relation [18]

$$V = \left(\frac{H}{H_0}\right)^{\alpha} V_0 \qquad [11]$$

Power increases with altitude as the cube of wind speed [18]

$$N = \left(\frac{H}{H_0}\right)^{3\alpha} N_0 \qquad [12]$$

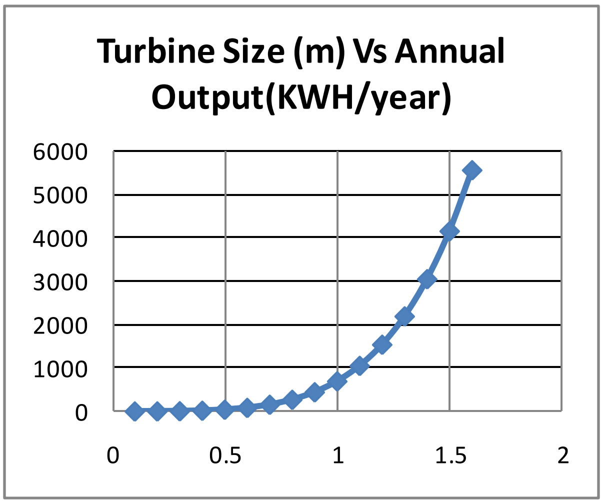


Fig.8 Annual Output of Turbine

VII. POWER ESTIMATION:

As mentioned above, to meet the requirement that the UAV utilises the power of the solar and wind to somehow power or propel itself, it was decided that solar panels and wind turbines would be installed on the aircraft. The efficiency and capacity of thesolar panels and turbine/generator system will determine the potential battery power available, and hence possible cruise endurance and loiter time.

The life of the battery is given by the equation:

$$T = \frac{\text{Capacity} \times \text{Battery Efficiency}}{\text{Current}} \qquad [13]$$

VIII. PRESSURIZED BODY DESIGN FOR LONG ENDURANCE:

From the tradeoff studies, designinglighter-than-air vehicles depends on thebuoyancy and the drag. To increase the floating effect, one must increase volume. For a given length, as one increases the volume of an envelope, one must increase the cross-sectional area and thus the drag. The drag determines key characteristics of the mission profile, vehicle speed, and power requirements. By looking at an analytical analysis of a common shape used for lighter-than-air vehicles, a body-of-revolution ellipsoid, one can readily see the relationship between volume, drag, and power to sustain flight [12]. The PB drag is a function of the mean wind velocity, airship size needed to lift the payload, and the air density at altitude. Assuming that the airship’s mass is linearly proportional to its volume, the drag (D) on an airship can be expressed in terms of the wind velocity (V) and air density. Drag varies inversely with the atmospheric density; consequently, drag will generally increase with altitude [19].

$$D \propto \frac{V^2}{\rho^{(2/3)}} \qquad [14]$$

The drag force on an object is produced by the velocity of a liquid or gas approaching the object. Drag force is dependent upon the drag coefficient of the object and the geometry of the object. For some objects, the drag coefficient is independent of the object's dimensions. However, for other shapes of objects, the drag coefficient is dependent on the dimensions and may be additionally dependent on the Reynolds number. At Reynolds numbers below 10^5, the boundary layer flow is completely laminar and drag coefficients tend to be at their highest overall value. Then a critical Reynolds number is reached between 10^5 and 10^6, where the boundary layer flow begins to undergo a transition from laminar to turbulent and a dramatic drop is seen in the drag coefficients. After reaching a minimum, the drag coefficients rise again slightly, as the boundary layer flow moves towards being fully turbulent between Reynolds numbers of 10^6 and 10^7. Finally, after reaching a Reynolds number of around 10^7, the boundary layer flowbecomes fully turbulent and the drag coefficients decrease again. Through all of the Reynolds numbers, the effect of the fineness ratio is the same with higher fineness ratios generally producing lower drag coefficients.

The drag force equation by (Blevins, 2003 and Munson et al., 1998 and others) is

$$F = 0.5 C_D \rho A V^2$$

The lift force equation is

$$F = 0.5 C_L \rho A V^2$$

For the ellipsoid, $A = \pi D^2/4$

Computational Data for Ellipsoid Envelopes [12]

L/D	Vol (m^3)	Cd	Lift (N)	Power hp
2	2.05	0.479	20.97	0.698
3	0.90	0.381	9.24	0.244
4	0.51	0.316	5.24	0.116
5	0.33	0.284	3.35	0.066
6	0.23	0.281	2.37	0.046

Within the table are computed values for envelopes of the same length (L), but varying diameters (D).

CONCLUSION:

This paper discusses the conceptual design of solar-wind powered HALE UAV with pressurized structure concept. Endurance for solar-powered Unmanned Aerial Vehicle (UAV) can be improved by using the high efficient and light weight solar panels and also by increasing the efficiency of the turbine with less diameter propeller. During perpetual flight, a positive total energy balance must be achieved over a solar day and night time. By using pressurized structure it can provide lighter weight, slow flying, reduced noise, and increased endurance capability to the extent of greater mission capability for future UAVs.

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