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DESIGN AND ANALYSIS OF HIGH ALTITUDE PSEUDO SATELLITE (HAPS)

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ABSTRACT

The objective of this project is to develop technologies for the unmanned aerial vehicle (UAV) to achieve a long endurance and other applications with the readily available renewable energy source. The air plane is driven by electric-based propulsion system with power supplied continuously by the endless solar energy. Suitable airfoil is selected in the design level and drag coefficient is estimated, the series of analysis are made with the existing airfoil regarding pressure distribution, flow analysis and other parameters. Unlike conventional aircrafts, a vehicle was designed with consideration of equipping more number of solar cells on the surface to generate sufficient electric power for flight and consequently enhance our main objective. Main priority is given to designing a wing, since it's the main lifting body, thus it should have moderate aspect ratio for better aerodynamic performance, capable of large number of solar cells accommodation and large volume for holding the payload near the center of gravity.

1. INTRODUCTION

The main motivation behind this project comes from the environmental challenges that the world has been facing over the last decade. From global warming to a lack of natural resources. Commercial aircraft currently use several thousand pounds of fuel to complete their flight, which has a negative impact on the atmosphere because of the carbon emissions that are released. One way to solve this environmental crisis is to eliminate the use of jet fuel and find an alternative source of energy, mainly renewable energy sources. This is why the idea of a solar-powered aircraft not only can be a successful one, but it can be a solution to current environmental problems and become the future of aviation. Apart from astronautics, the current state of solar technology allows limited number of applications in the field of aeronautics and UAV's. but nowadays there's a drastic improvement in the field of solar cells(especially in flexible solar cells by Alta devices), high energy density batteries and electronic systems including brushless motor with high power. The concept is so simple; an aircraft equipped with solar cells covering its most of the surfaces like wing, winglets, empennage system, where these cells absorbs the solar radiations from the sun directly and converts those to electrical energy to power up the propulsion system, other electronics and also to charge the battery with the surplus energy. High altitude pseudo-satellites (HAPS) are un-manned aircrafts which harnesses the sun's rays, running exclusively on solar power, above the weather and conventional air traffic. HAPS are able to fly for months at a time, combining the persistence of a satellite with the flexibility of a UAV. HAPS (High Altitude Pseudo Satellite) aircraft, being developed with a flexible wing for high-altitude unmanned flight, will provide unique opportunities for both civilian and defense areas, as well as for security tasks and also acts as pseudo satellites.

2. OBJECTIVES

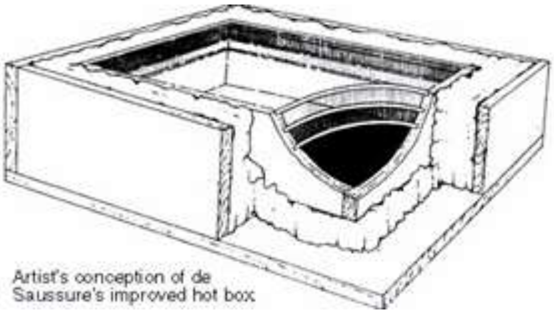
The primary objective for this project is to present a design of a solar-powered UAV and has a total mass of less than 10 kg considering the payload as transponder or camera.

Comparative study on previous solar powered UAV and their configuration. Discussion on electric propulsion system and mode of energy conversion. Integration of solar panels on the surfaces. Selection of suitable wing configuration and empennage configuration. Sequential analysis using soft wares and fundamental power equations for steady level flight.

3. BACKGROUND

To understand the history of solar-powered flight, a discussion of solar cell history is required. Humans started using the sun's rays to benefit themselves as early as 7th Century B.C., where they studied how a magnifying glass can be used to make fires. There were not many more advances in solar technology up until 1767 when Horace de Saussure built the world's first solar collector, later used for cooking. In 1839, Edmund Becquerel was experimenting with electrolytic cells and found that when these cells are exposed to light, they create electricity. This was the first ever photovoltaic cell, which is the basis of all solar cell technology. For the next fifty years, electrolytic cells were shown to power devices, including steam engines and water heaters. Also, selenium was shown to conduct electricity when exposed to the sun during this time. There were some advances in the early 1900s, but the key advancement in solar cell technology was in 1954, when photovoltaic technology was born in the United States. Daryl Chapin, Calvin Fuller, and Gerald Pearson created the first ever photovoltaic (PV) cell capable of using the sun's rays to power "everyday electrical equipment"1.

Thus, PV cells were built.



It will not be for another 15 years until the usage of solar cells will be incorporated into aircraft. The first solar aircraft was Sunrise I(a) built by Astro Flight and flown during the winter of 1974-751. It weighted 27.5 Ibs, had a 32 ft wing span and was powered by 450 watts of power from the solar cells. It was damaged by a sand storm in the spring of 1975. By the fall of 1975, Astro Flight constructed an improved version called Sunrise II (b)1. It had over 600 watts of power, weighed 22.5 Ibs and had 90 ft2 of surface area (32 ft span). The 600 watts of solar panels from Sunrise II were used to power Gossamer Penguin (c) (541 W of power were available from the cells). Gossamer Penguin weighed from 170 to 250 Ibs with the pilot (68 Ibs without) and had a wing span of 71 ft. Numerous flights were made between May and August of 1980 under solar power. The next airplane in the series was the Solar Challenger (d) It was designed to cross the English channel. The solar cells could deliver over 4000 W at altitude and 2500 W at sea level. It had a wing span of 46.5 ft, weighed 336 Ibs (with pilot). On July 7, 1981 the Solar Challenger flew across the English Channel.

(a)

(b)

(c)

(d)

Following Solar Challengers, Aero-environment was funded to work on a classified project for the U. S. government2.

They built an airplane designated HALSOL (High-Altitude Solar Energy). Three models and a final prototype were built. HALSOL was mothballed. A little over a decade passed before NASA's Environmental Research Aircraft and Sensor Technology (ERAST) program became interested in solar aircraft. In 1997 Pathfinder flew to an altitude of over 67,000 ft. Pathfinder had a wing span of 98 ft, weighed 486 Ibs and was powered by 8000 W from the solar cells. Pathfinder was modified, increasing the wing span to 12! ft. This version was flow in 1998 to an altitude of **80,000** ft. It was called Pathfinder Plus (e)

(e)

The next in the series of aircraft was Centurion (f). Centurion had a wing span of 206 ft and a gross weight of almost 1300 Ibs. It was powered with 31 kW of solar power, and flew in 1998. The latest of the non-micro solar powered aircraft built by AeroVironment was Helios (g). In the summer of 2001, Helios set the impressive altitude record reaching 96,500 ft. Helios has a wing span of 247 ft, weighs over 2000 Ibs and is powered with 42 kW of solar cells.


(f)


(g)

While AeroVironment and NASA have been making larger and larger solar aircraft, others have been working on a smaller scale. Several individuals and colleges have tackled the challenges of solar powered flight. In 1993 Mike Garton built and flew a solar plane weighing 4 Ibs, having a wing span of 18 ft and powered by 80 W of solar power. An enthusiast for solar powered R/C aircraft is Dave Beck. He has built at least two solar aircraft, one being Solar Solitude (h).

Solar solitude has a wing span of 106.6 in, weighs 4.4 Ibs and is powered by 63 W of solar cells and was flown in 1998.

Dave Beck maintains a web sited with useful information and links related to solar flight. From the site, information was obtained about Dave's first solar aircraft, Solar Excel; Wolfgang Schaeper; Oklahoma State University's Helios, University of Stuttgart's Icare 2 (i), Bernd Bobmann's Trosollmuffel; Todd Heimerk's Simple; and Bob Boucher's Solaris I and Stardust. The last solar aircraft to be discussed will be the small guys. These aircraft have the goal of being the smallest solar powered aircraft. The first is MikroSol.

MikroSol was built in 1996 by Dr. Sieghard Dienlen and weighed 1.9 N. The next Year, a smaller version was built. It was called NanoSol and was declared the smallest solar aircraft at the time (1997) by the Guinness Book of Records. NanoSol (l) has a wing span of 1.11 m, weighs 1.56 N and is powered by 8.64 W of solar power. The latest version is PicoSol weighing in at 1.24 N and having a wing span of 0.99 m.

(h)

(i)

Airbus (QinetiQ) Airbus, with its subsidiary Astrium, has been working on High Altitude Pseudo Satellites (HAPS) since 2008. In 2013 Astrium acquired the Zephyr(j) solar powered UAV assets from British defense technology company QinetiQ, integrating the QinetiQ Zephyr staff into Airbus' organization. Zephyr is a High Altitude Pseudo Satellite (HAPS) UAV running exclusively on solar power.

The Zephyr has a track record of breaking 3 world records in 2010, including:

1. Longest endurance flight for UAV (336hrs)
2. Highest altitude reached (18,805m)
3. Longest flight (23hrs, 47min)

Zephyr has evolved through the years with different models. Airbus is currently working on Zephyr 8.

Some Zephyr 8 specs:

Wingspan:	28 meters
Altitude:	approximately 21,000 meters
Cruising speed	55km/h
PV:	amorphous silicon
Batteries	lithium-sulfur (Zephyr 7)
Electric motors:	2x 450 Watt electric motors (Zephyr 7) Payload 5-10kg
Weight	60kg

Since 2014 Airbus has continued to develop the Zephyr and break records. In September 2014 the Zephyr became the first ever UAV to perform a flight authorized by a civil authority. The company aims at full commercializing of the Zephyr as an alternative to satellites. The UAV has all the advantages of an aircraft and satellite combined: it can be re-used and has a wide coverage due to its flexibility in location. At the same time it's capable of taking on similar tasks as satellites: it can fly at high altitudes, perform similar applications and is reliable. Airbus is targeting several applications with its Zephyr drone, including Full HD imaging, thermal imaging, the creation of temporary communications networks and emergency services support.

(j)

Boeing Phantom(k) Works
Boeing's dedication to solar power technologies dates back to 1973, which began after the oil embargo made it clear that fossil fuels cannot be relied on and that alternative energy sources are needed. Back then it already researched large scale solar power producing satellites, interesting read about Boeing's solar energy history here. Boeing SolarEagle (Vulture II) is a solar powered unmanned aerial vehicle (UAV). Unique about this drone is that it's built to eventually remain airborne for over 5 years, and therefore is considered a High Altitude, Long Endurance (HALE) plane. US' organization DARPA has injected USD 90 million in the project, with Boeing investing the rest.

Solar Eagle specs:

Wingspan:	120 meters
Cruising speed	<80km/h
PV:	5kw

(k)

Google (Titan Aerospace)(l)
Google got into the business of solar-powered drones with the acquisition of **Titan Aerospace,** a high-altitude, long endurance (HALE) solar-powered UAV manufacturer in April 2014. Titan Aerospace developed drones called **Solara 50** and **Solara 60** capable of flying at a reported altitude of 20km for impressive periods of over 5 years. That period is an estimate, however at these altitudes there's few that can disturb a plane to continue its steady path in the air.

Solara 50 specs:

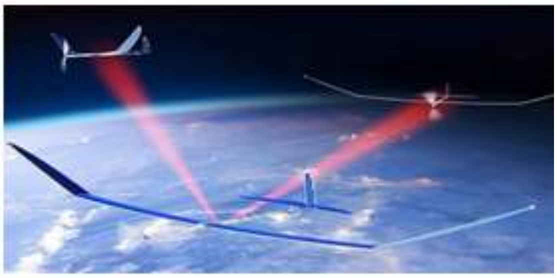
Wingspan:	60 meters
Cruising speed	105 km/h
PV:	3000 solar cells, producing 7kw
Launch:	with a catapult

Drones capable of flying near the edge of the earth's atmosphere, considered atmospheric satellite technology, would be more than suitable to offer cheap and widespread internet connectivity in remote areas, at costs well below those of commercial satellites. You may wonder if Google purchased Titan Aerospace because project Loon, with its large balloons that can travel the world in short periods of time, are perhaps considered less effective or reliable in providing internet connectivity in remote areas? Or perhaps the combination of perfectly controlled solar powered drones and Loon's fast to deploy and rapid moving balloons can be combined into a hybrid system, creating the ultimate internet coverage network.

Update 1 February 2016

The latest solar powered drone project from Google is called the Skybender. Google recently hired a large warehouse from company Virgin Galactic have rented in the US state of New Mexico. From here it's working on solar powered drone that can broadcast 5G internet all over the US. The Skybender drones are said to be experimenting with millimeter wave radio transmissions. These particular radio waves eventually will bring internet speeds of up to 40 times faster than we're seeing with 4G LTE systems. Google Project Skybender(m), It's still quite a challenge to roll out the millimeter wave chencology, as they have a much shorter range compared to current mobile phone signals. The current signals that Google is experimenting with at the moment are known to have only 10% of the range of an average 4G signal. One solution Google is working on is to implement focused transmissions from a phased array. Currently Google is using different types of drones for the Skybender project, including the solar powered Google Titan and the Centaur. Once multiple drones are flying in an area, they will be replacing the traditional towers and receivers. Also they will be able to reach remote parts of the country. Eventually with project Skybender Google is aiming at providing 5G coverage worldwide.

(l)



(m)

Facebook (Ascenta)(n)

Facebook got involved with solar powered drone technology with the acquisition of UK based Ascenta in March 2014.

Facebook's Connectivity Lab is committed with internet.org to to build drones, satellites and lasers to deliver internet to everyone, regardless if you're living in a world city or in a remote area of a developing country.

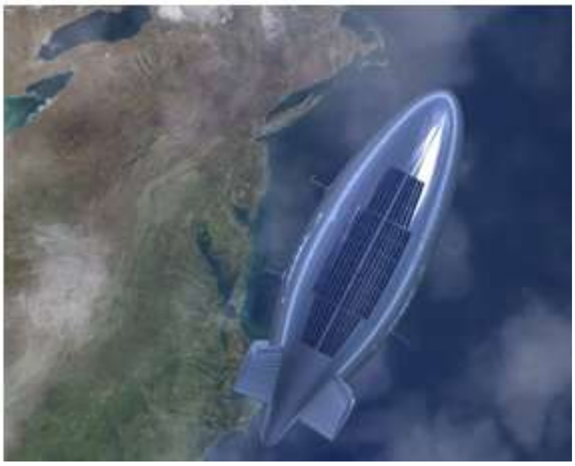
Connectivity Labs believes that **satellites** will be most suitable for remote places with low population living over wide areas. Internet can be beamed down from multiple low orbit satellites, providing a continuous coverage. For the more densely populated areas such as towns, villages and suburb areas, Connectivity Labs will utilize high altitude solar powered drones (UAV's)**.** These PV powered drones will circle at 20,000 meters altitude, well above commercial airlines, away from disturbing weather, and will beam down high speed internet. Newly developed laser communication systems can beam data from the sky into communities.

(n)

Lockheed Martin (Hale-D)(o)(lighter than air concept)
The HALE-D is a remotely-controlled solar-powered UAV that is designed by Lockheed Martin to float above the jet stream at 18,000 meters. HALE-D stands for High Altitude Long Endurance-Demonstrator. This unmanned lighter-than-air vehicle operates above the jet stream in a geostationary position and functions as a surveillance platform, telecommunications relay, or a weather observer. At the same time the HALE-D can be used in the defense industry as an ever-present intelligence and surveillance platform, offering rapid communications connectivity over the entire battle space.

HALE-D specs:

Hull volume:	500,000 ft3
Length:	240ft
Diameter:	70ft
Propulsion Motors:	2kw electric
Energy storage:	40 kWh Li-ion Battery
Solar array:	15 kW thin-film
Cruise Speed	20 ktas @ 60 kft
Station-keeping Altitude	60,000 ft
Payload Weight	50 lbs
Payload Power	500 watts
Recoverable	yes
Reusable	yes



(o)

Atlantic Solar(p)
Atlantic Solar is headed by ETH Zurich's Autonomous Systems Lab. The company has developed an a tonomous, solar powered drone (UAV) with a wingspan of 5.6 meters that can fly up to 10 days continuously.

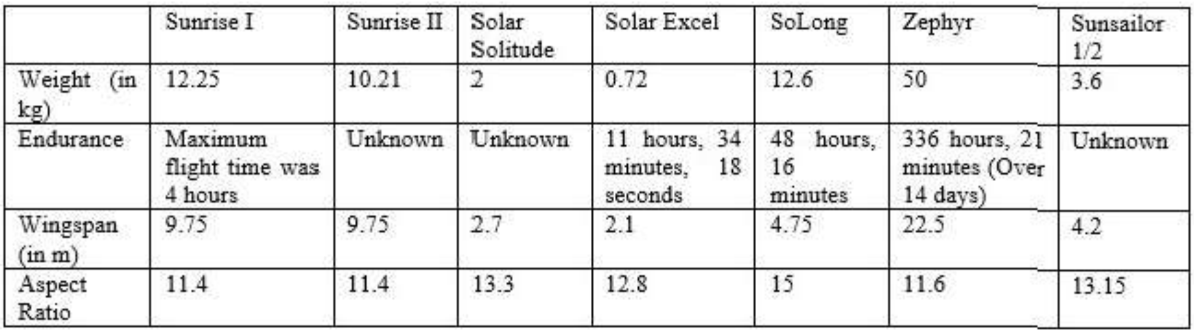
Objective of Atlantic Solar is:
"The first-ever crossing of the Atlantic Ocean using a solar powered Unmanned Aerial Vehicle (UAV)".

According to their project brochure Atlantic Solar is attempting to "cross the Atlantic Ocean with a 'swarm' of 4 UAV's by the end of June 2015, crossing 5000km of flight distance during 7 days of harsh Atlantic environment with potentially strong winds and thunderstorms".

As this deadline has already been passed, we expect the team has slightly postponed its efforts which is common for such projects, as often ideal weather circumstances are required.

4. DESIGN CONSIDERATION

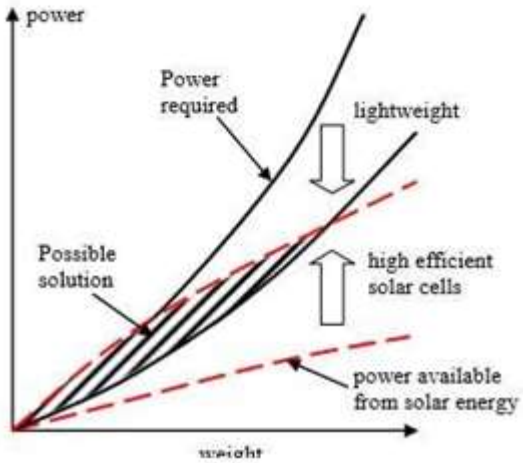
Important design parameters for similar UAV.



	Sunrise I	Sunrise II	Solar Solitude	Solar Excel	SoLong	Zephyr	Sunsailor 1/2
Weight (in kg)	12.25	10.21	2	0.72	12.6	50	3.6
Endurance	Maximum flight time was 4 hours	Unknown	Unknown	11 hours, 34 minutes, 18 seconds	48 hours, 16 minutes	336 hours, 21 minutes (Over 14 days)	Unknown
Wingspan (in m)	9.75	9.75	2.7	2.1	4.75	22.5	4.2
Aspect Ratio	11.4	11.4	13.3	12.8	15	11.6	13.15

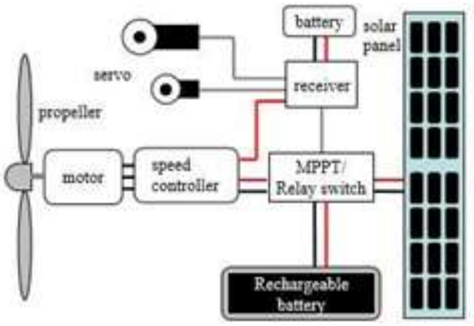
Preliminary design
The design procedure outlined by Anderson's in the text "Aircraft Performance and Design"6 was used as a guide. A set of input variables was established. From the input variables, the weight and surface area of the aircraft were found. Next, the drag polar for the aircraft was estimated. Lastly, the power available from the solar cells and the power required for flight were found and compared. Any design with excess power was determined to be a potential candidate aircraft. In the paragraphs that follow, more details about the process will be given. As mentioned above, first a set of input variables was established. The first two variables were the stall speed (Vstal) and the maximum speed (Vmax). A low stall speed will result in a larger aircraft and a high maximum

speed will require more power. Because the goal of this study was to design a small aircraft with a minimum amount of available power, the design velocity of the aircraft had a large impact on size and feasibility of the design. Initially, the baseline stall speed was selected as 6 m/s and the maximum speed was 10 m/s. These values were best guesses, coming from experience working with similar size aircraft. Later, it will be shown that the 6 m/s stall speed had to be increased to decrease the final size of the solar aircraft. The maximum speed of 10 m/s was a good estimate.



(1)

Power v/s weight graph and possible solution from previous UAVs



Power and control system

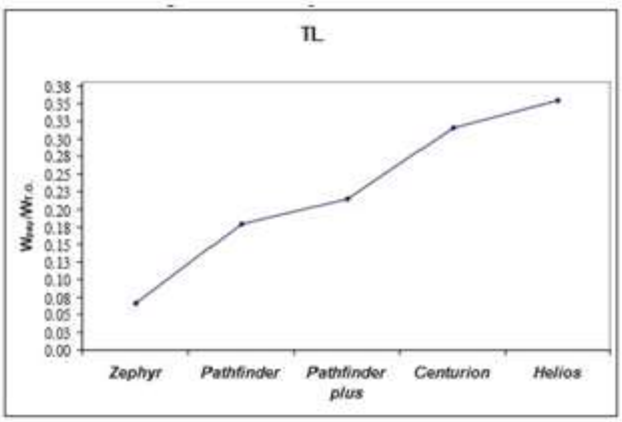
Traditional Conceptual Design Methods

Conceptual design is a process that a certain configuration is sized for the mission and performance needs. It begins with an initial configuration. This configuration is determined based on previous experience and engineering creativity and do not cover all the details about the aircraft. Traditional aircraft design approaches consist of two parts: constraint analysis and mission analysis13. In constraint analysis, power and thrust settings are determined based on different aircraft mission requirement such as takeoff length, rate of climb, maximum cruise speed, turn rate, acceleration, and approach h speed.

These requirements can be expressed as functions of power to weight ratio versus wing loading. Combination of these curves for different flight conditions would provide a solution space for the design. The designer selects a suitable design point based on engine options and technologies needed. In mission analysis, fuel weight fraction is determined based on statistical data for fractions of weight in mission parts. Weight T.O. will be derived from the aforementioned equations along with statistical data for empty weight versus Weight T.O..

Consequently, power required and wing area are determined. A set of parameters should be determined in conceptual design. This parameters based on Roskam method14 include: Takeoff weight, Empty weight, Maximum required takeoff power, wing area and aspect ratio, maximum required lift coefficient. These methods are not applicable to solar aircraft mainly because the aircraft does not consume fuel. In addition, available power is a function of aerodynamic surfaces area.

Therefore, many modifications are needed to be obtained a conceptual design method for solar aircrafts. Configuration selection is chosen to be the first stage for solar powered aircraft design. In this stage that is called feasibility study, parameters such as horizontal an vertical tail surface area to wing area ratios and desired fuselage volume are determined. Based on the available technologies, parameters such as solar cells efficiency and specific weight, energy storage system type, efficiency and density, and propulsion system (motor, gear, and propeller) efficiency are determined.



Payload to takeoff weight ratio for different aircrafts

Aerodynamic analysis

A solar-powered unmanned aerial vehicle should be capable of flying efficiently and embedding sufficient payload.

Compared with conventional design, 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 required power. For a solar plane, additional increase of weight includes solar cells, structure to hold solar cells and power system to control solar energy. Furthermore, to guarantee 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 (*Pa*), which is generated by the solar cells, should be larger than the power required (*Pr*). They may be estimated by using the following expressions.

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

It can be seen that high aerodynamic performance, lightweight and high efficiency of the power generation *Psolar* are necessary to obtain possible solutions. The relation of the power and weight is shown(1). 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 in the past. 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 *Pr* and save electric power. At the meantime, high efficiency of solar cells should be obtained to generate sufficient power for flight. However, the power generation is strongly limited by the energy conversion efficiency and the surface area available for t e solar cells. 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. There are several barriers in technology to be overcome in order to realize the solar plane.

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 for use on an airplane. To generate electric power as more as possible, the best way is to use high efficient solar cells. 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 to be placed on the surface of the plane. Although its efficiency is going up to 15% nowadays, it is very difficult to generate enough electric power to drive the plane for long endurance. 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 designed solar plane.

Aircraft (wing) surface area came from the equation:

$$W = L = \frac{1}{2}\rho S C_{L,max} V^2 \quad \text{or} \quad S = \frac{2W}{\rho C_{L,max} V^2}$$

where W is total weight, L is lift, p is air density, S is surface area, CL,max is the maximum lift coefficient, and V is the aircraft velocity. Iterating by first summing the component weights to find the total aircraft weight, and then calculating the required surface area, the surface area and weight of the aircraft were estimated. Once these were found, the aircraft wing loading (W/S), wing span (b) and average wing chord (c) were found. Wing span and chord were found from the relations:

$$b = \sqrt{SAR} \quad \text{and} \quad c = \frac{S}{b}$$

where AR is the wing aspect ratio. The next step in the design procedure was to estimate the drag polar for the aircraft. The drag polar has the general form:

$$C_D = C_{D,o} + KC_L^2$$

where CD is the drag coefficient, CD,0 is the zero-lift drag coefficient and KCL is the induced drag. A conservative estimate of the zero-lift drag coefficient was made, estimating it to be 0.05. This number came from considering the friction coefficient for laminar and turbulent flow for a flat plate at a Reynolds number of 107,000 (0.004 and 0.006 respectively). The friction coefficient was multiplied by the ratio of the wetted surface area of the aircraft to the wing area, which was estimated to be 2.2.

Also, the minimum drag coefficient for the EH 1590 airfoil was considered. It's value was 0.009. The largest of all these values for CD>0 was 0.016. Reference 1 states that adding solar cells to the wing of Sunrise I doubled the drag on the aircraft. Finally, the value of 0.05 was selected as a conservative estimate for CD,0- K was found from the relations:

$$K = \frac{1}{\pi AR\, e_0} \quad \text{where}$$

$$e_o = 1.78\left[1 - 0.045(AR)^{0.68}\right] - 0.64$$

Once the drag polar, aircraft weight and wing area had been found, the available power (Pa) and required power (Preq) could be determined. These values were defined as the power out of the solar cells and the power into the motor, respectively. Available power was found from the relation:

$$P_a = q_{sun} S \eta_{spacing} \eta_{cell} \cos(\theta_{inc})$$

where qsun was the specified solar energy flux, nspacing and nceii were the efficiency of solar cell spacing and the energy conversion efficiency of the solar cells, and theta was the incidence angle of the solar radiation on the wing. The required power was found with the relation:

$$P_{req} = \frac{T_{req} V}{\eta_p \eta_m} \quad \text{where } T_{req} = \frac{1}{2}\rho V^2 S\left(C_{D,o} + KC_L^2\right)$$

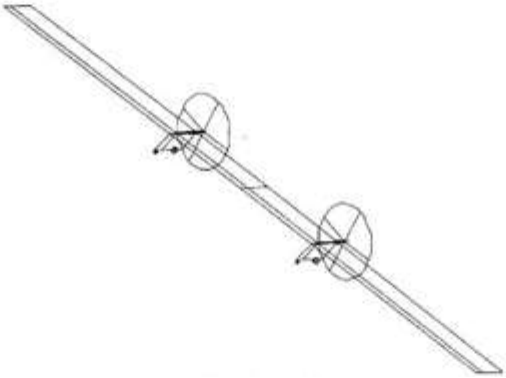
where Treq is the required thrust. The power required was found for velocities between Vstal and Vmax. At each velocity, the lift coefficient required for flight had to be found by setting the aircraft weight equal to the lift produced by the wing.

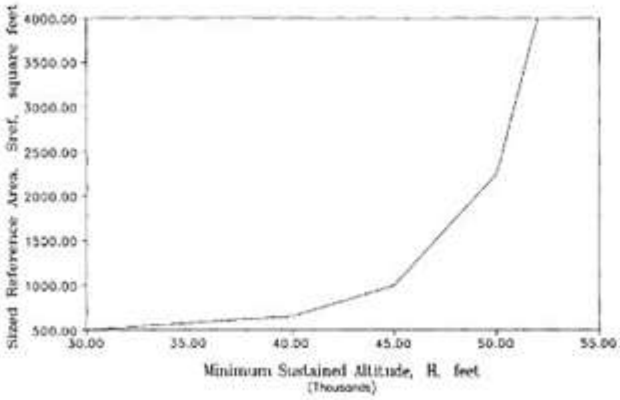
$$L = W = \frac{1}{2}\rho V^2 S C_L$$

5. CASE STUDIES

The methodology just described is applicable with some modifications to both heavier-than-air and lighter-than-air aircraft. The following four case studies of candidate configurations illustrate how the methodology is applied.

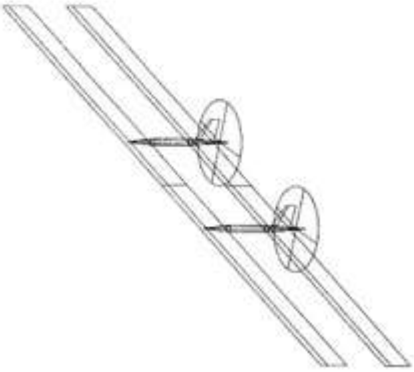
Case 1, Rectangular Flying Wing

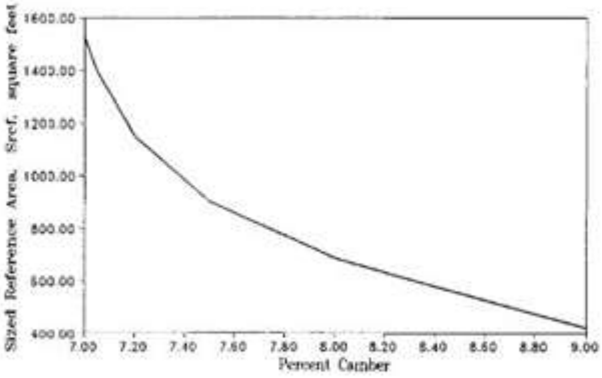




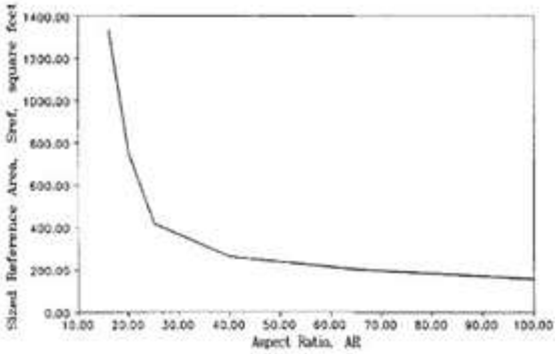
Wing area sensitivity to sustained altitude

Case 2, Tandem Wing



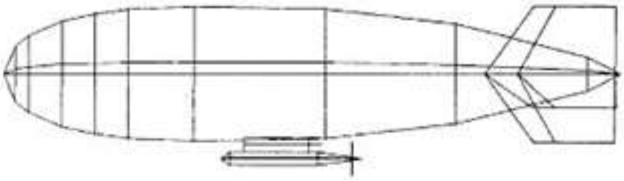


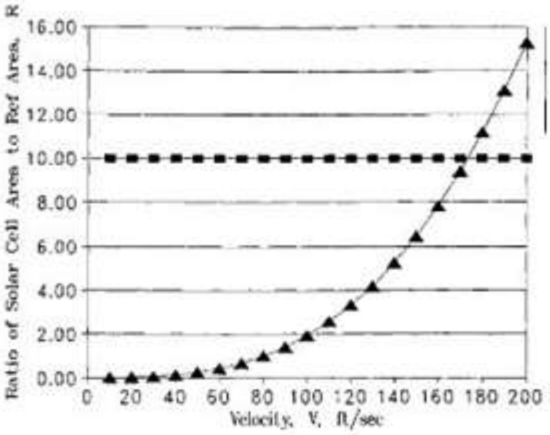
Tandem wing size sensitivity to camber



Size sensitivity to aspect ratio

Case 3, Lighter than Air





Airship concept speed sensitivity

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