16. ELLESAR – AROUND THE WORLD ON SUN AND JET STREAM

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16.1 Introduction

It has been an old challenge to travel around the world. First it was done by ship and now many attempts are made to circumnavigate the globe by flight. It is also true that the concept of 'sustainability' is becoming ever more important in all areas of life. To fly around the world using only sustainable energy sources is a true challenge which would demonstrate the potential of sustainable energy.

To do this using only the solar energy that is available during the day (as Bertrand Piccard is trying to achieve with the Solar Impulse) has been proven to be very difficult, because of the lack of sun during the night passages. The energy needed to sustain flight during these phases has to be stored in the aircraft resulting in a large weight. In turn this increases the required wing area and so on. Therefore an alternative method for achieving the flight around the world has been devised by incorporating the potential energy of the large wind gradients found high in the atmosphere. This potential is turned into useful lift and thrust by using two aircraft at different altitudes experiencing different wind speeds. These airplanes are interconnected by a cable. Especially in the region of the jet streams (bands of high wind speeds in the atmosphere) the amount of energy that can be obtained by means of this 'airsailing' principle can be impressive.

To complete the task of flying around the world on both sun and jet stream energy the design phase focused on a great number of aspects. These include aerodynamic and structural design, stability and control, design of the electrical power system and propulsion units, as well as calculations with respect to the performance of the aircraft. The most important part, however, is the investigation of the airsailing concept. Using a special Excel sheet a strategy has been devised with which two aircraft could stay in the air throughout the night without using any power other than the wind gradient between them.

16.2 Project objective statement and mission need statement

The project objective statement describes the overall objective of the project. For this project, the project objective statement has been defined as:

"Show the potential of the use of sustainable energy for flight by producing, with a group of eight people in ten weeks, a complete product lifecycle plan of a manned aerial vehicle, capable of flight using solely the energy of the sun and jet stream."

The mission need statement is the most basic "statement of use" that can be made about the system to be developed. If the system fulfils the mission need statement, the customer will be satisfied. For this project, the mission need statement has been defined as:

"Fly non-stop around the world in a manned aerial vehicle, consisting of multiple objects, using solely the energy of the sun and jet stream, with better performance than the Solar Impulse of Piccard."

The mission is aimed at setting a 'non-stop around the world' record in order to be able to show the potential of sustainable energy.

16.3 Requirements and constraints

The mission need statement is translated into the following requirements so that the system can be designed to fulfill the mission:

1. Performance and propulsion	**6. Stability**
a. Fly at maximum C_L^3/C_D^2 during night	a. Static longitudinal stability
b. Fly at maximum C_L/C_D during day	b. Static lateral stability
c. Propulsive efficiency > 70% during cruise	c. Dynamic stability
d. Propulsive efficiency > 75% during take-off	**7. Structure**
e. Engine efficiency > 90%	a. Comply with CS* regulations
2. Energy supply	b. Sufficient strength and stiffness
a. Power all subsystems	c. Be maintainable
b. Enough power to satisfy flight strategy	d. Be inspectable
3. Aerodynamics	**8. Materials**
a. $(L/D)_{max} > 15$	a. Sufficient mechanical properties over large temperature range
b. Withstand aeroelasticity according to CS*	b. Sustainable
c. Handle turbulence according to CS*	c. Corrosion resistant
d. Sufficient glide performance to reach one suitable airfield at any time	d. Fatigue resistant
4. Guidance, navigation and control	**9. Manufacturing, marketing and cost**
a. Determine flight parameters	a. Use sustainable production techniques
b. Determine optimal flight path	b. Cost must stay within the budget
c. Be controllable	
5. Operations	
a. Sustain pilots	
b. Provide up-to-date system info	* Certification Specifications

Table 16.1: The system requirements

Additionally, there are various constraints that have been imposed:

1. world record	**4. Operations**
a. Range > 36,787,559 km	a. At least 2 pilots
b. Take-off and land at same location	b. Take-off up to wind force 3
2. Better performance than Piccard	c. Landing up to and including wind force 4
a. Average speed > 55 kts	d. Stable in all weather conditions
b. 10,000 ft < altitude < 39,000 ft	e. Avoid extreme weather 100% of the time
3. Configuration	**5. Safety**
a. At least two flying objects	a. Supply oxygen for 5-10 minutes in case of an emergency
b. Take-off in combination	b. Safe landing at any time during mission
c. Able to land separately	
d. wing span < 60 m	

Table 16.2: The system constraints

16.4 The airsailing technique

The goal of the airsailing principle is to maintain altitude during the night, when there is not enough (solar) energy for propulsion.
The idea behind airsailing can best be explained with an example of a simple kite. Hereby it is of importance to know that wind speed increases with altitude. The difference between two wind speeds at different altitudes is called the wind gradient. Due to this wind gradient the kite will generate a force. A person on the ground, holding the cable which is connected to the kite, needs to exert a counterforce as can be seen in figure 16.1a. In this way the whole system of person and kite will stay at the same location and thus the system will have no velocity. If the person is a kite surfer, however, the whole system does have a velocity. If this velocity is larger than the wind velocity on the ground, then the kite surfer will feel an apparent wind speed working in opposite direction of the system velocity (figure 16.1b). Now the kite surfer can be replaced by a second kite, positioned upside down, to generate the counter force. This system of two kites will move in the direction of the wind velocity and maintain altitude. Finalizing this example the two kites can be replaced by two airplanes and the goal of the airsailing principle has been reached.
To obtain good airsailing performance a high wind gradient is necessary. A high wind gradient can be achieved when one aircraft is in the jet stream and the other is not. Jet streams are relatively narrow bands of fast flowing air that move around the Earth.

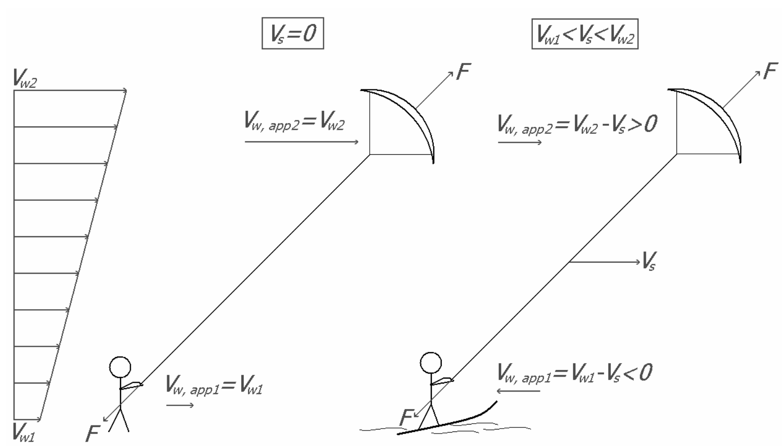

Figure 16.1: Person holding a kite (left) and the kite surfer (right)

16.5 Concept designs

Four conceptual designs were devised and explored during the conceptual design phase. The final concept choice for the detailed design has been made in a trade-off process.

Concept 1: Conventional configuration

The first concept is a conventional sailplane which is powered by electrical engines. This concept stands out from the other concepts due to its conventional shape (see figure 16.2). Advantages of this concept are that its design is based on proven technologies and that its wing has a large aspect ratio which minimizes induced drag. This large aspect ratio also has the disadvantage that it creates stiffness issues which in turn necessitates a strengthened and thus heavy wing.

Figure 16.2: The initial design of the conventional configuration

Concept 2: Twin fuselage airplane

The second conceptual design is a solar plane with two fuselages (see figure 16.3).

Figure 16.3: Twin fuselage configuration

The most striking element of this conceptual design is of course the fact that the plane has two fuselages, connected by the wing and a horizontal tail plane at the ends of the tail booms. The advantage of having two fuselages is bending moment alleviation on the main wing.

Also the large tail section increases the potential solar cell area. An immediate disadvantage of this is that the wetted area is increased which increases the profile drag. The large tail section and second fuselage also cause an increase in weight. Interference drag is also relatively large due to the two locations where the fuselages intersect the wing. Aeroelastic bending problems, caused by interaction between the connected tail booms, are also more common for twin fuselage designs than for conventional aircraft.

Concept 3: The blended wing body (BWB)

Another concept for the solar powered vehicle is a blended wing body (BWB).

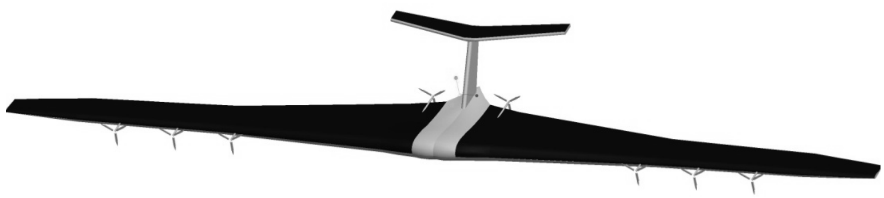

Figure 16.4: Impression of the blended wing body concept

In the BWB configuration the cabin is integrated into the wing (see figure 16.4), creating a smooth aerodynamic shape which minimizes parasite and interference drag. There also is a large area available for the placement of solar cells. The main disadvantage is the relatively unstable nature of the blended wing body due to the horizontal tail being close to the center of gravity. The relatively low aspect ratio of the BWB results in a large induced drag with respect to the conventional and twin fuselage concepts.

Concept 4: The Superblimp

This concept is not an aircraft, but a solar powered blimp. A blimp is a non-rigid airship containing a gas which is lighter than air. Underneath the blimp a solid cabin is attached which gives room to the pilots, the electric engines and propellers (see figure 16.5).

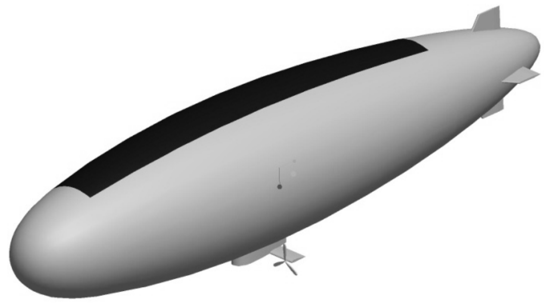

Figure 16.5: The Superblimp concept

Advantages of the Superblimp are its large potential area for solar cells, good turbulence resistance and that it does not use energy to create lift. Its large cross section though makes it susceptible to high head winds and it is not possible for the blimp to make use of the airsailing principle.

Trade-off

The final design has been chosen using qualitative and quantitative trade-off matrices. The Superblimp was not selected for the final design due to its incompatibility with the airsailing principle. The relatively unstable nature of the blended wing body caused it to be an unattractive choice for the final design and the aeroelastic bending issues expected with the twin fuselage design deemed it suboptimal. The final design would thus be based on the conventional configuration in combination with some good features of the other concepts.

For energy storage hydrogen fuel cells have been chosen above batteries. They have as advantage that they are not as heavy as batteries due to the high specific energy. The hydrogen needed for the fuel cells can be stored in filament wound tanks inside the fuselage of the aircraft where there is enough space. Also oxygen and water, needed for the energy storage in the fuel cells, are stored in tanks.

16.6 Final design

In this section the final design will be discussed. The system is called Ellessar, which stands for *"Electrical, Large, Long-Endurance, Sky-Sailing AiRcraft"*. An impression of the system is given in figure 16.6:

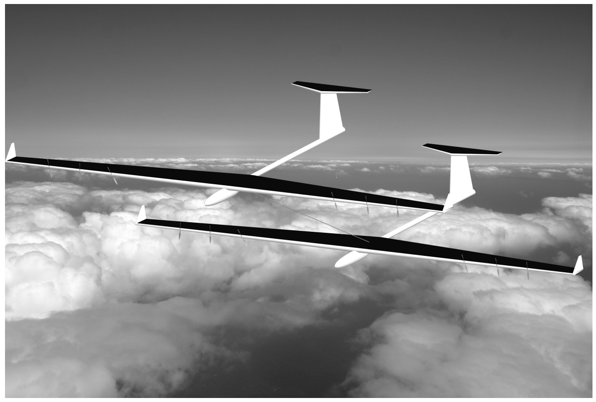

Figure 16.6: Impression of the Ellessar during cruise

Solar power

During the day the sun will provide energy via the solar cells. The system is designed for operation in the period around 9 June, at a maximum latitude of 35° North. This way, there is a good balance between the amount of energy received during the day and the time that fuel cells are needed to cover for the shortage of power short after sunrise and before sunset. The design latitude is also based on the availability of jet streams. The subtropical jet stream is located around 30° North, which is below the maximum latitude.

Airsailing

During the airsailing maneuvers of the two interconnected aircraft (see section 16.4), the cable will have to introduce a propulsive force for both aircraft to replace the engine thrust during the night. To achieve this, the aircraft will have to be positioned in opposite direction. To generate enough lift to stay at a certain altitude it is preferable to fly with a speed component perpendicular to the wind speed. Due to this so-called 'cross wind' flying a smaller wind gradient can be enough to maintain height. Because the aircraft are headed in different directions, at a certain time they will have to turn around and fly back due to the finite cable length and the absence of the propulsive force. This suggests that a 'pendulum' maneuver should be chosen in which both aircraft fly figures-of-eight in opposite directions. In the turns of the figures-of-eight the airsailing propulsion principle does not work (due to the absence of the cross wind component of the velocity) causing the aircraft to descend. To make up for this decrease in altitude the airplanes are able to climb with sufficient climb speed when they are not in the 180° turns of the figures-of-eight. .

Strategy and route

The chosen strategy for the mission is to take-off, climb and cruise (at h = 11 km and with V = 29 m/s) with the two airplanes connected by a cable. During daytime the airplanes will make use of solar energy. During the morning, afternoon and 20% of the night the airplanes will also use fuel cells. The landing is performed separately. The route (see figure 16.7) is chosen in such a way that the airplanes can make use of the wind gradient during the night and land in a safe manner most of the time. The selected route is also based on solar energy requirements.

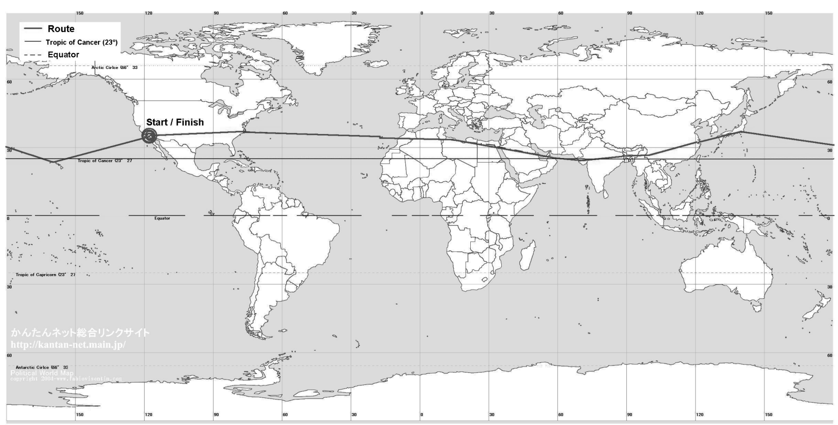

Figure 16.7: Proposed route

Energy supply, systems and propulsion

For the energy supply fuel cells were chosen as they have a high specific energy. This specific energy is about 555 Wh/kg. For the propulsion 6 propellers powered by electric motors were chosen. The diameter was chosen to be 2 meters, and the propeller efficiency turns out to be 84%. The propellers, motors, subsystems and energy supply for all of these were coupled in so-called 'power-packs', from which each provides 1/6th of the total power and propulsion. Using this design the system is modular, which makes it easier to connect and reduces the impact a failure has on the entire system.

Aerodynamic aspects

The initial wing parameters S, A and b are based on the wing span limitation and energy requirements. The selected FX 63-137DU MOD 4 wing airfoil ensures high values of $(C_L / C_D)_{\max}$ and $(C_L^3 / C_D^2)_{\max}$ at high lift coefficient values. The wing is not swept, which leads to a high effective dynamic pressure. Winglets (which contribute to profile drag) are used to reduce the induced drag. The selected taper ratio $\lambda = 0.4$ results in a near elliptic lift distribution for the trapezoidal wing. Due to C_L variations during the mission no wing twist is applied. The aircraft drag estimation method is based on a non-parabolic relation between C_L and C_D. The lift-drag polar during cruise, constructed with this method, is given in figure 16.8. This figure also presents the corresponding parabolic lift-drag polar. The non-parabolic drag estimation method, which is used for the design, results in more accurate C_D estimations than the parabolic drag estimation method.

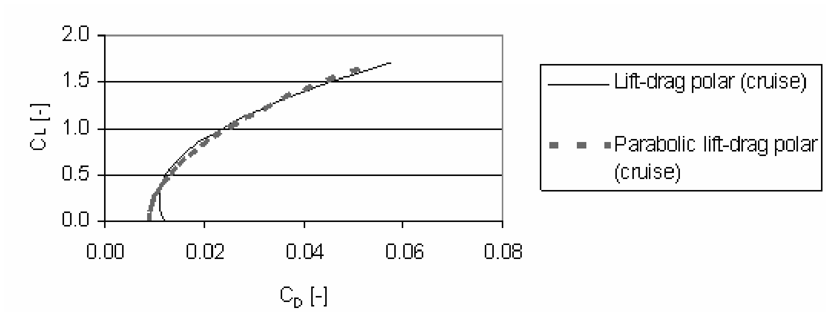

Figure 16.8: Lift-drag polar of the final design during cruise

Stability and control

In order to avoid the necessity of a complicated and heavy flight computer a statically and dynamically stable aircraft is desired. Calculations point out that the conventional configuration and the preliminary sizing of the horizontal and vertical tail planes produce a statically and dynamically stable aircraft, which is sufficiently controllable.

Guidance and navigation

Flying the ideal flight route through the relatively unpredictable jet stream is necessary for the mission to succeed. The guidance of the aircraft will result from a combination of information data uplink from the ground based mission control center and onboard autonomous weather monitoring. The navigation system of the aircraft is based on accurate GPS receivers.

Aircraft material, construction and aeroelasticity

For the wing and tail, the combination of high specific strength and stiffness results in a design that is made from carbon fiber epoxy composite (CFEC). This results in relatively small bending and twisting of the wing. Another advantage of the high stiffness is that the aeroelastic effects are uncoupled from the stability eigenmodes of the system.
The canopy consists of acrylic glass with an airgap. The main skin of the cabin is made of a sandwich of CFEC and isofoam, based on both heat flow and stress (caused by pressurization) calculations. The landing gear configuration was made as light as possible leading to a main nose wheel, two outriggers and ash wood blocks at the wing tips and the tail (to prevent damage).

Performance

From the performance analysis it was found that the airplane does not need any high-lift devices during take-off and landing. The initial climb to a cruise altitude of 11 km will be done at a power setting of 135% of the cruise power. During cruise the airplanes fly at a constant speed (29 m/s). The flight envelope presented an expected maximum load factor of 2.9 due to the airsailing maneuvers. The take-off and landing can be performed with headwind in order to avoid side wind during these mission segments (by taking off and landing always in the direction opposite to the wind, for example in a field).

16.7 Conclusions and recommendations

The analysis that has been performed during the detailed design phase shows that the system will be able to complete the mission, provided that the environment in which the two aircraft will fly does not vary significantly from what has been assumed. The important parameters of each of the two aircraft are summarized in table 16.3.

Component	**Value**
Aircraft length	20 m
Wing span	58 m
Average speed	29 m/s
Wing area	153 m^2
Solar cell area	150 m^2
Mass	1900 kg
Design latitude	35 degrees North
Design take-off date	9^{th} June
Total cost (for entire system)	U$ 23,600,000

Table 16.3: Final design parameters

In order to increase the probability of a successful mission, additional design, research and certification are required. For example more detailed sizing of the power subsystems (wiring, exact fuel cell stack geometry, etc.) should be done, as well as a study into the effects and gains of adding additional solar cells on the cabin and tail boom. To verify the feasibility of airsailing, more research into the properties and prediction of jet streams is required, as well as more detailed simulations of the airsailing motion.