Conceptual Design of a Stratospheric Hybrid Platform for Earth Observation and Telecommunications

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ABSTRACT

The interest in long endurance unmanned stratospheric platforms for Earth observation and telecommunications (also known as HAPS: high altitude pseudo satellites) has increased in the last years, because they represent a complementary solution to satellites and RPAS.
In this paper, we have focused our interest on a stratospheric platform for Earth observation and telecommunications having a maximum takeoff mass less than 1000 kg and a design airspeed equal to 16 m/sec.
We will compare the results obtained by our conceptual design loops concerning the following platforms: a flying wing, an airship and two hybrid platforms having a different configuration. The conclusion of our analysis is that hybrid platform represents the best configuration, in terms of power consumption, size, weight and safety.

KEYWORDS: *Stratospheric Platform, HAPS, HAA, Hybrid Airship, Long Endurance Flight*

NOMENCLATURE

AR - Aspect Ratio
AoA - Angle of Attack
BR - Buoyancy Ratio
FR - Fineness Ratio
GaAs – Gallium Arsenide
HAA – High Altitude Airship
HAPS - High-Altitude Pseudo Satellite
HTA - Heavier-than-Air
LTA - Lighter-than-Air
RPAS - Remotely piloted air systems
UAV - Unmanned Air Vehicle

1 INTRODUCTION

1.1 Stratospheric Platforms

The lower part of the stratosphere (around 20 km of altitude) is an interesting environment for Earth observation and telecommunications because weather is quite calm and the temperature is approximately constant, consequently, convective phenomena have low magnitude and the intensity of winds is lower than at different altitudes.
This region of the space is generally named Near Space Environment.
The interest in long endurance unmanned stratospheric platforms (also known as HAPS: high altitude pseudo satellites) has increased in the last years. Some applications are proposed in [2], [3], [4], [5], [6] and [7].
These applications concern essentially Earth observation and telecommunications. At this altitude, the platform will be able to view a 1000 km diameter footprint of the ground [1]. HAPS represent a complementary solution to satellites and RPAS. In comparison to satellites, they allow observation of a less extended area (local scale) but with greater resolution and greater revisit time than satellites. Moreover, they are able to maintain station (station-keeping) on a predefined area (at a significantly

lower altitude than geostationary satellites). Maintenance and updating of their equipment and payload is also possible because platforms can land and take-off again.
A fleet of RPAS could also guarantee local scale coverage, but in this case, the complexity of the system, in terms of management and maintenance, is greater in comparison to single HAPS.
Stratospheric platforms do not interact with commercial aircrafts during the operative phase of their missions. Obviously, during climb and descent phases, operators could agree some preventive measures with aviation authorities.
Different HAPS configurations have been developed in the last years. For example, Airbus Zephyr family and Facebook Aquila project fall within the flying wing configuration, HiSentinel80 is an airship, while Google Loon project is based on balloons. In the flying wing configuration, the weight is completely balanced by aerodynamic forces generated thanks to the relative speed of the air respect to the wing. In airships and balloons, the weight is balanced by the buoyancy due to the difference of density between the air and gas mixture inside the hull. A more exhaustive description of the different projects is available in [8].
Hybrid airships represent another interesting configuration, exploiting at the same time aerodynamic and aerostatic forces to balance the weight.
Considering that air density at 20 km is the 7% of the sea level air density, platforms may benefit of a reduced drag than at sea level (for equal volume/surface and speed), with enormous advantages in terms of power consumption; but, on the opposite, to generate sufficient aerodynamic or aerostatic forces, the required volume or speed can get larger (increasing again the drag) than at lower altitudes.
A large platform can be difficult to manage during climb and descent phases due to the higher loads, which are a consequence of the higher density and wind at intermediate altitudes.
Moreover, stratospheric platforms are typically designed with low power-to-weight ratios. This condition could lead to low controllability at lower altitudes, where higher intensity winds could move the platform from the predefined trajectory and the thrust generated by the power system could not be sufficient to control the platform.
The design of a stratospheric platform consists in a trade-off between the need of surfaces or volumes able to generate the required aerodynamic/aerostatic forces to balance the weight; but which, at the same time, are not too much large in order to do feasible operations on ground and during the flight phases in troposphere (climb and descent). At the same time, the shape of the platform shall minimize the drag at the different altitudes.
The purpose of this paper is the definition of different conceptual design processes for different configurations (flying wing, airship and two configurations for the hybrid platforms) in order to have a preliminary assessment of the main parameters: power consumption, size and mass, mass budget. We will compare the proposed configurations in order to show that the best one in terms of power consumption, volume and final mass, is the hybrid platform.

1.2 State of the art

Concerning hybrid platforms, several works analyzed the optimal buoyancy ratio. The buoyancy ratio is the buoyancy-to-weight ratio. In [9] the optimal buoyancy ratio for a hybrid platform is analyzed. The flight altitude is 20 km while the payload mass is set equal to 10000 kg. Moreover, the platform is powered by fuel. The optimal buoyancy ratio has been computed under the hypothesis of invariant zero-lift drag coefficient, independently from the size of the platform, because of the similarity in the shape. This hypothesis should be better investigated, because the zero-lift drag coefficient depends on the Reynolds number, which depends on the characteristic dimension of the platform and not only on the shape.
In [10] the authors propose a configuration for a solar powered hybrid high-altitude platform. A wing, to generate the lift, and two bodies, to generate the buoyancy, compose the platform (in addition to the tail, used to guarantee stability and control). The weight is balanced for the 55% by the buoyancy. The platform has been designed for a flight altitude of 20 km and a speed of 31.5 m/sec. The wing has a length of 66.3 m and a surface of 293.4 m^2. The two bodies have a length of 42.4 m and a maximum diameter of 4.71 m.
Other works take into account the conceptual design of hybrid airships for regional transport. In [11] the authors propose a multi-lobed shape, while in [12] the proposed configuration is a winged hybrid airship.

In [13] the conceptual design of a solar powered stratospheric airship is presented. The authors estimate the size and the mass budget for a stratospheric airship flying at an altitude of 20 km at two locations: Taipei and Bejings. The latitude at whom the mission is performed, together with the day of the year, influences the size/mass of the power generation system. Effectively, the wind speed and the solar irradiance magnitude depend on "where" and "when" the mission is performed, consequently the size/mass of the solar panel array and the required power depend on them.
The authors also investigate the technology trends in the fields of interest (for example solar-cell mass, battery efficiency, etc…) in order to determine which could be the improvements in the design of the airship.
In [14] the available methodologies for conceptual design of a solar powered stratospheric airship are analyzed. The authors propose a new methodology based on the coupling of the different available methodology.
In [15] the conceptual design of a HAPS, having a fixed wing configuration, is developed by analyzing energy balance and developing mass estimation model.
In [16] the authors compare performances and costs of several HAPS configurations for two missions: hurricane science and communications relay. HTA and LTA, powered by a consumable fuel or solar regenerative (SR) propulsion system are analyzed. A hybrid configuration (with 10% of lift generated by aerodynamic), powered by solar regenerative fuel cell, is examined.
The authors conclude their work asserting that the best configuration is an LTA powered primarily by consumable fuel associated with solar energy, because LTA have greater endurance but solar energy, as only power source, could not provide sufficient energy even in the most favorable day-night cycle of the required mission period.
This work is ten years old, nowadays technology innovations in the field of solar cells and battery have enabled longer endurance flights powered only by solar energy (in 2010 Zephyr HALE UAV obtained the duration record in stratosphere [17]).

2 METHODOLOGY

As stated, the aim of this work is to carry on a conceptual design of stratospheric long endurance platforms having different configurations in order to show that the best solution in terms of minimum mass, required power and volume and safety is represented by the hybrid platform.
Specifically, we have investigated the following configurations:

- Solar Powered Airship ("Fig. 1")
- Solar Powered Flying Wing ("Fig. 2")
- Solar Powered Hybrid platform with AR=10 ("Fig. 3")
- Solar Powered Three-lobed hybrid airship (FR=3) ("Fig. 4")

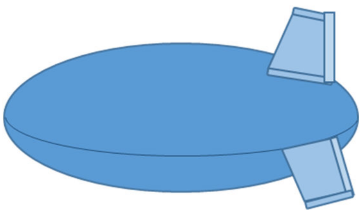

Figure 1: Airship

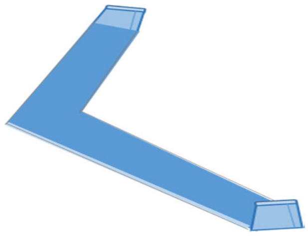

Figure 2: Flying Wing

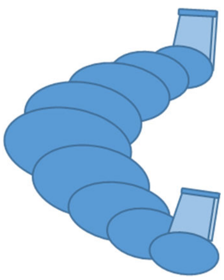

Figure 3: Hybrid Platform with AR=10

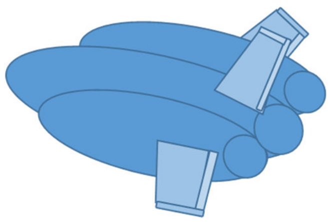

Figure 4 Three-lobed hybrid airship

A hybrid platform balances its weight by lift (aerodynamically generated) and buoyancy. In this paper, we have considered the helium as lifting gas for hybrid platforms and the airship. Concerning hybrid platforms, we have analyzed two configurations. The first one, identified by the aspect ratio equal to ten, has a shape more similar to a flying wing, while the second one has an airship-like shape; in fact, we have used the fineness ratio to describe proportions between in-plane dimensions.
For each one of this configuration we have defined a design process.

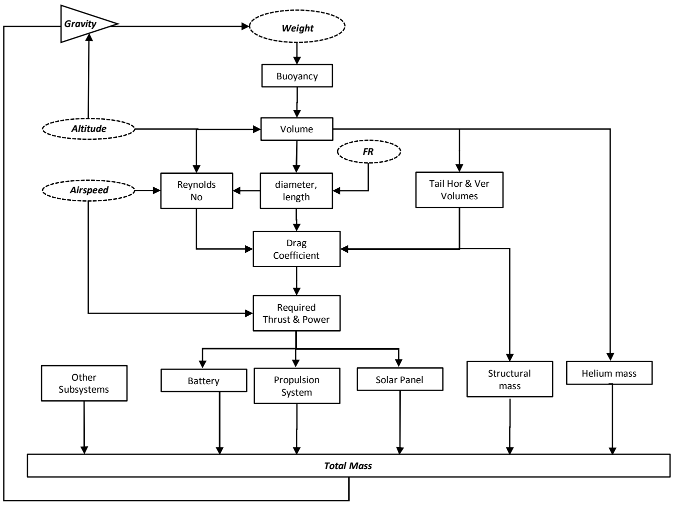

Figure 5: Conceptual design process for a solar powered airship

In "Fig. 5", we reported the process followed for the conceptual design of the airship. The input parameters are the initial guess weight, the flight altitude, the airspeed and the fineness ratio.

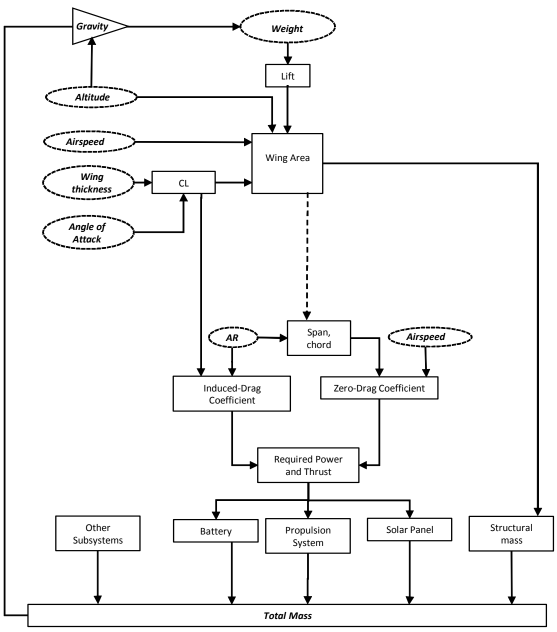

Figure 6: Conceptual design process for a solar powered flying wing

In the case of the flying wing conceptual design, the process is reported in "Fig. 6". In this case, the input parameters are the initial guess weight, the cruise altitude, the airspeed, the aspect ratio and chord thickness. In a more detailed design, the chord thickness can be set depending on both: the required storage area for batteries, avionic, other equipment and the required structural stiffness.

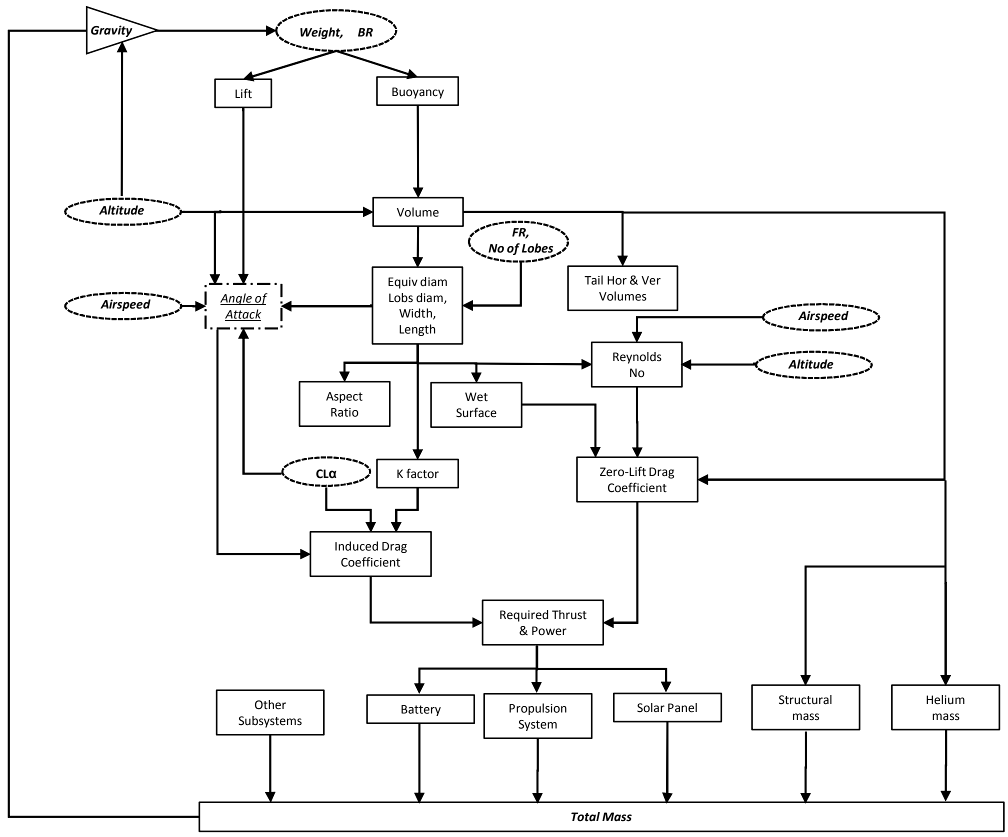

Figure 7: Conceptual design process of a solar powered hybrid three-lobed airship

In the case of a hybrid three-lobed airship, the conceptual design process, reported in "Fig. 7", is more complex because of the presence of the aerodynamic and aerostatic modules, which have different requirements. In this case, the input parameters are always the initial guess weight, the altitude and the airspeed, the fineness ratio as for the airship and some specific parameters as the buoyancy ratio, the number of lobes (three lobes for this study) and the lift coefficient curve slope. The required buoyancy, calculated as product between the weight and the buoyancy ratio, determines the volume and consequently the other geometric parameters. We have not directly used the required lift to size the platform, but it is considered a constraint. The geometry (particularly, the available reference area useful to generate lift), associated with the lift curve slope and the desired airspeed, determines the angle of attack to generate the required lift. The angle of attack shall be less than a predefined threshold in order to make flight feasible. This choice influences the conceptual design optimization in terms of the optimal buoyancy ratio, because we discard buoyancy ratios corresponding to an angle of attack greater than this threshold. The hybrid airship has a wide in-plane area but, compared to a wing which typically has a span several times greater than its chord, its ability to generate aerodynamic lift is limited because its greater dimension is in the direction of the airstream (the length is greater than the width). Using typical wing's parameters, an airship is characterized by a low aspect ratio (less than unity). If the required lift was used to design the surface, the hybrid airship should have a greater volume, more than is required to generate the required buoyancy, thus a certain volume should be occupied by ballonets with the negative consequence of a greater final weight.
Unlike the simple airship configuration, in the case of a hybrid airship the induced drag shall be also taken into account.

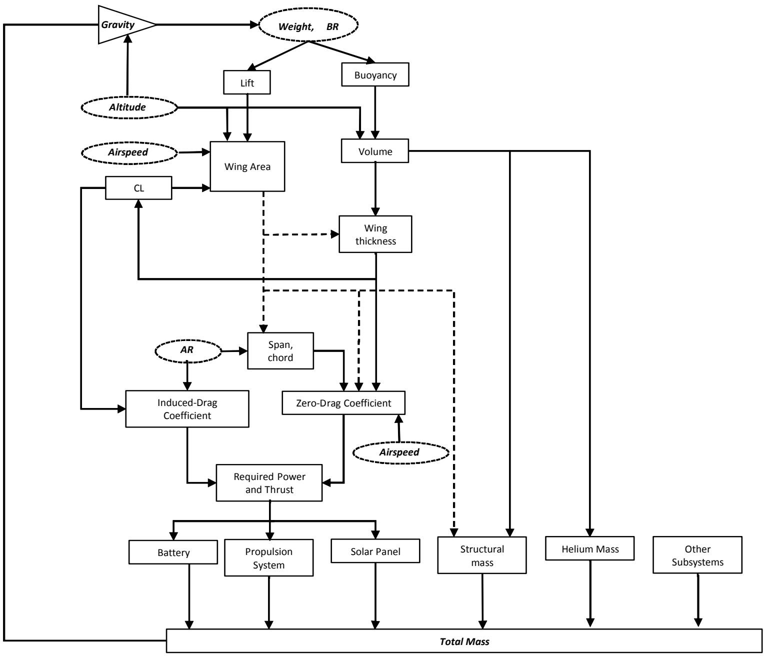

Figure 8: Conceptual design process of a solar powered hybrid platform with AR=10

In "Fig. 8", we reported the workflow for a hybrid platform having higher aspect ratio. This configuration is more similar, for example, to a hybrid flying wing which balances the gross weight (due to its structure, equipment and payload) using aerostatic (buoyancy) and aerodynamic lift. In this case, the required lift is a key parameter in the sizing process because it determines the in-plane area while the buoyancy determines the volume and consequently the profile thickness. We have included a first iterative loop to determine the platform in-plane area and volume, because the profile thickness influences the lift curve slope and thus the wing in-plane area.

3 RESULTS AND DISCUSSION

In order to select the best configuration, we have investigated the following case study: stratospheric platform flying in the skies over southern Italy, carrying a payload of 100 kg. The mission of this platform consists in maintaining station over a predefined area.
The geographical position of the platform determines statistics for wind intensity and the solar radiation, which are important factor in the platform's sizing process. Main parameters used in our calculations are summarized in "Table 1".

Table 1: Mission Parameters

Payload	100 Kg
Location	Southern Italy
Altitude	20000 m
Energy System	Rechargeable Batteries with Solar Energy
Power	Electric Engines
Airspeed	16 m/sec
Night Duration	15 h
Mass category	less than 1000 Kg

The desired airspeed has been set on the basis of wind statistics around the year at the selected altitude in Southern Italy. The mass category has been set equal to less than 1000 kg, which is considered achievable based on current prototypes and commercial platforms.

In the case of the three-lobed hybrid airship and pure airship, we have determined the aerodynamic coefficients, as well as, mass predictions for various subsystems, by semi-empirical formulation as suggested in [18], while, for the flying wing configuration and for the hybrid platform with higher aspect ratio, using semi-empirical formulation described in [19], [20] and [21]. We have updated the mass prediction models reported in [21], to take into account progress in aerospace structures and materials, battery capacity and solar panel density.
For this analysis, we have taken into account the properties and characteristics GaAs-based solar cells, while concerning the energy storage system, we have considered the properties of lithium-sulfur batteries as reference value, because they have a higher energy density. Batteries based on this technology have also powered the Airbus Zephyr high altitude pseudo-satellite.

We have firstly investigated the airship configuration. We have reported the results in "Table 2".

Table 2: Final results for the airship configuration

Mass [kg]	Volume [m^3]	Power [kW]
615	6910	3.6

In the case of the flying wing, the constraint on the final mass, limits the minimum airspeed. In fact, the desired airspeed (equal to 16 m/sec) is unfeasible with a platform having a mass less than 1000 kg. Thus, we have not further investigated the flying wing configuration.

In the "Fig. 9" and "Fig. 10" we have reported the mass, the required power and the volume for a hybrid three-lobed airship carrying 100 kg of payload. It is interesting to note that increasing the buoyancy ratio, the total mass and required power decrease as a monotonic function because lift induced drag decreases, but the volume has a minimum at BR equal to 0.8. The optimal buoyancy ratio is a compromise between the need to reduce the mass and the required power, avoiding an excessive increase of the volume.

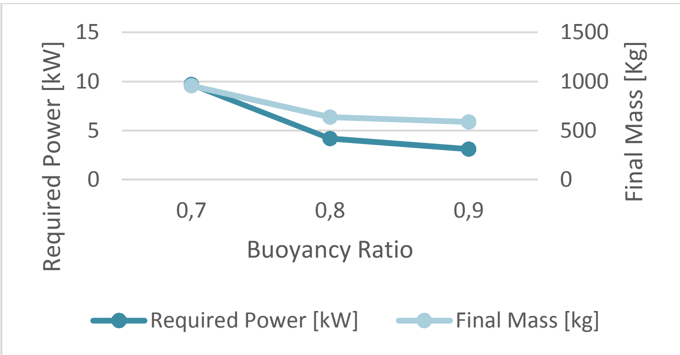

Figure 9: Final Mass and Required Power for the three-lobed hybrid airship

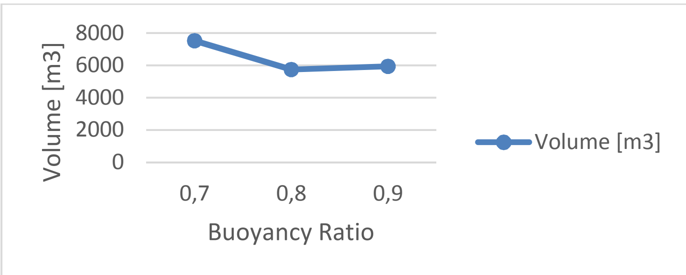

Figure 10: Volume for the three-lobed hybrid airship

The final mass, the required power and the volume of the hybrid three-lobed airship tend to the values of the pure airship when the BR approximates to the unity.

Table 3: Final results for the three-lobed hybrid airship

BR	Mass [kg]	Volume [m^3]	Power [kW]
0.8	640	5750	4.3

In the case of the stratospheric hybrid platform having AR=10, the optimal BR ("Fig. 11" and "Fig. 12"), in terms of required power and final mass, is equal to 0.2. The volume also remain limited for this buoyancy ratio.

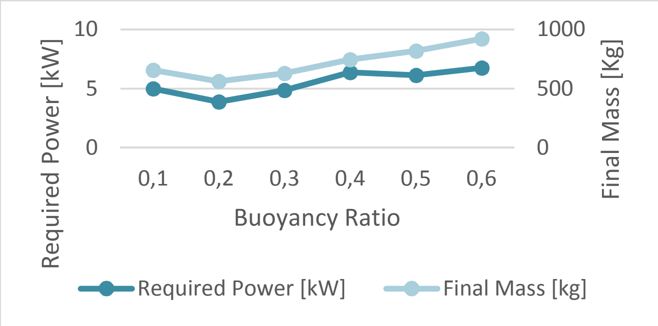

Figure 11: Final Mass and Required Power for the AR=10 stratospheric hybrid platform

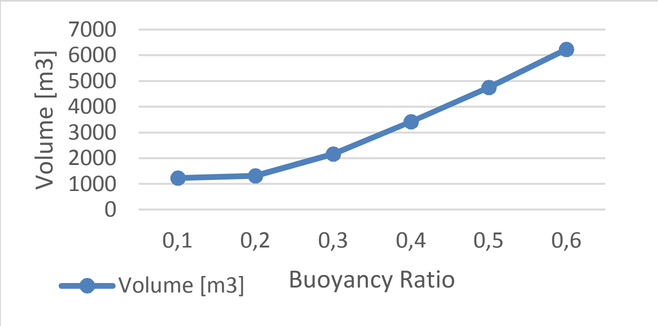

Figure 12: Volume for the AR=10 stratospheric hybrid platform

Comparing the optimal buoyancy ratios of the two hybrid platform configurations (three-lobed airship and AR=10 platform), two different behaviors emerge. Indeed, the optimal BR is strictly related to the chosen shape. This is an important result, because in previous works, the shape of the platform has never been considered a determining factor in the optimization process of the buoyancy ratio. The three-lobed hybrid airship has a limited capability to generate lift in spite of its wide in-plane area. This is due to its geometry, because the length, (which is in the direction of the airspeed), is longer than the width (which is in the direction orthogonal to the airspeed). Using the airplane wings terminology, it is like the three-lobed hybrid airship had a chord longer than its wingspan. A request of more lift means longer width and consequently longer length, greater mass and required power. Therefore, in the case of three-lobed airships the optimal BR has a high value (which means low percentage of lift) in order to limit the final mass, volume and required power.
In the case of the AR=10 platform, we have, on the contrary, the optimal BR is considerably lower than in the previous case. This is due to the higher capability to generate lift of a platform with a sufficiently high aspect ratio.

Table 4: Final results for the AR=10 stratospheric hybrid platform

BR	Mass [kg]	Volume [m^3]	Power [kW]
0.2	580	1700	4.3

Concerning safety aspects, the flying-wing platform, in case of a catastrophic failure could fall without control. In case of airship catastrophic failure, the fall could get slower than in the previous case (consequently, the kinetic energy would be lower too) because of the remaining buoyancy and the greater aerodynamic drag. In fact, the helium contained in the envelope, is not instantaneously expelled. Moreover, this configuration has a bigger external area, which would be subject to a greater aerodynamic drag during a hypothetical fall.
Thus, hybrid platforms have the advantages of the airship because they have greater external area and buoyancy; moreover, they could be aerodynamically controlled in case of helium losses (because the shape could be not instantaneously lost).

We have not included the design of ballonets for the platforms including buoyancy. This choice is motivated by the expected operation mode, because the platform will be operated at a quasi-constant altitude and internal pressure changes will be absorbed by structural elements.

4 CONCLUSIONS

In this paper we have presented four processes for the conceptual design of a stratospheric platform based on four different configurations. Specifically, we have analyzed the following configurations: flying-wing, airship, two hybrid configurations (the term "hybrid" is here used to indicate that the weight is balanced by aerodynamic and aerostatic forces). We have used the proposed processes in order to estimate mass, volume and required power for each one of the configurations under some specified hypotheses. The flying wing configuration is not suitable to be used with an airspeed equal to 16 m/sec at an altitude of 20 km, because it has a mass excessively beyond the desired mass limit (1000 kg). The airship configuration offers the minimum required power, because power is required only for in-plane movements of the platform while the buoyancy balances the weight. The drawback of the airship configuration lies in the big volume, which makes difficult ground operation. The two examined hybrid configurations have two different optimal BR. The first one, having a three-lobed configuration, has an optimal BR equal to 0.8; while the second one, having the AR=10, has an optimal BR = 0.2. At the optimal BR, these two configurations have similar required power (about 4.3 kW) and comparable mass (about 600 kg). The main difference in the two configurations lies in the volume. In fact, the volume of the hybrid platform with AR=10 is one third of the volume requested by the other hybrid configuration and by the airship.
This is a great advantage, which, even though the little handicap in terms of required power, makes this configuration more suitable to the stratospheric flight within our hypotheses.
Moreover, a hybrid platform has a greater safety because of less kinetic energy during a hypothetical fall and a residual possibility to control using aerodynamic or aerostatic forces.
Future works will concern a more detailed assessment of the geometry, mass and power budget for the analyzed configurations and the definition of operational aspects.

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