DOI: 10.13009/EUCASS2023-024
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

On the Optimal Preliminary Design of High-Altitude Airships: Automated Procedure and the Effect of Constraints

Carlo E.D. Riboldi[1†], *Alberto Rolando*[2], *Stefano Cacciola*[1], *Gregory Regazzoni*[1], *Ilaria Spadafora*[1]
[1]*Department of Aerospace Science and Technology, Politecnico di Milano*
20156 MILANO, Italy
[2]*PACE Aerospace & IT GmbH*
14059 BERLIN, Germany
carlo.riboldi@polimi.it · alberto.rolando@pace.de · stefano.cacciola@polimi.it
[†]Corresponding author

Abstract

This research introduces a methodology for the automated sizing of airships. Considering an electrically-propelled platform, responding to the requirements of high-altitude pseudo-satellite mission, it is shown how an optimal sizing solution can be obtained, through an approach targeting total mass. After validating the design algorithm on an existing machine, the method is employed to explore the features of designs corresponding to different settings of the optimal problem. In particular, the geographical position and the stationing altitude are considered as parameters. Finally, optimally-designed machines are tested in off-design conditions, highlighting pros and cons in the proposed design approach.

1. Introduction

Despite the growing availability of flying platforms for observation and signal-relay missions, the most widespread technological solutions for this task still suffer from relevant shortcomings. Considering space-based platform (i.e. satellites), these are invariably associated to extreme manufacturing and deployment cost. Furthermore, these are poorly flexible machines, hard to reposition and difficult to overhaul, hence not ideal for the quick deployment time and constant coverage requirements typically associated to missions over areas hit by disasters, or for tactical military use. Middle- or high-altitude fixed-wing UAVs are comparatively more flexible, allowing easy servicing, payload replacement, etc., yet they feature a limited (despite of course significant) endurance in flight, and need a serviceable runway for take-off and landing.

The high endurance of airships makes them attractive solutions when it comes to deploying a payload for observation missions, destined to station-keeping at a constant high-atmospheric altitude, with chance to recover the payload at the end of the mission.[14,19]

Actually, over the past two decades high-altitude airships (HAAs) have been proposed for high-altitude pseudo-satellite (HAPS) missions, exploring the space of design solutions both at a conceptual level[3,4,8] and involving the manufacturing of prototypes.[13,20]

Among the shortcomings of HAAs are those inherent to airships at large, namely controllability issues induced by the high ratio of size to inertia, and the related proneness to disturbance, making accurate trajectory-following harder than for other flying machines. However, given an assigned airship design, the study of attitude control and path-tracking or station-keeping problems has been carried out with promising purpose-envisaged solutions (like purpose-conceived layouts of the thrusters on board, granting good attitude control abilities) in the existing literature[2,11,15–17] and in practical experiments,[7,10] therefore further fostering the adoption of HAAs for HAPS missions.

Encouraged by the documented experience in this sense, a focused exploration of an optimal way to size-up an airship for an assigned HAPS mission has been carried out in this work.

In particular, starting from the analysis of well-documented preliminary design techniques,[1] an optimal approach is introduced, where the choice of a minimal set of sizing parameters is subjected to the satisfaction of an optimal criterion targeting take-off mass. Making use of solar cells and batteries, which are accurately sized like most other sub-systems on board, the mission profile is set so as to grant the satisfaction of an energy balance over a virtually unlimited time frame. An advantage of this procedure is the automated production of a complete set of design variables, which should be otherwise negotiated one by one. Furthermore, the optimization algorithm allows to assure compliance with respect to some technological constraints.

DOI: 10.13009/EUCASS2023-024

After showing the reliability of the sizing tool and demonstrating its ability to correctly retrace solutions manufactured in reality, an exploration of the effect of constraints on the quality of the design solution is presented. In particular, it is shown how the choice of the geographical position and stationing altitude considered for the design may ease or hamper its adaptability to missions, either considered for as a target for the design or as off-design test cases.

A critical discussion of the potential of the tool and margin of improvement are discussed in a last section.

2. Preliminary sizing of a high-altitude airship

As outlined in section 1, a high-altitude airship is considered as the main target application of the sizing procedure proposed in this paper [1]. The sizing loop and optimal sizing logic will be introduced in the following paragraphs.

The considered target airship is based on a single axial-symmetric envelope, and is propelled by electric motors fed by a mix of batteries and solar cells. The latter are laid on the external surface of the airship. The airship can be sized for a virtually permanent station-keeping mission at a desired stratospheric altitude, and its sizing may take into account also the ascent to the target altitude. The airship is unmanned, and the payload is represented by a mass and power requirement.

2.1 Optimal approach to sizing problem

As stated in the introduction, an optimal algorithm targeting overall mass has been envisaged for the preliminary sizing of a high-altitude airship. The logical scheme for this approach is reported in Fig. 1, and is based on the automatic selection of the geometrical parameters required for mathematically assigning the size of the airship envelope, as well as those pertaining to the solar panels put on the external surface.[18]

In particular, having chosen *a priori* the shape of the airship envelope as a low-drag bi-ellipsoidal solid, the sizing can be fully assigned through its length L and fineness ratio FR. Concurrently, highly flexible solar cells are considered, capable of adjusting to the local shape of the envelope. A symmetric placement to the left and right of the longitudinal plane of symmetry of the airship is hypothesized. The size of the cells and their placement are therefore assigned through limit azimuth values on a cross section, namely ϑ_{in} and ϑ_{out}, and through longitudinal positions of the extremities of the panels, measured along the longitudinal axis of the airship, namely through x_{le} and x_{te}. This takes the overall set of parameters managed by the optimizer to $\boldsymbol{p} = \{L, FR, \vartheta_{in}, \vartheta_{out}, x_{le}, x_{te}\}$.

Other environmental and technological parameters for the sizing need to be assigned, yet they are considered constant in the optimization process. These parameters can be collected in a few major containers as follows:

- *Mission parameters.* Stationing altitude and geographical position (coordinates), date of the year.
- *Payload parameters.* Payload mass and related power supply.
- *Envelope parameters.* Maximum wind speed for envelope sizing, envelope material, lifting gas.
- *Power system parameters.* Battery chemistry, solar cells material.

Starting from the assignment of these constant quantities and a choice of the optimization parameters $\boldsymbol{p}$, it is possible to invoke a set of models and regressions, producing the sizing of all major subsystems on board. This set of instructions – namely the *sizing loop* – constitutes a procedure which is called repeatedly by the optimizer, changing the input parameters $\boldsymbol{p}$ in seek for a mass-optimal design solution, compliant with a set of constraints described later.

2.2 Sizing loop

The operations required for completing the sizing of the airship starting from parameters in $\boldsymbol{p}$ and the assigned technological properties mentioned in the previous listing are wrapped in the sizing loop, which can be synthetically described as follows.

1. *Geometrical sizing of envelope and solar cells.* Through the assignment of the parameters in $\boldsymbol{p}$, it is immediately possible to build the complete geometry of the airship envelope, thus computing in particular its volume, area of the external surface and area of the cross and longitudinal sections. Correspondingly, the exact size of the solar cells and their orientation in space (dictated by the local orientation of the envelope surface) can be computed.

---

[1] High-altitude airships are the target application in this paper, and these will be employed as conceptual test-cases for easing the outlining of the design procedure, and for most of the practical results. However, the methodology introduced herein and coded in the tool `Morning Star` of the Department of Aerospace Science and Technology, Politecnico di Milano, is capable of performing the preliminary sizing for airships destined to whatever target altitude.

DOI: 10.13009/EUCASS2023-024

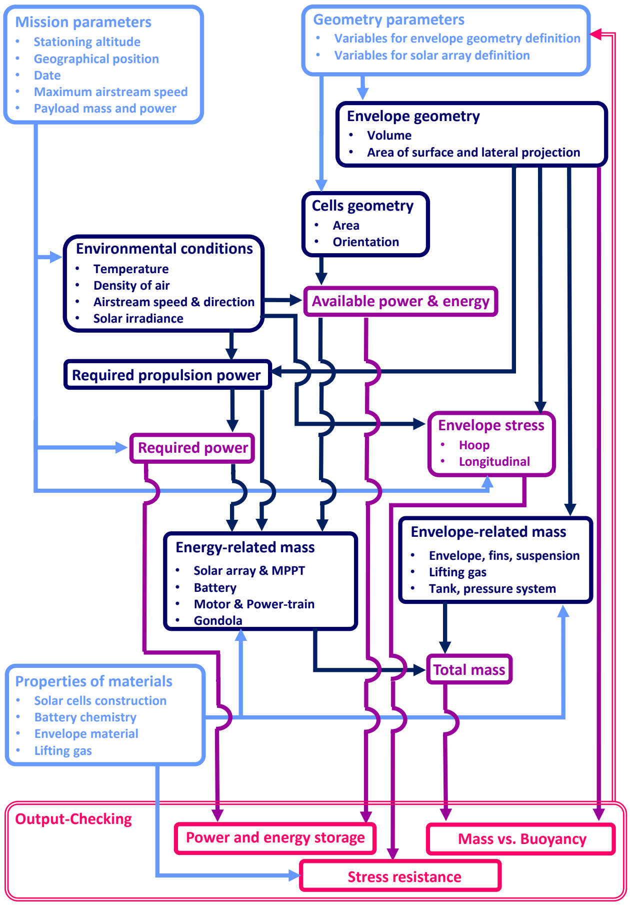

Figure 1: Outline of optimal sizing scheme. Cyan: input parameters. Blue: operations carried out via models and regressions. Purple: computed quantities relevant to optimization. Pink: optimization-related operations.

DOI: 10.13009/EUCASS2023-024

An estimation of the zero-lift drag coefficient can be carried out based on regressions for the envelope. Similarly, refinements of this preliminary estimation can be carried out based on the size of the fins and gondola (if any), themselves in turn obtained from regressions of statistical data given the size of the envelope (or payload and energy system for the case of the gondola).

2. *Environmental conditions at stationing altitude and during climb.* Through the assignment of the position on earth and time of the year for the ascent, it is possible to compute from dedicated models the temperature, pressure and density of air, the wind intensity and direction at altitude and the actual irradiance, in terms of intensity and direction. In particular, the international standard atmosphere (ISA) model has been employed for static air characteristics, whereas the horizontal wind model (HWM) has been employed for obtaining the wind characteristics.[5,6] The SMARTS model has been adopted for the computation of direct and diffused irradiance.[9]
3. *Computation of total power and energy required.* Having assigned the target stationing altitude and having computed the wind characteristics along the climb and at altitude, it is possible to define the peak power and energy required for a mission profile composed of an ascent and stationing at altitude for a certain time. In particular, it is assumed that the airship is flying in climb at a negligible angle of attack and with a given climb angle, and always oriented with the wind, so that non sideslip occurs. This allows to estimate the drag coefficient through the reference value for null angle of attack and sideslip. Similarly, at the prescribed stationing altitude the airship orientation on the horizontal plane is defined by the local direction of the wind, so as to obtain a null angle of sideslip. The computation of power for propulsion is therefore possible in climb assigning the climb speed (and climb angle as said), and at stationing altitude having computed the wind speed. Power for propulsion is complemented by the power required for the payload, and by power required for other plants on board, including losses (estimated via regressions). Once the power along the mission profile is known, peak power and the energy required for the mission are easily obtained.
4. *Computation of available power and energy.* Available power and energy are estimated starting from the geometry of solar cells and from the mission profile. The latter provides a flight trajectory and the orientation of the airship along it (through the assumptions introduced at the previous point). This knowledge can be employed to define the power capture based on the irradiance data coming from the corresponding model. By comparing the power available and the power required (previous point), a power balance can be carried out, yielding the size of the batteries required for covering the mission. In particular, batteries are required to adsorb excess power, and to release energy to cover power needs when power capture from the solar cells is insufficient.
5. *Mass of power system.* The power required for flight allows to assign the power of the motors and propellers. These are turned into corresponding masses, and complemented by those of the power-trains and sub-plants (cables, power electronics, etc.). Finally, the mass of the power system includes that of the batteries and solar cells, obtained starting from their respective sizing (see previous points).
6. *Stress analysis on envelope.* With a knowledge of the dynamic pressure along the mission and of the maximum wind speed to sustain (specified among the constant technological parameters), as well as of the external pressure, it is possible to compute the pressure differential, hoop stress and longitudinal stress on the envelope.
7. *Mass of envelope.* With a knowledge of the sizing of the envelope, its mass can be readily computed. It is noteworthy that thickness of the envelope is assigned *a priori*, since it is not considered as a continuous variable, being based on the number of layers of the same material which are superimposed, hence not practical to change in an optimization algorithm. In other words, the number of layers and their corresponding thickness are assigned among the constant parameters, and the sizing of the envelope is carried out accordingly. The mass of the lifting gas an of the pressure system required to fill and pressurize the envelope are computed at this step as well, together with the masses of structural parts like the fins and inner diaphragms, which are functions of the size of the envelope.

2.3 Steering the solution towards optimality

The procedure just outlined produces a complete candidate sizing, corresponding in particular to a total mass, which has been chosen as the cost function of the minimization problem solved by the optimizer.

However, as evidenced in Fig. 1, the outcome of the sizing loop just outlined also needs to guarantee the satisfaction of three constraints

1. *Buoyancy.* The buoyancy ratio of the airship should be over an assigned minimum. The latter is typically chosen very close to 1 for HAAs for safety reasons, unless the wind is expected to provide a steady and sufficiently predictable contribution to lift.

DOI: 10.13009/EUCASS2023-024

2. *Envelope stress*. The stress values on the envelope computed in the previous procedure are compared to the nominal stress values which the material (and number of layers) adopted for the envelope can sustain, obtained by datasheet.

3. *Battery power flow*. The sizing of the power system, in particular the batteries, is carried out without considering limits due to the power capacity of the lines and of the battery. In particular, the battery is capable of absorbing/releasing power proportionately to its mass. This constraint ensures that the power flowing to/from the battery as required by the mission is always within the limit for the assigned battery size.

Given the general regularity of the solution with respect to the proposed optimization parameters, even considering the action of constraints, a gradient-based algorithm has been employed to numerically solve the optimal problem. The stability of convergence generally displayed by the proposed algorithm has allowed its adoption as a sizing tool to carry out several parameterized analyses, outlined in the following section.

3. Numerical results

In this section, the proposed sizing methodology is firstly tested with respect to an existing test-bed, showing the reliability of the sizing loop, run independently from the optimal sizing procedure. Next, the entire optimal sizing procedure, based on the so-validated sizing loop, is employed to carry out parameterized analyses, inducing some speculation about the limits of HAAs for HAPS missions.

The methodology has been physically implemented in the airship design suite `Morning Star`, a project of the Department of Aerospace Science and Technology, Politecnico di Milano, which makes use of a gradient-based numerical solver for tackling the optimal sizing problem. The tool produces the preliminary sizing of an airship at whatever altitude, and in particular can be successfully employed for the analyses at hand, mostly concerned with stratospheric airships.

3.1 Validation of the sizing loop

To validate the core of the optimal procedure, i.e. the sizing loop, the latter has been fed with the known data for an existing airship, comparing the outcome of the sizing procedure (e.g. volume of envelope, mass, etc.) with the corresponding values for the actual airship.

The test case chosen for this validation is that of the HiSentinel80. That was a single-use, non-rigid, fixed volume, single chamber airship, with inflatable tail fins and a recoverable equipment pod.[12,20,21] It was 199 ft (60.6 m) long and featured a 45.5 ft (13.9 m) diameter, for a total gas volume of 6'846 m^3, and its envelope was made of a lightweight Vectran® based material, including Nylon as gas barrier. The non-gaseous mass of the airship without payload was 1'068 lbs (484.4 kg), while the helium mass was 212 lbs (96.3 kg). It was designed to operate at 65'000 ft (19'812 m) at an average cruise speed of 18 kts (9.3 m/s) and for a mission duration up to 24-h. Power was supplied by batteries supplemented by a non-pointed 1.2 kW thin-film, flexible photovoltaic array, mounted inside the hull near the nose (70% light transmission through the envelope). It was mounted such to reach a horizontal configuration once at altitude. Propulsion was provided by one tail-mounted electric-motor-driven propeller, and a minimum differential pressure exceeding 150 Pa was required across the envelope to avoid buckling in the conical section at the propulsion strut ends.

The HiSentinel80 mission payload was housed in an insulated, cuboid container with dimensions 23-23-30 in. Passive heating and active, electrical heating maintained internal temperature when the payload was not powered. Otherwise, power dissipated by the payload during operation maintained the internal temperature. The choice of the payload resulted in a payload mass of 86.2 lbs (39.1 kg), and a required power of 50 W.

Mission specifications for the design of the HiSentinel80 considered for the validation of the methodology are listed in Tab. 1. The location is assumed to be Page, Arizona, where the flight test was performed, and winter solstice is considered, as it is the most critical day of the year concerning solar energy harvesting. The airship had no ballonets.

Due to the lack of information on the HiSentinel80 concerning the technological part, some of the technological features required to carry out the sizing (see section 2) have been assumed. These include a low specific energy value of 200 Wh/kg for the batteries, and the employment of a-Si solar cells, similar to other airships with a similar mission.[13] Concerning geometrical sizing, the length and fineness ratio of the HiSentinel80 are known, but the remaining information is not. Assuming as stated a geometry more resembling the actual one, proper values for the semi-axes of the rear and front semi-ellipsoids are then determined with a trial and error approach, with the goal of obtaining an envelope volume sufficiently close to the real one. Concerning the solar array, since it is not located on the hull

DOI: 10.13009/EUCASS2023-024

Table 1: Parameters for the sizing tool validation on the HiSentinel80.

Parameter	**Value**	**Unit**
Altitude	19.812	[km]
Latitude	36.9142	[°]
Longitude	-111.4600	[°]
Date	December 21	-
Payload mass	39.1	[kg]
Payload power	50	[W]
Maximum design wind speed	13.38	[m/s]

surface as typically done in stratospheric airships, slight modifications are required with respect to the normal sizing methodology. The solar array arrangement can be modeled more simply as a single horizontal, rectangular array inside the hull. Consequently, ϑ_{in} and ϑ_{out} are not assigned, and the solar array layout can be defined by the two longitudinal coordinates x_{le} and x_{te}, plus a half-width Δy. This slightly modifies the constitution of the array of parameters $\boldsymbol{p}$ (section 2.1). Since the array is horizontal, its actual location inside the hull is not relevant to the incident solar radiation and power production calculations, so proper values for the three geometrical parameters are determined based on the required solar array area, which is known. Indeed, knowing that the solar array has a nominal power of 1.2 kW, once efficiencies are assumed, the area of the solar cells array can be determined. A value of efficiency of the cells of 8% is assumed, and an area of 15.002 m^2 is obtained here, which corresponds to the actual value ($A_{sc} = 15$ m^2). Values considered for the parameters defining the geometry of the airship and the arrangement of the solar array are listed in Tab. 2 (where a_1, a_2 represent the characteristic dimensions of the envelope section).

Table 2: HiSentinel80 assumed design parameters, measured or guessed for the real airship and fed to the sizing loop.

Parameter	**Value**	**Unit**
L	60.65	[m]
FR	4.374	-
a_1	19.05	[m]
a_2	26.94	[m]
x_{le}	5.50	[m]
x_{te}	10.00	[m]
Δy	1.67	[m]

It is worth making a few more comments about some differences in how validation is here performed, with respect to the sizing loop introduced in section 2.

Firstly, it is assumed that the system is sized in order to operate on a specific day and location, without satisfying the 24-h energy balance, that is, without respecting the constraint that the surplus energy generated by the solar array during daytime is sufficient to recharge batteries for nighttime operation, as required for more-than-one-day missions. In fact, since the HiSentinel80 is designed for a mission duration of up to one day, the need for battery recharge is not considered, and it is assumed that the system is sized such that the batteries, starting from a fully charged state, together with the solar array, can power the airship for 24 hours.

Secondly, the wind speed profile is not computed from models, but an average cruise speed of 18 kts (see Tab. 1), reported by references for this specific airship, is considered to compute the required propulsive power. It was however verified that this airstream speed value is close to the prediction of the adopted HWM model. Next, in order to take into account the fact that the solar array is located inside the hull and only 70% of the radiation is transmitted through it, after the broadband global radiation is computed starting from the SMARTS model, its value is multiplied by a 0.7 safety factor.

A comparison between the known details about the HiSentinel80 design and the predictions produced by the sizing methodology is shown in Tab. 3.

In Tab. 3, the airship solid mass is the total mass of the airship without gases.

Despite the many uncertainties in the technological parameters, coped with by making reasonable assumptions and in some cases taking values from airships with a comparable mission, the results obtained confirm the reliability of the sizing approach and of the specific models which have been adopted.

DOI: 10.13009/EUCASS2023-024

Table 3: Comparison between actual HiSentinel80 values and predictions from sizing methodology.

Parameter	HiSentinel80	Prediction	Unit	Error
Envelope volume	6846.02	6846.68	[m^3]	0.01%
Overall mass	-	627.43	[kg]	-
Airship solid mass (no gas)	484.44	480.88	[kg]	−0.73%
Helium mass	96.16	93.62	[kg]	−2.64%

3.2 Optimal design: solutions for a high-altitude airship

The optimal approach introduced in section 2.1 has been applied to a sizing scenario where an assigned HAPS mission payload of 10 kg and a required payload power of 100 W needs to be positioned and operated for one year at a fixed altitude of 20 km. In particular, in this scenario the airship is considered as the payload of an easy-transportable and quickly-deployable missile. This technological solution, called *satelloon*, has the advantage of bypassing the ascent phase, thus promising a better deployment speed and precision for a HAA on a HAPS mission. However, the overall weight of the payload, which in this case will include also the helium tanks needed to inflate the airship once at altitude, will be subjected to a severe constraint. This in turn makes the choice of the proposed optimal approach, targeting overall mass, even more technically relevant.

To better show how the automatic procedure can be exploited, and to appreciate the different optimal results obtained for a changing geographical setting, four sizing problems have been solved, where the location on earth is chosen corresponding to four towns, namely Pontianak (Indonesia), Port-au-Prince (Haiti), Houston (Texas), and L'Aquila (Italy), taken as examples since stricken by natural disasters over the last two decades. The corresponding coordinates vary significantly, as shown in Tab. 4.

Table 4: Mission design specifications assigned for optimal design solution at different geographical locations.

Parameter	Pontianak	Port-au-Prince	Houston	L'Aquila	Unit
Altitude	20	20	20	20	[km]
Latitude	-0.0206	18.5754	29.7499	42.3540	[°]
Longitude	109.3414	-72.2947	-95.3584	13.3920	[°]
Date	Jan. 26	Aug. 5	Aug. 3	Jan. 19	-
Payload mass	10	10	10	10	[kg]
Payload power	100	100	100	100	[W]
Maximum design wind speed	30	30	30	30	[m/s]

Two further remarks concern the settings of the sizing problems. The first is about the day of the year specified in the table. The sizing of a HAPS should be such to sustain operations over an unlimited time frame (which is equivalent to self-sustainment over an yearly cicle), as said. Once at stationing altitude, this would require in principle the analysis of power balance over the intended time frame, taking into account the worst conditions of solar energy harvesting, due to seasonal change in irradiance especially at higher latitudes, combined with the worst wind intensity, which produces a higher power needed to keep the airship in position. In order to save on computational time however, instead of analyzing the performance over the entire yearly calendar, the worst day is selected based on the worst (most intense) wind condition, which is typically the physical driver producing the hardest effect on sizing. The so-obtained sizing is checked on the day with the lowest overall solar power harvesting *a posteriori*, in order to make sure that that sizing allows to satisfy the power balance also in that case. If the latter turns out more requiring than the one initially hypothesized, the representative day for the sizing is changed correspondingly. However, it should be noted that this way of proceeding is not substantial - it is of course possible to simply extend the time frame of the analysis from one day to one full year, without the need to any crosschecks, at the price of some increase in the required machine time.

The second remark on Tab. 4 concerns the choice of the maximum design wind speed for station-keeping, which is chosen equal for all the sizing problems at hand, similarly to the stationing altitude. Specifically, the value chosen for speed is very conservative considering all four locations. This choice was made to allow a fairer comparison among the four proposed scenarios of interest, which will be analyzed next.

3.2.1 Comparison of optimal output for different locations

The output of the optimal computation is pictorially shown in Fig. 2, whereas numerical results are reported in Tab. 5.

Table 5: Comparison between the output of optimal design above the four considered locations (see Tab. 4).

Param.	**Unit**	**Pontianak**	**Port-au-Prince**	**Houston**	**L'Aquila**
L	[m]	43.84	128.53	68.92	117.42
FR	-	3.667	5.185	4.422	5.158
x_{le}	[m]	34.09	2.00	2.00	38.37
x_{te}	[m]	40.04	88.24	55.55	104.59
θ_{in}	[rad]	1.331	0.000	2.121	2.070
θ_{out}	[rad]	1.697	0.462	2.443	2.876
Envelope volume	[m^3]	3280.043	41365.970	8765.707	31858.069
Envelope area	[m^2]	1332.873	7991.302	2708.574	6703.987
Area of solar cells	[m^2]	9.014	435.005	118.360	544.908
Overall mass	[kg]	682.501	8607.296	1823.940	6628.923
Mass of airship	[kg]	291.628	3677.840	779.357	2832.494
Mass of helium tanks	[kg]	396.769	5003.812	1060.339	3853.694
Airship solid mass (no gas)	[kg]	235.809	3090.002	646.910	2377.471
Mass of envelope	[kg]	158.957	1499.369	375.410	1185.444
Mass of solar cells	[kg]	1.758	84.826	23.080	106.257
Mass of batteries	[kg]	16.909	897.510	111.764	624.135
Mass of lifting gas	[kg]	45.819	577.838	122.448	445.023

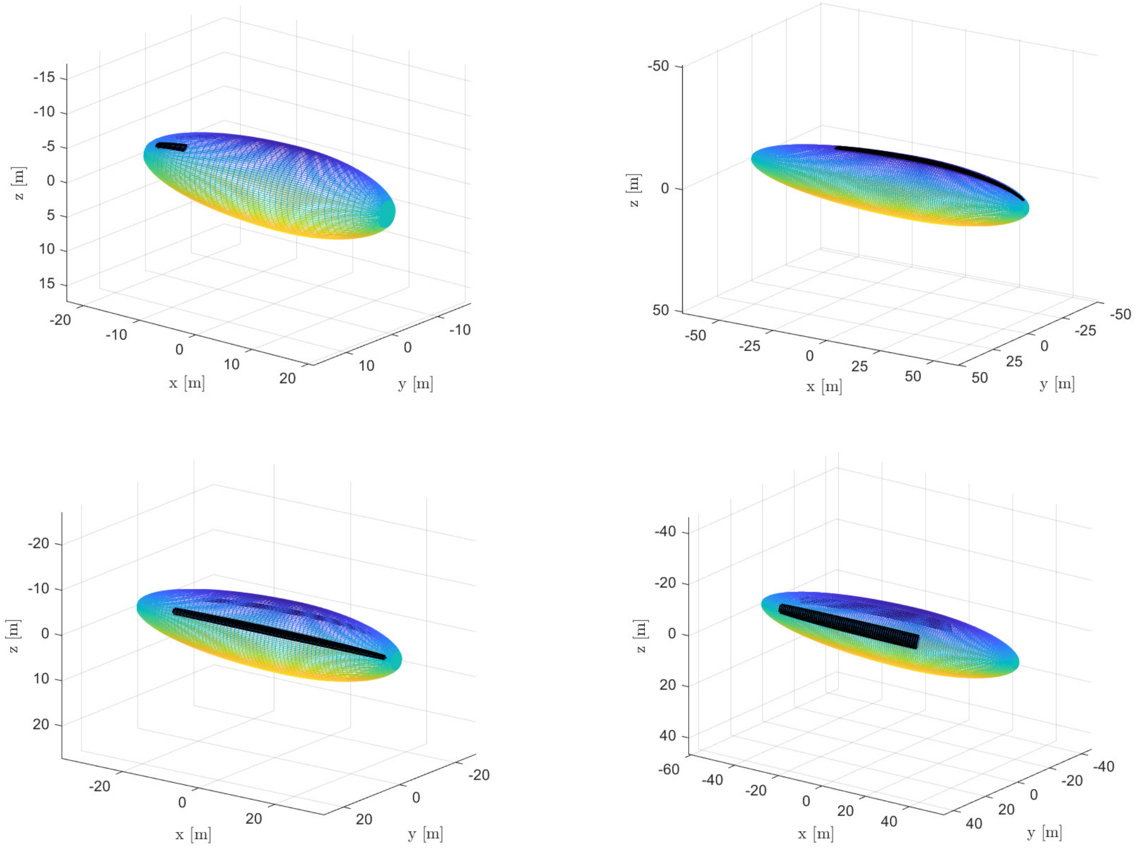

Figure 2: Effect of location on optimal design solution. Three-dimensional representation of optimal airship layout, for a target altitude of 20 km. Top-left: Pontianak (Indonesia). Bottom-left: Houston (Texas). Top-right: Port-au-Prince (Haiti). Bottom-right: L'Aquila (Italy).

DOI: 10.13009/EUCASS2023-024

From Tab. 5 it is readily apparent how the environment found at the stationing altitude influences the outcome of the optimal sizing.

Required propulsion power increases with the third power of the wind speed (which is computed with the HWM model and differs from the maximum design wind speed value in Tab. 5, required for structural sizing), increasing the need to store energy to ensure continuous operation. This results in an increase of the battery mass, as well as that of the solar array.

Furthermore, power consumption is also dependent on the geometrical size of the airship. Increasing airship volume provides increased buoyancy, required to balance the increased weight of the overall system. However, the increased size also induces an increase in power required, due to the larger drag of the airship. This in turn increases the mass of the airship again.

The coupling of the required and available power with the environment makes the sizing dependent on both where and when it has to be flown. Hence, the extremely low wind speed in Pontianak, combined with the fact that, lying on the equator, the number of daylight hours is practically unchanged throughout the year, result in a system with a size and weight which are smaller compared to those resulting for other locations - even by an order of magnitude comparing the cases of Port-au-Prince and L'Aquila.

Airstream speed, in particular, is a main driver of the sizing. Actually, the system designed for operation above Port-au-Prince, where wind speeds are the highest at 20 km altitude, is characterized by the largest size and energy storage requirement, and consequently also by the highest total mass, as well as the highest mass of many components. Similarly, the maximum wind speed from the HWM model at 20 km altitude above L'Aquila is higher than above Houston, and consequently the system designed for the former location features a higher power consumption, and larger size and mass.

However, where the difference in maximum wind speed are comparable, the increase in overall mass between L'Aquila and Houston is much larger compared to that between Port-au-Prince and L'Aquila. The reason, which can be understood by looking at the energy storage requirements, lies in the critical conditions that drove the design in the three cases.

On the one hand, at 20 km altitude Port-au-Prince and Houston have their critical day of the year in summer, when there are more daylight hours and thus the energy storage requirement is made less stringent by the shorter time for which the solar array is not capturing power. The opposite scenario is encountered in L'Aquila, where the most critical day at 20 km altitude occurs in the middle of the winter, when less than 10 daylight hours are available, and thus the energy storage requirement is more stringent. This difference is reflected also by the required area and mass of the solar array. Despite the lower energy storage requirement, the optimal solution for operation above L'Aquila is characterized by a larger solar array than the one designed to operate above Port-au-Prince. In fact, due to the fewer daylight hours on the critical design date, in the former case the energy for night operation must be collected in a shorter time, meaning that a higher output power from the solar array, hence a larger solar cell surface, is required.

Broadly speaking, it can be observed that for locations such as Port-au-Prince and L'Aquila, and to a lesser extent also Houston, a system with a large mass is required to carry a payload which is relatively limited in both mass and power consumption. This would practically result in the unfeasibility of a missile-deployed HAPS concept in such locations, at the considered altitude and with the adopted baseline technologies. This is due to the inability of such a heavy system to fit into any missile sufficiently small to allow the ease of transport and handling, and the fast deployment, required to meet the time responsiveness goal underlying the proposed concept. By carefully analyzing the weight distribution among the various components listed in Tab. 5, where envelope and batteries are the major contributors to the mass of the airship (except in the Pontianak case, in which the energy storage requirement is minimal), what actually contributes most to the excessive weight of the system is not the airship itself, but rather the lifting gas storage system, which due to the low gravimetric capacity of state-of-the-art tanks takes a portion around 58% of the total weight of the airship, and therefore of the potential missile payload.

3.2.2 Effect of stationing altitude on optimal sizing solution

Following the considerations presented at the end of the previous section 3.2.1, it is worth mentioning the effect of the choice of the target altitude in reducing the weight of the airship – which is the intended payload for a missile carrying the deflated platform to the stationing level.

To this aim, the sizing has been performed for a different target altitude, assigned by the user. A prediction model for an optimal altitude has been carried out based on the relative propulsive power, a combination of the wind speed and air density at a specific altitude, inspired by.[3] This quantity is loosely proportional to the size and mass of an airship optimized for that altitude. Therefore, it can be employed to indicate more and less advantageous altitudes (not strictly optimal, due to the inherent simplifications in the definition of the relative power figure of merit) for whatever position on earth, i.e. altitudes producing a corresponding optimal design which respectively more compact and lighter, or conversely bigger in size and heavier.

Analyzing the behavior of the relative propulsive power for all four locations in Tab. 4, considering the change of the wind and atmospheric conditions over the solar year and a range of altitudes of interest between 17.5 km and 20 km, it is found that the span between extreme values of the relative propulsive power is wider especially for Port-au-Prince. This suggests an extreme change in the optimal design solution for this location, considering the altitudes yielding the extreme values of the relative propulsive power, respectively 20 km and 18.06 km.

In Tab. 6 are reported the results of the optimal design for Port-au-Prince for a target altitude of 18.06 km, compared to those obtained for the original target altitude of 20 km.

Table 6: Comparison between HAPS optimal designs for operation at 20 and 18.06 km altitudes above Port-au-Prince, Haiti.

Parameter	Unit	20 km	18.059 km	Reduction
L	[m]	128.53	67.71	-
FR	-	5.185	4.791	-
x_{le}	[m]	2.00	2.00	-
x_{te}	[m]	88.24	40.98	-
θ_{in}	[rad]	0.000	1.703	-
θ_{out}	[rad]	0.462	2.184	-
Envelope volume	[m^3]	41365.970	7083.912	82.88%
Envelope area	[m^2]	7991.302	2406.371	69.89%
Area of solar cells	[m^2]	435.005	117.567	72.98%
Overall mass	[kg]	8607.296	1998.161	76.79%
Mass of airship	[kg]	3677.840	853.801	76.79%
Mass of helium tanks	[kg]	5003.812	1161.621	76.79%
Airship solid mass (no gas)	[kg]	3090.002	709.657	77.03%
Mass of envelope	[kg]	1499.369	379.407	74.70%
Mass of solar cells	[kg]	84.826	22.926	72.97%
Mass of batteries	[kg]	897.510	155.529	82.67%
Mass of lifting gas	[kg]	577.838	134.144	76.79%

The advantage of reducing the operating altitude of the HAPS platform is readily apparent from Tab. 6. The significant reduction of the maximum wind speed that the airship is expected to face when it is sized for the new altitude, together with the increase in air density, lead to a substantial decrease in power consumption, and therefore energy harvesting and storage requirement, as well as in the size of the airship. As a result, the mass of the batteries and all power system components is greatly reduced, and similarly is the mass of all other components on board. The final result is a dramatic 82.88% reduction in HAPS size and a 76.79% reduction in its total mass. Considered as the payload for a missile responsible for positioning the HAPS at altitude, the new values constitute a feasible solution, according to the technology and size of existing launchers.

3.3 Optimal design and off-design analysis for a medium-altitude airship

As anticipated, the optimal procedure presented in section 2 bends itself to the study of airships aimed at a generic stationing altitude. In this paragraph, the example of a medium-altitude airship, of limited size compared to those considered in the previous section, is introduced. In particular, differently from the missile-launched concept previously considered, this further example describes a platform with a flight profile including climb. From a mission design standpoint, this requires introducing values for climb speed and angle. In terms of technology, an airship facing a different change in altitude and not destinted to the stratosphere typically makes use of ballonets, which require the addition of some weight. Finally, the tropospheric environment requires the adoption of a cloudiness model, which allows to suitably simulate the lower solar power capture at the lower levels of the atmosphere.

3.3.1 Optimal design solution and parameterized analyses

Table 7 reports the settings for the optimal sizing procedure, considering Houston, TX, as the geographical location for the mission.

It is noteworthy that the obtainment of a target buoyancy ratio which is not unitary (as in Tab. 7) can be dealt with easily within the optimal scheme in Fig. 1, by suitably tuning the weight vs. buoyancy constraint.

DOI: 10.13009/EUCASS2023-024

Table 7: Parameters for optimal sizing of a medium-altitude airship.

Parameter	Value	Unit
Altitude	3.0	[km]
Latitude	29.7499	[°]
Longitude	-95.3584	[°]
Date	August 3	-
Payload mass	8	[kg]
Payload power	90	[W]
Buoyancy ratio	0.93	-
Climb angle	30	[°]
Velocity in climb	4	[m/s]
Percentage of cloudiness at altitude	0.48	-

Table 8: Optimal design solution for a medium-altitude airship.

Parameter	Value	Unit
L	11.15	[m]
FR	3.18	-
x_{le}	4.15	[m]
x_{te}	8.54	[m]
ϑ_{in}	0.84	[rad]
ϑ_{out}	1.46	[rad]

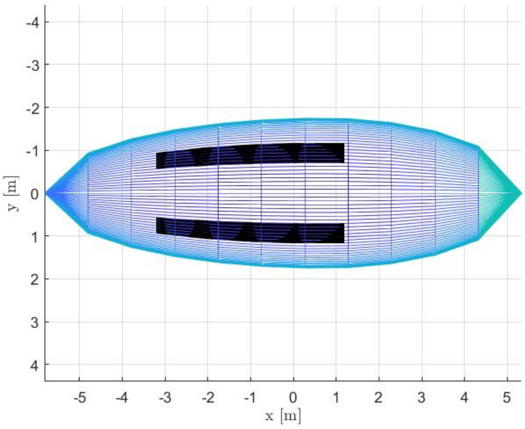

Figure 3: Optimal design for the medium-altitude airship with specifications in Tab. 8.

DOI: 10.13009/EUCASS2023-024

The resulting optimal design is reported in Fig. 3, and the numerical characteristics are presented in Tab. 8

As anticipated, the outcome of the design is significantly smaller than for higher altitudes (see section 3.2.1). As done in section 3.2.2, it is interesting to show how the solution may be affected by a change in the stationing altitude. The plots in Fig. 4 show the values of the overall mass and length, as well as the energy needed to fly the entire mission profile (including a station-keeping phase of 1 day) and the area of solar cells, for different values of the stationing altitude.

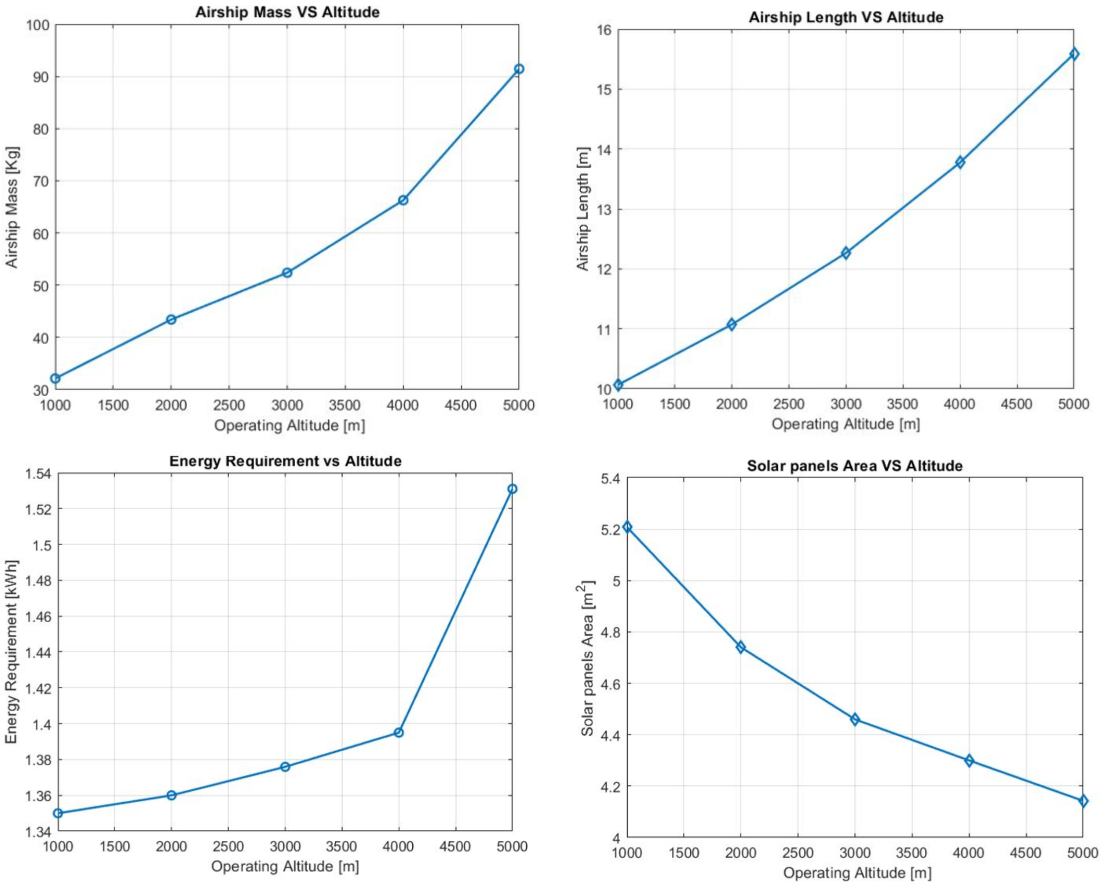

Figure 4: Effect of stationing altitude on the features of the optimal design procedure. Top-left: overall mass. Top-right: overall length. Bottom-left: energy requirement for the mission. Bottom-right: area of solar cells.

Looking at the plots for mass and energy requirement, it can be noted that the need to climb higher produces higher values of these quantities, despite the fact that more energy is obtained from solar radiation at higher levels of the atmosphere. In other words, an increase in battery mass drives the overall mass to higher values. However, the area of solar cells is reduced with altitude, witnessing the lower need for capture area which comes along with an increase in local irradiance for higher target altitude values.

3.3.2 Off-design analysis of a locally-optimal airship

With the understanding that design constraints significantly change the outcome of the optimal design procedure (as shown in the previous sections), it is interesting to investigate the usability of an assigned optimal solution for missions which differ from the one assigned for design.

In particular, since the geographical position has proven a relevant driver in steering the outcome of the optimal design procedure (see Tab. 5 and Fig. 2), a relevant analysis is concerned with the contouring of the area of the globe where an airship optimally designed for a certain location may still be employed. The latter concept is interpreted in quantitative terms by evaluating the constraints of structural integrity, buoyancy ratio (which needs to be over the design one) and energetic feasibility of the mission, i.e. the same constraints appearing to the bottom of the optimization scheme in Fig. 1. Clearly, the airship will not be optimally designed for a considered off-design test location, but the satisfaction of the constraints should at least allow to manage the off-design flight in any case.

DOI: 10.13009/EUCASS2023-024

For this example, an airship optimized for L'Aquila, Italy, considering otherwise identical settings to Tab. 7, is taken as a baseline. The plot in Fig. 5 pictorially displays a set of 61 locations where this airship has been tested.

Figure 5: Off-design testing of a middle-altitude airship. Feasibility check of a flight at different geographical locations.

Out of this set, only 25 locations allow the operation of the optimal design for L'Aquila, whereas for 27 of them that design violates some constraints for whatever day of the solar year. Finally, for a subset of 9 locations the airship can be employed for a limited number of days of the year. As previously explained, the choice of a geographical location and time of the year changes the values of wind and irradiance, which significantly impact the sizing of the airship, justifying the result just observed.

4. Conclusions

An automated methodology for sizing an airship has been introduced, following and optimal approach aimed at reducing the mass of the system as much as possible. Constraints allowing to guarantee the energetic self-sustenance of the airship, propelled by electric motors fed by a mix of batteries and solar cells, as well as the buoyancy and structural integrity of the envelope, steer the optimization towards a feasible solution.

The parameters set by the optimizer include those defining the geometry of the envelope and solar cells. Input to the design include the weight and energy requirement of the payload, as well as the geographical location and target altitude, and the buoyancy ratio.

The algorithm makes use of detailed models for the environment, including the static characteristics of the atmosphere, the intensity and direction of prevalent wind, the irradiance and the cloudiness, properly assumed as functions of the position on earth, of the altitude, and of the time of the year.

The target mission is composed of an ascent and positioning at a stationing altitude, considering a fixed geographical point on earth. Depending on the setting of the procedure, the airship can be sized for a mission limited in time, or for a virtually permanent positioning at the stationing altitude.

The proposed algorithm, implemented in a suite called `Morning Star`, is preliminarily tested for reliability. In particular, the sizing loop constituting the core of logical passages iteratively invoked by the optimizer, is tested to check its ability to capture the features of an existing high-altitude airship.

Then a parameterized study is presented, where a high-altitude airship is optimally designed for different locations on earth, leaving most of the other design parameters to the same values, so as to exacerbate the effect of this choice on the outcome of optimal design. Considering in particular the case of a *satelloon*, i.e. an airship conceived for deployment via a missile to the higher layers of the atmosphere, the choice of mass as a target for optimization is particularly meaningful, since the entire airship (including tanks for helium, to inflate the envelope when at stationing altitude) needs to be transported as the payload of a missile. The results of this analysis show that the airship may turn generally excessively heavy for a low-weight, easily deployable missile, thus hampering the suitability of this platform for the intended task. However, a further analysis through an approximate parameter (relative propulsive power) has allowed to indicate more convenient stationing altitudes. By designing an airship for such altitudes actually reduces the size and weight of the airship in a very significant way, in turn regaining the chance of a deployment via a missile.

DOI: 10.13009/EUCASS2023-024

Considered together, these analyses show that the choice of a geographical location and of a stationing altitude bear a substantial effect on the optimal design solution, and the result may turn out technologically feasible or not, depending on such choices. From a perspective of design technique, it should be pointed out that such parameterized analyses can be practically carried out and bear meaningful, fair results only thanks to the choice of the proposed optimal algorithm. Actually, the latter allows to coordinate the choice of several design parameters at one, targeting for whatever case always the same objective, thus making the outcome comparable.

A further analysis has been carried out on a medium-altitude airship, to show the ability of the algorithms in `Morning Star` to correctly manage also missions where the airship needs to transit through the lower layers of the atmosphere, where cloudiness reduces solar irradiance, and also accounting for a required climb performance. Besides showing such ability by proposing the optimal sizing of such an airship, optimized for a certain geographical location, a parameterized analysis is proposed where that specific airship is tested in terms of compliance with the constraints considered for optimization, when flying over locations different from that adopted for the design. This off-design test highlights that the choice of the geographical location appears such to significantly impact the ability of the airship to deploy to an arbitrary position on earth. On the contrary, the choice of the geographical position and the optimization of an airship for it make the outcome usable only on a limited range of geographical locations.

All such data are useful when approaching the problem of an airship from scratch, showing that where on the one hand the employment of an automatic, optimal design approach is of course useful for sizing up an airship platform, in particular reducing its weight (hence also size and possibly cost) as much as possible, on the other hand the settings of the optimal problem may produce a design solution which is sensibly different from that resulting from a different choice of such parameters.

References

[1] G. E. Carichner and L. M. Nicolai. *Fundamentals of Aircraft and Airship Design*. AIAA Education Series. American Institute of Aeronautics and Astronautics, Inc., 2013.

[2] L. Chen, H. Zhang, and D. P. Duan. Control system design of a multivectored thrust stratospheric airship. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 228(11):2045–2054, 2014.

[3] A. Colozza. Initial Feasibility Assessment of a High Altitude Long Endurance Airship. Technical Report NASA/CR–2003-212724, Analex Corp., 2003.

[4] F. A. d'Oliveira, F. C. L. de Melo, and T. C. Devezas. High-Altitude Platforms - Present Situation and Technology Trends. *Journal of Aerospace Technology and Management*, 8(3):249–262, 2016.

[5] D.P. Drob. An empirical model of the Earth's horizontal wind fields: HWM07. *Journal of Geophysical Research, Space Physics*, 113, 2008.

[6] D.P. Drob. An update to the Horizontal Wind Model (HWM): The quiet time thermosphere. *Earth and Space Science*, 2:301–319, 2015.

[7] A. Elfes, S.S. Bueno, M. Bergerman, and J.G. Ramos. A semi-autonomous robotic airship for environmental monitoring missions. In *1998 IEEE International conference on robotics and automation (Cat. No. 98CH36146)*, volume 4, pages 3449–3455. IEEE, 1998.

[8] J. Gonzalo, D. López, D. Domínguez, A. García, and A. Escapa. On the capabilities and limitations of high altitude pseudo-satellites. *Progress in Aerospace Sciences*, 98:37–56, 2018.

[9] C. Gueymard. SMARTS2, a Simple Model of the Atmospheric Radiative Transfer of Sunshine: Algorithms and performance assessment. Technical Report FSEC-PF-270-95, Florida Solar Energy Center, 1995.

[10] J. Jon, B. Koska, and J. Pospı̌šil. Autonomous airship equipped with multi-sensor mapping platform. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-5 W*, 1:119–124, 2013.

[11] T. Liesk, M. Nahon, and B. Boulet. Design and experimental validation of a nonlinear low-level controller for an unmanned fin-less airship. *IEEE Transactions on Control Systems Technology*, 21(1):149–161, 2013.

[12] P. Lobner. HiSentinel Stratospheric Airships. Technical report, Lyncean Group of San Diego, 2020.

DOI: 10.13009/EUCASS2023-024

[13] P. Lobner. Lockheed Martin HALE-D. Technical report, Lyncean Group of San Diego, 2020.

[14] S. H. Miller, R. Fesen, L. Hillenbrand, J. Rhodes, G. Baird, G. Blake, J. Booth, D. E. Carlile, R. Duren, and F. G. Edworthy. Airships: A New Horizon for Science. Technical report, ArXiv, 2014.

[15] B. L. Nagabhushan and N. P. Tomlinson. Thrust-vectored takeoff, landing, and ground handling of an airship. *Journal of aircraft*, 23(3):250–256, 1986.

[16] C. E. D. Riboldi and A. Rolando. Layout Analysis and Optimization of Airships with Thrust-Based Stability Augmentation. *Aerospace*, 9:393, 2022.

[17] C. E. D. Riboldi and A. Rolando. Thrust-Based Stabilization and Guidance for Airships without Thrust-Vectoring. *Aerospace*, 10:1–31, 2023.

[18] C. E. D. Riboldi, A. Rolando, and G. Regazzoni. On the feasibility of a launcher-deployable high-altitude airship: Effects of design constraints in an optimal sizing framework. *Aerospace*, 9:1–37, 2022.

[19] G. Romeo, G. Frulla, and E. Cestino. Design of a high-altitude long-endurance solar-powered unmanned air vehicle for multi-payload and operations. *Journal of Aerospace Engineering*, 221:199–216, 2007.

[20] I. Smith, M. Lee, M. Fortenberry, and R. Judy. Hisentinel80: flight of a high altitude airship. In *11th AIAA aviation technology, integration, and operations (ATIO) conference, including the AIAA balloon systems conference and 19th AIAA lighter-than*, page 6973, 2011.

[21] I. S. Smith. Hisentinel & stratospheric airship design sensitivity. In *Keck Institute for Space Studies (KISS) Workshop, 30 April-3 May 2013, Pasadena, CA*, 2013.