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Department of Aerospace Science and Technology

Master thesis in aerospace engineering

Preliminary design of an electrically propelled LTA UAV for low-atmosphere operation

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Abstract

The aim of this work is to carry out the preliminary design for a small, unmanned airship designed for operating at low altitude.

The first part of this work consists in a review of the state of the art of airships technology. From the researchs available it is clear how airships have a great advantage in those application that requires high quality data and long time spent in the air. We soon realized that for small airships UAVs operating at low altitudes there were not much in terms of industrial production, but a quite solid base of research attesting the possibility of using them with great advantages for specific mission profile.

In the second part of this text we made an analysis of the various mission profiles that really makes an airship shine, comparing the airship performances with that of conventional UAVs (fixed wing, helicopters and multirotors). From this analysis the dimensioning mission has been chosen. This mission in particular have been accomplished by a multicopter so there is also the possibility of confronting the performance with this class of UAVs.

In the third part of the report, the preliminary design is carried out through an iterative process and a confrontation of performance with the multicopter used for the original mission is carried out.

Estratto

Lo scopo di questo lavoro è quello di realizzare un dimensionamento preliminare di un piccolo dirigibile senza pilota destinato ad operare a bassa quota.

La prima parte della tesi consiste in una ricerca bibliografica con lo scopo di delineare lo stato dell'arte dei dirigibili. Dalle ricerche analizzate risulta che l'utilizzo di dirigibili sia decisamente vantaggioso per quelle applicazioni che richiedono dati di alta qualità e lunga permanenza in volo. Risulta anche che per dirigibili UAV di piccole dimensioni operanti a bassa quota non ci sia molto a livello di produzione industriale, ma una base di ricerca scientifica decisamente solida che attesta la possibilità di utilizzarli con grossi vantaggi per alcuni profili di missione.

La seconda parte del testo è un'analisi di vari profili di missione in cui i dirigibili risultano eccellenti, comparando le loro performance con quelle di altre tipologie di UAV. A partire da questa analisi è stata scelta una missione dimensionante. Questa particolare missione è stata realmente compiuta da un multicottero, pertanto è stato possibile confrontare le prestazioni con questa categoria di UAVs.

Nella terza parte della tesi, viene svolto il vero e proprio dimensionamento preliminare, realizzato attraverso un processo iterativo; successivamente viene presentato un confronto delle prestazioni con il multicottero utilizzato nella missione originale.

1. Introduction

From their first flight to nowadays, airships have known a fluctuating history: from the golden age between the first controlled flight made by *La France* of *Renard* e *Krebsand* and the Second World War to the almost total oblivion in the ’50-’70; partially back on the spotlight in the’80s and then back down again in the ’90; and finally to the growing interest from the beginning of XXI century to the present days [1].

Much of this new growing interest is due to improvements in the envelope fabric materials (see Figure 1), landing gears (air cushion landing systems), vectored thrust and hybrid design (combination of buoyant and aerodynamic lift) having more efficient lift generation [2].

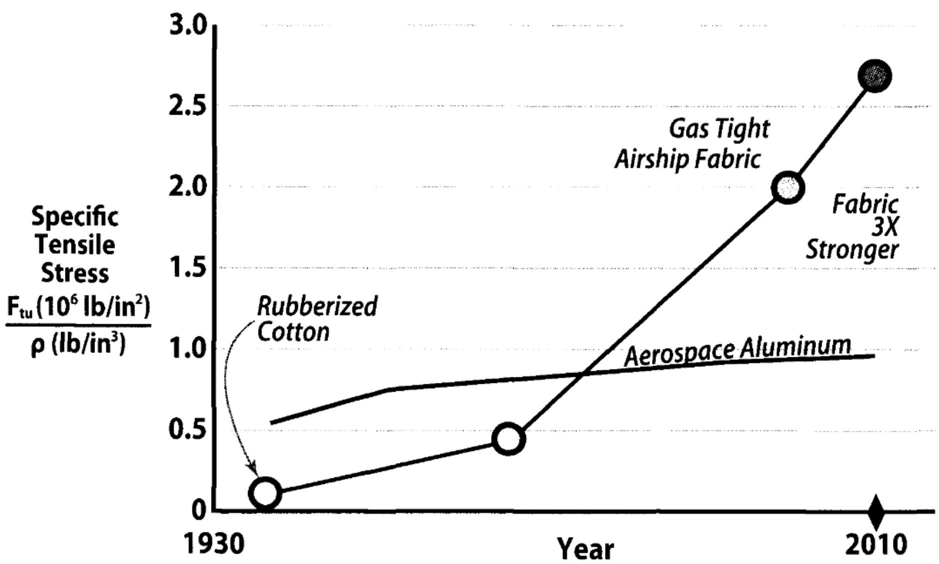


Figure 1: Specific tensile strength of envelop materials during last century [2]

Lighter than air vehicles offer great advantages in endurance and consumptions over time, and are extremely convenient, efficient and ‘‘green’’ for those mission profile that includes slow cruise speed and long or extremely long flight time (as shown in Figure 2), with also the possibility to operate in remote o damaged areas lacking of ground support infrastructures.

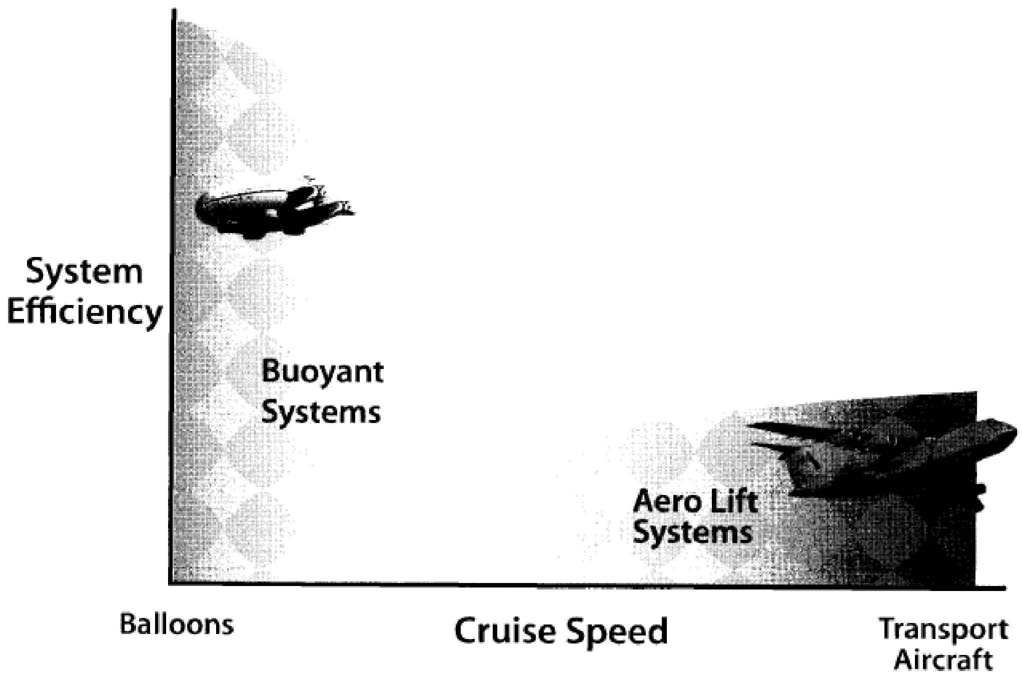


Figure 2:Comparison of relative efficiencies of aircraft vs bouyant vehicles [2]

Another scenario in the new renaissance of lighter than air vehicles is coupled with the large improvement and diffusion of UAVs. Un unmanned vehicle combines very well with long endurance and the necessity to operate in remote or dangerous areas.

Choosing an unmanned configuration for an airship gives the following advantages [2]:

1. The design of the unmanned system is not limited by the requirement to carry a human onboard and accommodate his frailties.

2. No human is at risk of capture.

3. No infrastructure is required to recover the crew if the airship crashes.

4. The unmanned airship does not need to fly to keep the unmanned system proficient.

Last but not least, Lighter Than Air (LTA) Stability qualities of the LTA unmanned aerial platforms directly favored the quality of the data provided by the sensors (EO-IR, atmospheric, radar, CBRN sensors) necessary to perform C4 or ISR military missions (such as border security, surveillance of areas port , critical infrastructure protection) or civil uses (sports and cultural events, communication routes, natural disasters and environmental protection) [3].

All these characteristics makes clear that buoyant systems can outperform other flying machines in a variety of profile mission.

2. Lighter than air vehicles (LTA)

We define Lighter Than Air vehicles those aircraft able to fly thanks to buoyant forces generated through Archimedes principle; this means also that the average density of this kind of flying machines is lower than the density of the surrounding atmosphere: such a task is achieved using a lifting gas that is lighter than air. Typical lifting gasses are Hydrogen, Helium and Hot Air. This method contrasts with a heavier-than-air aircraft, or aerodyne, which generates lift with the flow of air over an airfoil.

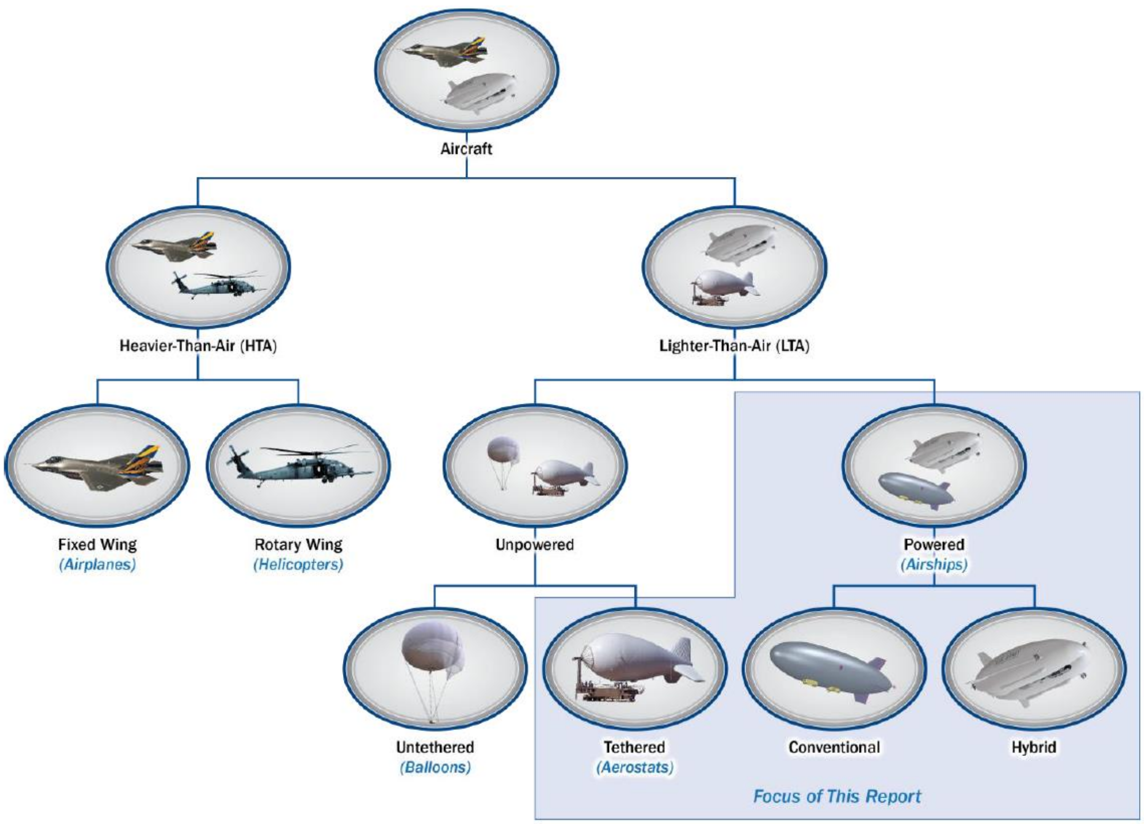


Table 1: Aicreaft calssification [4]

The buoyancy force is "always on" and doesn't need power and fuel consumption to be achieved, making extremely efficient for slow speed and hovering. The only downside is the necessity to have a large envelope that increase the drag of the machine, making it less suitable for speed higher than 150kn (see Figure 2).

There are two types of LTA: **balloons** that can' handle the airflow, and **airships** (also called **dirigibles**), powered and steerable aircraft that can operate independently of airflow movement. We will focus on the latter.

Airships can be classified according to the envelope construction type (see Figure 3):

- **Rigid** type, having a metal frame for maintaining the form of the vehicle covered with a flexible material; the lifting gas is stored in gas cells contained by the rigid frame. These gas cells were allowed to expand and contract as the lifting gas changed temperature and became fully expanded when the airship was at its maximum altitude. Very popular until 1930', they are always heavier than non-rigid counterparts for a given volume.
- **Non rigid** type (also called blimps) have no rigid frame inside and the shape is maintained thanks to the pressure of the lifting gas contained in the envelope. Unlike the rigid design the, uses a flexible bag (or more than one) called ballonets in order to maintain a constant pressure differential ($\Delta p = p_{amb} - p_{int-gas}$): If the pressure difference between external ambient conditions and internal conditions is held constant, the buoyant lift is also constant assuming perfect gas behavior, which means the envelope shape stays the same. At beginning of airship's era, non rigid design were small due to lack of materials capable and cheap enough for the envelope. It is the most common design today.
- **Semi-rigid** type attempts to combine the best features of the other two. This concept adds a pressure – stabilized envelope with a modest structure

running most of the length of the airship. Structural items such as engines and tails are attached to this internal structure. There are very few successful semi-rigid designs.

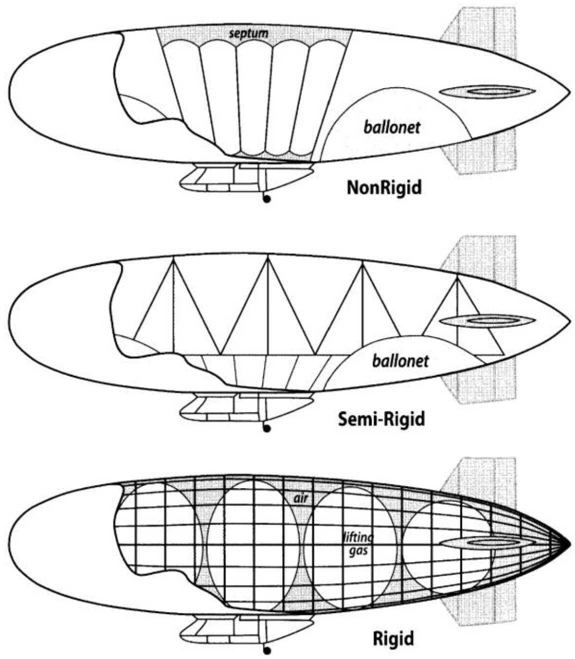


Figure 3:Comparison of structural concepts for body of revolution airship. [2]

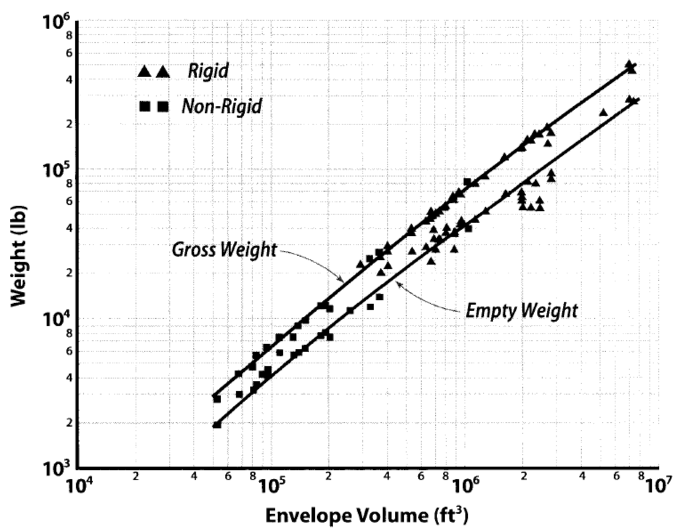


Figure 4: Weights of historical airships (bodies of revolution). [2]

Another classification can be made considering the lift generation method. To better understand what will follow, we need to define two quantity: the **Buoyancy Ratio (BR)** and the **heaviness**:

$$BR = \frac{Buoyant\ lift, L_{buoy}}{Total\ weight, W_g}$$

$$heaviness = W_G * (1 - BR)$$

Considering the BR, the airship can be classified:

- **Conventional** airships generate more than 90% of the total lift through buoyancy and only 10% or less is generated through aerodynamics forces, so have a **BR>0.9**; as can be expected, this kind of aircraft needs to load and unload ballasts if the payload is variable, i.e. during offloading payload or consuming fuel. Usually the envelope geometry is a Body of Revolution (BoR)
- **Hybrid** designs can generate up to 40% (**0.6<BR<0.9**) of the total lift through aerodynamic forces (see figure Figure 5). This characteristic, together with its unique shape, permits it to generate larger variable amounts of aerodynamic lift. The ability to modulate this lift vastly increases a hybrid's operational flexibility and allows it to offload larger payloads without any loss of control. The envelope is usually multy-lobed (Figure 6).

For BR<0.6, the increase in drag rapidly overcome the befits of buoyant lift.

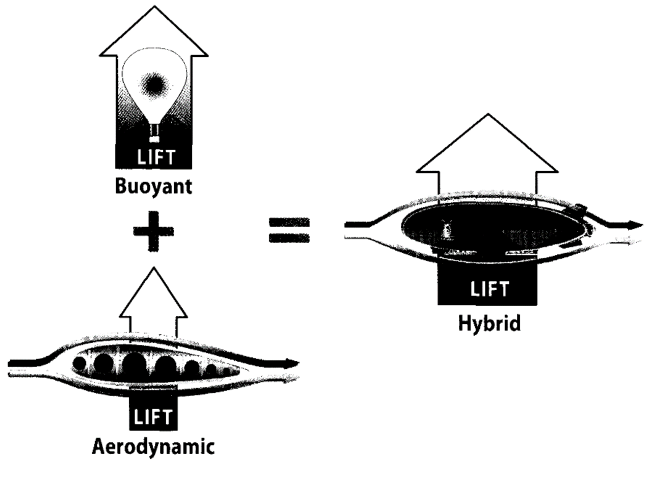


Figure 5: Hybrid airships combine aerodynamic and buoyant [2]

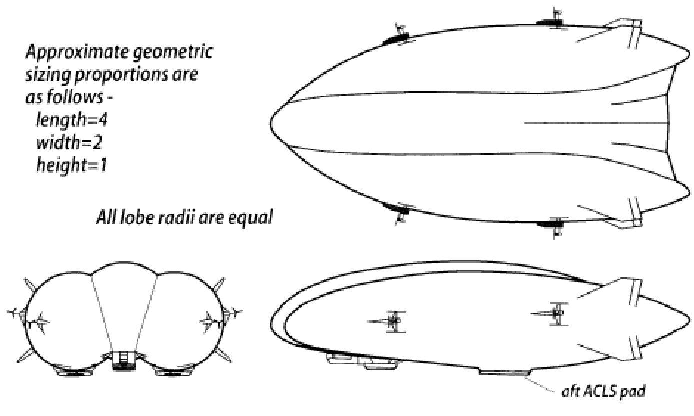


Figure 6: Typical hybrid design [2]

But how LTA vehicles perform compared to other kind of transportation? The famous Gabrielli- von Karman (Figure 7) chart helps us to answer this question. It shows the specific resistance needed to move a weight at a certain speed using various modes of transportation. It is clear how Hybrid Designs fit an unused niche.

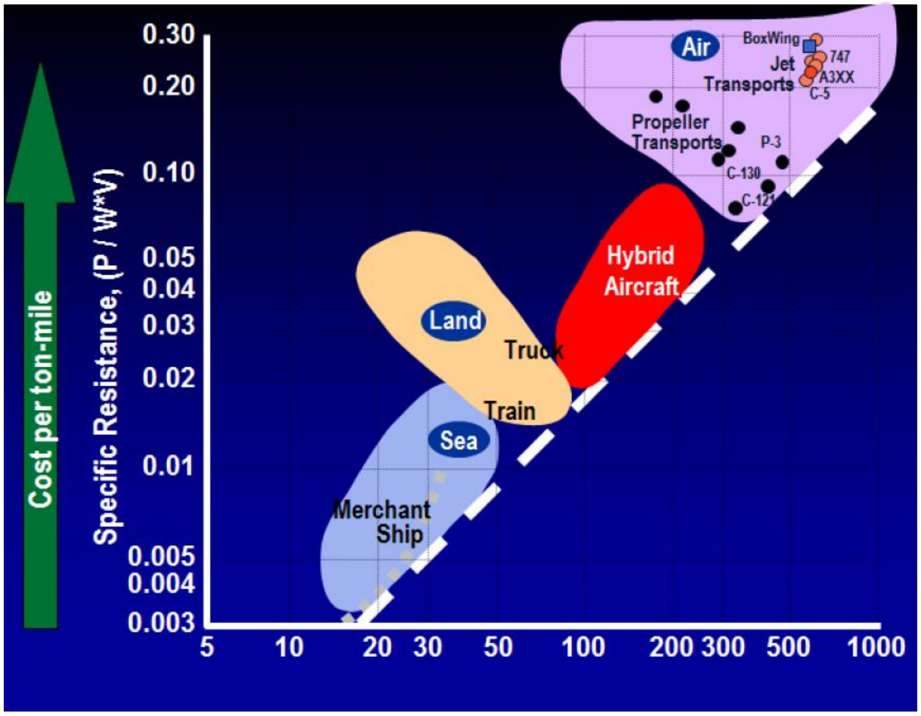


Figure 7: Gabrielli - von Karman specific resistance data for transportation systems [4]

3. UAVs … or UASs?

What is an UAV? And it really consists only in a flight machine? Well, let's try to make some clarification.

Un Unmanned Aerial Vehicle (UAV) is an aircraft without any human pilot, crew or passenger onboard. Between the various definitions of UAV, the USA DoD states:

"...a powered unmanned aerial vehicle that uses aerodynamic forces to provide some control, can fly autonomously or be piloted remotely, is expendable or recoverable, and can carry a payload."

the concept of reusability is very important because differs the proper UAVs from guided bombs and missiles

They differ from radio controlled aircraft (RC models) because of the flight range and cruise altitude, and the ability to perform autonomous tasks (e.g. autonomous follow of a GPS path).

To be precise the Unmanned Aerial Vehicle (UAV) is just a part of a larger, more complex Unmanned Aerial System (UAS). The International Civil Aviation Organization defines the UAS as:

"…an aircraft and its associated elements which are operated with no pilot on board, which is flown without a pilot-in-command on-board and is either remotely and fully controlled from another place (ground, another aircraft, space) or programmed and fully autonomous…" ((ICAO), 2011) [5]

UASs has 3 main components, and the development of the UAV can't be separated from the other two parts:

One or several UAVs

Ground control station (GCS)

Communication links

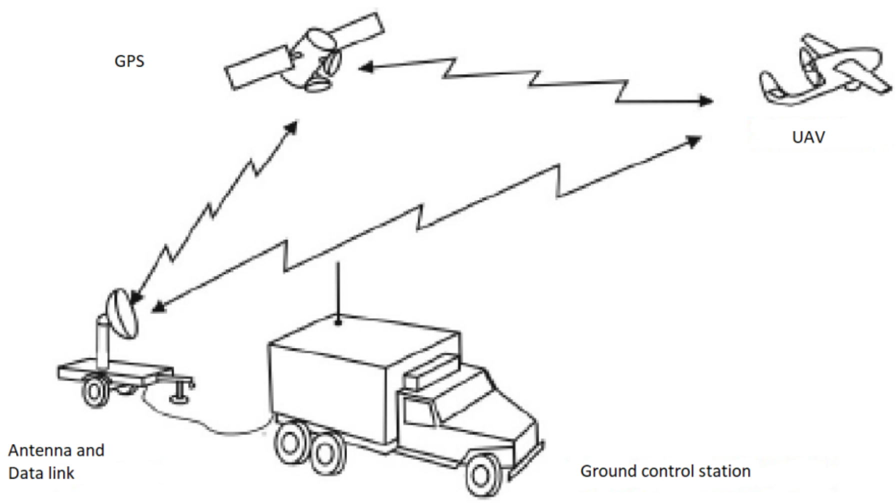


Figure 8: UAS composition [6]

An example of UAS can be a coordinated swarm of UAVs communicating between each other and the GCS for example using LTE (4G) communications system.

We are going to explain the concept of a coordinated swarm of drones in the next chapter but for now let's introduce some reason to do so. The use of swarms instead of single UAV introduce the following advantages:

- complementary team members
- cost reduction
- efficiency
- simultaneous multiple actions

- larger area covered
- improved autonomy and readiness

In this section we made a review of the current application of UAS both in military and civil application, with special regards towards those profile mission suitable for the potential use of an unmanned airship.

Between the range of possibilities, we decided to opt for those ones in which there have been less research nevertheless of the promising advantages a buoyant aircraft can offer.

3.1 UAS: fields of application and state of the art

In this section we made a review of the current application of UAS both in military and civil application (with focus on the latter), with special regards towards those profile mission suitable for the potential use of an unmanned airship. Drones for hobbyists will not be discussed.

UAS features may vary depending on the application in order for them to fit their specific tasks. Therefore the classification of UAVs needs to take into consideration their various features as they are widely used for a variety of civilian operations [6].

With respect to operational altitude they are usually divided in Low Altitude Platforms (**LAP**) and High Altitude Platform (**HAP**). For UAVs used as an aerial base station in communication networks, the two categories are shown in Figure 9, while in Figure 10 some key parameters of each platform are proposed

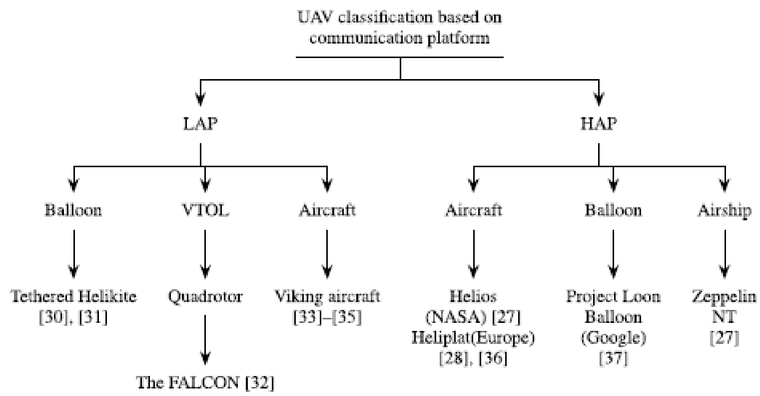


Figure 9: Classification based on operational altitude of UAV used for communication networks. [6]

Issues	HAP			LAP		
Type	Airship	Aircraft	Balloon	VTOL	Aircraft	Balloon
Endurance	long endurance	- 15-30 hours JP-fuel - >7 days Solar	Long endurance Up to 100 days	Few hours	Few hours	From 1 day To few days
Max. Altitude	Up to 25 km	15-20 km	17-23 km	Up to 4 km	Up to 5 km	Up to 1.5 km
Payload (kg)	Hundreds of kg's	Up to 1700 kg	Tens of kg's	Few kg's	Few kg's	Tens of kg's
Flight Range	Hundreds of km's	From 1500 to 25000 km	Up to 17 million km	Tens of km's	Less than 200 km	Tethered Balloon
Deployment time	Need Runway	Need Runway	custom-built Auto launchers	Easy to deploy	Easy to launched by catapult	Easy to deploy 10-30 minutes
Fuel type	Helium Balloon	JP-8 jet fuel Solar panels	Helium Balloon Solar panels	Batteries Solar panels	Fuel injection engine	Helium
Operational complexity	Complex	Complex	Complex	Simple	Medium	Simple
Coverage area	Hundreds of km's	Hundreds of km's	Thousands of km's	Tens of km's	Hundreds of km's	Several tens of km's
UAV Weight	Few hundreds of kg's	Few thousands of kg's	Tens of kg's	Few of kg's	Tens of kg's	Tens of kg's
Public safety	Considered safe	Considered safe	Need global regulations	Need safety regulations	Safe	Safe
Applications	Testing environmental effects	GIS Imaging	Internet Delivery	Internet Delivery	Agriculture application	Aerial base station
Examples	HiSentinel80 [38]	Global Hawk [39]	Project Loon Balloon (Google) [37]	LIDAR [32]	EMT Luna X-2000 [40]	Desert Star 34cm Helikite [30]

Figure 10: Platform classification of UAV types, and performance parameters. [6]

As can be seen in figure 8, UAS uses different kind of propulsion and power source:

- Aero fuel and Combustion engines
- Solar panels and electric motors
- Battery and electric motors

- Fuel cells

For this this work we will focus on the duo Batteries-electric motors.

The biggest problem for this kind of UAS is the battery capacity and therefore the maximum achievable endurance of the UAV. The battery specific energy density is way lower than other kind of energy sources. In figure there are some examples of technological properties of modern batteries

#	Model	W_{to}/g [kg]	W_e/g [kg]	W_{bat}/g [kg]	W_m/g [kg]	Pm [kW]	e [Wh/kg]	p [W/kg]
1	ElectroLight 2 [13]	315	188	34	7.0	19.4	163.2	795.6
2	LAK-17B FES [14]	550	246	32	7.3	35.3	131.3	910.9
3	Lange Aviation Antares 20E [15]	660	440	77	29.1	42.0	136.0	794.0
4	Lange Aviation Antares 23E [15]	850	496	77	29.1	42.0	136.0	794.0
5	Pipistrel Taurus Electro G2 [16]	550	253	42	11.0	40.0	113.1	952.4
6	UAV Factory Penguin BE [17]	21.5	9.83	4.41	0.650	2.7	145.0	807.1
7	Yuneec International E430 [18]	470	157	74	19.0	40.0	153.7	801.0
8	Silent 2 [19]	300	200	36	8.5	13.0	113.9	792.4

Figure 11:database of electrically propelled aircraft already flying [7]

In order to deal with batteries poor performance, modern UAS are prone to use a coordinated swarm of UAVs [8]: when one flying UAV is low on battery, it can be substituted by another aircraft Figure 12. Using two or more UAVs, if the mission profile allows to do so, it can be possible to use them alternatively with multiple changes of on board batteries, as shown in Figure 13

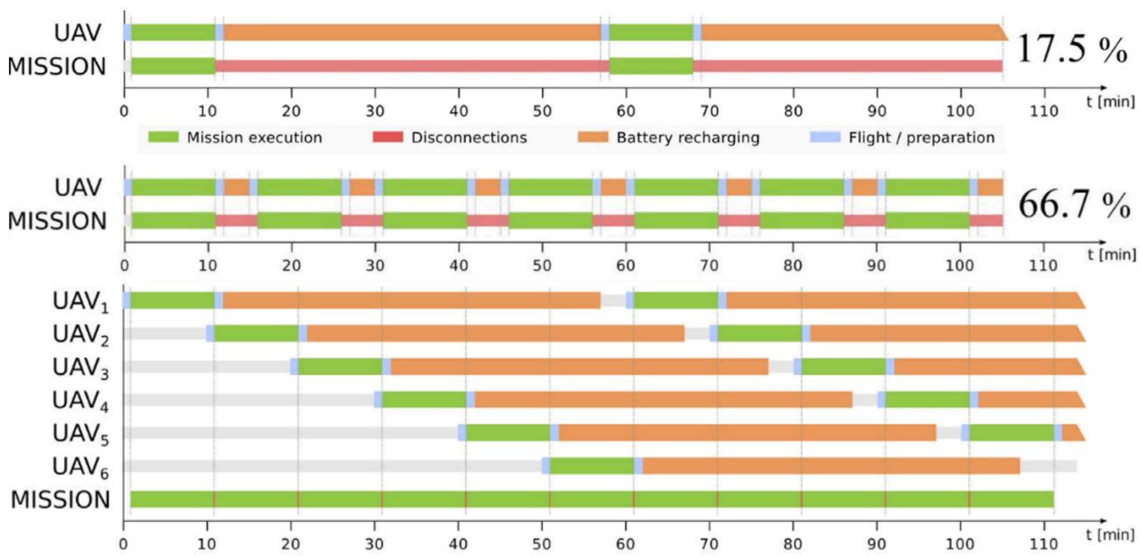


Figure 12: endurance extension using a swarm of UAVs with battery recharging [8]

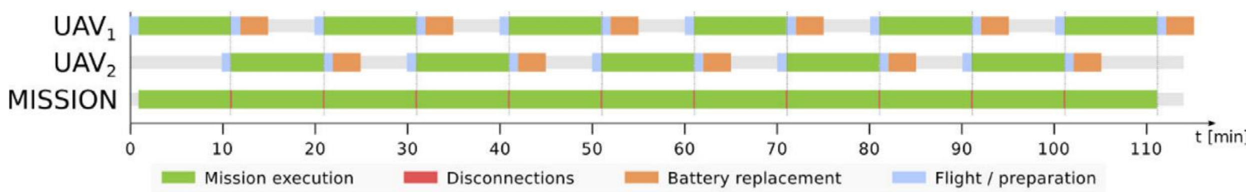


Figure 13: multi-UAV mission with battery replacements. [8]

As shown in the pictures above, the mission can be fully covered both with the use of multiple UAVs and battery recharging, or with just two fling machines and multiple batteries, the latter being effectively possible only for those kind of mission with the UAV not far from the operator.

Both the approaches, while permitting a total coverage of the required endurance, leads to increase costs and complexity: other than the obvious cost increase due to the number of UAVs and batteries there is the necessity of a much more sophisticated algorithm in order to make the swarm fly as a coordinated one, and this complexity brings an extra cost.

We have seen in the previous chapter that airships outperform other flying vehicles for low speed efficiency and endurance. So we bring the crucial question:

Can we design a single Airship UAV capable of achieve the same tasks a swarm of other UAVs can do?

Before responding to this crucial question, we need first to analyze the current fields of application of UAS and chose between the ones that best matches the characteristics of a buoyant vehicle.

3.2 Military application

The military have been the first to research and deploy UAS, and are now used for a multitude of mission profiles, as summarized in Figure 14.

Figure 14

Figure 14: various application of UAS in Military contest [9]

For the triple D roles it is necessary a deeper explanation:

- Dangerous rules: flight over highly fortified zones. The loss of an Unmanned Vehicle is more acceptable with respect to the death of the capture of the onboard crew
- Dirty rules: this can be military or civil applications, such us monitoring chemical or nuclear contaminated environment. They can also spray dangerous substances

- Dull rules: long, uninterrupted surveillance can cause fatigue and loss of concentration in the inboard crew, so an unmanned vehicle with HD cameras and sensors can be an ideal solution.

3.2.1 LTA UAS in military application

Stability qualities of LTA unmanned aerial platforms directly favored the quality of the data provided by sensors (EO-IR, atmospheric, radar, CBRN sensors) that made it possible to carry out C4 (Command, Communication, Control, Computer) or ISR (Intelligence, Surveillance and Reconnaissance) military missions, such as border security, surveillance of ports, infrastructure protection etc. [3] .

According to literature [3], for aerostats the most important uses are

- High Performance Systems Testing and Sensors (i.e. JLENS program, see Figure 15)

Figure 15: airborne aerial platforms, a. JLENS program, b. REAP aerostat [3]

- Framework for ISR missions as a real-time PGSS (Persistent Ground Surveillance System) for force protection and FOB (Forward Operating Bases) protection, threat detection system for long term ISR missions

For propelled airships the majority the modern fields of application are

- Airborne C4-ISR low-altitude overhead for the development of the Air Force Rapid Response capability
- Flight Demostrator for long and high altitude ISR (i.e. HALE-D aiship)
- Low-cost concept (i.e. Hi-Sentinel) for military security missions (communication relay and border protection)

Figure 16: current examples of unmanned military airships, a. HALE-D, b. Hi-Sentinel [3]

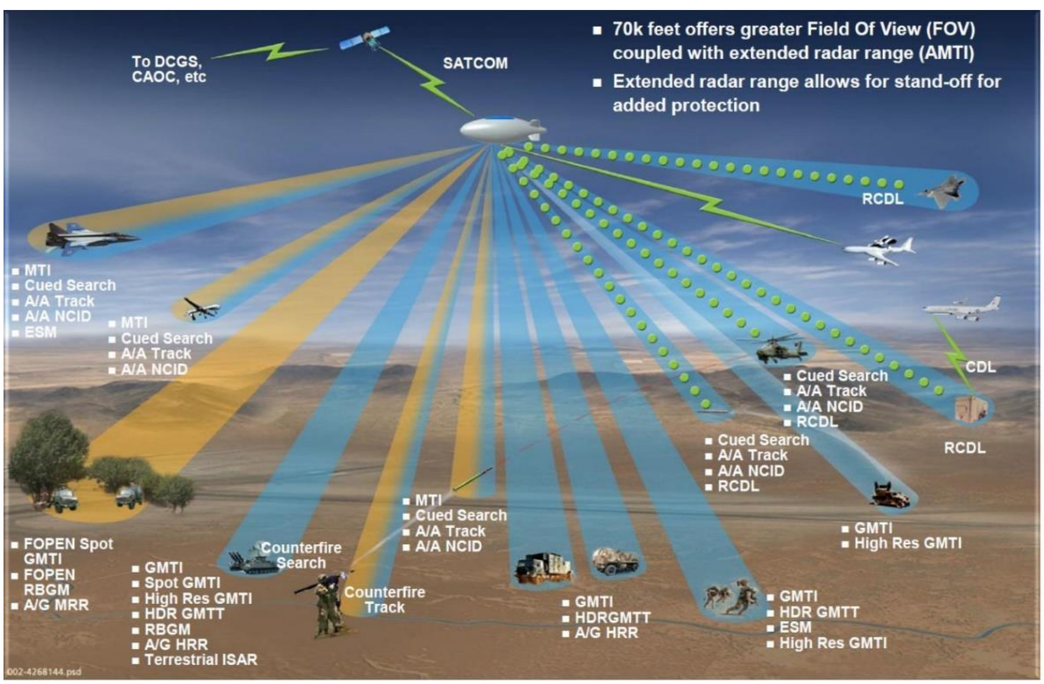


Figure 17: Example of LTA Vehicle Applications in ISR Mission Set [10]

3.3 Civil applications

In this chapter, the main civil application fields for UAS [6] are discussed (see Figure 18: civil application of UAS), with an in-dept view of those profiles of mission particularly suited for airships.

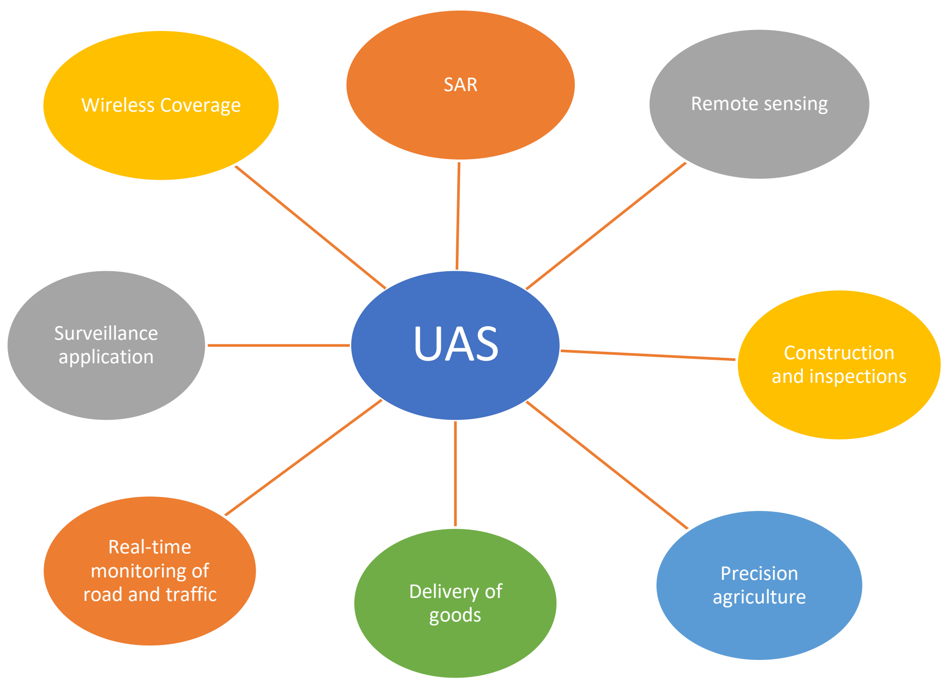


Figure 18: civil application of UAS (data from [6])

According to the PwC report [11] [6], the forecast of 2027 for the addressable market value of UAV uses is over $127 billion. Civil infrastructure is expected to dominate the addressable market, with an estimated value of $45 billion (see). In a report released by the Association for Unmanned Vehicle Systems International, is reported a forecast of more than 100000 new jobs in unmanned aircraft field by 2025 [12].

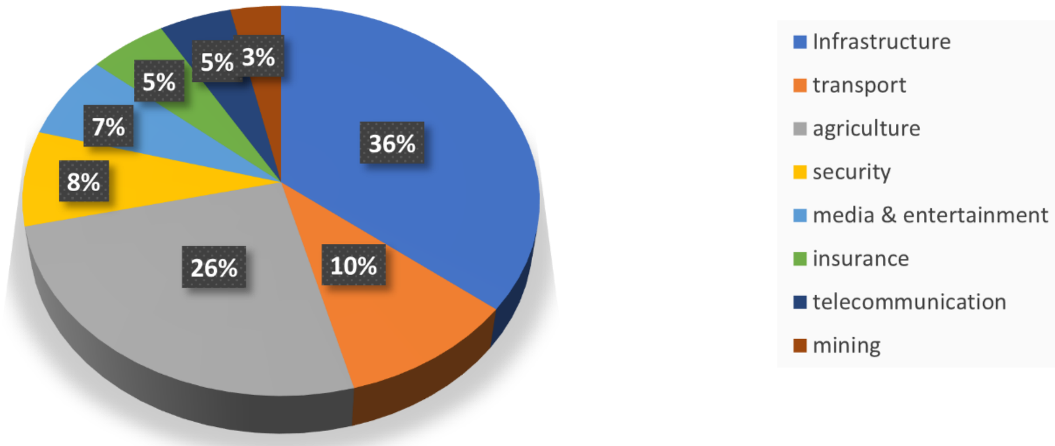


Figure 19:Percentage of market share between key industries (data from [11])

In order to better comprehend the requirements of the market, an analysis of the typical payload nature is required too. According to a report made by GlobalData in 2017 [13], the payload market is dominated by radars and communication equipment, with a market share close to 80%, followed by cameras and sensor segment with around 11% and weaponry segment with almost 9% (Figure 20). From this analysis, all payloads not coming from the industrial market (i.e. the water used for irrigation in precise agriculture), are neglected.

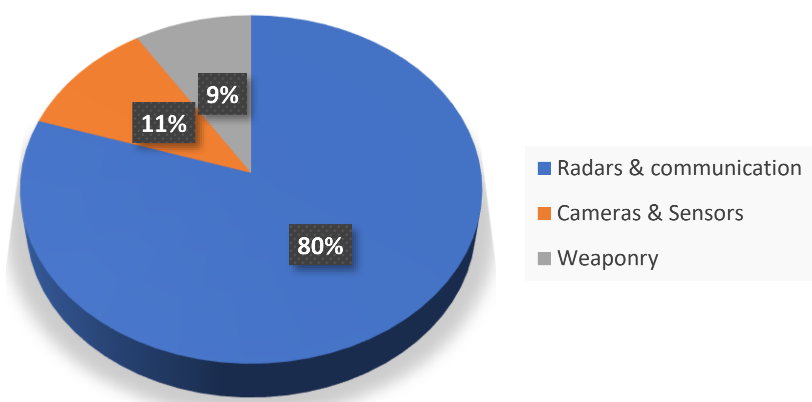


Figure 20: Global UAV payload market predictions 2027 (data from [13])

The nature of the dominant payload smiles to the possibility of utilizing LTA UAS: in fact radars, cameras sensors and communication equipment consists in fixed weight payload. This is a really important aspect, because makes even conventional airship design well suited to carry this kind of payload without any complication such as the necessity of ballasts.

Table 2 types, costs, and applications of the most diffused UAS types are summarized

UAS type	Pros	Cons	Application	Price range (US$)
Fixed-wing	Large area coverage	Inconvenient launch and landing price	Surveying, structural inspection, SAR	$20.000-$150.000
Rotary-wing (helicopter)	Hover flight Increased payload	Price	Aerial inspection, supply delivery, precision agriculture	$20.000-$150.000
Rotary-wing (multicopter)	Availability (price) Hover flight	Low payload Low endurance	Aerial inspection, filmography, photography	$3.000-$50.000

Table 2: UAV types, applications, costs [14]

Regarding the price of the single UAS, the tendency for professional application is a general decrease in prize (Figure 21: ASP Commercial vs Consumer droneFigure 21); this is due to the low level of maturity and diffusion of this kind of technology.

Figure 21: ASP Commercial vs Consumer drone [15]

3.3.1 Search and Rescue (SAR)

For this kind of mission, LAP multicopters and fixed wing aircraft are mostly used, usually arranged as swarms, following a path transmitted by the ground Control System.

The typical payload for this kind of mission is usually composed by

- RGB and IR cameras (research)
- first aid med kits, food supplies (rescue)

it is worth noting, that for the pure research task, the payload is constant over time, so no variation in BR is achieved in LTA vehicle.

The main difficulties of this application are:

- legislation: the use of a swarm of UAVs is not always allowed
- hostile weather condition
- limited endurance (specially for multicopters)

LTA vehicles have not been significantly used in this field. However, comparing the typical mission tasks with for example the one found in environment monitoring, we could suppose that using airships could lead to the following vantages and disadvantages

Vantages:

- higher endurance
- better data quality (low vibrations)

Disadvantages:

- slow speed

- maneuverability
- wind sensitivity

We can conclude that using a swarm of unmanned airships or blimps could greatly increase endurance of both single UAV and the entire swarm, but also makes it more weather condition dependent (unless “large” airships are used).

A great solution could be the use of both LTA and Rotary wing UAVs coordinated by a ground control station , as proposed by *Connie Phan* and *Hugh H.T. Liu* [16] of University of Toronto for wildfire detection; this would combine the possibility to scan a wide area for a long time thanks to the great endurance of the LTA vehicle with the ability to perform precise punctual observation with multicopters thanks to their superior mobility and control (see Figure 26). This kind of approach is discussed more deeply in the next paragraph.

3.3.2 Remote sensing and environmental monitoring

In this field of application both HAP and LAP are used according to the specific type of monitoring. Multicopters, fixed wing UAVs, airship and balloons have been successfully used.

The typical payload consists usually in sensors, both active (laser altimeter, radar, etc) and passive (accelerometer, RGB or thermal cameras, etc.)

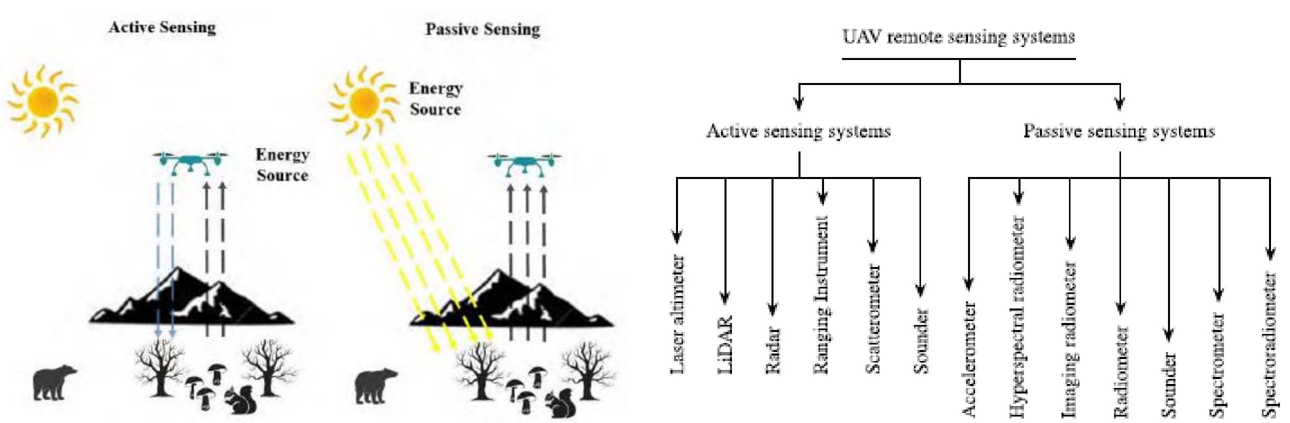


Figure 22: active and passive sensors [6]

The main challenges for this application are:

- Hostile natural environment: the mission could be done in hazardous environments such as extremely low temperature (de-icing capabilities, isolation of the avionics, etc.) [17] or volcanic plumes (resistance to electromagnetic interference, corrosion, debris collision) [18];
- Camera issues: the current UAV digital cameras are designed are not designed for remote sensing, tend to be too bulky to be used with lightweight

UAV and cameras specifically designed for UAVs may not meet the required scientific benchmarks [19] ;

- Illumination issue: can cause critical problems for the automated image matching algorithms in both triangulation and digital elevation model generation;
- Endurance: monitoring mission always come with long time of flight battery weight and charging time are critical issues that affect the duration of UAV missions. This aspect is critical for rotary-wing aircraft;

In the last 30 years, blimp and airships have been used for remote sensing and environmental monitoring due to their characteristics [20] [21] [22]. A confrontation with other types of aircraft is shown in Figure 23 [20]

Project requirement	*Airplane*	*Helicopter*	*Airship*
Low operation cost	✓✓	✓	✓✓✓
Long endurance	✓✓	✓	✓✓✓
Hovering capability	✓	✓✓✓	✓✓✓
Payload to weight ratio	✓✓	✓	✓✓✓
High maneuverability	✓✓	✓✓✓	✓
Low noise and turbulence	✓	✓	✓✓✓
Vertical take-off and landing	✓	✓✓✓	✓✓✓
Low fuel consumption	✓✓	✓	✓✓✓
Low vibration	✓✓	✓	✓✓✓

Figure 23: qualitative performance of various types of UAVs [20]

For this task, high quality data, long endurance and the lowest interference with the surrounding environment are extremely valuables characteristics [20]. A buoyant vehicle is naturally favored by its ability to float in air with the minimum possible use of motors and propellers, major vibration makers. Considering the literature, it seems that conventional, non-rigid airships have been preferred over hybrid designs, probably thanks to the constant weight payload and the necessity of long-time hovering [20] [22].

One of the pioneer projects was the *Autonomous Unmanned Remote Monitoring Robotic airship ("AURORA")*, developed starting from late 1990s by *Automation Institute of the Universidade de Campinas, Information Technology Center.*

	AURORA I	AURORA II	AURORA III
Mission duration [h]	1-2	8	>24
Distance [Km]	1-10	10-50	>100
Payload [Kg]	10	50	>100

Table 3: AURORA project phases [20]

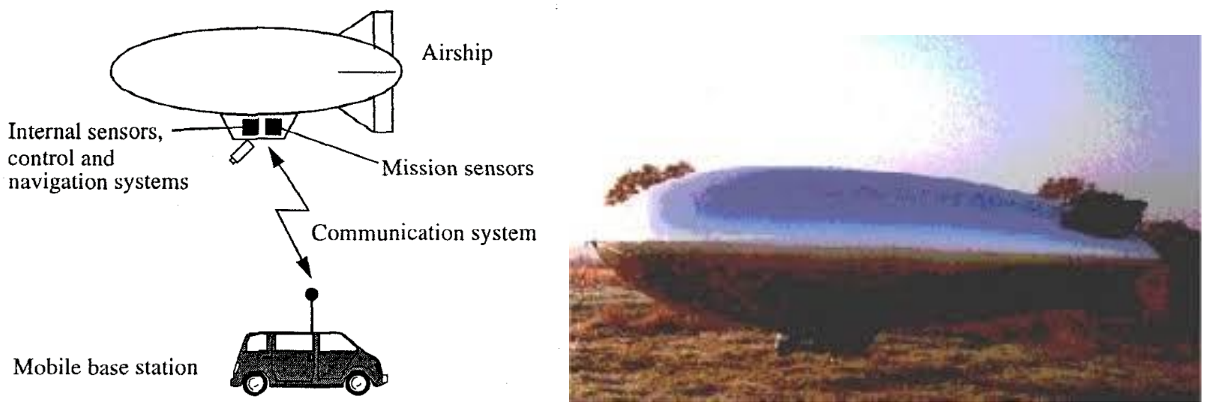


Figure 24: AURORA I project components (left); AURORA I airship: Airspeed Airship's AS800 (right) [20]

A more recent project is the area mapping platform developed by *Czech Technical University in Prague* based on the *ACC15X airship* [23]. It as a conventional non rigid design, and achieve the required maneuverability and stability level mainly through the use of thrust vectoring. It has autonomous navigation capability thanks INS / GPS navigation unit (iMAR iTracer – F200). The payload is composed by a laser scanner (SICKLD-LRS1000) with conical modification, digital camera in the visible spectrum (Olympus E-PM1) and thermometric professional camera (FLIR SC645). For logging data is used industrial computer Stealth LPC-125LPM. All components are mounted on one platform close to each other to prevent inaccuracies due to torsion of construction.

Figure 25: ACC15X airship (left); payload (right) [24]

In order to increase the performance of the UAS, a mixed swarm composed by LTA and HTA UAVs can be used, as suggested in the aforementioned publication of *Connie Phan* and *Hugh H.T. Liu* [16]. The core of the proposed solution is the capability of the ground control station to coordinate the various unmanned vehicles for completing the tasks. The blimp gives to the system the capability of long time monitoring and the ability to collect high quality visual data, while the rotary wing UAVs and the UGVs can perform ‘punctual’ inspection only when and where needed, exploiting their high maneuverability and control.

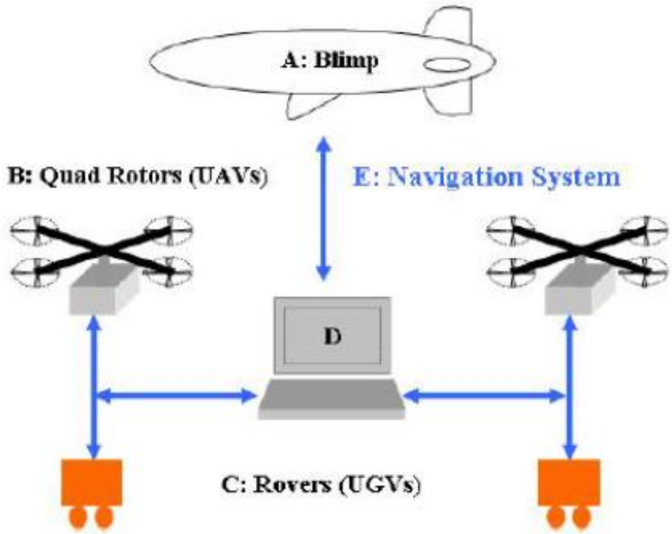


Figure 26: the UAV-UGV combination proposed by Connie Phan and Hugh H.T. Liu of University of Toronto [16]

As a conclusion, we can sustain that LTA aircraft are probably the best possible aerial vehicle for absolving these tasks in a wide variety of scenarios.

3.3.3 Infrastructure inspection

This sector is the knowing the largest expansion between professional civil application, forecasted to cover alone almost half the market for such kind of UAS.

Figure 27 summarize the different deployments of UAS for construction and infrastructure. At date of this work, it seems only HTA aircraft, both fixed and rotary wing, have been used. In

Table 4: example of UAV used in costruction and structure inspections some examples of current used UAVs are reported.

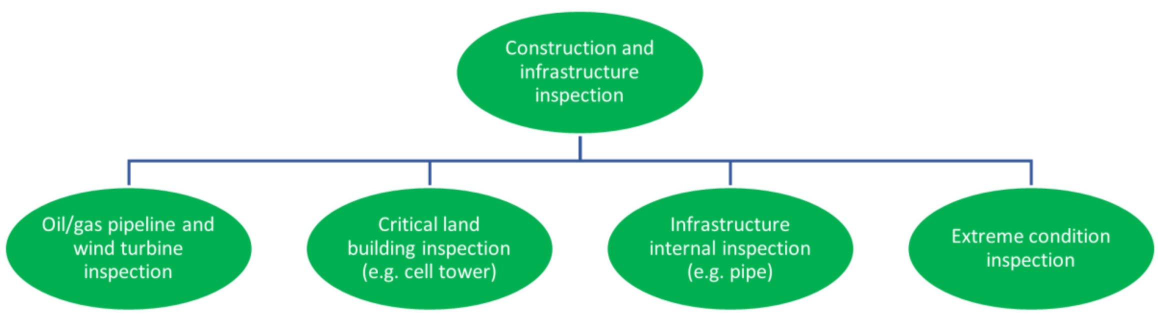


Figure 27: The deployment of UASs for construction and infrastructure inspection

UAV type	Applications	Payload/alt./end.	Sensor Type	References
AR. Drone French Company Parrot	Enhance safety on construction sites with real-time visual view	N.a. / 50m / 12min.	On-board HD camera , Wi-FI connection	[25]
MikroKopter L4-ME Quadcopter	Vertical inspection for high rise	500 g / 247 m / 13-20 min.	Laser scanner	[26]

	infrastructures (street lights, GSM towers, etc.)			
Fixed wing aircraft	Sketchy inspection, identify the defects of the power transmission lines.	Less than 3 Kg / 500 m / 50 min. (50 km)	TIR cameras, GPS	[27]

Table 4: example of UAV used in costruction and structure inspections [6]

The on-board loads could include optical wavelength range camera, TIR camera, different type of sensors such as gas detection, GPS, etc.

The main challenges faced in this field are:

- Limited energy available in flight, meaning short flight time and limited processing capabilities;
- Limited payload capabilities
- Lack of research to multi-UAV cooperation
- Necessity to allow autonomous UAV that can maneuver an indoor environment without GPS signal

No research was found about current application of LTA vehicles to structural inspection. This was quite surprising considering the great endurance an airship could offer. Probably this is due to higher level of maneuverability required on this type of missions.

3.3.4 Precision Agriculture (PA)

UAVs can be utilized for Croop management and monitoring, weed detection, irrigation scheduling, irrigation, disease detection, pesticide spraying and gathering data from ground sensors [6]. The deployment of UAVs in PA is a cost-effective and time saving technology which can help for improving crop yields, farms productivity and profitability in farming systems. Moreover, UAVs facilitate agricultural management, weed monitoring, and pest damage, thereby they help to meet these challenges quickly. in Table 5 a qualitative comparison with manned aircraft and satellite-based systems is presented [6].

Issues	UAVs	Manned Aircraft	Satellite System
Cost	Low	High	Very High
Endurance	Short-time	Long-time	All the times
Availability	When needed	Some times	All the times
Deployment time	Easy	Need runway	Complex
Coverage area	Small	Large	Very large
Weather and working conditions	Sensitive	Low sensitivity	Require clear sky for imaging
Payload	Low	Large	Large
Operational complexity	Simple	Simple	Very complicated
Applications and usage	Carry small digital, thermal cameras & sensors	Spraying UAV system pesti-cide spraying	high resolution images for specific-area

Table 5: comparison between UAVs, traditional manned aircraft, and satellite-based system for PA [6]

The possible applications in PA are summarized in Figure 28; as shown, the possible missions can be with in-flight variable payload, i.e. irrigation (i.e., 30% of rice fields have been irrigated using Yamaha RMAX [15]), or payloads that maintain a constant. The mission of the second type are mostly equal to environment monitoring missions.

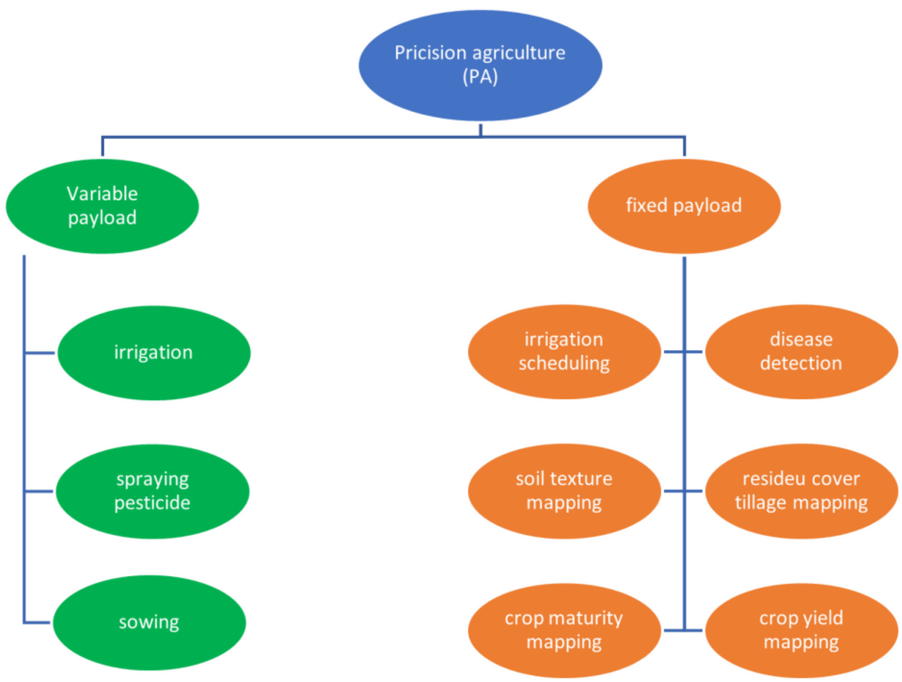


Figure 28: PA application divided by nature of the payload

UAV Type	Applications	Payload/Altitude/Endurance	Sensor Type
Yamaha Aero Robot "R-50.	Monitoring Agriculture, spraying UAV systems.	20 kg / LAP / 1 hour.	Azimuth and Differential Global Positioning System (DGPS) sensor system.
Yanmar KG-135, YH300 and AYH3.	Pesticide spraying over crop fields.	22.7 kg / 1500m / 5 hours.	Spray system with GPS sensor system.
RC model fixed-wing airframe.	Imaging small sorghum fields to assess the attributes of a grain crop.	Less than 1kg / LAP / less than 1 hour.	Image sensor digital camera.
Vector-P UAV.	Crop management (e.g. winter wheat) for site-specific agriculture, a correlation is investigated between leaf area index and the green normalized difference vegetation index (GNDVI).	Less than 1kg /105m-210m/1-6 hours deepening on the payload.	Digital color-infrared camera with a red-light-blocking filter.
Fixed-wing UAV.	Detect the variability in crop response to irrigation (e.g. cotton).	Lightweight camera/ 90m / Less than 1 hour.	Thermal camera , Thermal Infrared (TIR) imaging sensor.
Multi-rotor micro UAV.	Agricultural management, disease detection for citrus (citrus greening, Huanglongbing (HLB)).	Less than 1kg / 100 m / 10-20 min.	Multi-band imaging sensor, 6-channel multispectral camera.
Vario XLC helicopter.	Weed management, reduce the amount of herbicides using aerial images for crop.	7 kg / LAP / 30 min.	Advanced vision sensors for 3D and multispectral imaging.
VIPtero UAV.	Crop management, they used UAV to acquire high resolution multi-spectral images for vineyard management.	1 Kg / 150 m / 10 min.	Tetracam ADC-lite camera, GPS.

Table 6: some examples of UAS currently used in PA [6]

From the examples reported in Table 6 is clear that both fixed and rotary wing are currently employed, ranging from small multicopters carrying payloads lighter than 1 kg for a maximum flying time shorter than 15 minutes to big fixed wing and helicopter able to lift more than 20 kg and fly for several hours.

Considering the nature of the mission with constant weight it is quite surprising that LTA vehicles are not currently used for those applications. Looking at the typical mission requirements we can conclude that the airship capable of performig such mission should not differ very much from those developed for monitoring missions.

3.3.5 Delivery of goods

This particular area of UAS deployment does not particularly fit LTA vehicle, principally because:

- Extremely precise movement capability required
- Necessity to maneuver in small spaces and consequently necessity of smaller UAVs

Therefore, this field will not be deeply analyzed in this work.

3.3.6 Surveillance and traffic monitoring

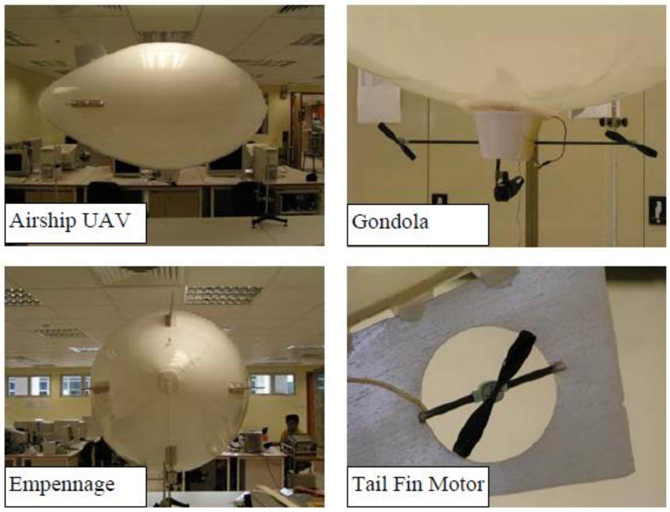
UAS are currently widely used for surveillance and security both outdoor [28] [29] and indoor [30] [31]. In table Table 7 advantages, disadvantage and concerns about the use of UAS in surveillance are listed

Advantages	Surveillance coverage, range improvement; Better safety for human operators; Robustness and efficiency in surveillance;
Disadvantages	High accidental rate ; High operating costs ; Difficulties in surveillance of risk society;
Concerns	Co-operation of multi-UAVs; Post-processing algorithm improvements; Privacy concerns; Law enforcements;

Table 7: advantages and disdvantages of UAS usage for traffic monitoring

For this applications, LTA UAS used are both large, high altitude LTA vehicles and small, low altitude platforms. The most appreciate characteristics of buoyant aircraft for mission of this kind is their long endurance, stability, low level of noise and low level of vibration.

In figure Figure 29 are reported 2 examples of small, low altitude UAV airships, the first one developed by *National University of Singapore* for outdoor employment [32], the second expressly designed for autonomous indoor navigation [30] *by Southern Federal university, Russia.*



Parameter	Value
Envelope volume	5.2 m3
Length	3.78 m3
Envelope mass	2.5 kg
Equipment mass	3.7 kg
Buoyant gas	Helium
Inertia moments:	
Jx	3.67 kg·m2
Jy	6.27 kg·m2
Jz	4.63 kg·m2
Aerodynamics:	
Cx	0.011
Cy	0.013
Cz	0.19

Figure 29: (top) UAV airship for patrolling of National University of Singapore [32]; (bottom) indoor use airship with parameter values [31]

For traffic monitoring UAS are cost-effective and can monitor large continuous road segments [33]. In figure 30 typical traffic monitoring tasks for UAV deployment are listed.

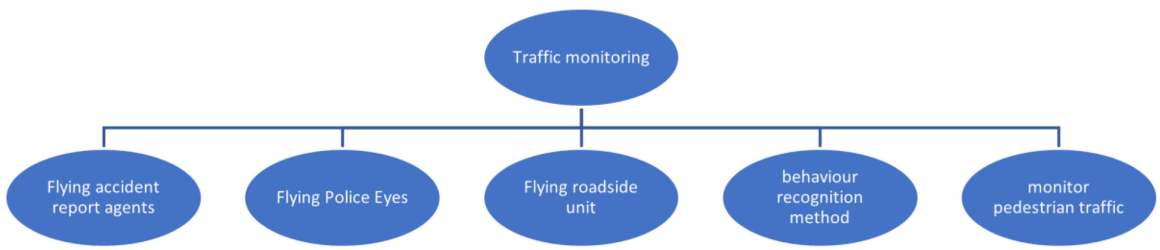


Figure 30: traffic monitoring applications

We can conclude that these mission profile strictly resemble any other monitoring mission, so LTA vehicles well fit this area of deployment

3.3.7 Wi-Fi coverage and communication

UAS can be used to provide wireless coverage during emergency cases where each UAV serves as an aerial wireless base when the network signal goes down i.e. after a natural disaster [14]. They can also be used to supplement the ground base station in order to provide better coverage.

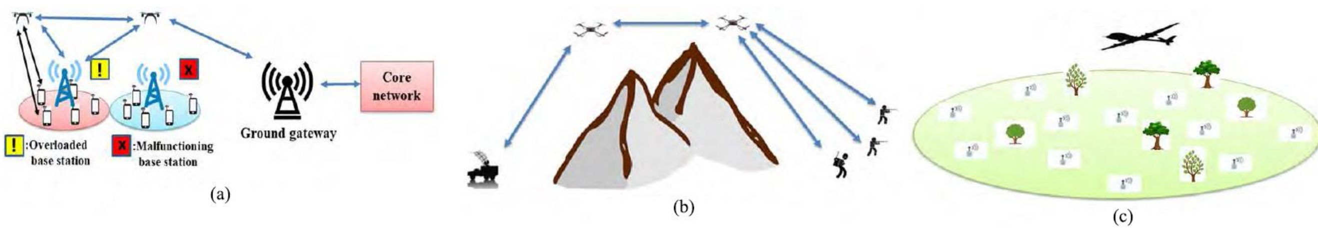


Figure 31: (a) UAVs as network gateways; (b) UAVs as relay nodes; (c) UAVs for data collection [6]

The UAV employed in this application should have big endurance and high energy reserve in order to supply the transmitting antennas on board with adequate power for the entire mission. LTA vehicles seem well fitted for this application, with tethered balloons being the most cheap and efficient solution for those application where the UAV does not need to move, while airship with high BR could be used to reach areas difficult to access.

4. Mission choice

Considering the fields of application discussed above, it is clear that many of these has pretty similar application. In particular LTA vehicles performs particularly well in all monitoring and fixed payload application. So, the most promising areas of deployments seems to be:

- Environmental monitoring and remote sensing;
- Precision agriculture;
- Inspection of structure;
- Surveillance and traffic monitoring;
- Wi-Fi covering and communication.

All these applications have similar mission tasks, require several hours spent in the air, gathering high quality data; the payload consists for mainly in sensors, thus its weight remain constant during the flying. This last aspect makes almost totally buoyant vehicles particularly suited for the task, because there is no need to largely vary the total lift in order to compensate the changing weight of the payload.

Considering the similarity for all these missions, it seems possible to develop a platform optimized for one particular mission, but able to perform in another fields with few modification (i.e. swapping between sensors sets)

Possible critical aspect of this kind of application are:

- hostile environment: i.e. volcanic ashes, corrosive gasses, strong winds, intense magnetic fields;
- instruments positioning and integration;
- possible necessity to periodically store the airship in hangar (even unattended by any operator).

For environmental monitoring, there are decades of research on how to use electrically powered unmanned airship [20] [21], such us the AURORA project [20], and the response is unanimous: LTA are probably the best vehicles for the tasks.

The same platforms could be used for precise agriculture, traffic monitoring and communication, with the latter being accessible both by conventional airships and aerostat.

The surveillance application well fit LTA vehicles too, but requires generally a more high capability of maneuverability and trajectory control. This too aspects are analogous to the requirements in structure inspection. Nevertheless, no current use of LTA in this area seems to happen. The reason could be:

- The fact that the use of LTA UAVs does not brings real advantages;
- No one have already invested energy on this path.

As said above, considering how similar the tasks are between the two application it seems the second option is the most probable, especially looking at the speed of development of UAS technology.

As conclusion we decided to take the less explored path, trying to test airships possibility in the field of structure inspections.

4.1 Dimensioning mission

We choose a powerline inspection for corrosion performed by Raecon Industries in 2017 across the Strait of Georgia, British Columbia, Canada [34]. The old powerline to inspect spanned from the mainland, 2.4 miles across the strait of Georgia, to an uninhabited island. The goal of the inspection was to determine whether the line needed to be replaced or not. They also inspected all the marker balls for hotspot. The entire mission was carried out in just one working day and the UAV was operated from the deck of a boat.

The crew of Raecon Industries was a three-man team:

- The project manager and pilot of the drone;
- A ground observer monitoring privacy, safety and trafline;
- A lineman performing the inspection via live video and completing the documentation

The UAV chosen for the mission was the MD-4 1000, a multi-copter manufactured by Microdrones®, shown in Figure 32; some of the UAV specification are posted at page 54.

Other than the small amount of time available for performing the mission, the operators faced other difficulties:

1. The powerline was very high over the sea level, placed between 750 and 1800 ft, and as a consequence the crew on the boat could almost not see it;

2. The weather was particularly harsh, with wind gusts up to 25km/h and sunlight reflected by water that could interfere with the images taken by the camera ;

3. Both take-off and landing had to be performed on the deck of the boat;

4. The strait was heavily trafficked;

5. The Payload was quite heavy for the multi-copter;

6. Environment protection law: in British Columbia, if the drone crashes and sinks in the ocean, the operators would be liable in environmental lawsuits; as a consequence the crew considered to put pool noodles on the drone, then opting for just maintain the boat underneath and fetch the UAV in case something happened

Figure 32: Microdrones MD-4 1000, on next page the UAV specifications [35]

MD-4 1000 key specs	
Number of rotors	4
Max flight time	88 minutes*
Max speed	12 m/s
Control system	Remote Control
GPS	Yes
Automatic landing	No

Battery	
Capacity	13000 mAh
Type	Lithium Polymer
Controller	
Frequency	2.4 GHz
Range	500 m

The mission was performed correctly in the available time and the client highly pricing the quality of the data gathered, judging them way better than that taken from a manned helicopter used in a previous inspection [34].

However a serious consideration over the drone endurance it is necessary; the combination of heavy payload and strong winds dramatically reduced the flying time from the declared **88 minutes** (see **Errore. L'origine riferimento non è stata trovata.**) **to 25-27 minutes.** The flying time was divided as follow:

- 3-5' for climbing from the boat to the power line
- 2' for positioning the UAV
- 12' for the inspection
- 5-7' for the descent.

Each time the on-board crew replaced the exhausted battery with a charged one before the MD-4 could take of again. This presents the second scenario reported in Figure 12, with only one flying UAV and a set of already charged batteries. Even considering the battery is replaced almost instantly, thus considering it negligible, the time spent to perform the mission is less than 50% of the total flight time.

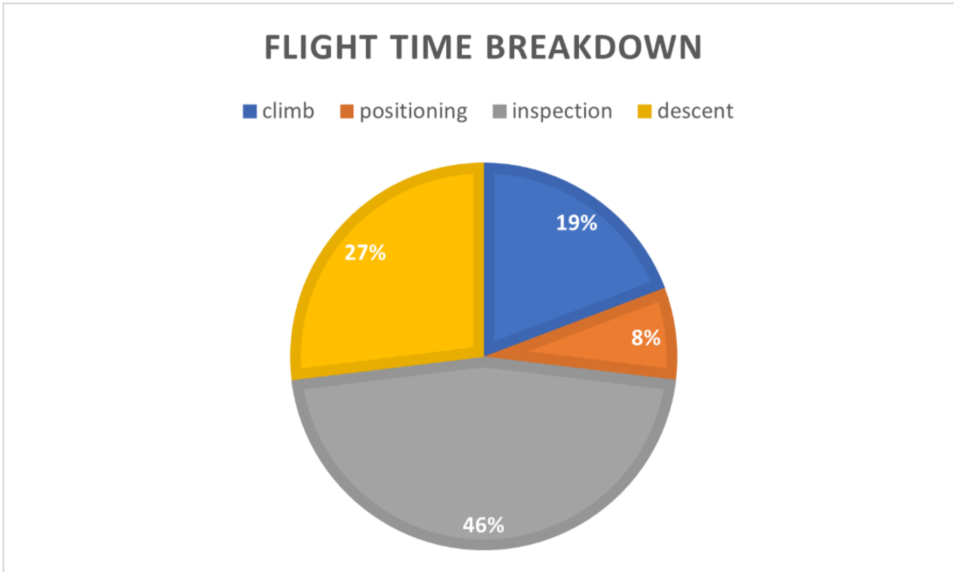


Figure 33: percentage of the flight time divided between the different parts of the mission [34]

This data could be improved by using at least 2 UAVs, but in order to do so another pilot should be added to the crew or the UAS should have had autonomous flight capability. Both these two scenarios would have increased the costs or complexity of the mission.

We decide to set our goal high: can we design an unmanned airship capable of doing the entire mission with the same identical condition with only one take-off and one landing?

5. Preliminary design

In this part of the thesis the preliminary design of the UAV is carried out, not considering other parts of the whole UAS (possible ground control station, controller, software).

The first step is to analyze the mission requirements and from them:

- Create an index of merit of differ characteristics
- Chose the LTA layout (conventional airship, Hybrid, baloon)

After the identification of priorities in the characteristics the real dimensioning algorithm is carried out. the process itself is an adaptation of the sizing algorithm for conventional airships presented by **Grant E. Carichner** and **Leland M. Nicolai** [2]**.** Most changes between the cited method and the one used here are due to the different source of energy used: internal combustion engines and aero-fuel for the first one, electrical motors and lithium-ions batteries for the second.

Mass of antennas and other onboard systems are estimated from literature

5.1 Mission characteristics and design consideration

In paragraph 514.1 the dimensioning mission is deeply described. In Table 8: mission requirements the main requirements are summed up.

Powerline length	3.9 km
Fling altitude	0 – 600m asl
Wind speed (gust)	7 m/s
Take- off and landing	From a small boat deck
Payload	Optic sensors (RGB high resolution camera, infra-red camera)
Time limit	One working day
Crew for the mission	3

Table 8: mission requirements

In order to perform the mission, the airship should be able to climb up to the powerline in a reasonable amount of time, at least comparable or slightly higher than the climbing time of the multicopter originally used to perform the mission.

Considering the original mission was characterized by take-off and landing performed from a boat, the target UAV will be very small for airship standards, so a non-rigid design would probably be the best option. In addition, a non-rigid design could allow the airship to be deflated and inflated at necessity of deployment, meaning it could be way easier to store and transport between location.

To inspect correctly the structure, the UAV have to be sufficiently maneuverable to get in the right position around the powerline as fast as possible and stable enough for gathering high quality data. In particular it has to be able to stay almost stationary even in condition of the aforementioned wind speed.

Considering the height over the water of the powerline, and how the flight time was distributed in the original mission (see Figure 33: percentage of the flight time divided between the different parts of the mission), a UAV with high endurance would likely reduce both duration and complexity of the mission.

Finally, the payload is fixed, so there is no need of greatly varying the aerodynamic lif.

From all this consideration we can compile the following table for all the indexes of merit:

Importance	**Low**	**Moderate**	**High**
Maneuverability			
Low vibration			
Controllability			
Speed			
Climbing speed			
Endurance			
Portability			
Variable lift			
Hovering			

Table 9: qualitative index of merit for the chosen mission

Starting from the low importance of highly adjustable aerodynamic lift and speed, and the high priority of hovering capability and endurance, **a conventional design seems favorable over a hybrid one**.

The necessity to maximize time endurance and hovering capability also suggests using a **high value of BR**. Nevertheless, a very high BR reduces descending speed and landing abilities

The necessity of high maneuverability and controllability during hovering impose to maneuver and stabilize using **vectorial trust instead of aerodynamic control surface**. This scenario seems to adapt well to a multi-motor, tailless layout [22].

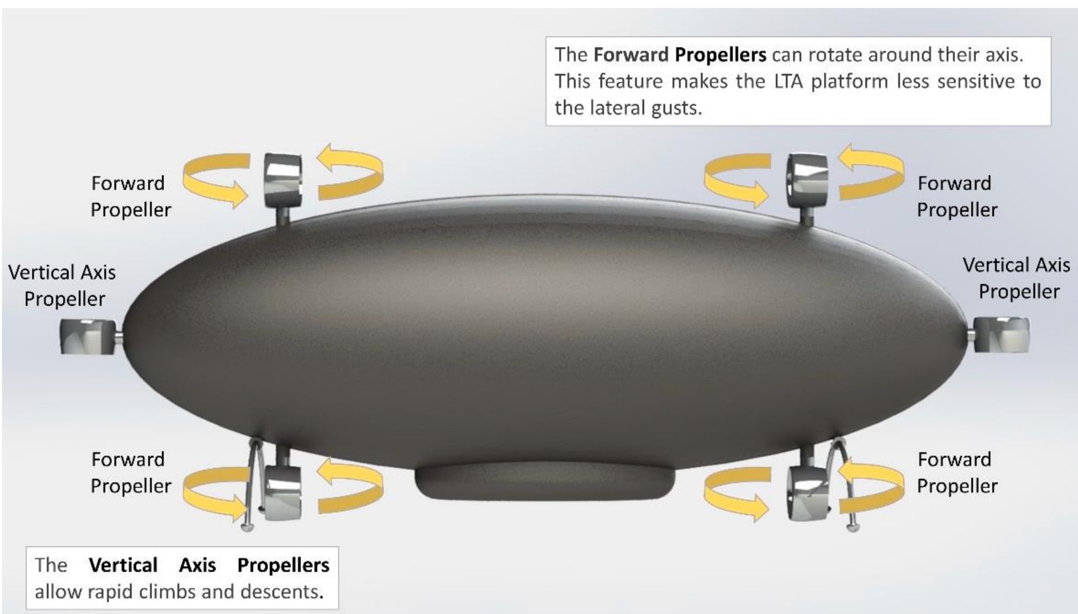


Figure 34: tailless design proposed by Piero Gili, Marco Civera, Rinto Roy and Cecilia Surace of Politecnico di Torino for area mapping [22]

Nevertheless small tail surfaces can help stabilize the UAV in strong winds with less effort from the control system and motors (weather-cock stability), with a large reduction on energy consumption so we decided in first instance to combine both tail stabilizing fin and control surfaces with thrust vectoring engines. A qualitative analysis between fixed wing, rotary wing, conventional airship and tailless, thrust vectoring design is reported in Figure 35: Comparison between various types of UAV

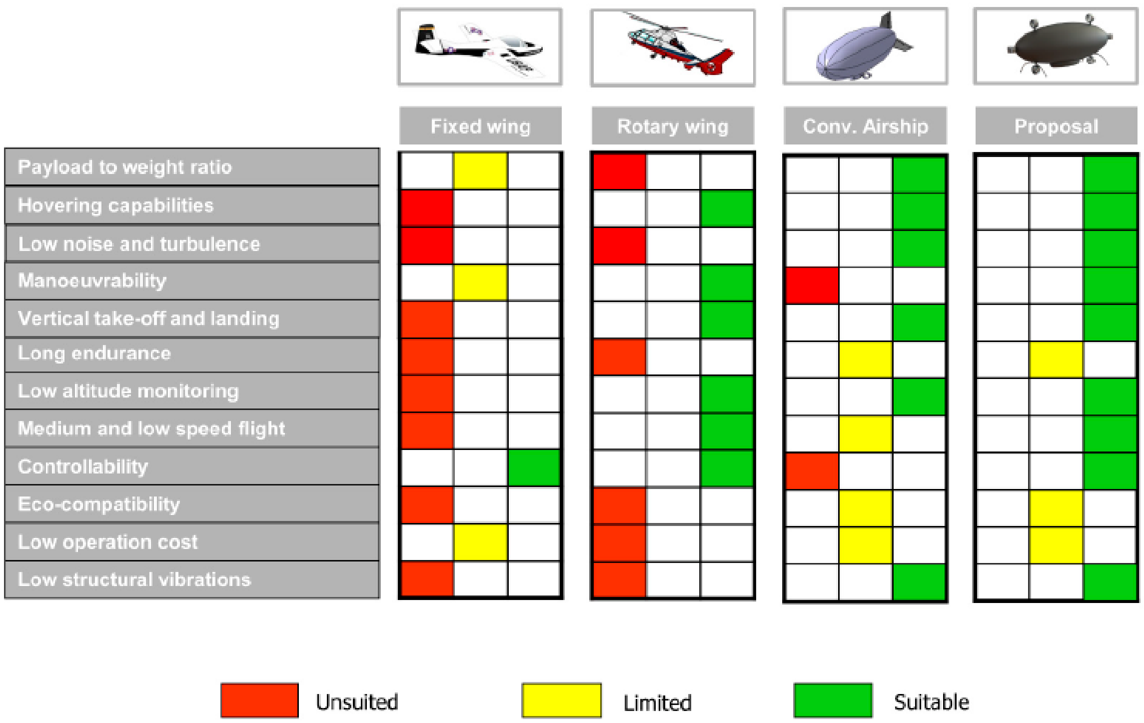


Figure 35: Comparison between various types of UAV [22]

5.2 Algorithm modification

In figure Figure 36 and Figure 37 the Carichner-Nicolai algorithm and the one used for the dimensioning in this work are summed up.

As said at beginning of Chapter 5, some adjustments and adaptation were necessary, both for the unmanned nature of our project and the different source of energy and power. In fact, we opted for the battery-electric motor combination instead of the internal combustion engine and aero fuel.

Another adjustment was dictated by the different profile of the dimensioning mission: the first algorithm designs an airship meant to fly at cruise speed for the majority of the time spent in the air and, as a consequence, the range is the main requirement for endurance; in our scenario, the UAV will hover around specific position in order to inspect the structure, so the flight time has been set as the critical aspect for endurance, and after the estimation of the total energy and power required, a check on the operational range is performed.

Another aspect that allowed us to modify the original algorithm is the fixed BR that characterize the combination of a fixed payload and an electric UAV: in fact the weight of our airship remain constant over the entire mission and so does the buoyant lift making the Buoyancy Ratio constant (BR_{Land} = BR_{TO}= BR) for the entire flight, meaning there is one variable less. On this base we decided to opt for an iterative process based on the different between an estimator of BR and his target value. The original algorithm used instead two different estimates of the final weight, one coming from the endurance requirement, the other from the calculation of all systems and main components weight: then the difference between the two estimators goes to zero, the convergence is obtained.

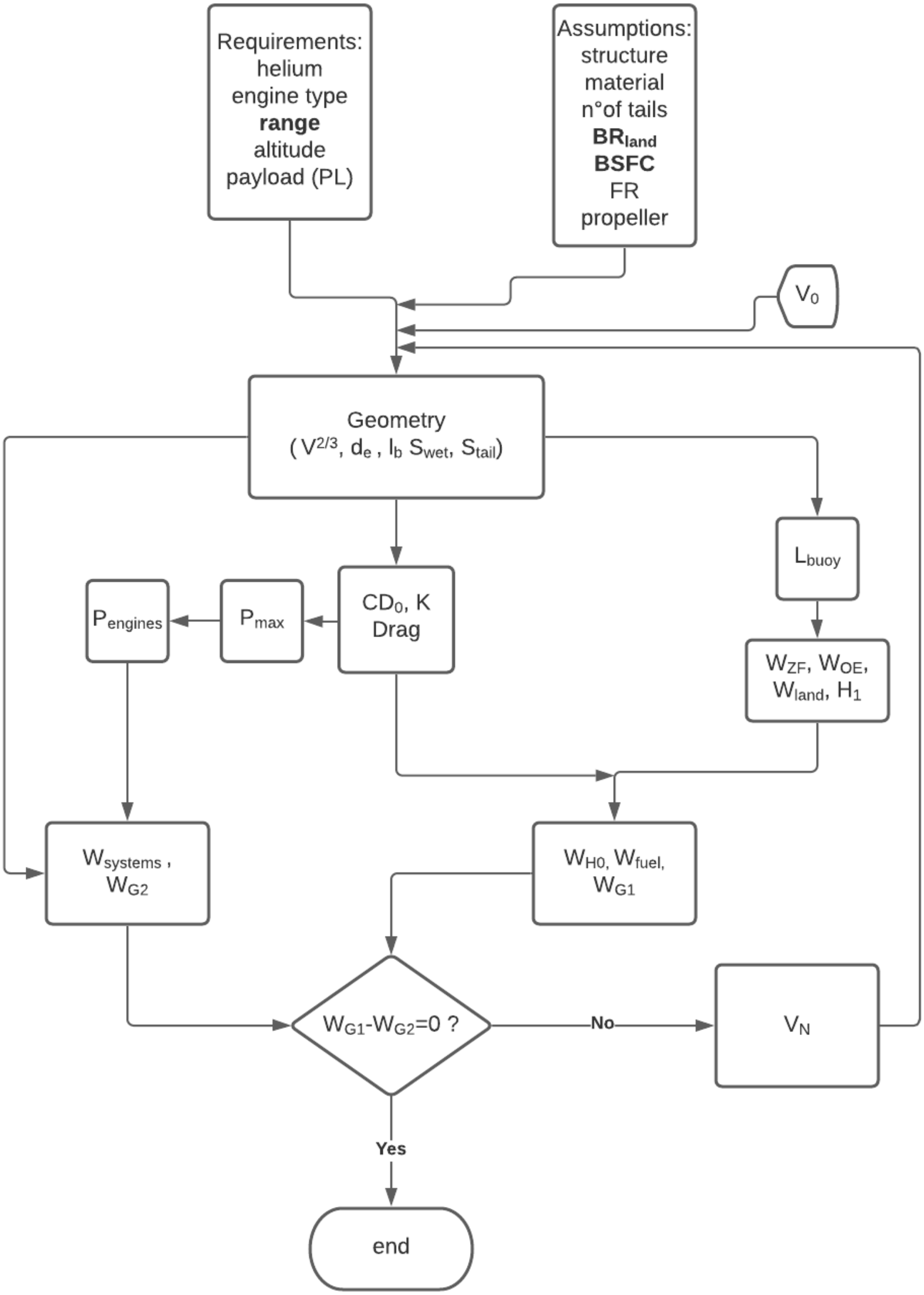


Figure 36: original Charichner-Nicolai algorithm

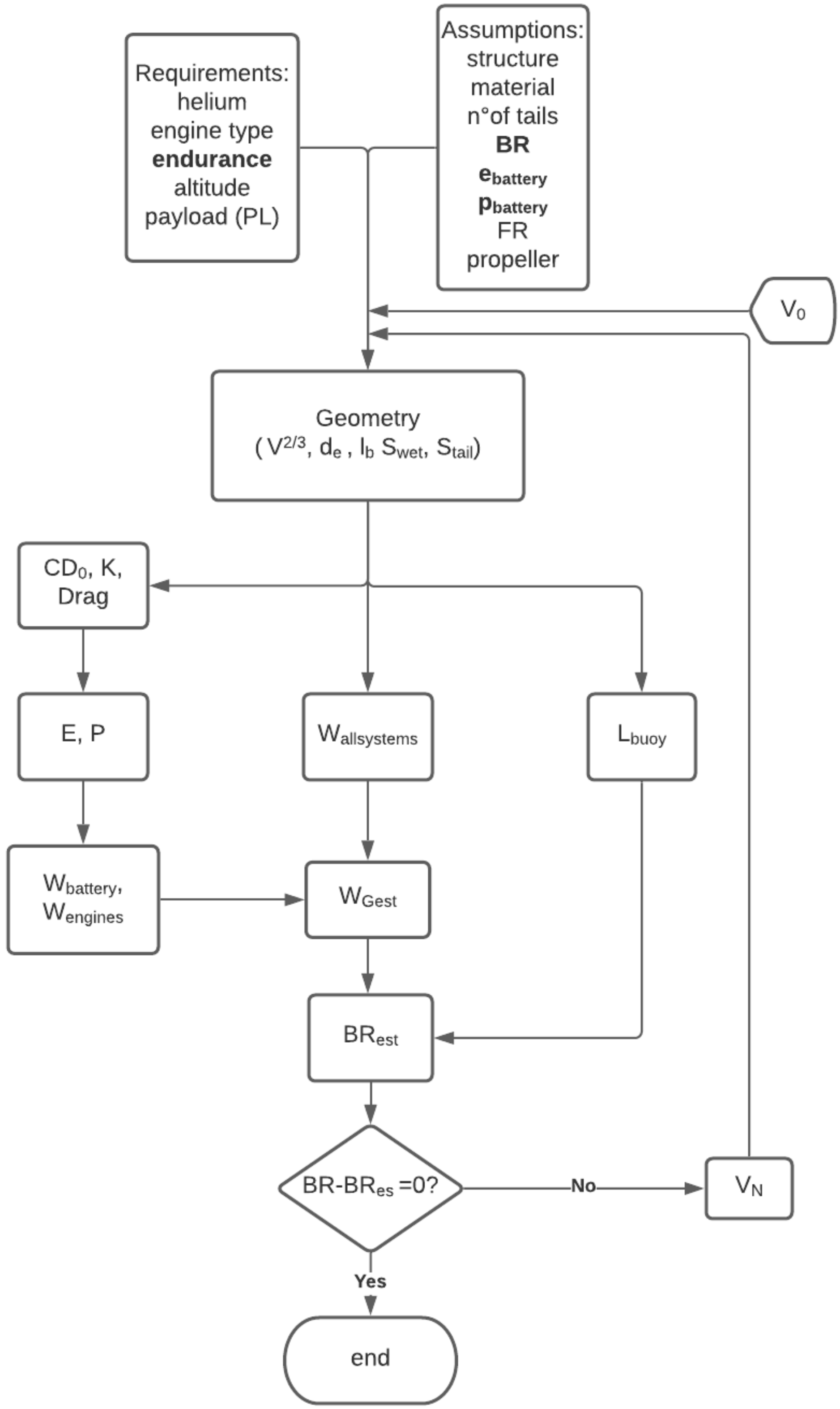


Figure 37: modified algorithm for electrically powered - fixed payload airships

5.3 The sizing process

Optimizing performance (endurance, range, speed, etc.) for an airship is a complicated trade study that includes several new variables. The trade study process is virtually identical to that required for winged aircraft. These variables include volume (buoyant lift), body cross-section, shape, envelope material properties, amount of buoyancy or buoyancy ratio (BR), and size of ballonets.

After choosing the main layout of the airship in the previous chapter (traditional type, non- rigid, thrust vectoring, electrically propelled), the second step is to set some parameters (summarized in Table 10.) with respect of the mission requirements. Energy and power density of batteries, power-to-weight ratio of electric motor , envelope material density and strength (Figure 38) are estimated from the literature.

Payload [23]	1.080 kg [23]	**Cruise speed**	6 m/s
Endurance (wind)	5 h	**Max speed**	12 m/s
Max altitude	3000 m	**Range**	>4 km
Cruise altitude	600 m	**Buoyant lift He@98%**	1.034786 Kg/m^3

Table 10: mission parameters

Energy and power density of batteries, power-to-weight ratio of electric motor , envelope material density and strength (Figure 38) are estimated from the literature.

	Motor		**Battery**	
Model	**W [kg]**	**P [kW]**	**e_m [Wh/kg]**	**p_m [W/kg]**
ElectroLight2	34	19.4	163.2	795.6
LAK-17B FES	7.3	35.3	131.3	910.9

Lange Aviation Antares 20E	29.1	42.0	136.0	794.0
Lange Aviation Antares 23E	29.1	42.0	136.0	794.0
Pipistrel Taurus ElectroG2	11.0	40.0	113.1	952.4
UAV Factory Penguin BE	0.650	2.7	145.0	807.1
Yuneec International E430	19.0	40.0	153.7	801.0
Silent 2	8.5	13.0	113.9	792.4

Table 11: Database of electrically propelled aircraft already flying [7]

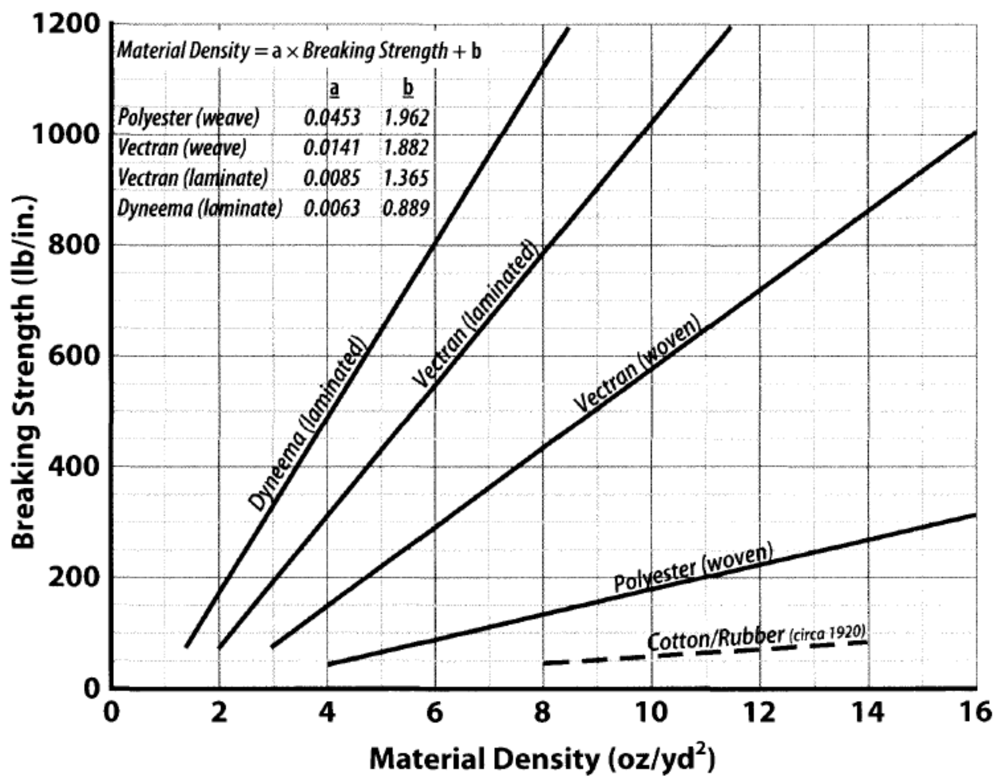


Figure 38: Hull fabric strength to weight [2]

For the choice for the shape, we opted for a Prolate Spheroid Body of Revolution (BoR), principally for drag reduction and for the more wide literature database available for this particular shape. Finally, considering the nature of the payload and the high requirement on endurance, we opted for a highly buoyant vehicle (high BR); the assumed parameters are listed below:

- N° of lobes =1 ⇒ NL=2
- $BR_{TO} = BR_{Land} = 0.95$;
- $e_m = 163.2$ [Wh/kg];
- $p_m = 795.6$ [W/kg];
- $\eta_{pro} = 0.75$;
- FR=3;
- N° of tail surfaces = 4;
- Tails arrangement = "+"

The choice of the Fitness Ratio (FR) needs a bit of explanation. FR is defined as:

$$FR = \frac{l_b}{d_e} \qquad with \begin{cases} l_b \coloneqq body\ lenght \\ d_e \coloneqq diameter\ of\ the\ BoR \end{cases}$$

the lower is the FR, the higher is the ratio between buoyant lift and envelope surface, that is minimum for a sphere (FR=1); however, for typical Reynold's number values during cruise flight, the value of the CD_0 increase for small values of FR (Figure 39). So lower FR are more suited for low speeds, where drag reduction is less critical, because it leads to a lighter airship.

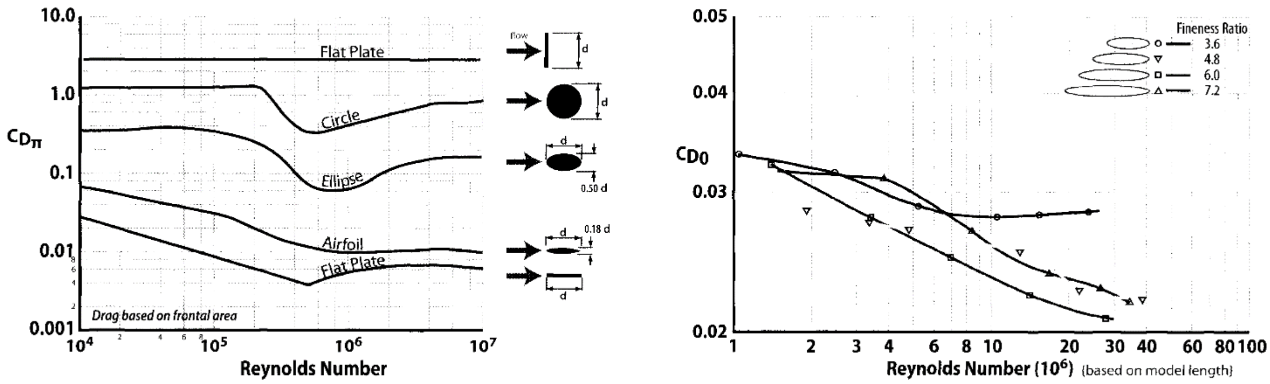


Figure 39: (left) 2-D drag coefficients variation with Reynolds number; (right) CD0 plotted with respect to Re and FR. [2]

Another important consideration regards flight condition and endurance. Between the mission requisites there is no indication on mean wind speed, so we set it close to the maximum gust speed over the mission, a quite severe and conservative choice, that will greatly effect the energy needed to perform the mission.

5.4 The sizing process: iterative algorithm

Here below the sizing algorithm. All formulas and notation is taken from [2] at chapter 11; some coefficients and constant terms could differ from the original equation due to the different measuring units (imperial measurement system for the book, IS for this work).

1. Assume an initial volume V_0, it does not have to be very close to the final value. Further iteration will assume new volumes based on the difference between the calculated and target BR. When this difference goes to zero the solution is exact.
2. Calculate $V^{2/3}$. Given the FR and the number of lobes, the equivalent diameter d_e , body length l_b and the aspect ratio AR are calculated

$$d_e = \left(\frac{6 * V}{\pi * FR}\right)^{\frac{1}{3}}$$

$$l_b = FR * \ d_e$$

$$AR = \left(\frac{4 * d_e}{\pi * l_b}\right)$$

3. Calculate the body surface S_{wet} assuming the shape of a prolate ellipsoid

$$S_{wet} = \pi \left(\frac{{l_b}^p * {d_e}^p + \ {l_b}^p * {d_e}^p + \ {d_e}^p * {d_e}^p}{3}\right)^{\frac{1}{p}} \quad with \quad p = \ 1.6075$$

4. Estimate tail coefficient C_{HT} and $C_{VT}$from literature [24] [36]

5. Assuming the moment arm l_{tail} is 38% of l_b [2], calculate the tail surfaces

$$S_{HT} = C_{HT}\left(V^{2/3}\ l_b\right)/l_{tail}$$

$$S_{VT} = C_{VT}\left(V^{2/3}\ l_b\right)/l_{tail}$$

where tail coefficient C_{HT} and C_{VT} are estimated from literature [2] [24] [36]

6. Calculate the dynamic pressure at cruise condition q_c

$$q_c = 0.5\ \rho\ {v_c}^2$$

7. Assume no laminar flow (conservative condition). Find the Re for the body and the friction coefficient $C_{f_{body}}$

$$Re = \rho v l_b/\mu$$

$$C_{f_{body}} = 0.455/(log_{10}(Re))^{2.58}$$

Calculate the form factor for body drag

$$FF_{3Dbody} = 1 + \frac{1.5}{FR^{1.5}} + \frac{7}{FR^3}$$

Zero lift body drag is:

$$C_{D0_{body}} = FF_{3Dbody}\ C_{f_{body}}\ S_{wet}\ /V^{2/3}$$

8. Given the thickens ratio of tail surfaces t/c , the drag coefficient of the tails is

$$FF_{tails} = 1 + 1.2\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4$$

Assuming the aspect ratio $AR_{tail} = 1.0$

$$\bar{c}_{tail}(avg) = (AR_{HT}S_{HT}/2)^{1/2} + (AR_{VT}S_{VT}/2)^{1/2}$$

$$Re_{tail} = \rho v \bar{c}_{tail}/\mu$$

$$C_{f\,tail} = 0.455/(log_{10}(Re))^{2.58}$$

$$S_{wet_{tails}} = 2.2(S_{HT} + S_{VT})$$

$$CD_{0_{tails}} = \frac{FF_{tails}C_{f\,tails}S_{wet_{tails}}}{V^{\frac{2}{3}}}$$

9. CD_0 for gondola, engines, cooling, mounting structure and landing gear are

$$CD_{0_{gondola}} = (0.108\,CD_{0_{body}}V^{\frac{2}{3}} + 7.7 * 0.092903\,)/V^{\frac{2}{3}}$$

$$CD_{0_{engines}} = 4.25\;\,n_{engines} *\; 0.092903/V^{\frac{2}{3}}$$

$$CD_{0_{cooling}} = \;\, n_{engines}\,(2 * 10^{-6}\,V/35.31 + 4.1)\;\;\, 0.092903/V^{\frac{2}{3}}$$

$$CD_{0_{mount}} = (0.044\,CD_{0_{body}}V^{\frac{2}{3}} + 0.92 * 0.092903)/V^{\frac{2}{3}}$$

$$CD_{0_{LG}} = \left(1.76 * \frac{10^{-6}V}{35.31} + 0.92\right) * \frac{0.092903}{V^{\frac{2}{3}}}$$

10. Interference drag coefficient is

$$CD_{0_{int}} = (4.78 * 10^{-6} V)/V^{\frac{2}{3}}$$

11. Calculate the total zero-lift drag coefficient

$$CD_{0_{ecm}} = CD_{0_{engines}} + CD_{0_{cooling}} + CD_{0_{mount}}$$

$$CD_0 = C_{D0_{body}} + CD_{0_{tails}} + CD_{0_{gondola}} + CD_{0_{ecm}} + CD_{0_{LG}} + CD_{0_{int}}$$

12. The drag-due-to-lift factor, K, is obtainable from Figure 40: drag-due-to-lift coefficient vs aspect ratio (AR) knowing the body aspect ratio (AR). Nevertheless, given mission requirements and assumption, the required aerodynamic lift will be around 5% of the total weight, so it's influence on the total drag is considered negligible.

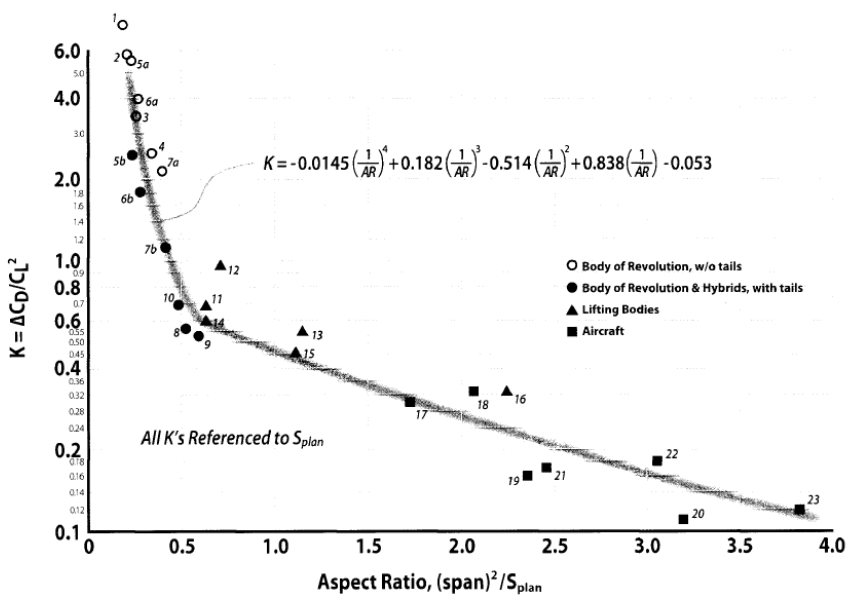


Figure 40: drag-due-to-lift coefficient vs aspect ratio (AR) [2]

13. Considering helium buoyancy for unit volume $L_{buoy_{He}}$

$$L_{buoy} = L_{buoy_{He}} V \sigma_{max} \qquad with \qquad \sigma_{max} = \frac{\rho_{hmax}}{\rho_0}$$

14. From this point the procedure starts to differ from the original algorithm: instead of estimate the operative empty weight, calculate the power in cruise condition, the maximum required power (assumed to be at max speed at sea level).

$$q_c = 0.5\rho_c v_c \qquad | \qquad q_{max} = 0.5\rho_0 v_{max}$$

$$D_c = CD_0 \; q_c V^{\frac{2}{3}} \qquad | \qquad D_{max} = CD_0 \; q_{max} V^{\frac{2}{3}}$$

$$P_{c_{drag}} = D_c v_c \qquad | \qquad P_{max_{drag}} = D_{max} v_{max}$$

$$P_{c_{battery}} = P_{c_{drag}} \eta_{prop} \eta_{eng} \qquad | \qquad P_{max_{battery}} = P_{max_{drag}} \eta_{prop} \eta_{eng}$$

15. Considering battery power and energy density p_b and e_b , after computing the energy needed for the mission, calculate 2 values of the battery weight, one for maximum power and one for total energy required; assume the highest of the two as the new battery weight.

Note that for first iteration the energy needed to reach the cruise altitude is neglected, while from second iteration is estimated from the previous value of the total weight multiplied by the correction coefficient Γ (defined at the end of this process).

$$E = P_{c_{battery}} * endurance \qquad (first\ iteration)$$

$$E = P_{c_{battery}} * endurance + \Gamma W_{g(x-1)} \qquad (iteration\ n°\ x)$$

$$W_{batt1} = \frac{E}{e_b} \qquad W_{batt2} = \frac{P_{max_{battery}}}{p_b}$$

$$W_{batt} = \max(W_{batt1}, W_{batt2})$$

16. Calculate engine power

$$P_{eng} = \frac{P_{max_{battery}}}{\eta_{eng}}$$

17. Knowing the required power for each engine, retrieve engine weight W_{eng} from Figure 41

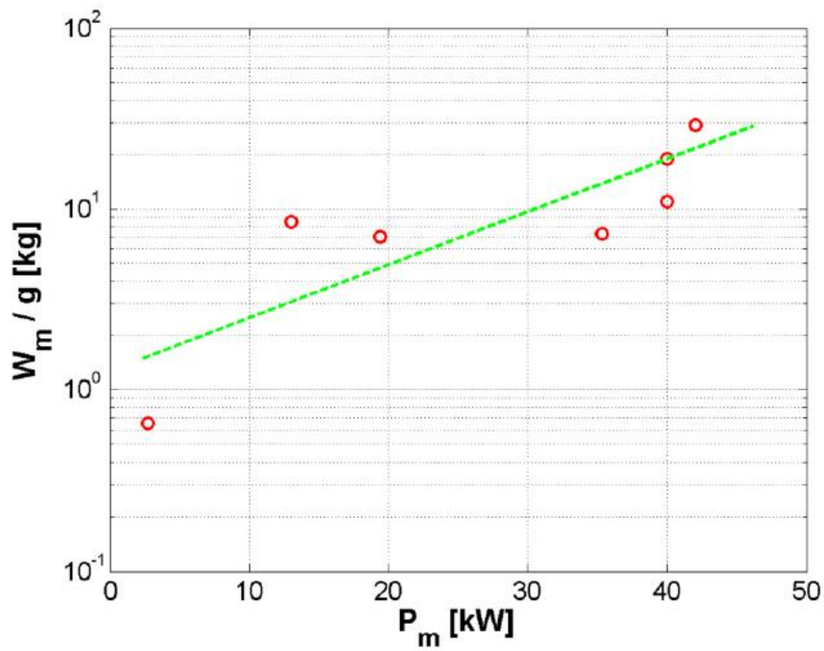


Figure 41: weight vs power for electric engine [7]

The weights of the remaining parts of the airship are defined in the next steps, that are again identical to those reported in [2].

18. Calculate the internal pressure in the hull

$$p_I = 1.2q_{max} + 0.0635d_e$$

19. To calculate the weight of the body fabric, include factors for manufacturing (1.2) and attachments fitting (1.26). Assume envelope and septum materials have the same areal density. Assume a factor of safety (FS)of 4.

$$Load_{hull} = FSp_I\left(\frac{d_e}{2}\right)$$

Retrieve fabric density ($\rho_{hullfabric}$) from literature (Figure 38) and calculate the envelope weight:

$$W_{env} = \rho_{hullfabric} * 1.2 * 1.26$$

Assume there is one septum that has an area equal to 20% of the sideview area. Assume the septum load to be 1.5 grater than the hull load.

$$W_{sept} = \rho_{sept} * (0.2)(\pi htl_b)$$

20. Ballonet weight is calculated for 2 hemispherical ballonets.

$$V_{bal} = V\left(\frac{1}{\sigma_c} - 1\right)$$

$$S_{total} = (4\pi)^{\frac{1}{3}}(3V_{bal})^{\frac{2}{3}}$$

$$W_{ball} = \frac{0.035\, S_{total}}{2.2046}$$

21. Assume a rigid space-frame structure for the tail and consider the area of the control surfaces is 20% of the total area. The F_{PSQ} and F_{AF} coefficients are respectively 1.26 and 1 lb/ft^2. The total weighr of the tail is given by the sum of the stabilizer fin weight and the control surface weight.

$$W_{SSF} = F_{PSQ}(S_{HT} + S_{VT})F_{AF} * 0.8$$

$$W_{CS} = F_{PSQ}(S_{HT} + S_{VT}) * 0.2$$

$$W_{tail} = W_{CS} + W_{SSF}$$

22. Gondola weight considering dimensions of $l = 0.6m$, $w = 0.20$, h =0.20:

$$W_{gond} = \frac{353[(0.32808\, l)^{0.857}\ (w + h) * 0.32808(V * 3.315)^{0.338}]}{2.204}$$

23. Calculate the weight of all the engines and engine mounts

$$W_{all-eng} = n_e W_{eng}$$

$$W_{eng-mt} = 0.57 W_{all-eng}$$

24. Landing gear:

$$W_{LG} = 0 \qquad (first\ iteration)$$

$$W_{LG} = 31.2\left(\frac{W_{G(x-1)}(1 - BR)}{1000}\right)^{0.84} /2.204$$

25. The payload specification are taken from [23] using the same RGB camera, camera lens and IR camera for a total weigh of 1.080 kg.

26. Weight of other on-board systems is taken from [30] and estimated at 2 Kg

27. Sum all the weight components to obtain the total weight W_G

28. Calculate the estimation of BR

$$BR_{est} = \frac{L_{buoy}}{W_g}$$

29. Finally, compute the difference between the BR estimation and the target BR

$$\Delta BR = BR_{est} - BR$$

30. Choose the new value of V and start a new iteration until $\Delta BR = 0$

$$V_x = V_{x-1} - f(\Delta BR)$$

With

$$f(\Delta BR) = 0.5V_{x-1}\left(\frac{\Delta BR}{BR}\right)$$

31. After all calculation is completed, calculate the speed of movement v_m in windy condition (v_w).

$$v_m = v_c - v_w$$

32. Calculate the maximum distance and the operative radius in such condition

5.5 Results analysis

The sizing algorithm converge independently of how close the initial guess of the volume is to the final value, as shown in figure Figure 42. In Table 12 some of the computed results are presented.

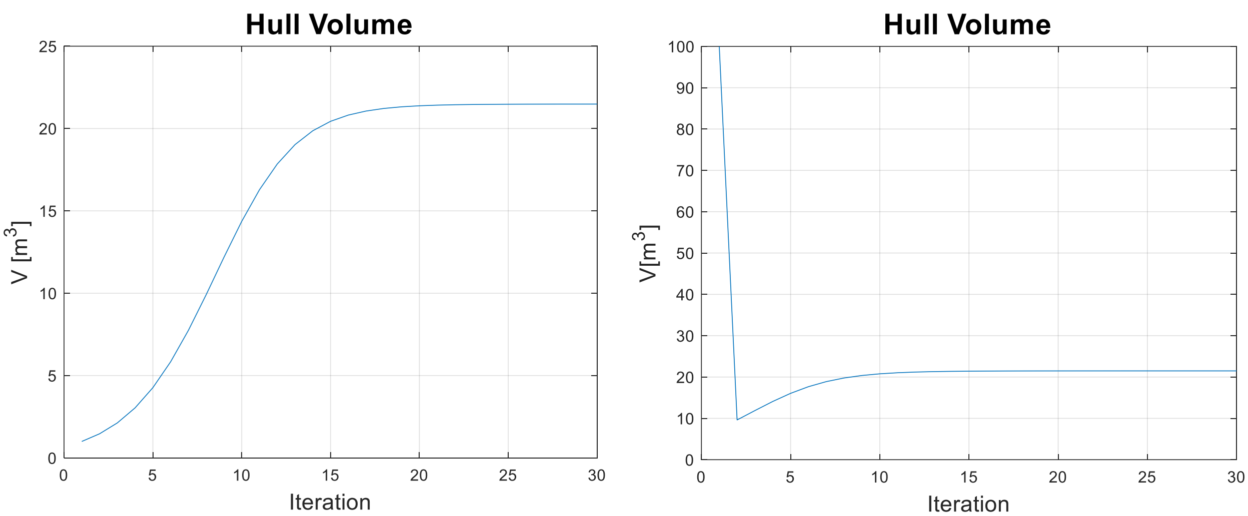


Figure 42: Hull Volume calculation for low value of initial guess (left) and high value (right)

V	21.49 m^3
W_G	21.42 kg
L_{buoy}	199.6 N
d_e	2.3915 m
l_b	7.17 m
Range (no wind)	49 km
Range (wind)	9.32 km

Table 12: computed results

The first consideration to do is about the ability of the designed airship to perform the mission with **one single take-off, with no need for any battery replacement**. Considering Figure 33: percentage of the flight time divided between the different parts of the mission, it is clear how this aspect could potentially **reduce the total time for the mission of almost 50%**. It would also reduce the stress for the pilot, as from the original mission emerged that the descent to the boat deck demanded the pilot to be extra careful [34].

As stated in Chapter 5.3, we set very demanding requirements for wind speed, leading to a high conservative value of the needed battery energy. Nevertheless the consumption of data link and control equipment is not taken into account in the sizing process. Further considerations are needed on this aspect in order to refine the model and the estimate of energy required.

We assumed the same conservative approach for the estimation of the payload and of on-board systems; in fact we chose instruments and components used in previous research, not considering the trend of miniaturization and weight reduction of optical and data-link devices.

Considering the requirements on deployment of the UAS, it seems a good choice to **provide the UAV the ability of being deflated and disassembled in order to be carried to the deployment site easily** (i.e from a boat deck).

From the computed values for operational range, it seems clear that the designed UAV could perform the entire mission taking-off from the mainland, perform the inspection and then come back to landing site (assuming it is capable of transmitting the data from the maximum dstance). This would mean the dimensioning **mission could be performed without the need of a boat, leading to a great cost and complexity reduction**.

We can conclude that the application of an UAV airship for the designed mission could greatly reduce mission length and complexity, thanks to the greater performances in terms of endurance and operational range. Further studies are needed for determinate proposed airship controllability and maneuverability, thus that a more detailed comparison with the original UAV could be done.

6. Sensitivity analysis

In Figure 43 and Figure 44 the hull volume (V) in order to achieve a set endurance is plotted with respect to fitness ratio (FR) and the cruise speed.

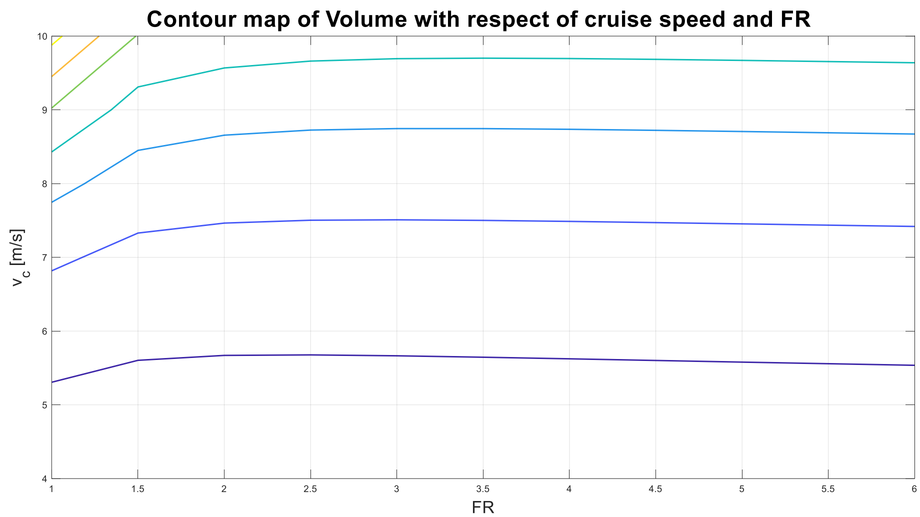


Figure 43: contour mapping of Volume vs FR and cruise speed; the arrow means increasing volume

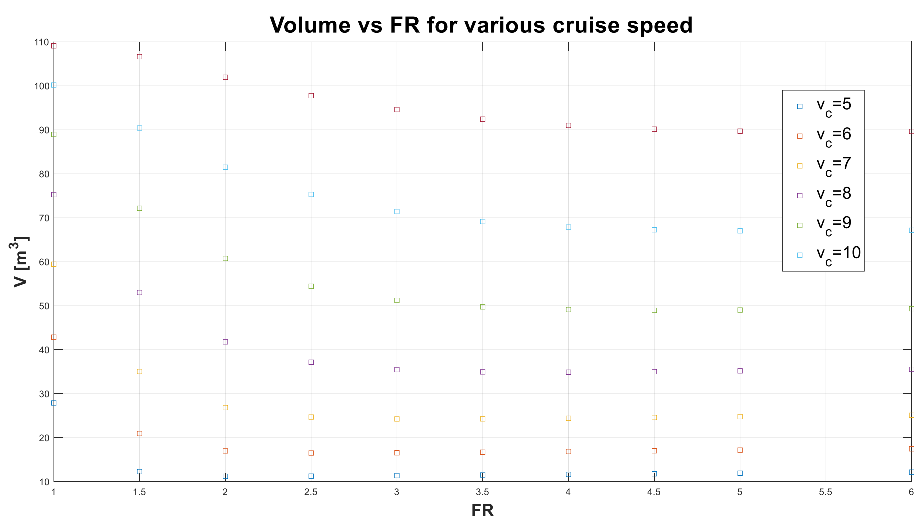


Figure 44: Volume at varying of FR for various value of cruise speed

As can be seen, the volume greatly vary with the increase of speed due to the drag being proportional the square of the speed. The drag define the amount of energy needed and so the weight of the batteries that largely effect the total weight and so the volume.

It is worth noting that with increasing speeds, the value of FR that minimizes the Volume slightly increase.

In figure Figure 45 and the volume is plotted with respect to required endurance at fixed speed for different value of fitness ratio. The volume increase almost linearly with respect the endurance as shown in Figure 46.

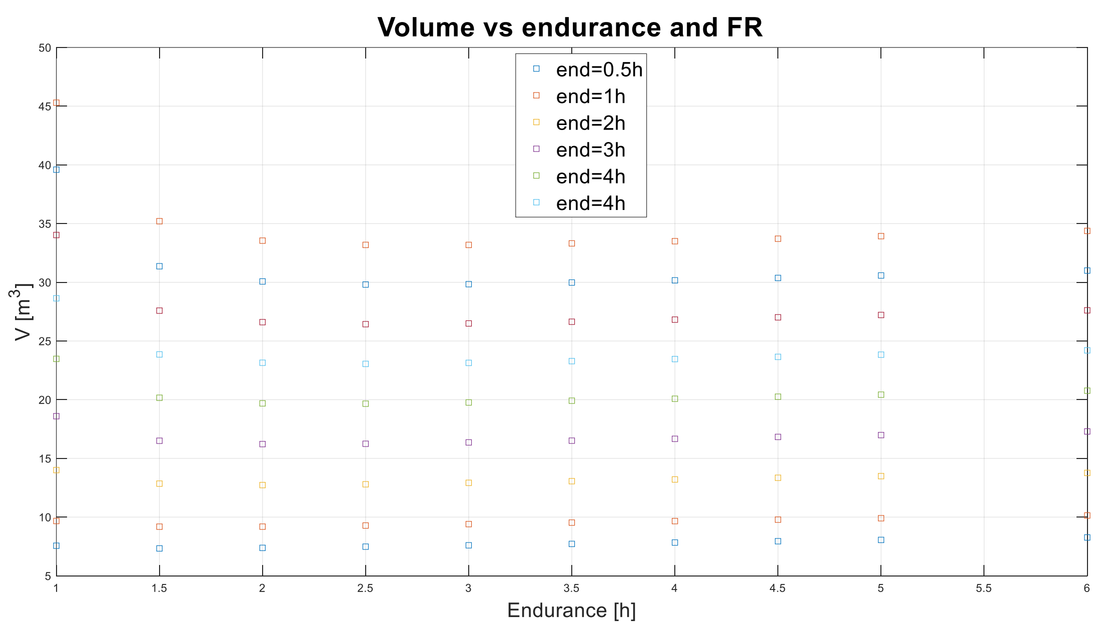


Figure 45: Volume computed for different endurances and FR with fixed cruise speed

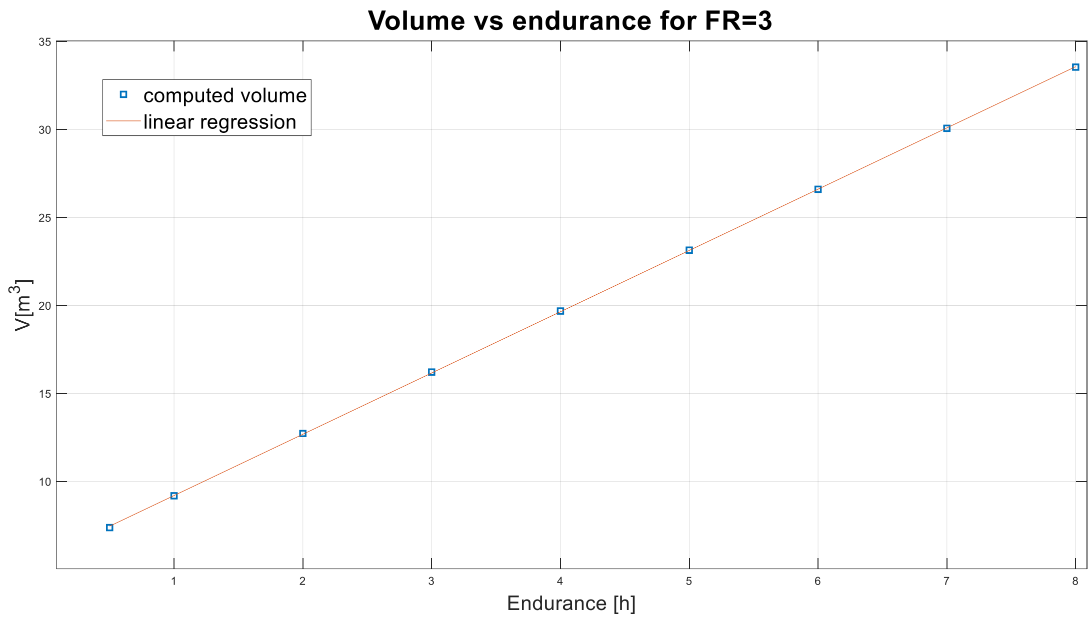


Figure 46: Volume for different endurance with fixed speed and FR

7. Conclusions

From the results discussed in paragraph 5.5, it seems clear that **the usage of a UAS based on an airship platform could greatly decrease both time and complexity of the mission described in paragraph 4.1.**

The only real disadvantage of the use of a LTA UAV multi-purpose platform for civil application and optimized for structural inspections, seems to be the larger volume when compared to HTA platforms. This could lead to some difficulties in deployment when compared for example to multicopters, smaller and easy to transport on the ground. However, thanks to its great endurance an unmanned airship does not have the necessity to take-off ‘’really close” to the structure; combining this aspect with an UAS equipped with a kit for inflating and deflating the UAV, the problem of the large size is greatly reduced.

Another interesting aspect is that the large endurance allows LTA vehicles to cover great distances even if moving slowly, meaning that a single platform could also perform some mission where fixed wing UAVs are generally preferred. This could lead to a **cost reduction** for those companies that needs to cover both mission profiles and are currently forced to use at least two different UAS platform (based on fixed wing and rotary wing respectively) for different mission profile.

These conclusion open an optimistic scenario over the possibility of employment in structural inspection application. This fact, united to the great similarity in mission profiles for various fields of application, suggest the possibility to use the designed airship as a **multi-purpose platform, capable to operate in multiple fields simply by changing the payload alone.**

Acknowledgement

A special thanks goes to Professor Carlo E. D. Riboldi both for proposing a so interesting topic and for his patience and support. The Plutarch’s famous citation ‘the mind is a fire to be kindled and not a vessel to be filled’ perfectly fits him.

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