The Legitimacy of a Blimp as an Autonomous Vehicle Platform

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Introduction

Autonomous unmanned vehicles have become a staple within industrial, military, and exploratory applications in within the last 20-30 years. Specifically, lighter than Air Crafts within robotics had serious academic attention in the late 90's to the 00's. This platform was recognized as a match for rescue, surveillance, ecology work, for several reasons related to the nature of its movement scheme as sell as its performance. Fundamentally, blimps fit in a niche that the alternative platforms didn't due to their specific range of motion and agility, endurance, and scalability in terms of payload. (Liu 2009) (Fukao, 2003) (Rottman, 2007) (Ko, 2007). Figure 1. Describes several areas in which blimps would excel as a platform, and Figure 2. Provides a list which summarizes the current state of the platform from a standpoint of active research groups in 2009. The historical utility hasn't declined, Lockheed Martin is actively developing a hybrid airship for industrial, and commercial applications, and although it doesn't represent autonomy in robotics, it is an excellent example of what an extreme case of this platform is physically capable of.

Industrial Areas	Application Example
Environment	. Greenhouse gas emission detecting and climate change monitoring.
Disaster Rescue	. Monitoring and rescue services in inaccessible environment.
Infrastructure	. Working platform for spiderman.
Astro Exploration	. Monitoring and service for planet exploration.
Transportation	. Big carriages and low costs for the long distance transports.
Telecommunication	. Relaying the communication signals in remote areas.
Military Operation	. Monitoring and weapon platform in tactics tasks.
Security	. Mobile monitoring guard and anti-terror attack.
Science and Research	. Astro and environmental research.

Figure 1. Liu, 2009 discusses industrial settings in which a blimp would be a strong candidate as a host platform.

Name/Maker	Time	Experimental Airship	Main Research Achievements	Reference
Autonomous Institute of CTI Campinas, Brazil	1998-2003	AURORA Airship	. Environmental monitoring missions. . Airship dynamic model. . Optimal visual servoed guidance. . Internet-based solution in airship control.	[23],[1],[12],[24]
University of Pennsylvania USA	1998-2003	GRASP Blimp	. Computer vision-based navigation. . Motion Planning.	[10],[11],[25],[3]
LAAS/CNRS France	2002-2003	Robot Karma	. Backstepping control methods. . Terrain mapping.	[17],[26],[27],[28]
Kyoto University Japan	2003-2005	Indoor Blimp	. Image-based tracking control. . Inverse optimal tracking control.	[14], [29],[19]
Technical University of Lisbon,Portugal	2005-2008	AURORA Airship	. Robust control. . Hovering motion control.	[20], [9]
Evry Val d'Essonne University, France	2005-2006	LSC Airship	. Characterization of non trim trajectories. . Calculation of the trim trajectories.	[30], [8]
Hokkaido University Japan	2006	Balloon Robot	. Motion control.	[7], [31]
University of Tokyo	2006-2007	Indoor Blimp	. Model predictive control.	[21],[32], [33]
NASA JPL USA	2003-2008	Planet Blimp	. Optimal aerobot trajectory planning. . Human robot Lunar exploration.	[4], [34]

Figure 2. Liu, 2009 reveals research investments toward blimp/LTA/hybrid technology from other organizations around 2009.

The field of autonomous blimps experienced numerous phases, but was academically most active in the late 90's and early 00's. Best recognized papers entail mapping (Lacroix 2002), visual servoing (Zhang 1999), and in the mid to late 00's as a platform for developing trajectory optimization, control in classical and machine learning contexts (Fukao 2005) (Kawai 2004) (Ko 2007), as well as exploring nontraditional systems (Burri 2013). The popularity of this platform died down upon the emergence of the multirotor in late 00's to 10's. Quadcopters provided a fast, maneuverable, and predictable platform, one that ultimately provided imperative control structure that robotics researchers may have found more attractive. The multirotor platform is the Blimps primary competition, as fixed wing aircraft are well characterized as cumbersome, and higher velocity tools; for this reason, fixed wing crafts are considered a separate category. A high level representation of the benefits and drawbacks of the blimps can be seen in Figure 3.

Blimp (LTA, Hybrid)	Quadcopter/Multirotor	VTOL	Fixed Wing
• Maneuverable • Versatile • Good flight time • High payload • Good take off/land • Safe • Challenging Controls	• Maneuverable • Versatile • Predictable (complex) control • Fast • Poor Flight Time • Quick Decision Making • Limited Payload • Loud	• Strong Flight Time • Good take off/land • Some Maneuverability (better than FW) • Cumbersome • Nuanced Contro • Limited Payload	• Best Flight Time • Explored discipline • High payload • Clumsy at low speed/altitude • Difficult Takeoff/Land

Figure 3. A table highlighting pros and cons of flight-capable autonomous platforms.

Based off the collective analysis of a plethora of academic papers, we've concluded that salient limiting factors to blimps before their popularity decline were related to computation and hardware constraints. To further elaborate, real time data processing and collection for trajectory optimization, as well as edge decision making were constrained by processing information processing capabilities. The substantial jump in information processing technology, both in terms of sheer "umph" (performance), as well as accessibility (increased number of flexible source tools/API's), and size, justifies a revisitation of the blimp as a platform for autonomous systems. Problems encountered in the past related to processing may be resolved, or at least reformulated, ultimately improving the readiness of the overall readiness of the technology within its use cases. The same principle described above is applicable for power sources; battery, as well as solar technology has experienced a substantial maturity increase in the decade blimps were dormant. Finally, we can conclude that adjacent industries such as manufacturing, astrophysics, planetary exploration, and communications are ever developing, which in a less valid sense indirectly contributes to the feasibility of placing blimps, LTA's, and hybrid airships alongside multirotors, and fixed wing air crafts as top tier flight autonomy platforms, which will ultimately dictate the future of robotics in the coming years. To substantiate our argument that blimps are a valuable platform for autonomous systems we elect to analyze the mechanisms that facilitate fundamental blimp technology.

Blimp Lift

A Blimp flies by way of buoyancy. Buoyancy is a force all objects experience in a fluid, but for most scenarios the buoyancy force is much smaller than other forces such as weight, that it becomes insignificant to everyday objects. Buoyancy is a function of displaced volume, density of fluid displaced, and acceleration due to gravity (equation 1).

To accurately calculate the buoyancy force, the variation in density of the atmosphere and the acceleration due to gravity need to be considered. Both the density of the atmosphere and the acceleration due to gravity decrease with altitude (equation 2,3).

From these equations the buoyancy force can be calculated and plotted for various shapes of objects. The general trend can be seen in graph 1 for a displaced volume of $1m^3$.

For a Blimp the single source of lift is the buoyancy force. Abying by Newton's first law of motion, for the blimp to hold altitude the buoyancy force must be equal and opposite to the total weight of the Blimp. The weight of a Blimp is the total multiplied by g'. The mass of the Blimp includes the shell or skin of the Blimp, any hardware that is attached to the Blimp shell including computers, battery, and propulsion, as well as the gas that is used to fill the shell.

Equation 1: Buoyant force of a blimp. ρ is the density of the fluid being displaced. Density is only valid between 0 and 11000 meters . g' is the acceleration due to gravity as a function of altitude "h" in meters (Engineering ToolBox).

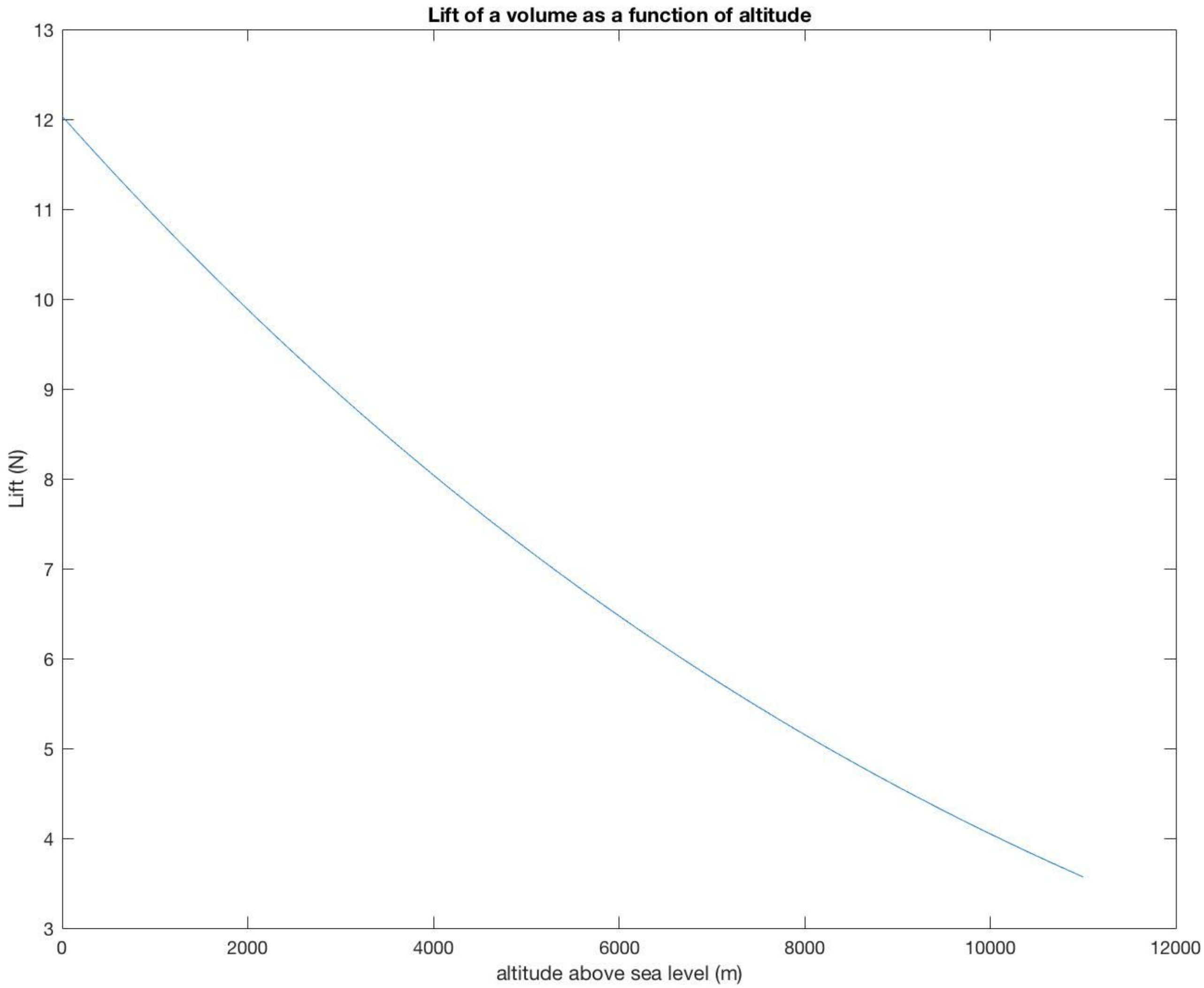
$$Buoyancy = \oiiint_{cv} \bullet \rho \bullet g' (\mathrm{N})$$

Equation 2: The acceleration due to gravity at a specific altitude h(m) above the ground (The Variation in g with Altitude).

$$g' = 9.81 \bullet (1 - 2 \bullet \frac{h}{6371*10^3})\ (\frac{m}{s^2})$$

Equation 3: The density of air as a function of the altitude in m (Earth Atmosphere Model).

$$\rho = \frac{101.29 \bullet (\frac{(15.04-0.00649 \bullet h) + 273.1}{288.08})^{5.256}}{0.2869 \bullet ((15.04-0.00649 \bullet h) + 273.1)}\ (\frac{kg}{m^3})$$



Graph 1. The lift force in Newtons for $1m^3$ volume of displaced Earth atmosphere as a function of altitude in meters.

Blimp Drag

Drag force is an important factor to consider on any aircraft design. Drag affects lift, velocity, efficiency and is a major factor in control and maneuverability. Determining the drag on a blimp is complicated analytically due to the complex, and often variant shape.

To analytically determine the drag force on a blimp, consider the drag force on a sphere. The benefit of this method is the equations for drag on a sphere are simply to calculate and well known. This will provide a good estimate to what the drag force on a blimp would be in a variety of scenarios.

For calculations, the cross-section of a Blimp will be considered an ellipse. The z radius will be 1.5λ radius (Diagram 1). The z radius of the ellipse will be used as the radius of the sphere. This is because the projected area of a blimp orthogonal to the velocity of fluid flow is a circle of radius r. This projected area is commonly used in drag equations. Note, the larger λ becomes the less accurate the drag prediction becomes as the shape of the object in question becomes less like a sphere.

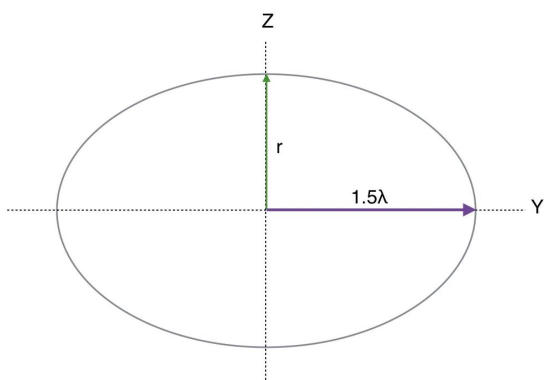
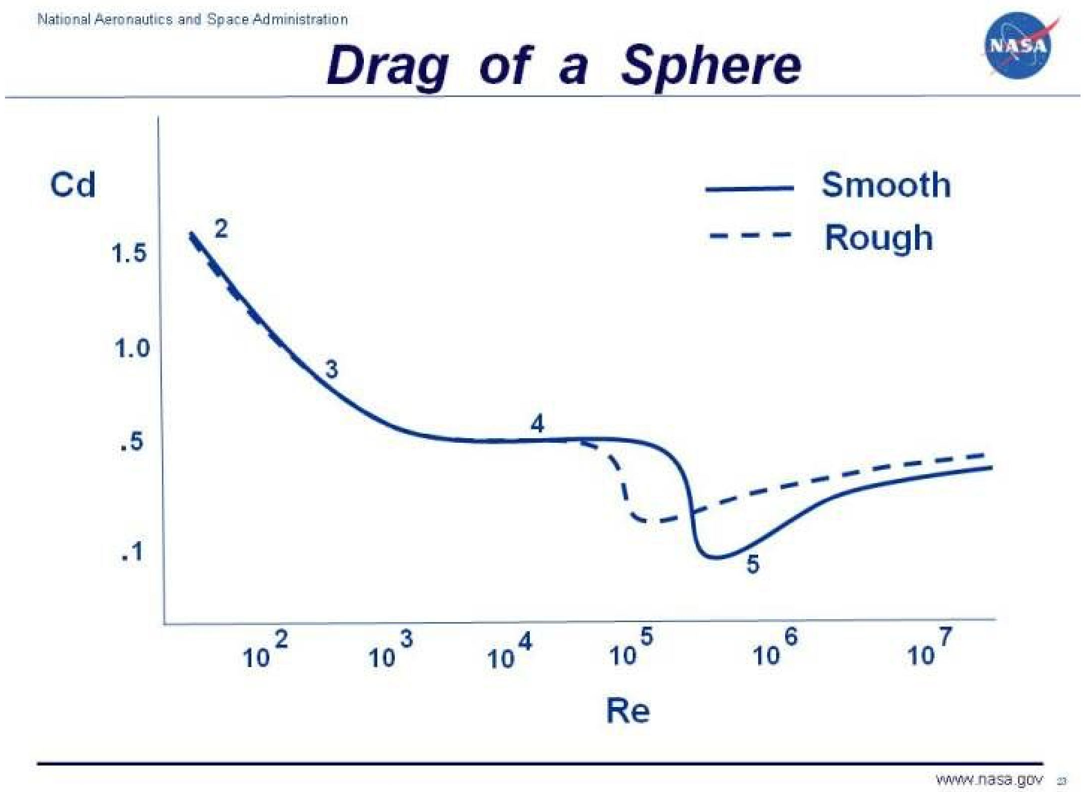


Diagram 1. The cross-sectional view of the blimp showing the radius compared to the length.

The drag on a sphere can be calculated using equation 4. The reference area is the area orthogonal to the flow of fluid as previously described. ρ is the density of the fluid which the object of interest is traveling through. C_d is the drag coefficient. The drag coefficient is a dimensionless number that characterizes and accounts for the variations in drag due to shape velocity and other factors. The drag coefficient is usually determined experimentally. For the calculations to proceed, the value of the C_d has been predetermined based off of previous experiments of a sphere and can be seen in Graph 2.

Equation 4. The Force of drag on a sphere (Drag of a Sphere).

$$F_{Drag} = \frac{1}{2} \bullet \rho \bullet V^2 \bullet A_{reference} \bullet C_d$$



Graph 2. Value of C_d as a function of reynolds number.

As seen in Graph 2, the C_d for a sphere is a function of the Reynolds number. The Reynolds number is a dimensionless number used to describe the dynamics of a flow under certain conditions. Reynolds number is a function of density, airstream velocity, diameter of reference area, and the dynamic viscosity of the fluid (equation 5).

Equation 5. Reynolds number. ρ is the density of the fluid. V is the airstream velocity. D is the diameter of reference area. μ is the dynamic viscosity of the fluid.

$$\text{Reynolds number} = R_e = \frac{\rho V D}{\mu}$$

To determine the drag force the design of the Blimp must be taken into account. The drag force will change for different designs. The three design parameters that affect the drag are the volume of the blimp, the velocity, and the altitude of flight. Once these have been decided the drag force can be calculated for different airstream velocities.

Blimp Design

When designing a Blimp several factors have to be considered. There are four forces that affect the dynamics of a Blimp. These forces are buoyancy, weight, drag, and thrust. Buoyancy and weight act in the Z plane. Thrust and drag act in the y plane. The first step in the design process is to identify the payload and total weight of the Blimp. The total weight of the blimp determines the volume required to create the buoyancy lift to counter the force due to gravity. The required volume also determines the drag force present at specific velocities

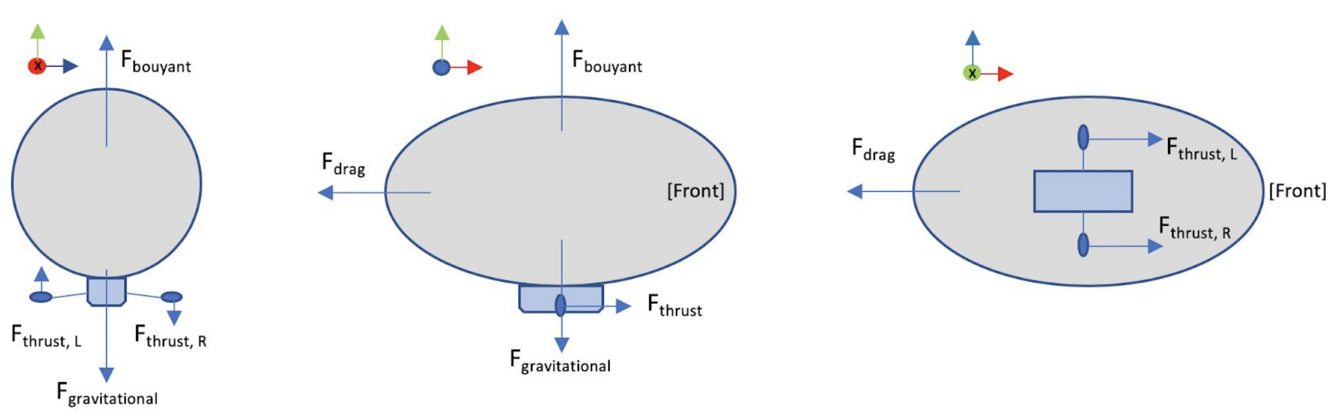


Diagram 2: Free Body diagram of forces acting on Blimp. First diagram is a front view. Second diagram is a side view. The final diagram is a Top View. The Third diagram appears to have the thrusters on the top of the aircraft, but they are still below as seen in diagram one and two.

4. Application of Blimp Design

For the application of the Blimp design a few parameters have to be chosen. For this design the Blimp is going to have a total mass of 10 kg. The Blimp is going to be flying at an altitude of 100m above Tempe, AZ, which is an absolute altitude of 450m. The Blimp will be the shape of a sphere. The last design criteria is the airstream velocity. For the simplification of calculations, the air is going to be assumed still. This assumption means the ground velocity is equal to the airstream velocity. For this design we are going to require a velocity of 2 $\frac{m}{s}$ for the ground velocity, which as previously stated is equal to the airstream velocity.

Based off of these initial design requirements using Graph 3, the volume needed to create a buoyancy force equal to the weight force is 8.52 m^3 . From this the diameter can be calculated to be 3.712m. This is an important value in determining the drag force. The drag force as previously stated is a function of ρ, Velocity, Area, and C_d. From equation 3 the density of the air at 450m can be calculated to be 1.746 $\frac{kg}{m^3}$. The Velocity was predetermined to be 2 $\frac{m}{s}$. The area using the equation of a circle is 10.822 m^2. In order to determine the drag force, the Reynolds number must be calculated first to determine C_d . The Reynolds number is dependent on μ, the dynamic viscosity, which varies the most with temperature. Assuming the temperature of the air is at STP, the value of $\mu = 1.849 \bullet 10^{-5}$ Pascal. From this, the Reynolds number can be calculated to be $2.044 \bullet 10^6$. Using Graph 2, the value of $C_d = 0.45$. Having all the values needed the drag force can be calculated to be about 17 Newtons.

Efficiency of the drone is what separates the platform from other autonomous air vehicles. The dynamics of a Blimp means no propulsion system or energy source has to be used to counter gravity. This has two major benefits. One, the only energy that has to be consumed is for hardware and propulsion. Two, the Blimp has the ability to drift with air currents while using minimal energy. In fact, If the drone has light weight solar panels mounted to its shell, the Blimp could simultaneously run a mission and recharge. This feature could not be said about any other platform with the munvervariblty present with a Blimp. For the Blimp previously discussed a light solar panel would be used to charge the Blimp while drifting. Also, it will be powered by two ducted fans that have a max output two times that of the thrust required to overcome the drag force moving at 2 $\frac{m}{s}$.

Interplanetary Blimps

The notion of interplanetary exploration via autonomous systems is currently embodied by the rover. Issues with this platform are associated with mobility, not only is the top speed of a rover limited, but its movement is impeded by natural terrain. A flight-capable platform has the potential to avoid terrain, ultimately cover more ground. When Larry Mathias from JPL visited the Dreams Lab at ASU SESE, they discussed the current state of the art of flight on Mars, the current realistic target for exploration with UAVs. Their statement was (roughly) that although balloons had been an active research area in the past, the current state of the art is a helicopter with 90 minutes of flight time per day.

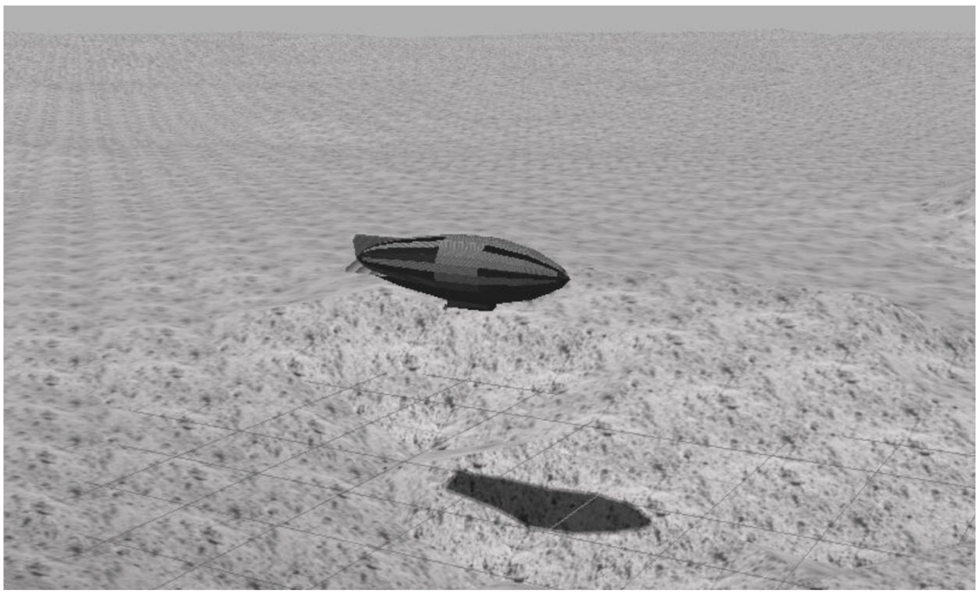
To generalize the argument of a blimp (LTA), or hybrid aircrafts as a planetary exploration vehicle, the fundamental properties described earlier must be retained to some degree.

1. There must be some buoyant force to facilitate vertical upward force
2. There must be some mechanism for facilitating horizontal thrust

These conditions suggest an atmosphere, and the “interplanetary” qualifier suggests a gravitational force downward which will be combated with the first condition. At its core, the statement asks for a planet with relatively similar qualities of our own. Mars’s atmosphere has a surface density of about 0.02 $\frac{kg}{m^3}$ (Mars Fact Sheet). This is about 60 times less dense than Earth's atmosphere at sea level. A Blimp or LTA on Mars would require a buoyancy volume 60 times greater than on earth. Although sizable volume, this platform is, by default airborne, whereas a helicopter is not.

Beyond the unusually sizable volume of this theoretical blimp, and associated disadvantages like material weight, and size, this big advantages are efficiency and scalability. The Blimp platform has the ability to be inherently more efficient than its counterparts. Furthermore, which is important for space exploration, is the scalability of a Blimp. Unlike a Plane or a Drone, the Blimp shell can be enlarged to suit atmospheric conditions of other planets fairly easily without much change in design. This is important when considering a possible universal platform for several planetary missions rather than a vehicle created around the service of a single planet.

In an effort to better describe our argument within the SES 494/598 course, we also put together a representation of our vision of a blimp within the context of another planet's exploration. Using Gazebo, we could construct the following simulation, in which a zero gravity system represents net zero force on the blimp (buoyant force fights gravitational force; they are equal magnitude and opposite direction).



The simulation was demonstrated in front of the final class, and by applying force to the blimp in specific directions about the center of mass we could model the movement envisioned in this write up.

Initially this portion of the project was supposed to include the ROS API for the sake of implementing skills learned in the course, but we encountered time constraints that didn't make it realistic to meet the deadline. In theory, however, we would attempt to implement commands that would represent the policy of a controller that decided a mundane task: performing a lawnmower pattern for a searching/mapping task. Beyond this, we could in the future improve our simulation by including the lift/drag plugin into our gazebo model. This would make hybrid airships possible to model, as well as the notion of drag from the surface of the blimp; a factor that heavily dictated the agility of a blimp.

This assignment was incredibly educational. Our (Evan and Benjamin’s) work distribution was 50/50, although we did divide and conquer tasks. The academic research invested in the literature review was an even split, Benjamin’s more focused on historical, as well as computational work, Evan’s more focused on the technical details of blimps, including aerospace topics, and dynamics. Evan completed all technical calculations, and analysis, while Benjamin made the simulation. A special thank you is necessary for Harish, and Zhiang for being so generous with their time, and patience with us. Of course, thank you Dr. Das for making your resources (computational, and personal) available to us - the opportunity harvested from this project and course was unusually generous, and considerate.

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