LOW ALTITUDE PSEUDO SATELLITES AND PLATFORMS BASED ON LTA-UAVS

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Abstract

This paper explores the development and evaluation of Low Altitude Pseudo Satellites (LAPS) using Lighter-Than-Air Unmanned Aerial Vehicles (LTA-UAVs), focusing on their application in Beyond Visual Line of Sight (BVLOS) operations. The study describes the prototype design of LTA-UAVs, emphasizing aerodynamic efficiency, autonomous navigation capabilities, and payload optimization. Experimental investigations assess the platforms' structural robustness, bidirectional communication capabilities, and global range controllability under varied atmospheric conditions. The research highlights the integration of advanced multiprocessing algorithms for autonomous BVLOS operations and the implementation of redundant communication systems, including satellite networks. Results demonstrate the viability of LAPS as a cost-effective, scalable solution for lower altitude applications, complementing conventional satellite systems. The findings indicate significant potential for LAPS in earth observation, connectivity enhancement, and integration with Internet of Things (IoT) frameworks. This research contributes to the aerospace field by detailing innovative applications of LTA-UAVs and enhancing the efficiency and global operability of airborne platforms for BVLOS missions.

Keywords: BVLOS, LAPS, HAPS, LTA, UAV, IT, Cybernetics, IoT, EO, Satellite, Multichannel, Connectivity

INTRODUCTION

Over the past decades, the concept of High Altitude Pseudo Satellites and Platforms (HAPS) has garnered significant attention in the aerospace industry. These platforms, operating in the stratosphere at altitudes of 20-50 km, promise to bridge the gap between conventional satellites and ground-based systems[1]. Projects such as Airbus's Zephyr, Facebook's Aquila, and Google's Loon project have made notable advancements in this field, focusing on long-endurance flights and wide-area communication coverage[2].

Despite these advancements, LTA and HAPS projects face considerable challenges, particularly in terms of technical complexity, high development costs, and lengthy development cycles. In this context, the concept of Low Altitude Pseudo Satellites (LAPS) is proposed here while gaining increasing relevance in BVLOS earth and climate observation missions.

Image 1 Google Loon (HAPS) [1]

Image 2 h-aero® zero (LAPS, 500g payload capacity)

1 Peter Lobner (9 January 2023), "5.6 Stratospheric airships", Modern Airships – Part 1
2 Buchaniec, Catherine (22 July 2022). "Up, up and away: Airbus' Zephyr drone breaks flight record high above Arizona". Defense News.

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LAPS, operating at altitudes ranging from a few hundred meters to several kilometers, offer a more efficient alternative for many applications previously envisioned for HAPS.

The efficiency in developing analogous tasks, early market entry, and a significantly faster learning curve are the main advantages of LAPS over HAPS. To illustrate this, let's consider some concrete examples:

Helium consumption: While a typical HAPS requires several thousand cubic meters of helium, a LAPS system like the h-aero® one operates with just 8.7 m³. This not only reduces costs but also significantly diminishes logistical challenges. As the helium resources are finite, there is also an issue with sustainability related to HAPS.

Experiment duration and costs: A typical HAPS test flight can last several days or even weeks and incur costs in the millions. In contrast, a LAPS experiment can often be conducted within a few hours, at costs that are orders of magnitude lower.

Development cycles: While the development of a HAPS system often takes years, LAPS systems can be developed and iterated in much shorter timeframes. This allows for faster adaptation to market requirements and technical advancements.

These efficiency advantages make LAPS a promising option for a wide range of applications, from earth observation to connectivity enhancement and integration into the Internet of Things (IoT). In this paper, we examine the development and evaluation of LAPS using Lighter-Than-Air Unmanned Aerial Vehicles (LTA-UAVs), highlighting their potentials and challenges, which are unsolved today also for HAPS.

Furthermore, we will explore how LAPS can complement future HAPS and current satellite systems, offering a more versatile and cost-effective solution for the specific developments. By leveraging advanced cybernetic algorithms and optimized system integration, LAPS present opportunities for improving BVLOS real-time data collection and transmission efficiency in various fields including environmental monitoring and disaster response.

LTA-UAV PROTOTYPE DESIGN

The development of effective Low Altitude Pseudo Satellites (LAPS) is fundamentally rooted in the meticulous design of Lighter-Than-Air Unmanned Aerial Vehicles (LTA-UAVs). Our prototype design carefully balances three critical aspects: aerodynamic efficiency, autonomous navigation capabilities, and payload optimization, each playing a crucial role in the overall performance and versatility of the system.

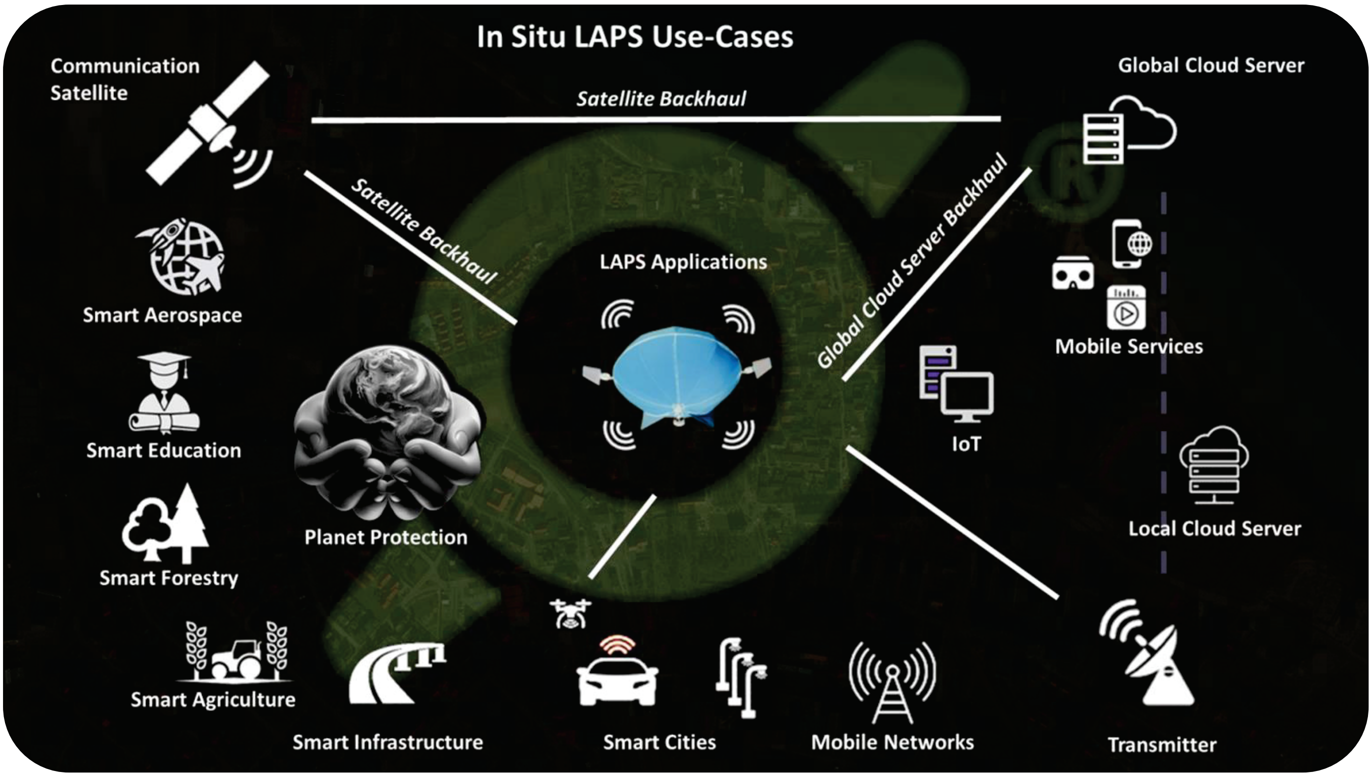

Image 3 Illustration of the manifold use-cases for LAPS Systems and the intersections to existing frameworks

At the heart of our design is a lenticular hull, a shape that offers significant aerodynamic advantages. As outlined in Singer's NASA paper, this configuration minimizes drag during forward flight, enhances stability in varying wind conditions, and optimizes the distribution of lifting gas, typically helium[3]. The h-aero® series, particularly the h-aero® one model, embodies this design philosophy. With its compact dimensions of 300x160cm and a volume of 8.7m³, it achieves an ideal balance between lift capacity and maneuverability, making it well-suited for LAPS applications.

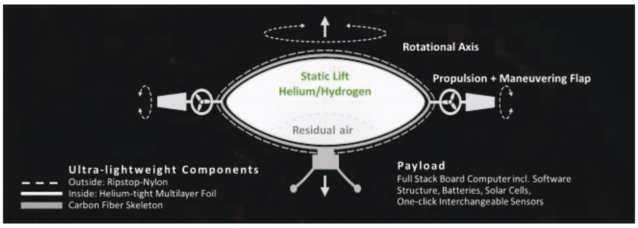

Image 4 Principle of the carrier hardware configuration

The exact technical teachings are laid down in the following patents:

- DE102006028885
- ES2881902
- EP3464059
- US20190152576
- WO/2017/207666

To function effectively as LAPS, our LTA-UAVs incorporate advanced autonomous navigation systems. These include GPS for precise positioning, Inertial Measurement Units (IMUs) for attitude determination, and onboard computational systems running full Linux distributions. This integration enables real-time data processing and decision making, allowing for waypoint navigation, adaptive flight path adjustment based on wind conditions, and autonomous take-off and landing procedures[4]. Such capabilities are essential for the long-duration stable flights required in LAPS operations.

Payload capacity and versatility are crucial for the diverse applications of LAPS. Our prototype design boasts a payload capacity of up to 3kg at sea level and standard atmosphere. This is complemented by a modular payload system that allows for easy customization based on specific mission requirements. The LTA-UAVs can be equipped with a variety of sensors, including high-resolution cameras, multispectral and hyperspectral imaging systems, environmental sensors for measuring parameters like temperature, humidity, and air quality, as well as communication relay equipment. The ease with which these payload systems can be swapped out enables rapid reconfiguration between missions, enhancing the platforms' versatility for roles ranging from earth observation to communication relay.

The carrier equipment’s mass distribution is depicted in the following:

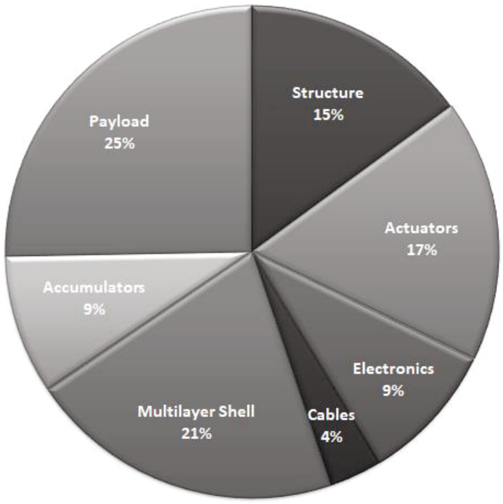

Image 5 Component mass distribution of h-aero® one

Power management is a critical aspect of our prototype design. We structured our LTA system so that the required buffer, commonly referred to as ballast in LTA flight systems, is integrated into the specified payload capacity. Instead of using traditional ballast, we utilize an accumulator with a higher weight and capacity to trim the system before liftoff. This approach eliminates the need for separate ballast and additional structural bearings, as the trimming buffer is always composed of extra energy in the form of a larger battery. This method is justified because the payload itself draws power from the battery, making it reasonable to include the battery in the payload weight. As a result, we achieved a fully operational, levitating system capable of over 5 hours of flight with our h-aero zero+ (1 kg payload capacity, 4S 2300mAh LiPo battery). The system supports BVLOS (Beyond Visual Line of Sight) flights with redundant communication via satellite links[4]. Combined with the inherent energy efficiency of LTA designs, this setup allows for significantly extended operational times, far exceeding the endurance of traditional UAV platforms, making it ideal for long-duration LAPS missions.

[3] Singer, Cs.: “Ultralight Solar Powered Hybrid Research Drone”, NASA Astrophysics Data System, June 2012

[4] Pahls, B. et al.: „Development of an Aerial Cybernetic IoT System Based on LTA-UAVs for Multifaceted Applications“, Deutsche Luft- und Raumfahrtkongress 2023, April 2024.

Image 6 Improved GUI with Integrated Waypoint Selection and Wind Database[4]

The synergy of these design elements - the aerodynamically efficient hull, advanced multi-processing algorithms for autonomous BVLOS operations[5], flexible payload capacity, and extended power capabilities - results in a LTA-UAV prototype that is uniquely positioned to serve as a versatile and effective platform for LAPS applications.

Compared to previous versions, the web-based GUI for sending command parameters to the system via the multichannel communication module has been enhanced. In Image 6, the red dot on Google Maps indicates the system's current position, while the green arrow shows its current orientation. The yellow arrow represents the target direction the system is expected to follow. The white dot marks the selected next waypoint, which is used in conjunction with the current position to calculate the updated target direction. The blue arrow indicates the wind direction, along with the projected system position in five minutes, assuming no corrective actions are taken. The text field below the "Execute Command" button allows the input of command parameters that are processed by the system in real-time.

To accurately quantify the system's abilities in terms of the aforementioned aspects, we utilized Grafana to visualize bidirectional data in near real-time. This included system-to-ground metrics and command parameters for onboard autonomous algorithms, transmitted from the ground to the aerial system.

<u>Assessment of Robustness</u>

The robustness of our LTA-UAV system was evaluated under various challenging conditions:

- Tethered Wind Exposure: The system was tethered and exposed to wind conditions, simulating sustained environmental stress.
- Dynamic Wind Testing: In stronger wind conditions, the system was released and subsequently recaptured, demonstrating its stability and recoverability in adverse weather.

<u>Bidirectional Communication</u>

We conducted comprehensive communication tests across diverse geographical areas with varying levels of mobile network coverage:

- Data Transmission: Key metrics such as temperature, ambient pressure, system altitude, position, and mobile signal strength were successfully transmitted.
- Video Feed: Real-time camera footage was transmitted, demonstrating the system's capacity for visual data relay.
- Autonomous Algorithm Control: Parameters for onboard autonomous algorithms were transmitted, and subsequent system changes were observed and analyzed.
- Failsafe Mechanisms: We executed failsafe protocols using only SatCom communication, bypassing LTE networks to ensure reliability in low-coverage scenarios.

[5] These will be described in a specific paper

Global Range Controllability

To assess global controllability, we conducted a series of free-flight tests:

- Worldwide Access: Partners worldwide were granted access to the system via a web-based control interface, allowing them to interact with the LTA-UAV over the internet.
- Dual Communication Pathways: We observed the communication path from the ground server to the aerial system via both mobile networks and SatCom from the client's perspective.
- Real-time Data and Video Display: The transmission and display of system data and camera feed were tested at the client end.
- Remote System Manipulation: Changes in system behavior were observed in response to globally initiated commands.

RESULTS AND DISCUSSION

The experimental investigations have comprehensively validated the capabilities of our LTA-UAV prototype across key performance metrics. The visualization offered valuable insights into the system's communication performance at various altitudes, guiding future optimizations for LAPS applications.

Assessment of Robustness

Our LTA-UAV system demonstrated significant structural integrity under challenging conditions.

When tethered at a 30° angle of attack, the system began to show signs of flexing. In wind gusts of up to 40 km/h, while some carbon rods did break, all failsafe mechanisms remained intact, allowing for problem-free retrieval of the system.

Image 8 Wind-influenced load test w. tethered system

Notably, we were unable to test the system to the point of catastrophic destruction due to wind influence, as it proved more robust than anticipated. This unexpected level of durability suggests that our design may exceed initial expectations for structural resilience, potentially expanding the operational envelope for LAPS applications.

Bidirectional Communication

The bidirectional communication capabilities of our system proved highly reliable across various environments.

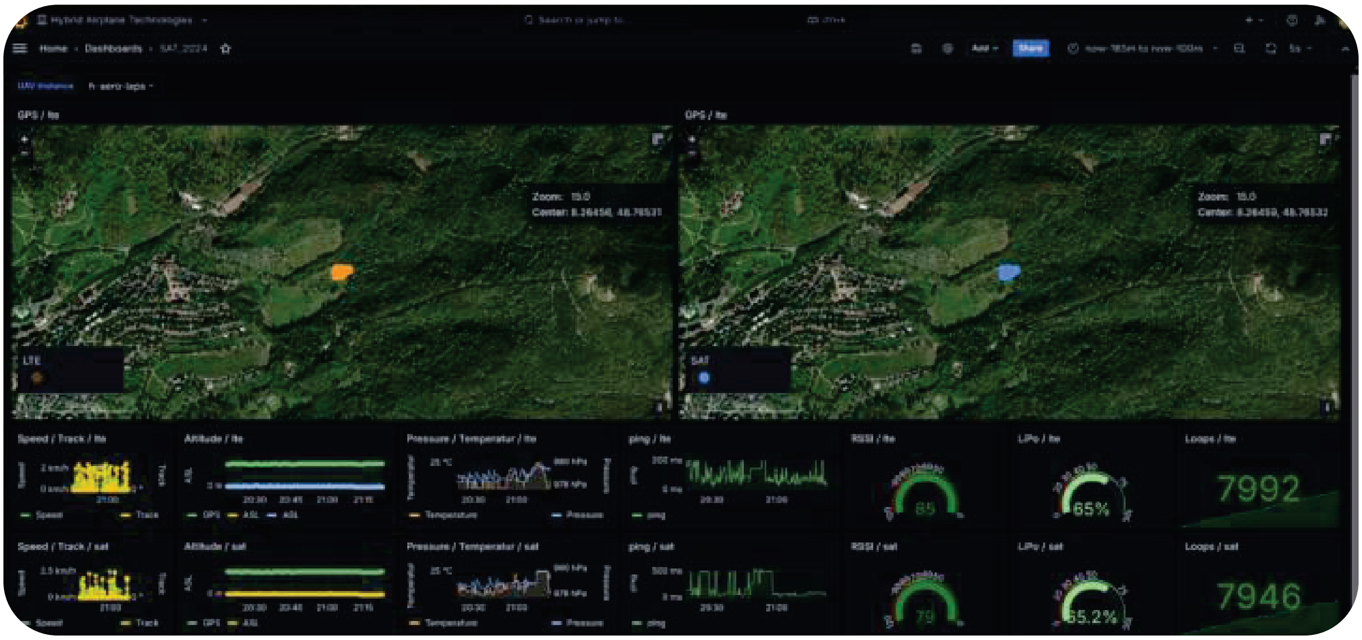

Image 7 Simultaneously sent to Grafana to visualize the real-time conditions and performance of the carrier system

As long as the system had a clear view of the sky and the client maintained a stable internet connection, communication functioned flawlessly.

In the used satellite network, even under the most challenging conditions of our tests (between 300m high mountains in the Black Forest), we registered a minimum of two bidirectional data packets per minute. This ensures a consistent communication link even in areas with poor terrestrial coverage.

In LTE network areas and higher frequencies of the mobile network (4G, 5G), there was no perceptible delay between control commands and execution for human operators, provided that the mobile signal strength (measured by RSSI) of the used provider was not worse than -75dB. Below this threshold, slight delays were observed, but these did not impair system functionality.

This robustness is due to the system's design, which relies on onboard multiprocessing algorithms for primary control, with external commands serving as parameters for these algorithms to respond to. Once commands are received, the system communicates successful execution back to the client.

<u>Global Range Controllability</u>

We tested the system's global range capabilities by allowing partners to control it simultaneously from different locations (Bavaria, Hungary, Dubai). Initial anomalies were observed, which helped identify and rectify errors in the control algorithms. Subsequent tests showed no further anomalies, demonstrating the system's ability to handle distributed inputs.

Clients were able to both view the system's camera feed live and execute various commands, such as changing thrust, altering direction, and initiating descent. The effects of these commands were clearly identifiable at the system itself. This functionality was particularly effective when the system was within a sufficiently strong mobile network.

In the absence of a mobile network, camera transmission was not possible over the Iridium network with our current modem. However, metrics were still transmitted at 30-second intervals, and commands could be sent and clearly correlated with system responses.

CONCLUSIONS AND OUTLOOK

The tests confirmed the structural integrity and electronic resilience of our LTA-UAV prototype under real-world environmental conditions, demonstrating stable, bidirectional communication across diverse network scenarios. The results highlight the platform’s strong potential for BVLOS LAPS applications, with promising performance in terms of robustness, communication capabilities, and global range control.

From our experiments and results, we draw several conclusions for free flight missions in aerosol mode beyond visual line of sight (BVLOS):

<u>Structural and Electronic Robustness:</u>

- The system has proven sufficiently robust, both in terms of its structure withstanding wind forces and its electronics and algorithms, to be safely deployed for BVLOS operations. Notably, the forces experienced in tethered conditions are orders of magnitude higher compared to when the system is freely drifting.
- When equipped with a gimbal for camera stabilization, image fluctuations are imperceptible, ensuring stable visual data collection.
- The system experiences minor oscillations only near the ground and upon release, quickly settling into a stable orientation. Once stabilized, the system remains steady within the inertial system of the prevailing air current, with only slight fluctuations due to steering movements.

<u>Bidirectional Communication and Global Range:</u>

- The implementation of autonomous multiprocessing algorithms enables targeted control of the system BVLOS and worldwide through control parameters transmitted via satellite network.
- Waypoint control via a web-based control interface functions effectively, even over satellite communication.
- With the increased payload capacity of future models, it will be possible to carry Starlink modems, potentially enhancing communication capabilities.
- The system's communication functionality is independent of the client's location, demonstrating true global operability.
  - We have successfully demonstrated, for the first time, the global range controllability of our system. Both in terms of communication and flight behavior, the system can be considered redundantly secure due to failsafe processes integrated into the autonomous multiprocessings.

Looking ahead, our future work will focus on several key areas:

- Optimizing communication over satellite networks to enhance data transmission rates and reduce latency.
- Further enhancing the system's structural durability for extreme weather conditions, pushing the boundaries of operational limits.
- Incrementally increasing flight altitude, duration, and overall complexity in future tests to fully explore the system's capabilities.
- Integrating more advanced payloads, such as Starlink modems, to expand communication options.
- Refining autonomous algorithms to improve responsiveness and adaptability in varied environmental conditions.
- Exploring potential applications in environmental monitoring, disaster response, and global connectivity solutions.

These findings provide a foundation for further development and refinement of LAPS technologies based on LTA-UAVs. As we continue to advance this technology, we anticipate significant contributions to the fields of aerial observation, global communication, and environmental monitoring, opening new possibilities for sustainable and efficient airborne operations.

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Finally, we want to acknowledge and thank everyone who contributed, directly or indirectly, to these projects. Their combined efforts were instrumental in helping us achieve our goals.

Image 9 h-aero zero+ while testing over the Black Forest