

RESEARCH PLATFORM AIRSHIP: DESIGN AND FLIGHT CHARACTERISTICS FOR URBAN OPERATIONS

Hannah Reindle[1], Julius Hoffelner[1], Niklas Sekyra[1], Nils Schlautmann[1], Marius Weber[1], Victor Sittel[1], Chinmaya Mishra[1] & Florian Holzapfel[1]

[1]Institute of Flight System Dynamics, Technical University of Munich, Boltzmannstraße 15, 85748 Garching, Bavaria, Germany

Abstract

Identifying a suitable research platform for aerial experiments in urban environments is nontrivial, since testing under these conditions imposes stringent operational and safety requirements. In certain scenarios, such as extended flight missions at low speeds within safety-critical areas, airships offer advantages over conventional fixed-wing aircraft and multicopters. Motivated by benefits such as hover capability, efficiency, or crash safety, an unmanned airship, approximately $15m$ long, was developed to investigate the potential of radar systems for supporting positioning and navigation in complex urban areas. The requirements resulting from these operating conditions guided the airship's design. Successful flight test campaigns demonstrated the feasibility of employing airships as research platforms. Furthermore, analysis of the collected flight data enables the assessment of use cases for airships of comparable size and configuration. These findings indicate that such airships are particularly suited for steady, low-speed missions that require high endurance and a high level of operational safety, with medium positioning accuracy and a moderate payload capacity up to the lower tens-of-kilograms range, while tolerating the weather dependency.

Keywords: Airship, Research Platform, Flight Testing, Urban Environment, Navigation

1. Introduction

Airships are an early technological development within the field of aviation, especially promoted in the first half of the 20th century, both for military and civilian purposes, including, for example, reconnaissance during World War I and passenger transport in the 1920s and 1930s [1]. Over time, this technology was largely replaced by conventional fixed-wing aircraft, primarily due to their superiority in speed. However, airships can offer advantages for missions where low-speed operation is beneficial. For example, when an airship is equipped with the corresponding control system, there is no need for ground infrastructure like runways since the airship can takeoff and land vertically. In addition, the airship can maintain a hover state. Compared to multicopters, airships exhibit significantly higher hover efficiency due to their buoyant lift and resulting lower overall weight, and are therefore suitable for long-endurance missions. Furthermore, employing a soft, non-rigid blimp design minimizes risks to people on the ground in the event of a crash, while the large physical dimensions of airships enhance visibility to third-party flight operation. These characteristics motivated the development of the unmanned airship presented in this paper as a research platform for evaluating the potential of radar sensors to support aerial navigation and positioning in urban environments. Over the past decades, airships have been the subject of investigation by various research institutions. In this context, the University of Stuttgart should be particularly highlighted for its solar-powered research airship Lotte. This platform has served as a foundation for comprehensive studies across multiple domains of airship development, including controller design [2], aerodynamic analysis [3], and flight testing [4]. Beyond characterizing the airship itself, Lotte has also been used as a versatile research platform for

applications such as photogrammetry and air pollution monitoring [5]. Airship-related research is also conducted at other institutions, addressing diverse configurations and application scenarios. Prentice et al. [6] and Pflaum et al. [7] focus on the benefits of airships for the use-case of transportation. At the Politecnico di Milano, high-altitude airships are under investigation [8]. Some organizations or start-ups are pursuing similar-scale airship concepts to the one described in this paper, such as Roboloon (Germany) [9], Hylight (France) [10] or Cloudline (South Africa) [11]. However, differences in mission objectives result in distinct design priorities and system configurations.
This paper presents an airship designed as a research platform for urban operations. The paper is organized as follows. Section II defines the design and configuration of the airship and its subsystems. Section III evaluates the flight performance and handling qualities based on flight test data, and lastly, Section IV concludes the paper.

2. Airship Subsystems and Features

The key design requirements for research flights over populated areas include the capability to operate in both hover and forward flight modes. To enable extensive and detailed testing, the platform must demonstrate significant endurance while carrying a payload of several kilograms. Compliance with regulatory requirements for operations over populated areas, as defined by the European Union Aviation Safety Agency in [12], necessitates a target level of safety. The ability to conduct beyond-visual-line-of-sight missions underscores the need for redundant and reliable systems. From an economic perspective, the system must be modular to allow the integration of various payloads. Additionally, a time-saving, prototyping-oriented manufacturing approach and a cost-effective, simplified setup are desirable. The design derived from these requirements is sketched in Figures 1 (side view) and 2 (bottom view). The airship features an approximate length of $15\,m$ and a maximum diameter of $3\,m$, corresponding to a total envelope volume of approximately $76\,m^3$.

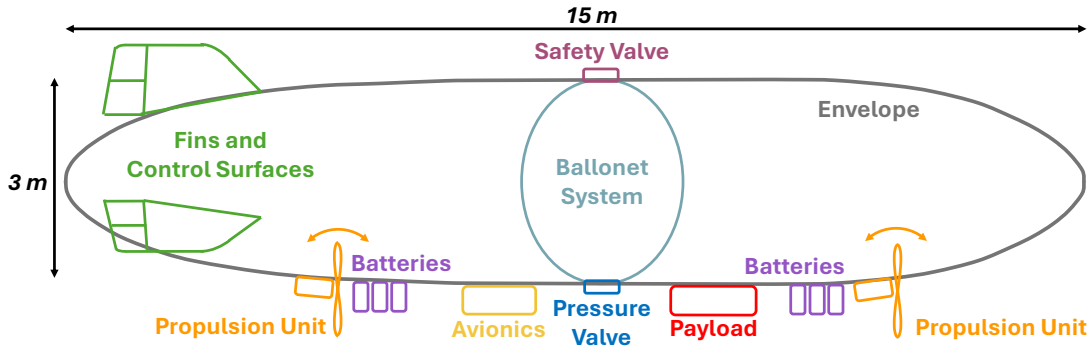


Figure 1 – Airship configuration (side view)

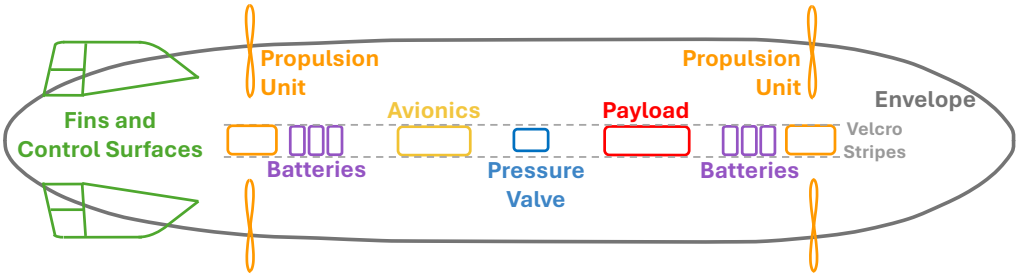


Figure 2 – Airship configuration (bottom view)

The following sections provide an overview of the subsystems, their design principles, and functional roles.

2.1 Envelope

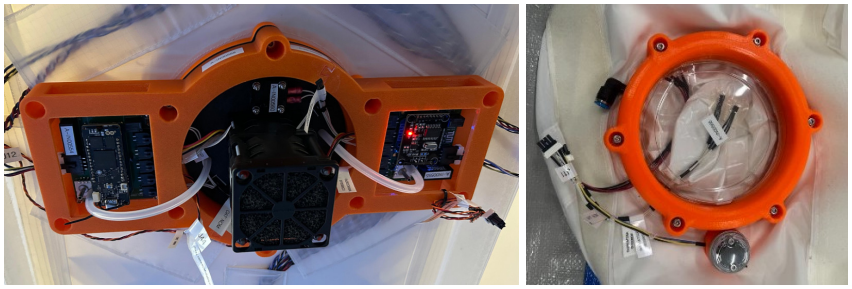
The primary subsystem of the airship is its envelope, which serves as the carrier for all other components and contains the lifting gas helium. A non-rigid blimp design is used for its simplicity, cost-efficiency, and crash safety. The blimp consists of two layers: An inner PU foil layer required for helium tightness and an outer, robust layer made from ripstop nylon. Emphasis is placed on achieving a modular, straightforward integration of subsystems through hook-and-loop attachments along the underside of the envelope and at fin mounting points. To enhance structural safety, these hook-and-loop-based connections are supplemented with tethers, for which dedicated fixation points are incorporated into the design. Additional features, including integrated cable channels or trim-weight storage pockets, further enhance functionality.

The envelope contains a ballonet system consisting of two ballonets: a separate helium ballonet and an air ballonet. The ballonets have two main functions: pressure regulation and weight adjustment in the event of system failure. The pressure valve system located at the bottom of the airship controls the airflow between the external environment and the internal air ballonet, maintaining a constant pressure differential between the envelope and ambient air regardless of temperature or altitude variations. A loss of internal pressure would compromise controllability, as aerodynamic and propulsive forces cannot be effectively directed through a slackened envelope. Excessive overpressure within the air ballonet is equally critical, as it may cause the ballonet to burst, resulting in an abrupt pressure drop. Since the pressure valve runs continuously during flight, its power consumption must also be considered. To meet these requirements, the valve system was designed with two independently controlled fans arranged in a vertical stack. Each fan is assigned a distinct pressure setpoint. The fan diameter must be sufficiently large to ensure adequate relief capacity in cases of overpressure caused by rapid altitude reductions. The inner or nominal and more efficient fan operates at a higher setpoint than the outer fan. Therefore, under normal flight conditions, only the inner fan is active, maintaining an envelope overpressure of $3.2\,mbar$. Overpressure protection sensors are integrated into the system to prevent the envelope pressure from exceeding safe limits in the event of a controller malfunction. The sensor associated with the emergency fan additionally ensures that this fan remains inactive during standard operation and is only engaged in response to large pressure fluctuations caused by significant altitude changes or failures of the nominal system. This configuration ensures that the internal pressure remains within the permissible bounds while enabling energy-efficient operation of the pressure regulation system.

In the event of critical failures, such as loss of control, the safety valve at the top of the airship (see Figure 1) is activated to release a predefined volume of lifting gas by emptying the separate helium ballonet. This reduces buoyancy lift, ensuring the airship descends. As the safety valve is part of the flight termination system, it constitutes a safety-critical component and is therefore designed with full redundancy. Two independent electrical circuits each supply a resistive wire embedded between two foil layers. Upon activation, the wire heats up and melts circular openings in the foil, allowing the lifting gas within the separate helium ballonet to escape. Subsystem tests demonstrated that the valve opens in less than $5\,s$ after triggering, which is more than sufficient given the comparatively slow flight dynamics of an airship.

Both the pressure valve and the safety valve are based on 3D-printed housings, resulting in cost-efficient and modular components. In addition to their primary functions, these housings also serve as structural interfaces that seal the individual layers of the envelope, namely the outer envelope and the two ballonets. The safety valve housing also includes an anti-collision light. Both valves are shown in Figure 3.

Continuous helium diffusion through the envelope, along with the significant influence of temperature fluctuations on the envelope system, necessitates careful helium management throughout operations. The filling port located at the aft end of the envelope allows visual inspection of the ballonet system's filling state. Operational experience has shown that regular monitoring is essential, particularly during days with pronounced temperature variations. The envelope filling level determines the volume of air in the ballonet required to achieve a given overpressure. The air ballonet should be as empty as possible to minimize the loss of usable helium volume and thus buoyant lift. However, the air ballonet filling level also determines the ceiling altitude, as the ballonet shrinks under the reduced



(a) Pressure valve (b) Safety valve

Figure 3 – Envelope management system

ambient pressure at higher altitudes. Consequently, a medium to high filling level is required on the ground. When rising temperatures or strong solar exposure are expected during flight operations, helium expands, which is why a high air ballonet filling level is required on the ground. Conversely, a reduced filling level is advisable when a temperature drop is anticipated.

2.2 Avionics and Ground Control Station

The avionics system governs control, communication, and monitoring of all airship processes. Given the system's critical role in ensuring operational safety, a high degree of redundancy is implemented. The design objective is to eliminate single points of failure. To achieve this, two independent flight control systems powered by separate power busses, supplemented by an additional emergency battery, are integrated. A dual redundant communication bus architecture facilitates on-board data exchange, while multiple redundant communication links ensure a reliable connection between the remote pilots and the unmanned airship. Although both flight-control units are housed within the same gondola, they are installed on opposite sides to maintain spatial separation.
On the ground, redundancy is provided by a Ground Control Station (GCS) developed specifically for the airship project. In addition to direct communication between the pilots and the airship via remote controllers, the GCS relays the pilots' control commands via two independent communication links. During flight operations, the airship's state is monitored via four displays (see Figure 4) presenting, among others, a navigation interface (left), system-health information (right), and a live feed from the first-person-view camera (center, bottom).

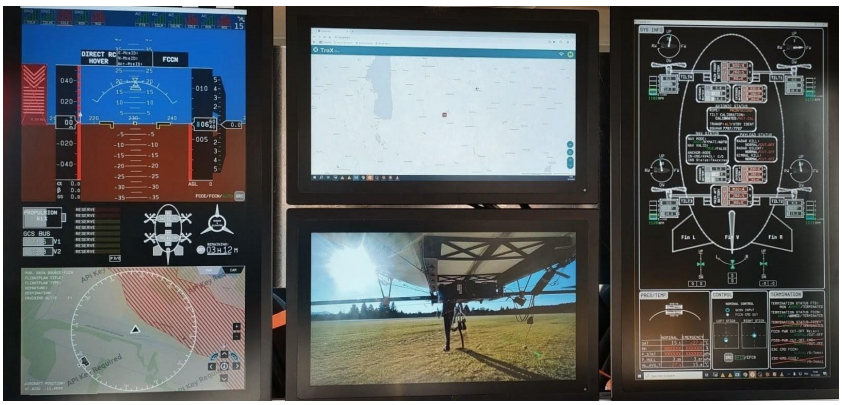


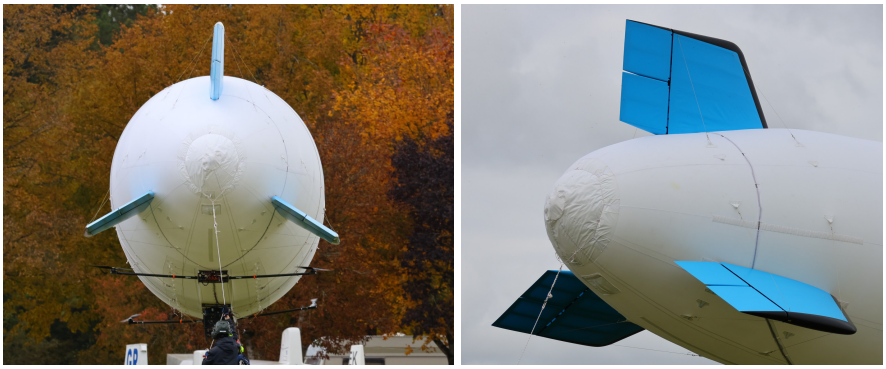
Figure 4 – GCS displays

Several safety-critical commands can also be issued directly through the GCS, including activation of the flight-termination system. This system ensures that the airship transitions into a safe state even in the event of a loss of control by cutting power to the propulsion system and opening the safety valve, thereby guaranteeing an unpowered descent. Flight termination can be triggered in multiple ways: via commands from the remote controllers or the GCS transmitted through the nominal communication links mentioned in the previous paragraph, or through a fully independent termination system. The

vehicle-side receiver of this independent system is installed in a second avionics gondola to avoid any potential single point of failure. In addition to these active mechanisms, the flight termination system is passively triggered if communication is lost completely for more than $10\,s$.

2.3 Fins and Control Surfaces

Control authority in both hover and forward flight is achieved through two subsystems: the propulsion units and the aerodynamic fins equipped with integrated control surfaces. The fins are arranged in a lambda configuration, consisting of three fins positioned at regular intervals: one mounted at the top and two mounted laterally at an angle of 30° downwards relative to the horizontal plane. The main reason for adopting the lambda configuration is to ensure adequate ground clearance. Each fin incorporates two independent control surfaces of comparable dimensions. The actuators driving the inner and outer control surfaces are powered by separate batteries, thereby providing redundancy within the control system. The aerodynamic characteristics of the envelope, including the fins and control surfaces, were analyzed by Oberndorfer in [13]. A key challenge in this analysis was the consideration of a full $360°$ aerodynamics, which is relevant for an airship operating in hover within a variable wind field. Figure 5 shows the fins with the split control surfaces attached to the airship during tethered flight tests.



(a) Lambda configuration (b) Fins and control surfaces

Figure 5 – Fin arrangement

2.4 Propulsion System

In hover flight, aerodynamic control surfaces are ineffective. To ensure controllability, a propulsion system comprising four propellers, arranged in a front and a rear pair, each attached to one gondola, is integrated. As depicted in Figure 5a, the propellers are connected to the gondola via carbon-fiber booms of approximately $1.3\,m$ length. They are tiltable in the airship's vertical plane, enabling thrust vectoring for attitude and position control. Each unit generates a maximum thrust of approximately $50\,N$. The propellers can be tilted by nearly $360°$ and are individually controllable for both tilt angle and rotational speed. As a result, the propulsion system governs not only forward velocity but also pitch, yaw, and roll motions. Roll control, however, is generally of limited operational relevance for the airship. A key limitation of the tiltable propulsion units is their inability to generate direct lateral forces, which means that lateral drift must be tolerated during hover in windy conditions. Consequently, yaw control becomes particularly important. By orienting the airship's nose into the wind, lateral drift can be minimized.

The propulsion system offers more degrees of freedom than a pilot can practically control in unassisted, direct manual flight. To reduce operational complexity while maintaining sufficient controllability, selected commands are combined, and certain motions are synchronized. Rather than allowing continuous $360°$ tilt control, the pilot can select among three predefined propeller orientations: *hover*, *climb*, and *cruise*. In the *cruise* and *climb* configurations, all propellers share a common orientation, either fully forward or tilted $45°$ upward. In *hover*, the propellers are oriented upward, with the front pair tilted $10°$ forward and the aft pair $10°$ backward. Figure 6 shows the thrust vectors for the different configurations.

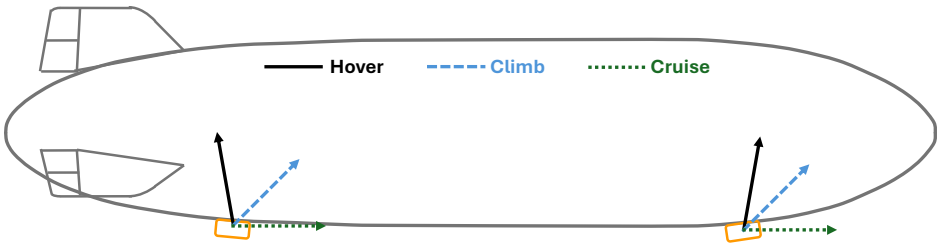


Figure 6 – Thrust vectors in propeller modes hover, climb, and cruise

The four propellers of the airship have the same rotation direction and therefore induce the same yawing moment. Nevertheless, an outward tilted hover configuration enables yaw control solely through differential rotor speeds between the left and right propellers of a single gondola, without the need for tilt-angle adjustments. Owing to the outward inclination of the propulsion units, each rotor produces a small forward or aft thrust component in hover. Consequently, unequal rotor speeds at one gondola generate a non-zero yawing moment. During hover, asymmetric rotor thrust between left and right side additionally induces a rolling moment. Because of the airship envelope's flexibility, the gondola can rotate about its longitudinal axis, introducing a lateral thrust component. Since the front and aft gondolas roll in opposite directions, these lateral forces act in opposite directions and create an additional yawing moment. Initial tests showed that sufficient yaw authority can only be achieved when this additional yaw moment reinforces the moment generated by the differential forward/aft thrust components. The outward-tilted configuration shown in Figure 6 is therefore essential, whereas an inward-tilted arrangement does not provide adequate yaw control in hover.
Yaw and pitch control via differential propeller speeds is automatically mixed with the pilot's nominal pitch and yaw inputs on the main control sticks, provided the remote controller is set to the *hover* mode. When flying with an active velocity command control law, full authority of the propulsion system is available, and all rotor speeds and tilt angles can be commanded individually. [14] and [15] outline possibilities for the efficient utilization of tiltable propeller systems for airship control.
Under load, the booms the propellers are mounted on exhibit significant bending, creating a risk of propeller-envelope contact. Additionally, under asymmetric loading conditions, the propulsion gondolas rotate about the roll or yaw axis because they are attached to the deformable envelope via a hook-and-loop interface. This further increases the risk of envelope damage. To mitigate these effects, asymmetry in the commands to the two propulsion units mounted on the same gondola must be limited. Furthermore, stiffeners were integrated into the propulsion units, as illustrated in Figure 7. These stiffeners provide additional support at the midpoint of the boom.

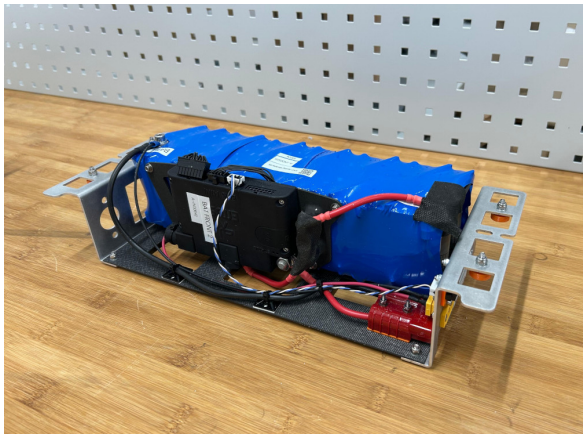


Figure 7 – Propulsion boom stiffeners

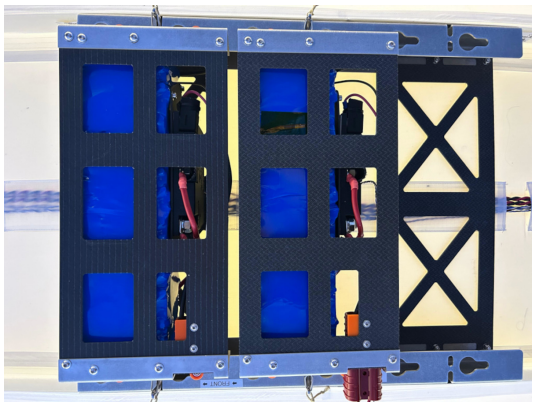
2.5 Battery System

The battery system is designed with a focus on modularity and operational flexibility. Two independent systems, each composed of individual battery packs, supply electrical power to the airship. These systems provide energy not only to the propulsion units but also to the avionics and all auxiliary subsystems, including the control surfaces and the envelope-management system. Each subsystem is connected to both power buses, ensuring its functionality is maintained to at least a limited extent even in the event of a failure on one power bus.

Each battery system consists of up to three battery packs, with a capacity of approximately $20Ah$ per pack. Since maintaining a consistent total weight is critical for airships, battery mass, and consequently endurance, can be traded against payload capacity. The battery attachment mechanism enables rapid replacement, minimizing downtime between flights. This mechanism is based on a two-part battery gondola constructed from robust, low-cost bent aluminum components combined with lightweight carbon-fiber plates. One section is permanently attached to the airship via a hook-and-loop interface, while the second section carries the battery pack and can be latched into the fixed structure and secured with safety lines. The state of the battery system is monitored through feedback from the integrated Battery Management System (BMS). Figure 8a shows a single battery pack with its BMS mounted on the carbon-aluminum structure, while Figure 8b illustrates two integrated packs installed on the airship.



(a) Battery pack



(b) Battery gondola with two installed battery packs

Figure 8 – Battery system arrangement

2.6 Payload

The use of hook-and-loop-based mounting points facilitates flexible integration of a wide range of payload systems. To reduce overall mass, payloads can be powered directly from the airship's battery systems, with the avionics gondola providing four selectable voltage levels. The gondola can be positioned in accordance with the payload requirement. For example, the radar payload for which the airship was originally developed requires an unobstructed antenna view in both the downward and forward directions. Therefore, placement ahead of the avionics gondolas proved to be optimal. However, gondola placement cannot be chosen arbitrarily, as the center of gravity shall remain slightly forward of the airship's center of buoyancy. This ensures that the pitch-down moment generated by gravity and buoyant lift counteracts the pitch-up moment produced by the propulsion system, whose thrust line lies below the center of gravity in *cruise* mode. Having the center of gravity in front of the center of buoyancy reduces the continuous elevator deflection required to maintain level flight. Flight operations showed that the mass of the gondolas, which could be placed in front of the center of gravity, was insufficient to counterbalance the weight of the fins at the aft end of the airship, resulting in the center of gravity typically lying aft of the center of buoyancy. Trim weights can be added to the pockets at the airship's nose to shift the center of gravity forward, though this reduces the available payload capacity. A further constraint on payload placement is that attachments are only feasible on the underside of the airship. Because the envelope lacks a rigid internal structure, mounting heavy payloads on its upper or lateral surfaces would cause excessive deformation.
Figure 9 depicts the airship outlined in the preceding section in operation. The gondolas are labeled accordingly. The flight was without a payload.

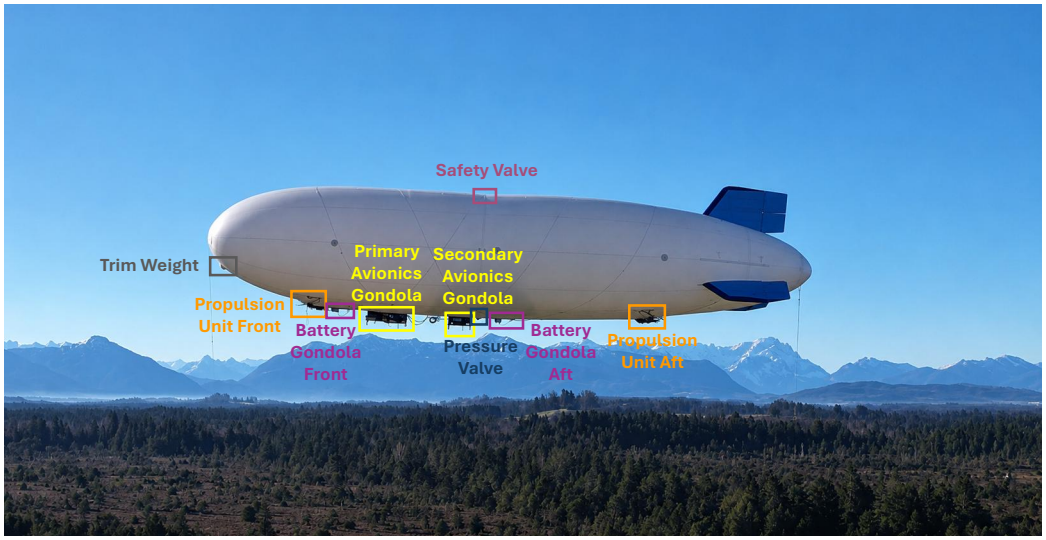


Figure 9 – Airship during flight operation

3. Flight Testing and Characteristics

A series of systematic flight tests has been conducted with the airship, following procedures developed at the Institute of Flight System Dynamics, Technical University of Munich [16] [17]. To date, these tests have accumulated more than 16 hours of flight time. The tests were performed under a variety of external (environmental) and internal conditions, including different vehicle configurations and initial states. The structured test approach enables the identification of key flight dynamics and performance characteristics of the airship, such as the achievable flight envelope and the airship's agility. The collected data also provides insights into safety-relevant properties of the vehicle. Moreover, the influence of environmental conditions, as well as general operational advantages and limitations, can be assessed based on the conducted tests. A thorough understanding of these characteristics is indispensable for assessing the potential use cases applicable to airships of comparable size and configuration. Consequently, the investigation of the airship's flight behavior provides the basis for evaluating which types of system and sensor tests are particularly suited to airship platforms, as opposed to fixed-wing aircraft or multicopters.

Several general considerations apply to all analyses presented in the following subsections. During manual flight, under which most of the subsequent data were collected, it is challenging to trim the airship to a perfectly steady initial condition or to maintain constant parameters such as velocity or altitude while varying others. Nevertheless, the data quality is sufficient to derive the quantitative insights needed to identify relevant use cases. Most of the flight tests were conducted with the propellers in the *cruise* configuration. If a different configuration was applied, it is stated explicitly. Unless stated otherwise, the term 'Velocity' refers to the kinematic velocity. 'Altitude' is the distance to the WGS84 ellipsoid. Although detailed wind measurements were not available, the flight-test data evaluation allows conclusions about the prevailing wind conditions.

3.1 Flight Envelope

The flight envelope characterizes the range of achievable velocities and altitudes of the vehicle. To determine the maximum attainable velocity, tests were conducted at full thrust (throttle command (cmd) $= 1$) while maintaining an approximately constant altitude. A zero thrust command corresponds to -1. The results, shown in Figure 10, indicate a maximum velocity of approximately $14\,\frac{m}{s}$. A comparison of westbound flight (heading $= -90°$) and eastbound flight (heading $= 90°$) reveals similar velocities, with slightly higher values during eastward flight, which can be attributed to a weak westerly wind. Although higher velocities are technically achievable, flight-test experience indicates that the optimal aerodynamic velocity range lies between $6\,\frac{m}{s}$ and $12\,\frac{m}{s}$, especially for unassisted, manual control. At lower speeds, the effectiveness of the aerodynamic control surfaces decreases, resulting in limited yaw authority and reduced ability to cancel wind. At higher velocities, the airship exhibits mild oscillations about the pitch axis, which complicates precise control.

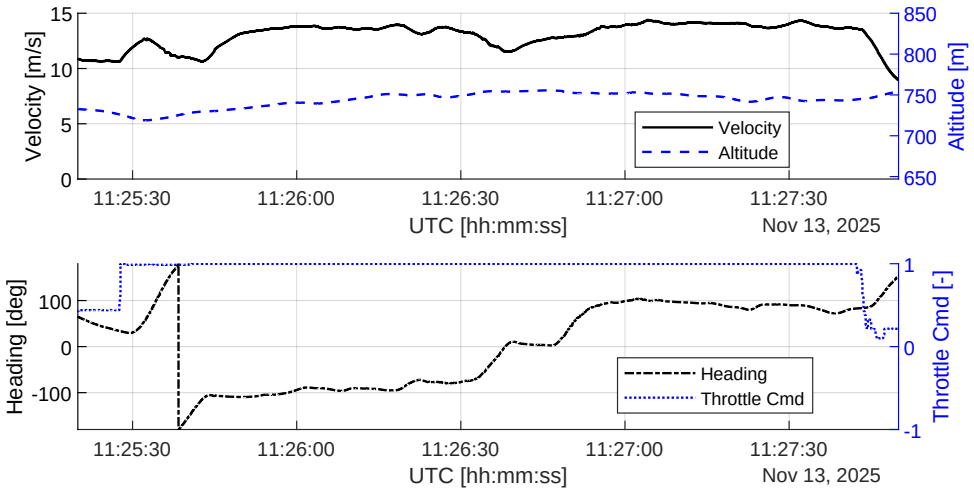


Figure 10 – Velocity at maximum thrust command

The maximum operating altitude of the airship is constrained by the volume of the air ballonet. As ambient pressure decreases with increasing altitude, the helium inside the envelope expands, reducing its density. To maintain a constant internal envelope pressure, air must be released from the ballonet. Once the ballonet is fully emptied, any further ascent would cause the internal pressure to rise until the envelope bursts. The air ballonet volume was designed to occupy maximum $14\,\%$ of the envelope volume. Assuming International Standard Atmosphere conditions and a fully inflated ballonet at takeoff, the resulting ceiling altitude is approximately $1600\,m$ above ground, with slightly lower values for elevated launch sites. However, operating with a fully inflated ballonet is not recommended, as it leaves no margin for environmental variations such as temperature increases and reduces the available buoyant lift. During flight tests, typical filling levels were around $5\,\%$ of the blimp volume, corresponding to a ceiling altitude above ground of roughly $550\,m$.
In addition to the ceiling altitude, the pressure-valve system limits the maximum permissible rate of altitude change during both climbs and descents. This limitation is governed not by the ballonet volume but by the valve design, particularly the outlet size, fan characteristics, and controller settings. Figure 11 illustrates that the internal pressure does not remain constant at the setpoint of $3.2mbar$ (marked in red) but instead follows the altitude variation. Two factors especially contribute to this behavior. First, the fan controller is not optimally tuned and responds relatively slowly, as indicated by the dashed blue line showing the fan command (with $100\,\%$ representing maximum rotational speed and $0\,\%$ representing standstill). Second, the air mass flow exiting the ballonet is limited by the small outlet and the low overpressure, and is further impeded by the fans, even when they are not actively running. This restricts the maximum venting rate and explains the pressure increase during ascent. During descent, the fans are not powerful enough to compensate for the pressure drop. These effects were amplified in the test shown in Figure 11 , as the emergency pressure-valve system was not used. No dedicated tests were conducted to determine the minimum internal pressure required for sufficient envelope stability or the maximum allowable pressure before structural failure. Operational experience indicates that an overpressure between $2\,mbar$ and $4\,mbar$ is safe to fly.
If higher ceiling altitudes or larger altitude variations are required, both the air ballonet volume and the capacity of the pressure valve system could be increased. However, these modifications reduce payload capacity: a larger ballonet decreases the helium volume, while a more capable valve system increases structural mass. For this reason, an airship of similar size is not recommended for applications requiring large altitude ranges or frequent and fast altitude oscillations.

3.2 Agility

Compared with heavier-than-air aircraft, the weight of the air volume displaced by the airship is of the same order of magnitude as its own weight. Consequently, added mass and added inertia significantly influence the vehicle's overall mass and inertia, thereby affecting its stability and agility. The dynamic response of the airship to step inputs in roll, pitch, and yaw was investigated using only the

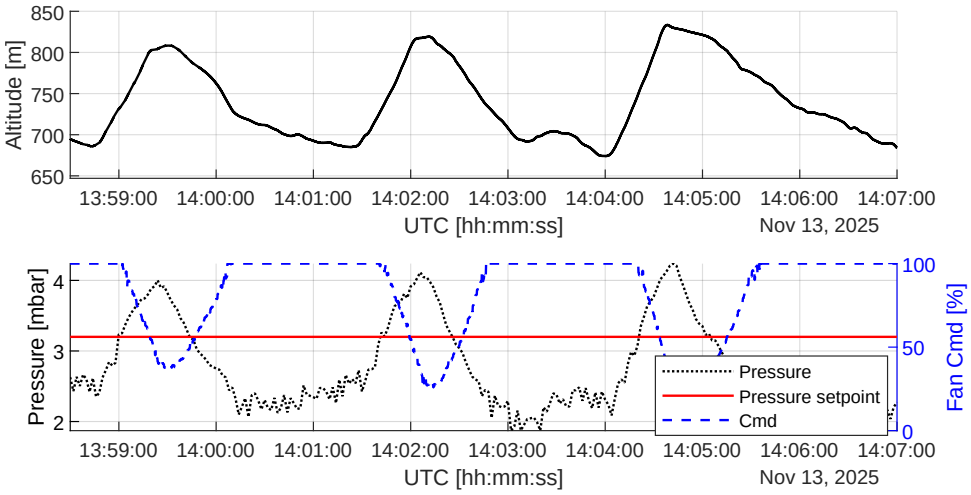


Figure 11 – Envelope pressure variation with altitude variation

aerodynamic control surfaces; the propellers were fixed in a forward-thrust orientation. Pitch control is provided exclusively by the lateral fins, whereas both lateral and vertical fins contribute to roll and yaw control. Figures 12, 13, and 14 illustrate the airship's response to isolated step commands in each axis. Each command varies between -1 and 1, with 0 representing the neutral position of the control surfaces. The extreme command values correspond to maximum surface deflections of $\pm 29°$ for roll and pitch. For yaw, the lateral fins are deflected such that the rolling moment induced by the top fin at maximum deflection is compensated. During each test, only one control input was varied while the remaining control surfaces, as well as altitude and airspeed, were kept constant.
The pitch response (theta) exhibits a delay of slightly less than one second relative to the input. Although the durations of the pitch-up (cmd = -1) and pitch-down (cmd = 1) commands are similar, the airship shows a tendency to pitch upward. As shown in Figure 12 , a $20°$ pitch-down maneuver requires approximately $3\,s$, whereas a $20°$ pitch-up maneuver is achieved in under $2\,s$. This asymmetry results from the propulsive force acting below the center of gravity, which generates a persistent nose-up moment. This effect is also evident in steady-state cruise flight data, where a continuous pitch-down command is required to maintain level flight.

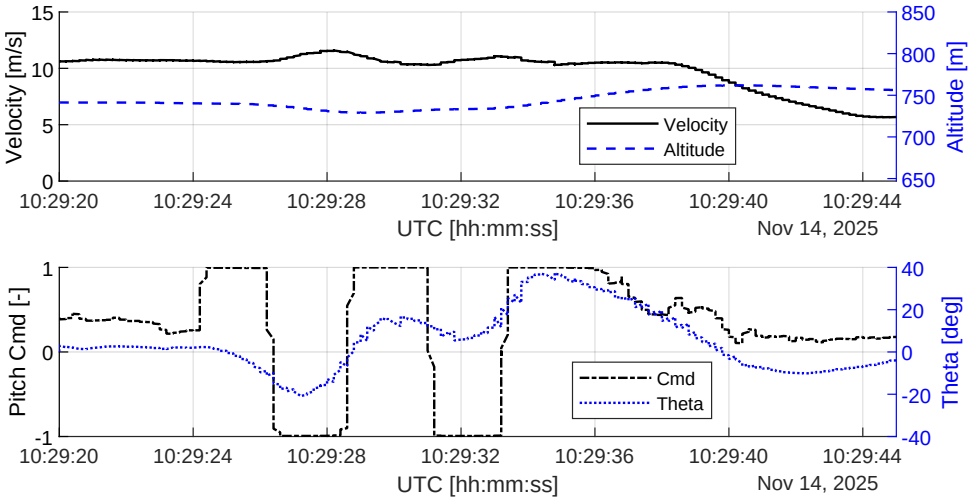


Figure 12 – Airship response to step command in pitch axis

The yawing motion (Figure 13) exhibits dynamics comparable to the pitching motion, which can be attributed to the similar moments of inertia about the respective axes. Moreover, the absence of significant asymmetry about the yaw axis results in nearly identical responses in the heading for left yawing (cmd = 1) and right yawing (cmd = -1).

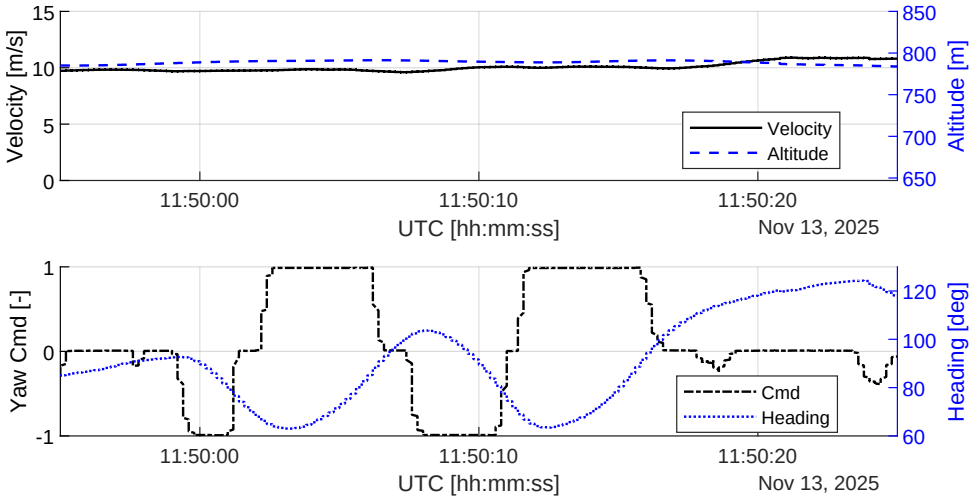


Figure 13 – Airship response to step command in yaw axis

Although the control surfaces have a substantially shorter lever arm for roll motion than for pitch or yaw, the response to a roll command remains highly sensitive due to the lower moment of inertia about the roll axis. Consequently, the delay between the control input and the resulting motion is significantly smaller for roll than for pitch or yaw, as shown in Figure 14. While the immediate effect of a roll command is predominantly observed in the roll axis (phi), the induced roll motion generates dynamic couplings with both the pitch and yaw axes, producing a flight condition that is difficult to control. However, since roll maneuvers are not required during standard airship operation, this limitation is not operationally significant.

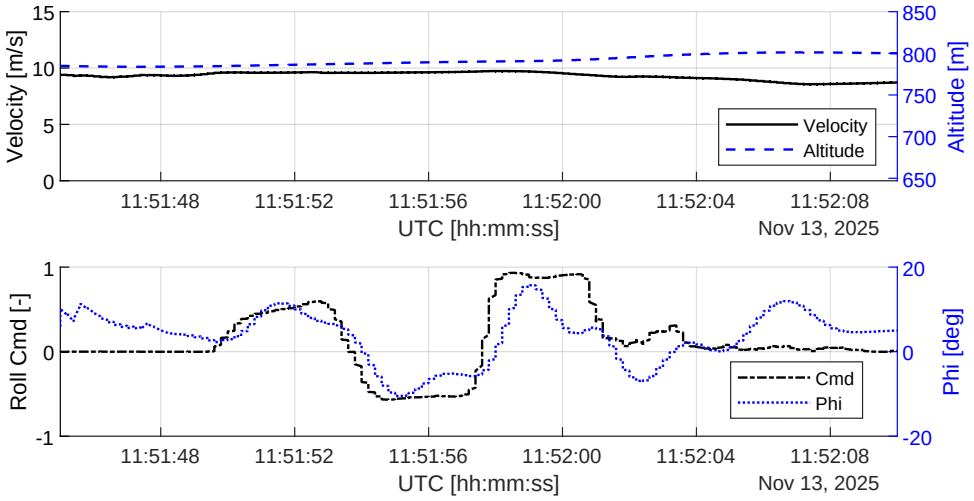


Figure 14 – Airship response to step command in roll axis

Further measures of the airship's agility are its achievable turn and climb rates. Figure 15 shows a turning maneuver of more than $360°$ in both left and right directions, identifiable by the yaw command and performed at a medium throttle setting that yields a cruise velocity within the optimal velocity range. Throughout the maneuver, the pilot tried to maintain constant altitude by adjusting the pitch command. The resulting turn rates for left and right turns are of comparable magnitude: right turn = $13.7\,\frac{°}{s}$; left turn = $12.8\,\frac{°}{s}$. The small discrepancy can be attributed to minor variations in airspeed or environmental conditions.

Figure 16 shows two straight climb trials, both performed at full throttle. Their start is marked with a vertical red line. The primary difference between the two maneuvers is the average pitch angle: the first trial was flown at roughly $20°$, whereas the second was conducted at approximately $25°$. The climb rate increases proportionally with pitch angle, yielding average climb rates of $4\,\frac{m}{s}$ and $5\,\frac{m}{s}$, respectively. It should be noted that these values do not represent the limits of the flight envelope;

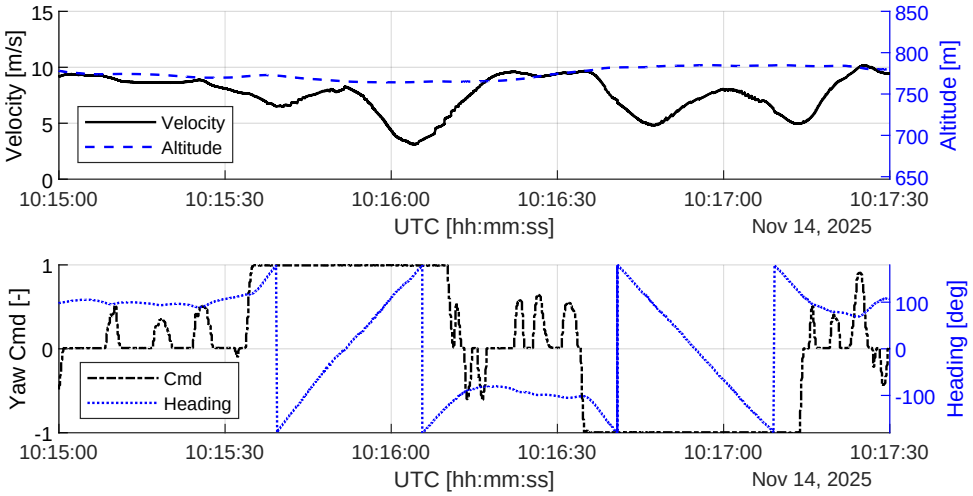


Figure 15 – Turning flight

higher climb rates are expected at larger pitch angles. However, during manual flight, these conditions were considered to mark the boundary of a safe and comfortable operating regime for the pilot.

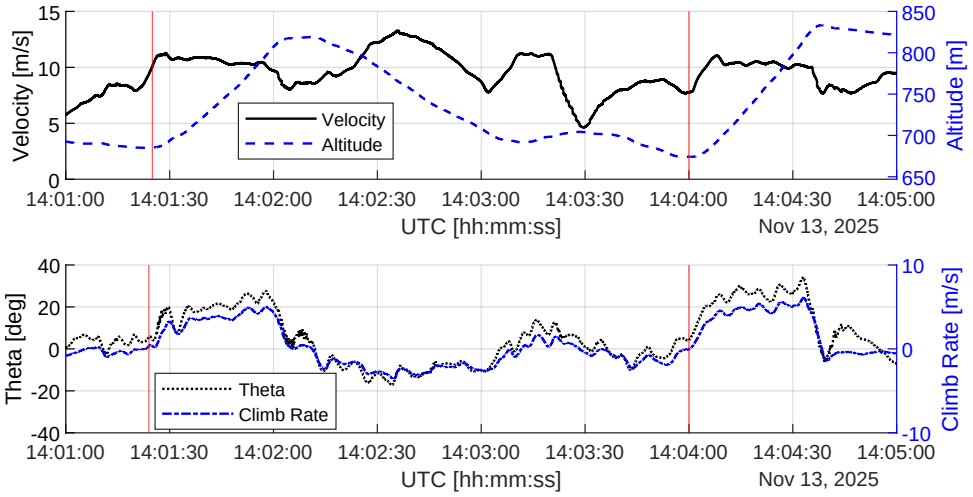


Figure 16 – Climbing flight (start of climb indicated by red vertical line)

Compared with other aerial vehicles such as multicopters, airships generally exhibit lower agility and are therefore not suited for missions requiring rapid maneuvering or high-precision control. Nevertheless, the previous analysis showed that airships do provide a moderate degree of maneuverability, ensuring that their operational capabilities are not overly constrained.

3.3 Safety

A key safety benefit of airships is their high visual detectability, both for ground observers and for other aircraft. This characteristic enables even in the event of a malfunction, such as a loss of control, surrounding air traffic and people on the ground to identify the hazard with sufficient time to respond appropriately. However, for authorization reasons, it may not be assumed that uninvolved people will avoid the airship in the event of flight termination. To provide evidence of the airship's low risk, flight tests must be conducted to analyze its dynamic behavior following a flight termination event. In these tests, the thrust was intentionally set to zero at various combinations of initial velocity and altitude, while no further control inputs were applied. Figure 17 presents five test runs, each identifiable by the commanded thrust reduction to -1, marked by a red vertical line. The airship is configured to operate slightly heavier than air, ensuring a descent, respectively a negative climb rate, in the event of control loss. The flights shown were performed in a comparatively heavy condition, with approximately $10.5\,kg$ heavier than neutral buoyancy. The safety valve, which would increase the

descent rate, was not activated in these tests. The selected mass state represents a medium-payload configuration with an open safety valve.

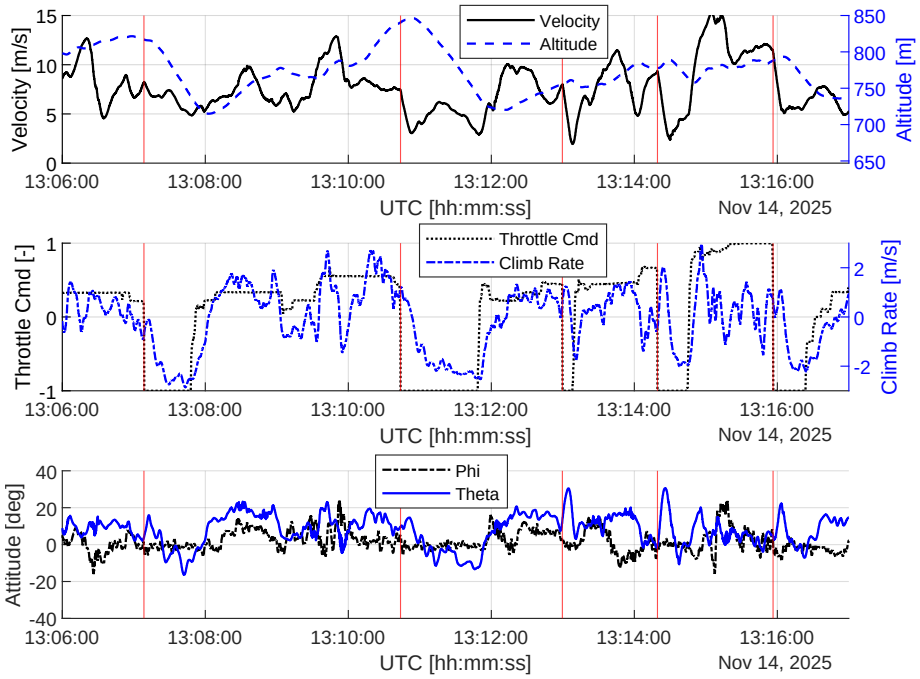


Figure 17 – Descent tests without control inputs (start of descent indicated by red vertical line)

After thrust cutoff, the airship pitches downward and begins to descend. Both pitch and roll show small oscillations. Roll oscillates around 0° and remains within a safe range. The pitch angle initially increases on average, then gradually stabilizes, approaching a steady attitude. Under extended no-control condition the average descent rate settles between $2\,\frac{m}{s}$ and $2.5\,\frac{m}{s}$. This characteristic is relevant for the flight authorization. The airship is operated in the specific category, meaning that its flight authorization is based on the Specific Operational Risk Assessment (SORA) framework defined by JARUS [18] and adopted by EASA (see [12], AMC 1 to Article 11). For the project, version 2.0 of SORA had to be applied, while SORA 2.5 is now the current version. Two provisions within SORA allow airships to reduce their risk class, which directly affects the flight authorization requirements. First, the ground risk classification, which is linked to a vehicle's characteristic dimensions, may be reduced for airships. This is because the German national aviation authorities (Luftfahrtbundesamt) acknowledge that the actual risk posed by an unmanned airship is not adequately reflected in the standard SORA classification, as the expected impact energy is disproportionately low relative to the vehicle's size [19]. Second, according to [20], the ground-risk class can be further reduced if it is demonstrated that the impact energy does not exceed $175J$. The airship consists of several discrete point masses connected by a soft envelope. Therefore, it can be argued that only the individual point masses are relevant for determining the maximum impact energy. Given a maximum point mass of $10kg$, which was imposed as a design constraint, an allowable impact velocity, resulting from the combination of descent rate and wind drift, of approximately $6\,\frac{m}{s}$ follows. Given that the measured descent rates during testing were significantly lower, providing additional margin for heavier configurations or adverse conditions, this mitigation is valid for the airship design. These considerations, among others, enabled the application for a flight authorization classified as SAIL II for test operations and SAIL III for flights over sparsely populated areas.

Another safety advantage of the tested configuration is the propulsion-system redundancy. The airship remains controllable even if one propulsion gondola fails completely. This was verified by deactivating either the forward or the aft electrical propulsion units in flight. In this condition, hovering is not possible because the pitching moment induced by a single propulsion unit is no longer balanced, but cruise flight can be maintained. Landing is also feasible, though more demanding than in a hovering-capable state. The following figures show two-minute flight segments with only the forward propulsion units active (Figure 18) and only the aft propulsion units active (Figure 19), each

at constant throttle. Due to the reduced available thrust, the airspeed is low, but the airship can be controlled and stabilized. According to pilot feedback, apart from reduced climb performance and maximum speed, maneuverability is not further impaired in forward flight using control surfaces. The segment with the forward propulsion system deactivated includes a turn, while the segment with the aft one deactivated shows straight-flight operation.

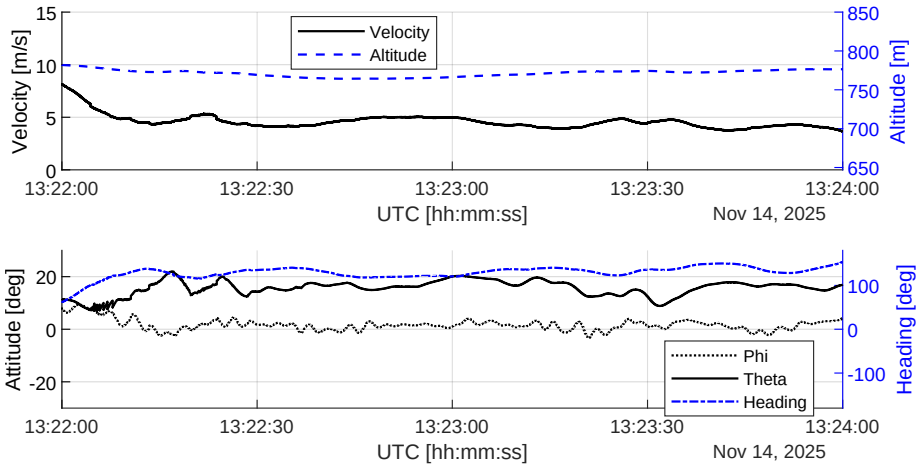


Figure 18 – Flight test with solely front propulsion units

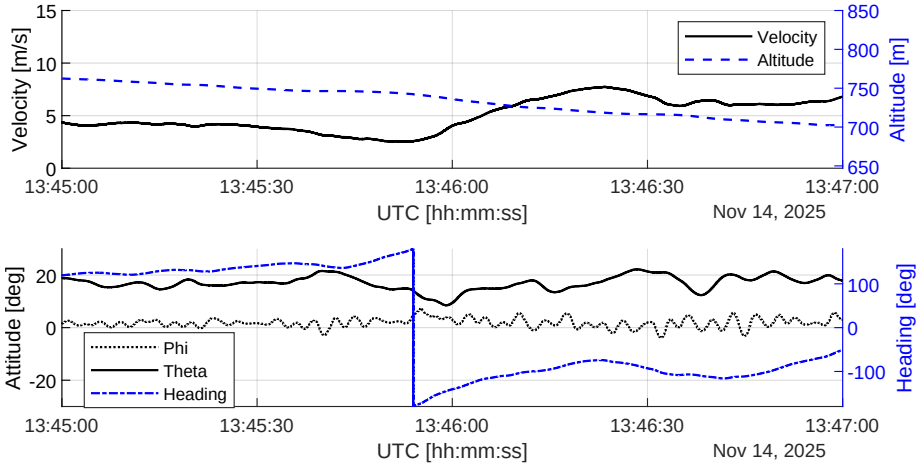
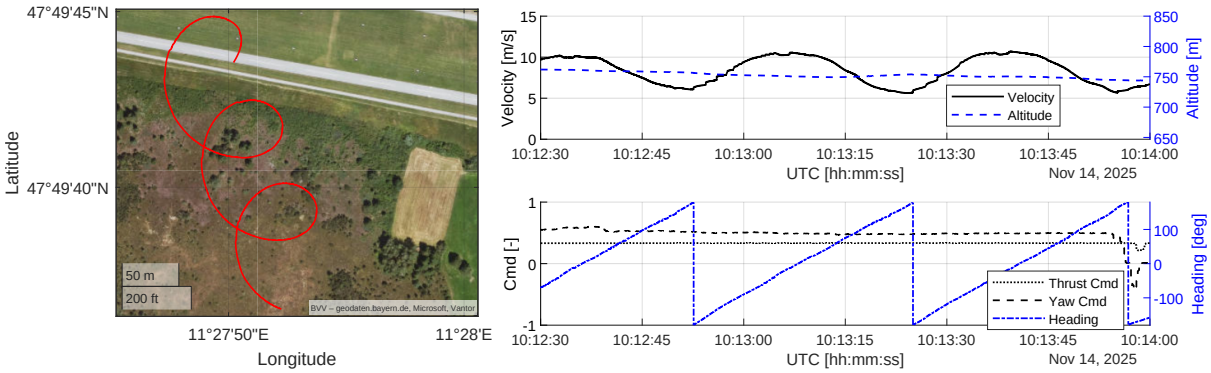


Figure 19 – Flight test with solely aft propulsion units

Since neither a partial nor a complete loss of control is probable during operation and the impact is non-critical, an airship is an optimal platform for testing in safety-critical areas, such as urban regions.

3.4 Susceptibility to environmental conditions

Because of their large surface area relative to mass, airships react strongly to atmospheric disturbances. The developed airship was therefore operated only under calm conditions with wind speeds below $5\,\frac{m}{s}$. Flying a circle at constant thrust clearly reveals wind influence and enables estimation of wind direction and approximation of its magnitude. Figure 20 presents the flight path and the velocity, altitude, and yaw angle over time for constant thrust and yaw input. A distinct relationship between velocity and yaw angle is observable: the maximum velocity of roughly $10.5\,\frac{m}{s}$ occurs at a heading of $-10°$ to $-15°$, whereas the minimum velocity of about $6\,\frac{m}{s}$ appears at an orientation rotated by $180°$. This pattern indicates a southerly wind with a slight easterly component and a magnitude of approximately $2\,\frac{m}{s} - 2.5\,\frac{m}{s}$. The resulting drift is also evident in Figure 20a where the airship, starting at 10:12:30 UTC at the southeastern point of the plot, is displaced by around $75\,m$ during a single circle. Even in low-wind conditions, the airship experiences substantial drift, underscoring its pronounced sensitivity to ambient wind.



(a) Flight path (b) Flight data

Figure 20 – Wind circle

Because the airship is highly susceptible to wind, aligning the cruise flight path with the prevailing wind direction is generally preferable. When mission constraints require following a specific ground track, flying with a kinematic sideslip angle in lateral winds helps to reduce wind influence during cruise. Since the airship cannot generate direct lateral forces, it must point its nose into the wind to maintain a stable and controllable state in hover conditions. With an active velocity command control law, the hover condition can be maintained reliably, as the full control range is available, including independent rotational velocities and orientations for all propellers. Figure 21 illustrates this. For more than $30\,s$, no vertical velocity, horizontal velocity, or yaw rate commands were issued, meaning the airship was intended to remain in hover. During this period, external disturbances were introduced by pulling on a rope attached to the nose. Despite these perturbations, the airship maintains its position with a stable attitude, showing only a slow yaw drift and small roll and pitch oscillations. This demonstrates that the tested configuration enables rather accurate control when all degrees of freedom are utilized. In manual flight, hover controllability is reduced because several control inputs are combined to simplify the pilot's workload. As a result, the airship typically exhibits stronger drift.

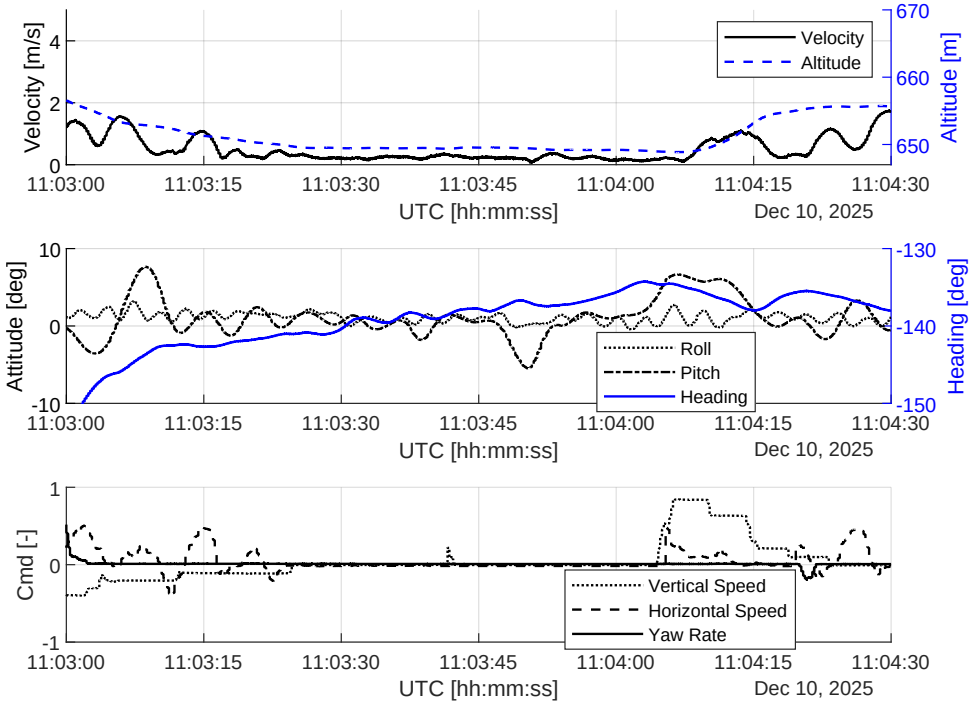


Figure 21 – Hover with active velocity command control law and external forces

In addition to wind, solar radiation is a significant factor for blimps. As long as the internal gas temperature follows the ambient air temperature, buoyancy remains largely unaffected by temperature

changes. As noted in Subsection 3.1, daily temperature variations only affect the buoyancy passively by determining the required air ballonet volume. However, solar radiation can cause superheat: the lifting gas warms more than the surrounding air because convection inside the envelope is limited, similar to a greenhouse effect. As a result, the density ratio between the lifting gas and the ambient air decreases, increasing the available buoyant force. This phenomenon, also described by Carichner et al. [1] and Leishman [21], becomes particularly pronounced during winter tests at low temperatures but with strong sunlight, as encountered in several campaigns with the described airship. Payload capacity can decrease substantially toward dusk as the envelope cools compared to a sunny midday, and the superheat effect is lost. This must be considered during mission planning.
Overall, environmental conditions play a crucial role in airship flight planning. Operation in strong winds requires an airship design with high controllability and agility in all axes. An airship with characteristics similar to the one described here - good pitch control but slower response to disturbances in the heading - is therefore best suited for missions where precise position control or accurate path following is not essential.

3.5 Operational characteristics

When designing an aerial vehicle for a specific mission, not only its flight properties but also its operational characteristics must be considered. These include endurance, payload capacity, and the required infrastructure, effort, and personnel for flight operations. In [22], Maly et al. state best practices for the development of a concept of operations for novel aerial systems.
Since the total mass of an airship must remain in a certain range, payload and battery mass can be traded. The modular power-system architecture allows the number of batteries to be adapted to mission needs: additional batteries can be installed when endurance is prioritized, while fewer batteries can be used when a higher payload mass is required. When evaluating the endurance–payload characteristics of the airship described here, it should be noted that this vehicle represents a first prototype and has not undergone multiple design iterations aimed at weight reduction. Although weight minimization was a key design objective, subsystem tests and flight operations identified several components that were unnecessary or could be redesigned to lighter forms. Furthermore, certain additional masses were accepted for operational convenience. One example is the set of ropes used to secure the airship in its transport frame, which remained attached during flight.
The airship was typically operated with a net weight between $6\,kg$ and $12\,kg$, with the upper limit approaching the threshold for a controllable hover state. The longest flight lasted nearly one hour and carried approximately $12\,kg$ of weight heavier-than-air, including a payload of about $5\,kg$. For this mission, the airship was equipped with only two battery packs, one per propulsion unit. The flight was mainly conducted in *cruise* mode. After landing, the batteries still showed a State of Charge (SOC) of roughly 25% (see Figure 22).
This flight was not optimized for endurance. Instead, it focused on radar-sensor testing and therefore required continuous maneuvering and altitude changes, resulting in fluctuating current consumption. Since the airship operates more efficiently in steady cruise at moderate throttle without frequent maneuvers, longer endurance can be expected under optimized conditions. The airship's weight during this flight was at the upper limit, despite carrying only two battery packs. The reason is that the mission took place at the end of the test campaign, when the helium purity had noticeably deteriorated, resulting in reduced buoyancy. Considering these factors, an airship of similar size and configuration can reasonably be expected to carry payloads up to $10\,kg$ for at least one hour of flight time. With a lightweight payload and double the battery capacity, flight durations of more than two hours are well within reach.
The main infrastructure requirement for airship operation is a suitable hangar for storage. Once filled, an airship can remain in service for several weeks using the same helium, requiring only minor refilling to compensate for diffusion losses. Because helium is costly and deflation-inflation cycles are time-consuming, it must be possible to store the airship in an inflated state. Although fixed-wing aircraft and multicopters are also typically housed in hangars, their space requirements relative to payload capacity are significantly lower. Beyond hangar space, no specialized infrastructure is needed for takeoff or landing. However, due to the risk of wind drift, a sufficiently large obstacle-free area is necessary. Based on flight-testing experience, an area with a radius on the order of twice the

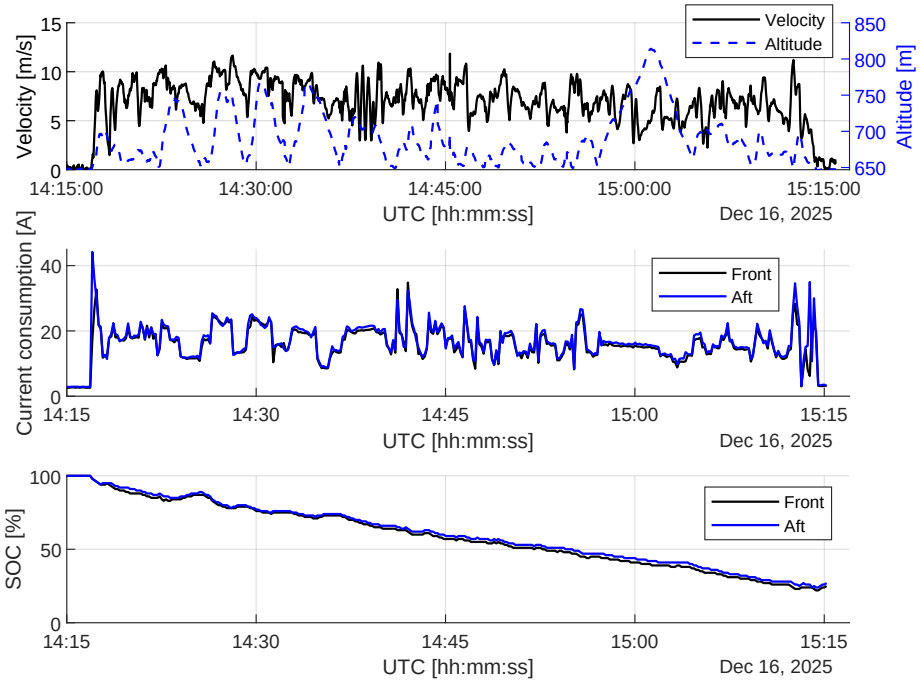


Figure 22 – Battery SOC development during one flight test

airship's length is considered adequate. For inflation, storage, and transport of the inflated vehicle, a dedicated support frame was used, as shown in Figure 23.



Figure 23 – Airship support frame

For an airship of this size, a remote crew of at least five people is recommended. This includes the pilot, a flight-test engineer, a ground-control-station operator, and two support staff responsible for takeoff and landing. The support staff holds the airship above the ground prior to takeoff and secures it during the hover phase of landing. The required preparation time depends on whether the airship is already inflated or has just been transported to the test site. Inflation and assembly, including functional checks, require between one and two days. Pre-flight preparation can be completed within approximately 1.5 hours by an experienced team. This process includes verifying the helium volume and performing any necessary refills, powering up and testing safety-critical systems in a structured sequence, and conducting the crew briefing.

Airship operation involves several requirements that differ from those of other aerial vehicles. These include handling helium and relying on ground support staff during takeoff and landing. Despite these specifics, the overall infrastructure demand remains low. An airship can be transported easily in its deflated state using standard trailers, providing considerable operational flexibility. Combined with the demonstrated payload capacity and endurance, this makes an airship a suitable and versatile platform for research missions at various locations.

4. Conclusion

A detailed description of the subsystems, their design, and functionality highlights the unique characteristics that make the airship designed for radar sensor evaluation in urban environments particularly suitable as a research platform. Successful flight tests with this airship demonstrate the feasibility of using such platforms for research purposes, and extensive flight test data provide the basis for analyzing additional potential applications, both within research and beyond, for airships of similar size and configuration, i.e., with lengths on the order of $15\,m$ and volumes in the upper double-digit cubic-meter range.

The main motivation for selecting an airship as a test platform is its inherently high level of operational safety. Features such as good visibility, low-impact energy, and, consequently, low risk even in the event of complete loss of control make unmanned airships intrinsically safe aerial vehicles, as reflected in regulatory acceptance. Medium-sized blimps are particularly well-suited for steady, low-speed missions. As long as only small variations in altitude and velocity are required, airships operate efficiently and can achieve long endurance. Payload capacity is limited to the lower tens of kilograms, and increasing payload mass reduces endurance by decreasing the allowable battery mass. Nevertheless, this payload range is well matched to the testing and application of subsystems, such as specialized avionics, alternative propulsion concepts, and new sensor technologies for navigation, positioning, surveillance, or inspection, including optical, infrared, or acoustic systems. This assessment is supported by the use cases of existing airship operators ([9], [10], [11]). From a payload integration perspective, a constraint is that the payloads can only be mounted beneath the airship, unless they are very lightweight.

Although maneuvering reduces endurance, the airship exhibits good agility in yaw and pitch, particularly in cruise flight. Position hold is also feasible, though with limited accuracy due to the vehicle's high sensitivity to environmental disturbances. This sensitivity represents the main operational limitation and reduces mission availability. If high positional accuracy is required under moderate wind conditions, the system must be augmented, for example, with propulsion units capable of generating direct lateral forces. Adverse weather conditions such as strong winds or heavy rain are not suitable for blimps.

In contrast, airships offer considerable flexibility regarding the location of operation, as they can be transported easily in their deflated state, albeit with an extended preparation time after transport. Once inflated, however, the required effort for flight operations is manageable.

Taken together, these findings show that medium-sized airships provide a robust, safe, and versatile platform for scientific experimentation, particularly when long endurance, low-risk operation, and moderate payload capacity are required. As such, they represent a valuable complement to existing aerial research platforms.

5. Contact Author Email Address

For inquiries about this paper, the author Hannah Reindle (PhD candidate at Technical University of Munich) can be reached via email at hannah.reindle@tum.de.

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