Design, realization and testing of an azimuth-stabilized modular stratospheric platform

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Abstract. In recent years, increasing investments from space industry are directed towards single or constellations of small satellites orbiting in LEO, which have significantly low cost with respect to other types of space missions, but require many years of development and large sums on an absolute scale. The development of new facilities that can cut costs during this phase is therefore of primary interest. One of the main cost items is the development and testing of space hardware, which shall be exposed to high-vacuum and high-level-radiation environment, that is both extremely difficult and expensive to recreate in laboratory. The cheapest option is the use of near-space platforms lifted by small-scale sounding balloons; however, they are not commonly employed because state-of-the-art gondolas for such balloons do not offer a stabilized frame. The work presented in this paper shows a successful attempt at designing and realizing a low-cost yaw-stabilized stratospheric platform, able of self-orienting at set azimuth direction. Active attitude stabilization was achieved via the use of a single reaction wheel placed along the main vertical axis of the platform, controlled by a PI software, and was accompanied by passive attitude stabilization techniques. Tests prove that a stabilized position can be achieved within ±5° of the selected pointing direction, which is preset or directly inputted by the user during platform operations. In this paper, a first application of the platform to host a payload of four solar cells is presented, but particular emphasis was given to modular design, so that the integration of a different payload would require the minimum amount of re-design.

Introduction

Modern scientific ballooning is targeting the development and implementation of high-altitude pseudo satellites (HAPS) flying in the near-space region, that extends from 20 to 100 km in altitude. Applications for HAPS, other than meteorology, range from remote sensing to telecommunication such as, but not limited to telescopes, radio occultation and regional monitoring [1, 2, 3]. Sounding balloons are the small-scale category of stratospheric balloon and have the advantage of being at least two orders of magnitude cheaper than the zero-pressure and super-pressure large-scale counterparts, at the expense of a reduction in payload capability and time of flight, which is usually no longer than 3,5 hours [1], yet reaching the same maximum altitude of 30-35 km. However, many studies to obtain an extension in flight time via altitude stabilization have been made recently, therefore a larger number of users could be interested in this kind of balloons in the future. Nevertheless, many HAPS applications require active attitude stabilization, which is a state-of-the-art technology on platform for large-scale balloons, but not a feature currently offered by platforms for sounding balloon. Active attitude stabilization on small-scale gondolas can be implemented using different strategies, such as reaction wheels [4], motorized pivots [5], cold gas thrusters [6] and propellers [7], but no standardized practices are present in literature. Moreover, since at state-of-the-art a custom gondola tailored to the specific instrument is developed for each launch and/or has not an active attitude stabilization system, no

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proper HAPS in literature can be accounted for. The work presented in this paper addresses this issue and describes the development, realization and testing of a small-scale reaction-wheel-azimuth-stabilized HAPS which can be suited for different instruments, when properly joined with a custom interface. As a first application example, four solar cells for space have been selected as payload.

Driving Requirements and Platform Design

The purpose of this work was the production of an azimuth-stabilized stratospheric platform suited for sounding balloons and able to accommodate scientific instrumentation of different nature. Starting from this statement, different requirements were defined.

Structural Requirements.

- *Total mass < 4kg* - to be compliant with the ICAO rules;
- *Modular design* - to accommodate payload of different nature, avoiding radical redesign.

Attitude Control System Requirements.

- *Azimuth stabilization* - i.e. around vertical axis;
- *Pointing capability* - stabilization shall be of ±5° around the selected azimuth;
- *Decoupling capability* - techniques to promote decoupling from roll-pitch motion and launch train motion shall be taken into consideration during its design.

Functional Requirements.

- *Telemetry and data accessibility* - telemetry must be accessed during platform operations, via a wireless connection, and produced data must be stored on board;
- *Payload accommodation* - shall accommodate 4 solar cells and their electronics;
- *Monitoring capability* - the platform shall be provided with imaging system that shall take pictures of the attitude control system and the payload to assess their correct functioning.

Starting from requirements, all tasks that the platform should be able to perform were defined and for each task, the suitable instrumentation was selected. Following the preliminary evaluation, single components were organized in different subsystems, which are: imaging, attitude control and power supply. The subsystems were subsequently integrated and structural design was conducted to obtain the most compact and lightweight platform as possible, which was 3D modeled and then 3D printed using PLA filament. The basic unit of the main body is of cubic shape, with a 15cm edge. To implement a modular design, the interior of the cube was divided with planes and the reaction wheel was placed on the top part of the platform. Interface for the payload was designed so that they could be exposed to sunlight in the most effective way, and it is placed below the main structure. Payload electronics are accommodated inside the platform, on the bottom plane.

Testing and Results

Indoor experiments were conducted: the platform was suspended to simulate the actual operational condition and a fan was directed towards the platform to recreate disturbances generated by winds' action.

Performance Assessments. Performances were assessed measuring the platforms efficiency in matching the assigned azimuthal direction and maintaining the position, with minor oscillations around the equilibrium point. After the power on and the attitude sensor calibration, starting form rest, the platform oriented towards the magnetic North and kept itself around said position. Then, two different target azimuth commands were sent in sequence. After the third equilibrium point was reached, the test was ended. The total duration of the test was fixed not to be less than 4 minutes and 30 s were awaited after the stabilization before sending the new command. As an example, an individual test, called test A will be analyzed. Fig. 1 depicts the graphs of the azimuth

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and unwrapped azimuth as a function of time. From the upper graph, the presence of three distinct stabilization segments around 0°, 60° and 270° is evident. Rotations from a target azimuth to the subsequent one are managed performing the minimum angular displacement either in clockwise or counterclockwise rotation. A slight tilting of the actual azimuth stabilization angle with respect to the target one is noticeable, due to the non-linear motor stall of the brushed motor. Nevertheless, the recorded medium of absolute tilting with respect to nominal heading is of 1.72° and the maximum deviation around the actual stabilization value is of 2.45°, in compliance with pointing requirements.

Operational Limits. The reaction wheel saturates at known angular velocity thresholds called ω_t, known from controller gain. A test was conducted to assess the behaviour in case of saturation: after the power on of attitude control system and the attitude sensor calibration, the platform was kept at a stable position and quickly rotated in clockwise direction, so to induce saturation. A sufficient time was then awaited so that the platform could stop its spin and position itself around the target 0° azimuth. Once the platform stabilized around the target azimuth, the procedure was repeated once again in clockwise direction and twice in counterclockwise direction. The overall duration of a single test was fixed not to be less than 4 minutes. As an example, an individual test will be presented, referred to as test C. Upper graph depicted in Fig. 2 shows a peak in correspondence of the instance where the rotation is applied. Middle graph indicates the PWM value, which is in the interval [−255, 255]: *saturation segment* - corresponds to the flat part of the graph; *rotation segment* - it corresponds to the highly dense part of the graph; *stabilization segment* - has an oscillatory pattern. Comparing upper and lower graph, it is evident that during the saturation segment the platform is subjected to full rotations, that progressively become slower as

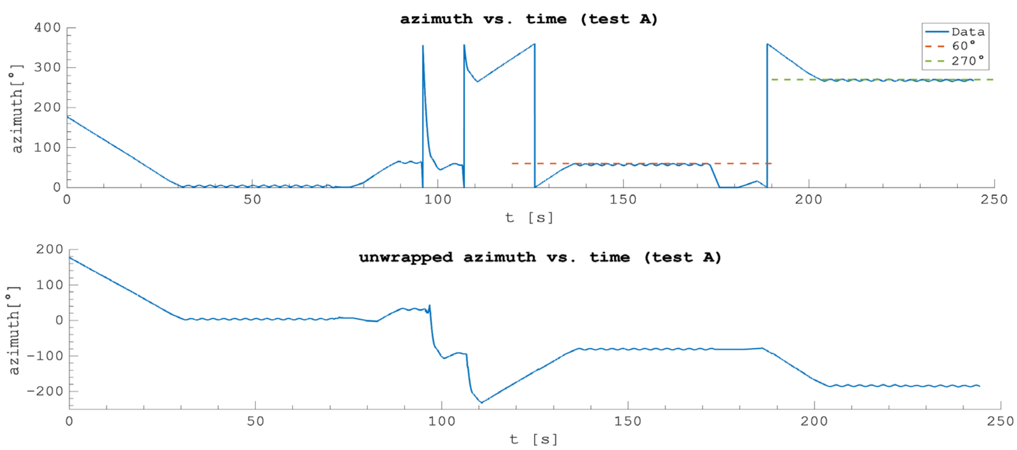

Figure 1. Azimuth (up) and correspondent unwrapped azimuth (down) recorded during test A

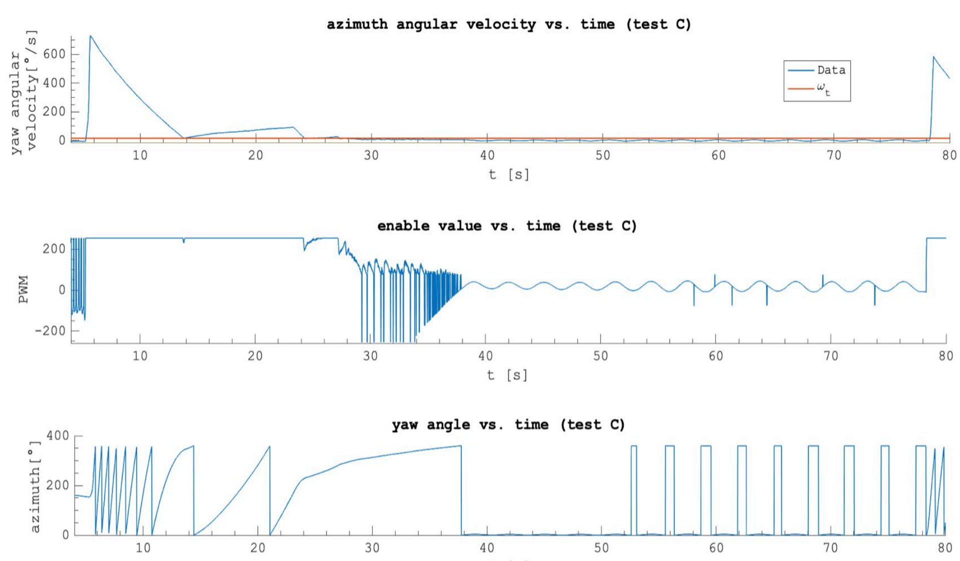

Figure 2. From top to bottom graphs: azimuth angular velocity, PWM, azimuth angle for the first clockwise disturbance in test C

the platform decelerates. In the final part of the saturation segment and throughout the rotation segment, the platform is rotated in a controlled approach towards the target azimuth, decelerating a gradually until the 0° azimuth is reached. When the stabilization segment is reached, PWM values are very far from saturation. It is therefore evident that reaction wheel desaturates spontaneously and efficiently, independently from its starting angular speed, due to the continuous exchange of momentum between the platform and the surrounding air.

Conclusion

The successful development of a modular stratospheric platform was demonstrated. Tests have shown that stabilization is achieved within the limits of $\pm 5°$. Despite the great results obtained, the platform has only been tested indoor and few open issues remain to be solved. The platform will be subjected in the future to: the integration of a low-power-consumption long-range telecommunication system; mathematical modeling and direct testing, with launch campaigns, to analyze variations of desaturation effect offered by air and torque disturbances due to wind action with altitude; the replacement of the motor with a brushless one, to reduce tilting in stabilization angle and oscillations; the integration of solar cells to improve its operational life, which is of particular interest for altitude-stabilized balloon application.

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