Altitude control of a remote-sensing balloon platform

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Abstract

This paper addresses the problem of altitude control of stratospheric balloon platforms. Over the last years, there has been an increasing interest in the development of balloon platforms with the ability of maneuvering and fluctuating at the stratosphere for different applications on the basis of remote-sensing. Considering the current trend of a high connected world with sensor grids spread in wide geographical areas, the interest in balloon platform applications has increased posing new challenges for future applications. One of the major problems encountered in this context is how to guarantee constant altitude sustainability. Although the technologies required to address this problem already exist, low cost and easy to launch solutions are still needed considering applications on a wide scale. In this work, a theoretical model of the balloon dynamic is presented and validated. A valve control loop mechanism is proposed for rubber balloons. The controller is tuned empirically and numerical simulations conducted for performance analysis and a case study in a real mission. The proposed solution contributes to increase the capacity of rubber balloons by proposing an altitude control system that allows fluctuation stages which, in general, are not common with this type of balloon.

Keywords: High Altitude Platform, Altitude control, rubber balloon, CubeSat

1. Introduction

Nowadays, no one doubts the importance and fundamental role of using scientific balloons floating in the stratosphere. Since the modern era of these lighter-than-air platforms in the early 1930s, characterized by the development of low density polyethylene films, many different balloon missions were developed, tested, and successfully demonstrated for a variety of applications [1]. For example, from a commercial point of view, balloon platforms provide a way for companies to explore surveillance applications, communication and data services in remote areas, vertical sensing for meteorological applications, and alternatives to conventional rocket launching [2], [3]. From a scientific perspective, they represent a low cost tool for conducting educational activities [4, 5, 6] or to perform experiments in a near-Earth environment [7]. Programs from national space agencies in Europe, USA and Japan, and the recent Google Loon are among some of the efforts to use high altitude balloons for data and connectivity services [8], [9].

In order to increase the scale and applicability of balloon systems, it is necessary to improve the capability of achieving altitude control, a problem that is currently debated in the literature [10], [11], [12], [13], [14], [15]. Different factors contribute to make ballooning systems very challenging, as for instance unknown and constantly changing surface layer winds, high temperature and pressure gradients along the flight path, nonstandard and also changing atmosphere resulting in uncertainties on estimation of height, ascent/descent rate, besides others. Moreover, despite the advances in the mathematical models providing a better description of a balloon flight, most of the data are still unknown to some extent.

Future trends in balloon activities are aligned with the current era of high connectivity, internet of things and device to device communication. In this new paradigm, the ability to provide quick response is crucial, and the use of ballooning systems can be of great relevance in supporting activities on ground such as navigation, remote sensing, surveillance and monitoring, specially in remote areas underserved by terrestrial networks or dispersed over a wide geographical area. Lightweight, low-cost platforms that are easy to launch, capable of sustaining its altitude for a period of time, and equipped with a landing control system are among the most suitable solutions to respond quickly. This means extending the application of rubber balloons, used mainly for the measurement of meteorological parameters, for more complex missions. Different from zero-pressure and super-pressure balloons, rubber balloons are inexpensive, easy to handle at launch, and safer with respect to flights over densely populated regions due to their lighter weight.

It is important to emphasize that rubber balloons have been used primarily for meteorological remote sensing since 1920s. They are indispensable for observing weather in the upper atmosphere, as in the case of observations that exploit the reduction in atmosphere influence, or with the observation of the thin atmosphere [16]. It is possible to expand their capabilities to cope with a wider range of applications by adding an exhaust valve that automatically release the lifting gas to control its altitude.

Within this context, the Laboratory of Simulation and Control of Aerospace Systems at the University of Brasília, Brazil, has been developing a modular platform able to fluctuate at high altitudes. The platform, called LAICAnSat, is equipped with a system for automatic deployment of small payloads for quick return from the stratosphere. A landing control system enables trajectory control in the landing stage, a solution that is very useful for instance to enable easy rescue [17]. The platform is carried to high altitudes using a free-flying, low-cost rubber balloon enabling wide range observations. In its current version, the platform is manufactured in accordance with the CubeSat standard [18] using rapid prototype technologies and exploiting current technological advances such as miniaturization of electronic components and devices.

Altitude control of a balloon is achieved by either changing the buoyancy of the balloon or its mass. Changing the buoyancy is obtained by changing the volume of the balloon, as done, for example, in [19] by mechanical compressing the balloon, or in [20] by heating the gas inside the balloon. Mass alteration requires the capacity of ejecting air (or another kind of ballast) out of the balloon, as done with the Google Loon super pressure balloons [21]. Many methods have been proposed in the literature for the problem of positioning control of high-altitude platforms and airships, such as PID controllers [22], backstepping [23], and sliding mode control [24]. On the other hand, very few sources can be found focusing on the design and implementation of altitude control systems for rubber balloons. The altitude control of a rubber balloon presents some peculiar difficulties, indeed. For example, they can not withstand high pressures and the allowed weight is reduced - usually no more than 10 kg.

This work aims at presenting a simple and practical altitude control system for the rubber balloon used in LAICAnSat missions. The development of the control system involves the design and manufacturing of a valve for the balloon and a proportional–integral–derivative (PID) controller based architecture, with position and velocity feedback loops. A simple mathematical model of the vertical motion is also developed, which includes some of the most relevant parameters of the balloon, such as the radius and the drag

Figure 1: **LAICAnSat-5 and LAICAnSat-5.1 flight models at launching site.**

coefficient. These parameters are determined in this paper comparing the model with real data collected in previous flights.

This paper is organized as follows. Section 2 gives an overview of the LAICAnSat platform and of the main stages of the project so far; Section 3 describes the altitude control system; the numerical simulations are reported in Section 4; final conclusions are given in Section 5.

2. The LAICAnSat

The LAICAnSat project was started in 2013 at the University of Brasília as an initiative to stimulate the study of aerospace systems and to provide a low-cost platform for hands-on aerospace education. The first flight tests took place in 2014 (LAICAnSat-1 and LAICAnSat-2) [25], [26], and allowed to test early hardware solutions. Other four launches occurred in 2017 (LAICAnSat-3, LAICAnSat-4, LAICAnSat-5 and LAICAnSat-5.1). LAICAnSat-3 and LAICAnSat-4 were launched in order to validate a new mechanical structure fabricated in accordance with the CubeSat standard and using rapid prototype technologies based on 3D printer manufacturing [27], the new PC/104 standard PCB with the on-board computer and embedded sensors [28], as well as two 360^o spherical cameras.

LAICAnSat-5 (CubeSat 3U standard) and LAICAnSat-5.1 (CubeSat 1U standard), shown in Fig. 1, were launched within the NASA Space Grant Eclipse Ballooning Project [29]. The goal of this mission was to record a 360^o video reproducing the flight experience up to the stratosphere during

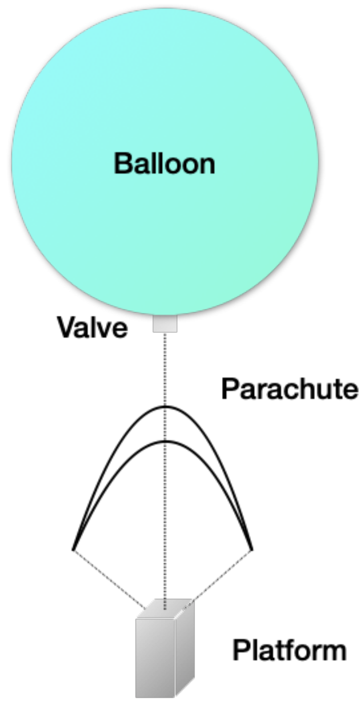
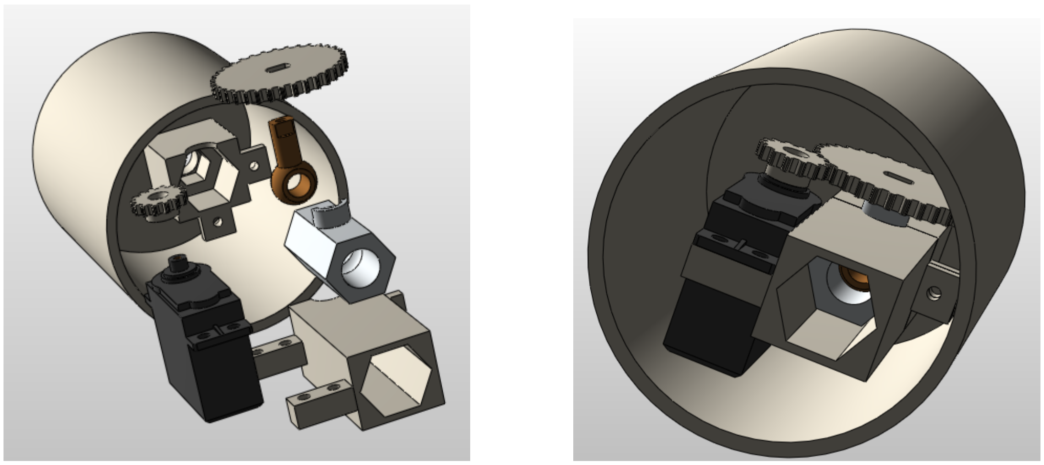


Figure 2: **LAICAnSat system main elements.**

the total solar eclipse of August 2017 in North America [30], and a vertical meteorological mapping of the whole flight path [29].

In order to improve the platform, making it more robust and reliable for more complex missions, a solution capable of performing a completely autonomous mission, including data collection and safe landing using an airdropped system was studied in [31]. The use of an airdropped system to accomplish these tasks is inspired by different types of applications, such as aerial delivery applications and recovery of payloads from the International Space Station (ISS), among others.

Fig. 2 shows the concept of the LAICAnSat system. The three main elements are the balloon, the valve, and the platform. A rubber balloon is used to raise the platform to the stratosphere, where the mission takes place. The platform is a pseudo-satellite carrying on the payload and all the subsystems needed for the execution of the mission. A parachute is always used to safely land the payload in any situation, that is, when released by using a separating mechanism, or when the balloon suddenly bursts.



(a) **Expanded view** (b) **Compact view**

Figure 3: **View of the valve and the actuation system.**

2.1. The balloon

Rubber balloons (sometimes called also meteorological or stratospheric balloons) are inflatable, rubber-made balloons that can rise up to more than 20 Km in the sky, when filled with a lighter-than-air gas like Helium. They have great elongation characteristics being able to stretch more than 500% in one direction. After being partially inflated on the ground, they start to ascend. The size of these types of balloons is limited by the manufacturing method applied. Different from zero-pressure, super-pressure and dual-balloons, they are inexpensive and easy to handle when launched. They do not have a fixed volume, and once their expansion limit is reached at high altitudes, they burst. Moreover, they are classified by their total mass [16].

2.2. The valve

In order to allow for some fluctuation around a specific altitude, there must be the possibility to control the amount of internal gas, so that the internal pressure can be adjusted. This can be done with a valve and a dedicated strategy for the control of its opening. A valve prototype was developed, whose main features are low cost, low weight, modularity, and simplicity of operation.

The valve was manufactured with rapid prototyping employing polylactic acid (PLA). The main component of the project is a commercial-off-the-shelf (COTS) ball valve, made of copper and zinc. The ball valve was selected taking inspiration from the models used in rocket competitions to control the flow of nitrous oxide for hybrid rockets. The valve has been mechanically coupled to a servomotor and a set of gears to form the actuation system, as shown in Fig. 3. Based on the flight heritage of past tests [31], this system is placed inside the nozzle of the balloon, in order to avoid contacts with the rope that connects the balloon to the rest of the platform.

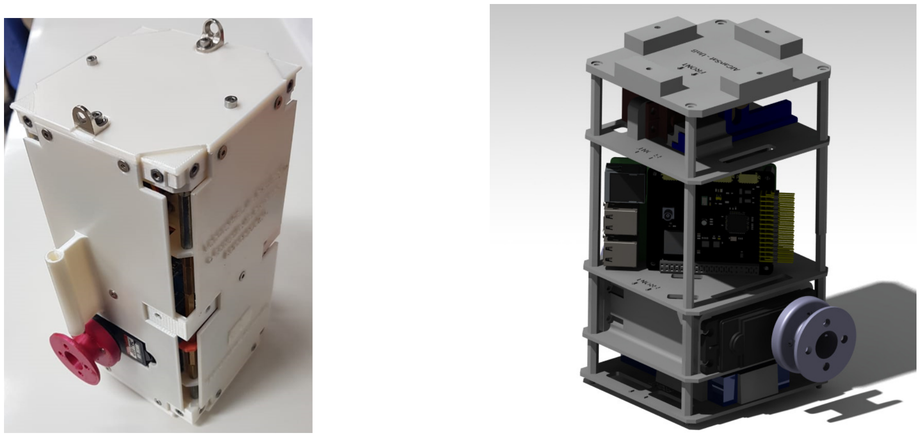
To determine the performance of the 1 cm diameter ball valve, a leak test was performed using a 0.5 m diameter rubber balloon filled with Helium. The valve did not show any noticeable leak for more than 15 minutes. When the valve was opened, the balloon completely deflated in few seconds.

2.3. The platform

The platform of the LAICAnSat is designed following the criteria of the CubeSat standard [18]. The result of this choice is a simple, easy-to-manufacture, and easy-to-access structure. Other advantages of using a CubeSat structure are the possibility to train students in the study and design of aerospace systems and its modularity. The latter allows to develop and internally rearrange the subsystems in accordance to the mission. For example, the payload might change from time to time, but its dimensions will remain defined by the standard.

Apart from the first two missions, the platform has been defined as a two (2U) or three-unit (3U) CubeSat. Each unit has dimensions of $10\times10\times10$ cm and the internal volume is compatible with the PC/104 standard for embedded systems, see Fig. 4. This allows to store the on-board computer, the tracking hardware, batteries, actuators, the payloads and thermal insulation material, if needed. It is important to notice that the final structure might not fully adhere to the CubeSat standard, because of appendages or actuators leaning off the walls. For example, a system of servos and pulleys was designed to control the actuation of the parachute, with the actuators and the parachute attachment point being on the external faces of the structure, as shown in Fig. 4a. The platform is manufactured using 3D printing technology and PLA filaments that provide a robust, lightweight, and UV-resistant structure.

The on-board avionics consists of a set of meteorological sensors, a GNSS module, an inertial measurement unit, and a tracking and telemetry xBee-based system working at 900 MHz. The microcontroller is based on a 32 bit ARM processor, Cortex-M4, 72 MHz, compatible with Arduino software and libraries [32], [33]. The tracking hardware is a COTS solution that uses



(a) **Detail of a LAICAnSat 2U with external servo motors and parachute attachment point.**

(b) **Internal structure concept of the LAICAnSat 2U.**

Figure 4: **LAICAnSat current version.**

the Automatic Position Reporting System (APRS), which is an AX.25-based amateur communication protocol [28]. A redundant tracking system based on a commercial satellite service is also used.

The payload changes in accordance with the missions. As remote sensing was among the primary goals in all the missions so far, a number of different cameras were tested throughout the project, namely a GoPro (LAICAnSat-1 and 2), an LG 360CAM and a HackHD 1080p (LAICAnSat-3), a Nikon KeyMission 360 (LAICAnSat-4) and two Kodak Pixpro SP360 4k Virtual Reality (LAICAnSat-5).

Lithium Iron Phosphate (LiFePO4) batteries are used to power the on-board computer due to their light weight and high-energy density. Other devices like the cameras require further batteries (e.g. Lithium-ion ICR) to produce the necessary power. All batteries are fitted inside a box that provides the necessary thermal insulation.

3. Altitude control design

Altitude control is a very important feature in balloon missions in view of a more complete trajectory control. The flight of a balloon is heavily influenced by the winds, which vary very much according to the altitude [13]. Requirements on balloon stabilization are dictated by the remote sensing application and the instruments. For example, in [5] a stable flight of at least 1 hr is required for a multi-spectral imaging system mounted on a balloon. It is important to stress that the main goal of the proposed solution is to provide a complete mechanism (exhaust valve and control system) to allow rubber balloon missions to have a fluctuation stage. Moreover, due to its technical characteristics, missions using rubber balloons are designed to have a short lifetime. This section will describe the altitude control strategy designed for the LAICAnSat.

3.1. Dynamical model

Before designing the altitude control law for the balloon system in this work, a dynamical model is needed to describe the vertical motion of the balloon. The ascent in the sky of a balloon filled with Helium can be described by the equilibrium of buoyancy F_B, gravity F_G and aerodynamic F_A forces. Papers focused on simulating and analyzing balloons flight performance have considered mass variations resulting from temperature variations in accordance with the standard atmosphere model, solar radiation, and infrared radiation models [34, 35]. The model used in this work does not include all these effects, since it is meant at designing a practical control system that will be compared with real flight data. The equilibrium of forces is, therefore:

$$\dot{v} = \frac{F_B - F_G + F_A}{m}, \tag{1}$$

The flat Earth approximation allows to consider gravity as a constant force directed along the local vertical direction, proportional to the product of the mass m and the constant gravity acceleration g:

$$F_G = mg \tag{2}$$

The buoyancy is given by the difference between the weight of the volume of gas inside the balloon and the weight of the corresponding volume of air:

$$F_B = V_b(\rho_{atm} - \rho_b)g \tag{3}$$

where V_b is the volume of the balloon, ρ_{atm} is the atmospheric density and ρ_b is the gas density inside the balloon. The aerodynamic force is essentially the drag force opposed to the motion of the balloon:

$$F_A = \frac{1}{2}C_D\rho_{atm}Sv^2 \tag{4}$$

where C_D is the drag coefficient and S is the cross sectional area of the balloon. The cross sectional area and the volume are not constant, since the balloon increases its radius r as it rises up in the sky as an effect of the pressure variation. Initial and burst diameters are provided by the balloon supplier. The rate of expansion with altitude of the balloon follows a simple homogeneous dilatation: the balloon geometrical shape is assumed to be a sphere throughout the whole ascent phase.

3.2. Altitude control strategy

The altitude control architecture (represented in Fig. 5) is based on two feedback loops, one on the altitude measurement and the other on the velocity, alternatively used to open and close the valve of the balloon. Each control loop is feeding a PID controller that produces an opening command for the valve, which is implemented by the valve servomotor. The valve servomotor is modeled as a second order transfer function W_{act} with damping factor ζ and natural frequency ω_n:

$$W_{act} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{5}$$

The altitude control strategy adopted to switch between the two loops depends on the current mission, flight phase, altitude, and vertical velocity. It is represented in the flowchart of Fig. 6.

The velocity and position reference signals are alternated as references for the altitude control system, in accordance with the phases of flight. Each phase, in fact, has a different task with respect to velocity or altitude. The typical phases of a LAICAnSat mission and their control tasks are defined as follow:

1. **Ascent:** The balloon ascends in free flight until reaching a predefined altitude.
2. **Altitude control:** Upon reaching the predefined altitude, the control system is activated acting on the valve. First, the vertical velocity is reduced to zero. Then, the strategy switches to the position control loop until it reaches the desired altitude. This floating phase lasts for the time needed for the system to perform the tasks of the mission.
3. **Landing:** When the mission is terminated, the velocity loop is activated once again, making the platform land at a prescribed touch-down speed.

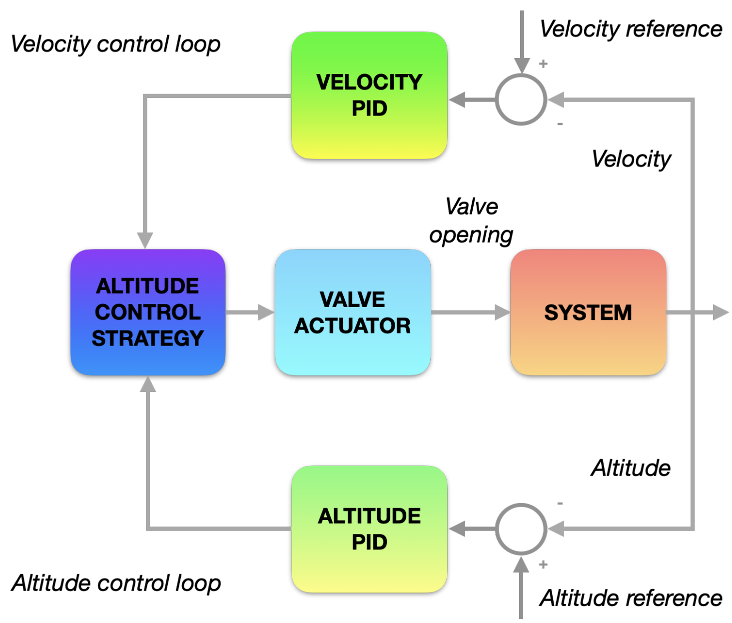


Figure 5: **Altitude control architecture**

4. Simulations and flight results

In order to validate the dynamic model of Eq. 1 and the control strategy of Fig. 6, two simulations were performed. The first simulation aims to reproduce the flight data of the LAICAnSat-5 mission [29], so as to define values for the parameters of the model in Eq. 2-4. Some of the flight data, like the temperature, pressure, altitude and vertical velocity profiles, of this mission are represented in Figs. 7 - 10. The mission reached an apogee of 30 Km in an hour and then touched down in less than another hour. The second simulation is a representation of an entire mission with the altitude control strategy described in Section 3.2.

The first simulation reproduces the climb and descent of a rubber balloon. In doing so, the unknown parameters of the model are adjusted so to match the trajectory with that of the LAICAnSat-5 mission. The adjusted parameters are the drag coefficient C_D and the final radius of the balloon r_f at burst. For calculating r_f, a linear expansion model has been assumed, starting from the known initial radius r_0 until finding a suitable value for r_f. The values of the parameters used in the simulation and the estimated ones are resumed in Table 1.

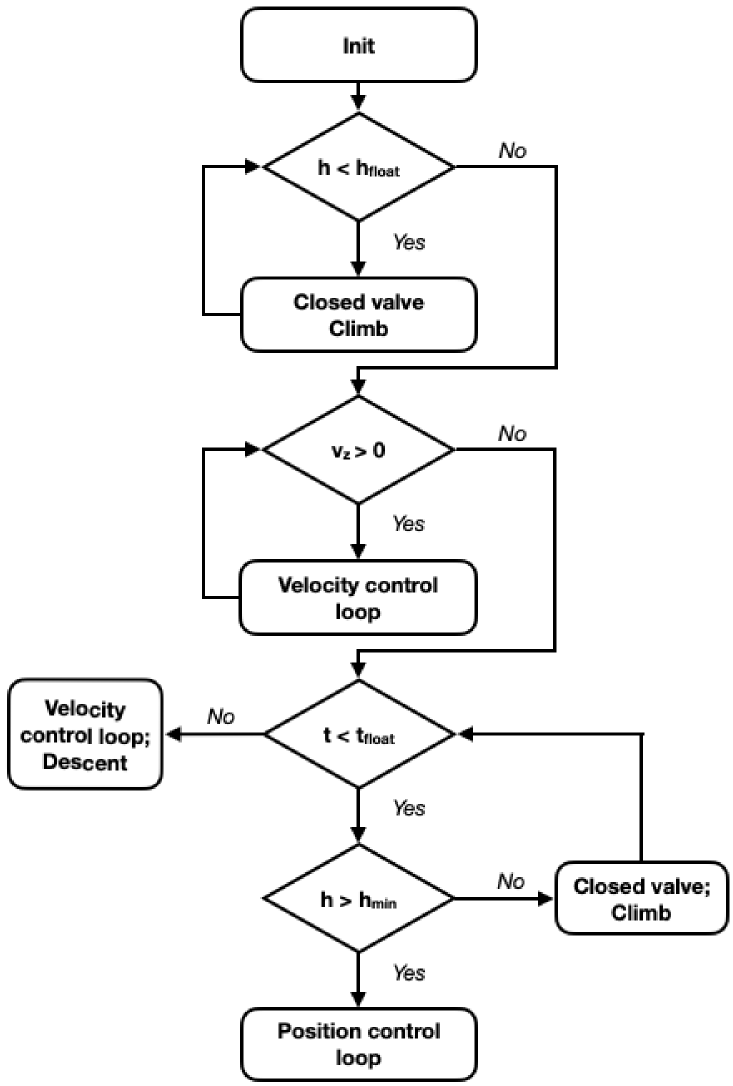


Figure 6: **Altitude control strategy**

Table 1: **Input variables for the simulation of the dynamic model.**

Parameter	Value	Parameter	Value
g	$9.81\ m/s^2$	C_D	0.85
r_0	$1.7\ m$	r_f	$4.65\ m$
m	$4\ Kg$	Initial Speed	$0\ m/s$
Initial Position	$1452\ m$	Integration Step	$0.02\ s$
ω_n	$150\ rad/s$	ζ	0.7

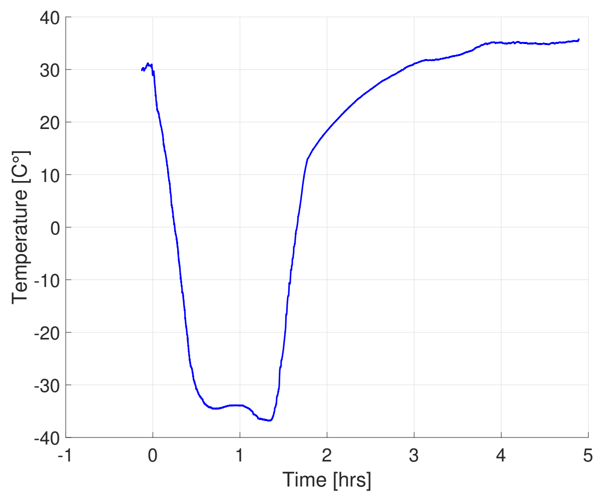


Figure 7: **Temperature profile from the flight data.**

Fig. 9 shows the altitude profiles for the LAICAnSat-5 mission and the simulation. When the balloon reaches the burst altitude observed in the mission data, the lift force within the simulation is removed and the drag force is modified to emulate the descent from the platform with a circular parachute. The two trajectories are quite close, which validates the parameters found for the dynamic model. Fig. 10 represents the comparison between the vertical velocity in the simulation and the actual flight data. Even in this case, the simulated velocity profile is quite close to the recorded data. Flight data were smoothed using a finite impulse response (FIR) low-pass filter.

The second simulation builds upon the model validated in the former simulation, implementing a complete mission with a fluctuation stage. Fig. 11

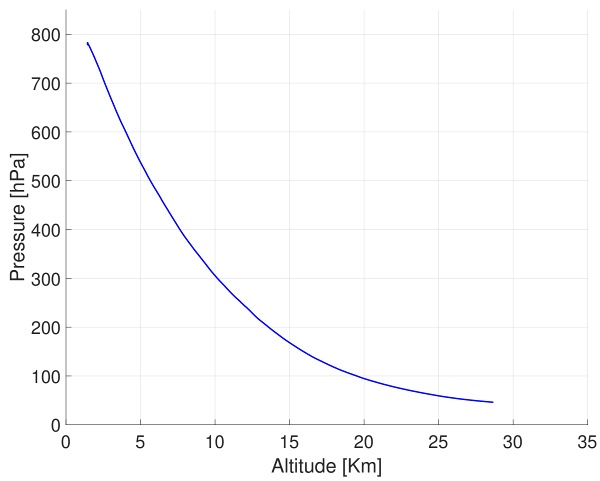


Figure 8: **Pressure profile from the flight data.**

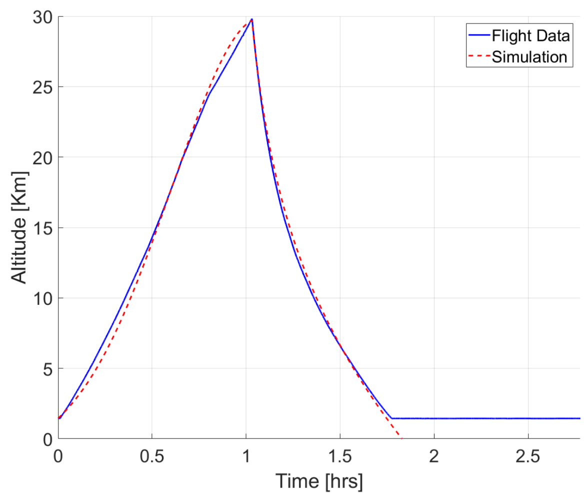


Figure 9: **Altitude profile from the simulation and flight data.**

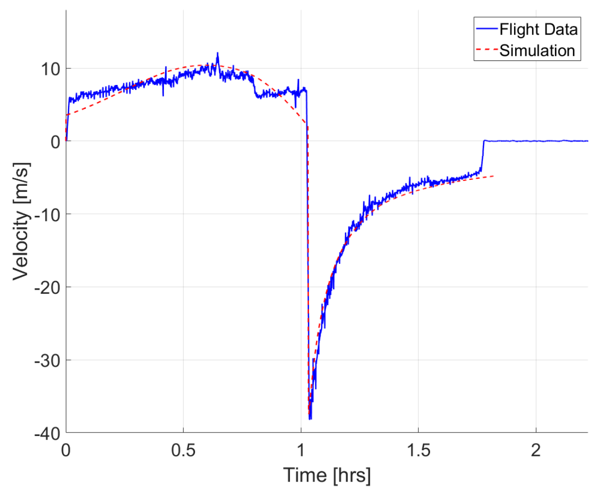


Figure 10: **Vertical velocity profile from the simulation and flight data.**

shows the entire altitude profile of a mission taking off at sea level and with null initial speed. The trajectory has been obtained including in the model the altitude control strategy described in Section 3.2. The three flight phases of Section 3.2 have been highlighted to indicate the steps of the mission.

Fig. 12 shows the vertical velocity of the system during the simulation. As expected, it initially grows until the end of the ascent phase and it is then reduced during the altitude control phase. It can be observed that, after some chattering in the altitude control phase, the velocity remains at zero, meaning that the system has reached an equilibrium between the internal and the external forces. During the landing phase, the velocity becomes negative. Its absolute value reaches a maximum after 4 hours and then decreases. This is because gravity acceleration is counteracted by aerodynamic drag, which is more effective when the speed increases. The drag force allows a reasonably safe touchdown speed value, around 1 m/s, which is fundamental in order to preserve the payload.

These results show that the proposed control scheme is capable of regulating the altitude and vertical velocity of the balloon in accordance with the phases of flight. The flight trajectory of the LAICAnSat-5 mission, in fact, has been reproduced in simulation while considering practical aspects as the valve actuator and the physics of the ascent phase. Of course, the full effectiveness of the control system can be assessed and validated only with

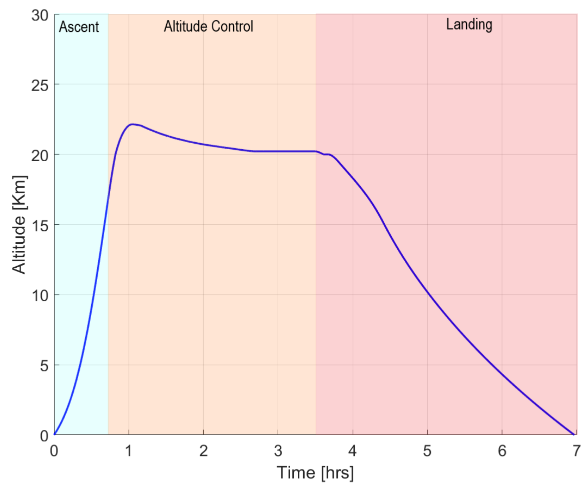


Figure 11: **Altitude profile of the simulated mission with altitude control.**

further practical tests. However, the simulation shows that the proposed system allows to achieve a substantial floating stage of two hours (see Fig. 12), during which the vertical velocity is regulated to 0 m/s. This is sufficient to meet the duration required for the experiment in [5].

5. Conclusions

In this work, a simple solution for an altitude control system for a rubber balloon platform is proposed. The design of an actuation system based on a COTS ball valve for this task has been presented. The actuator is mounted in an *ad hoc* structure manufactured with rapid prototyping attached to the balloon nozzle. The proposed approach for the altitude control strategy is based on the typical phases of a balloon mission. Two PID controllers are employed for adjusting position and velocity of the platform. The use of two control loops allows to track the goals of each mission phase. In addition, this work suggests a simple switching strategy for the PID controllers, and derive a dynamical model of the vertical motion of the proposed platform. The parameters of the model are estimated using sample data from a previous flight of the LAICAnSat system. The results of the simulation show that the proposed control scheme is able to provide a suitable vertical stabilization. Future work considers conducting exhaustive flight tests to assess attributes such as reliability, efficiency, maintainability, among others.

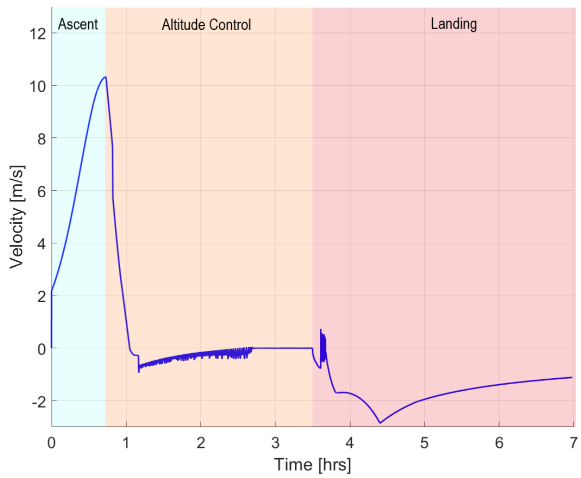


Figure 12: **Altitude profile of the simulated mission with altitude control.**

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