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Numerical evaluation of station-keeping strategies for stratospheric balloons

Sai Sudha Ramesh [a],*, Ma Juanli [b], Lim Kian Meng [c], Lee Heow Pueh [c], Khoo Boo Cheong [a]

[a] *Temasek Laboratories, National University of Singapore, 117411, Singapore*
[b] *Department of Mechanical and Industrial Engineering, Ryerson University, M5B 2K3, Canada*
[c] *Department of Mechanical Engineering, National University of Singapore, 119260, Singapore*

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ABSTRACT

The trajectory control of stratospheric balloons poses a great challenge, given their importance in scientific explorations and military applications. This has led to the investigation of several trajectory control methods, which aim to retain the balloon system within a specific region. In particular, the use of a control device tethered to the main balloon is required to provide sufficient lateral forces to counteract the air drag on the main balloon. The present study evaluates the performance of two kinds of balloon systems namely, the dual-balloon and balloon–stratosail systems that have a control device tethered to the main balloon. The study compares their performances in the context of realistic wind conditions, and presents the best working range for each of the system, which may be useful in improvising the design of control devices for future applications.

1. Introduction

Stratospheric balloons that are designed to float in the stratosphere at altitudes ranging from 18 km to 35 km play a key role in numerous applications, such as scientific exploration of the atmosphere, astrophysical observations from above the atmosphere, and defense operations. These high altitude balloons are known to be cost-efficient, easily deployable and retrievable compared to satellites. However, unlike satellites which can be controlled to travel along a specific path, single balloons drift freely with the prevailing winds, offering little or no control over trajectories. Despite their advantages over satellites, trajectory control and station-keeping of these balloons pose a great challenge. This has led to the investigation of several trajectory control methods, which aim to retain the balloon system within a specific region. Trajectory control and station-keeping of high-altitude balloons offer several advantages such as increased flexibility on flight operations, flight avoidance to uncooperative countries, and planning of appropriate landing site to ensure safe descent of payload in sparsely populated regions [1].

The key factor that aids in trajectory control is the availability of favorable wind speed and directions at altitudes close to the desired float altitude of the balloon. By changing the float altitude, one can steer the balloon to a desired location. Several methods were employed to achieve altitude changes, such as the venting of buoyant gas, dropping of ballast, and alternate filling/emptying of high-pressure ambient air (air-ballast) [1]. However, from a practical viewpoint, such altitude variations should be effected over small ranges, where the air density variations are less. Furthermore, the use of pressurized air-ballast system is limited by factors such as the power required to pump air into the high pressure chamber, difficulty of pumping air at very low pressure, and additional mass of the pumping equipment.

Other methods employed to achieve trajectory control include propeller-driven airships, use of drag chutes on tethers, and lift-generating devices such as a wing attached to a long tether [1]. Of these methods, the use of propeller driven airships are restricted to low altitudes (<21 km) as they require large propeller size at high altitudes, which renders them impractical. Akita [2] investigated the feasibility of sea-anchored stratospheric superpressure balloon that has the capability for long-duration flights, fixed-point observations, and flexible launch windows. However, the feasibility of sea-anchored balloon depends significantly on the vertical wind speed gradient, and requires the velocity of the jet stream to be sufficiently low.

E. van Wynsberghe and Turak [3] proposed the use of electro-hydrodynamic (EHD) thrusters to overcome stratospheric winds, and maintain lateral station-keeping in superpressure balloon platform that can be deployed to an altitude of 25 km. The study also suggested the use of wireless power transmission from the ground

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* Corresponding author at: Temasek Laboratories, National University of Singapore, T-Lab Buildingal, 5A, Engineering Drive 1, #09-02, Singapore 117411.
E-mail address: tslssr@nus.edu.sg (S.S. Ramesh).

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station to meet the continual supply of power needed to operate the on-board propulsion system, which is crucial for station-keeping. Although their study demonstrated the feasibility of using EHD thrusters for station-keeping, a major challenge to its implementation could be the lower air density at higher altitudes, which limits the availability of air particles that are needed for efficient operation of the thrusters. Fesen and Brown [4] proposed a system (i.e. a 'tug' vehicle connected to the balloon) that utilizes the stratospheric wind shear to achieve station-keeping.

Among the various strategies for station-keeping mentioned earlier, the use of aerodynamic device tethered to the main balloon has been shown to provide the best and efficient solution, since it exploits the natural stratospheric wind shear to provide the lateral control forces on the balloon, thereby demanding less energy for its operation [5]. A comprehensive account of the capabilities of stratospheric balloons along with a tethered guidance system (called as StratoSat system) is given by Pankine et al. [6]. The study mentions the pioneering work of Aaron et al. [1], Nock et al. [5] who explored the aerodynamic system performance, and concept of operations related to the stratosail balloon guidance system (BGS) (developed by Global Aerospace Corporation [7]). They estimated the drift velocity of the balloon–stratosail system by iterating over the force balance equation (i.e. balancing of aerodynamic drag forces on the balloon and the stratosail), and demonstrated the capability of the BGS in control implementation.

Fu et al. [8] also developed a trajectory control strategy for the balloon–stratosail system by adjusting the sideslip and azimuth angles. Zhu et al. [9] studied the effects of gravity, aerodynamic force and tensile force of the tether on the stratosail. They calculated the inclination angle, deviation angle and tensile force of the tether at different attitude angles of the stratosail in accordance with moment-equilibrium principles. Xu and Huo [10] used a six degree of freedom (DOF) dynamic model of the stratospheric satellite (StratoSat) system to model the trajectory along a constant latitude. They also deduced a three subsystem model from the 6-DOF model to develop a sequential nonlinear control strategy that was robust to uncertainties in balloon-sail parameters, and provided the desired trajectory track [11]. Zheng et al. [12] controlled the longitudinal drift of a novel stratospheric satellite which consists of two motor-driven propellers attached to the main helium balloon. The stratospheric satellite was modeled using Newton–Euler equations. The latitudinal orbit keeping was achieved using path-following controllers for both straight-line and circular-arc paths based on the theories of vector field and sliding mode control.

Meng et al. [13] developed a novel dynamic model of the stratospheric satellite that included thermal effects to describe the balloon system's thermodynamic and kinetic characteristics. The stratospheric satellite system was controlled by adjusting the TCS rudder angle. In their work, stratospheric balloon thermodynamic models were used to calculate the temperature of the balloon film and the internal helium, followed by the calculation of equilibrium point of the satellite and implementation of control laws for adjusting trajectory. Further, the thermal effects on the balloon launch time were discussed. Other studies pertaining to thermal influence on stratospheric balloon ascent rates can be found in Shi et al. [14] and Liu et al. [15]. While the aforesaid studies discuss trajectory control of balloon during its flight using control devices, several studies focus on the prediction of balloon trajectories that might be subjected to various uncertainties. Sóbester et al. [16] described a new balloon flight simulation model, that took into account a range of environmental, physical, and operational uncertainties to generate a predicted trajectory. Lee and Yee [17] also considered various uncertainties using a Monte Carlo simulation that enabled better prediction of balloon trajectories.

A majority of the studies mentioned so far have focused on long duration flights employing trajectory control systems that restrict latitudinal excursions [10–13]. On the other hand, some applications involving military surveillance over a specific region, or countries that restrict free balloons flying over their territory, may require the balloon trajectory to be within a specified radius with respect to the launch location. In order to meet such a stringent trajectory criterion, the balloon may be flown for a shorter duration (say few days to a week) during a favorable time-window of the year, and then recovered safely for future missions.

Considering the stringent trajectory control criterion, and the shorter flight duration, it is then important to study the performance of balloons in combination with a trajectory control device subjected to realistic wind conditions, and thereby identify favorable float altitudes associated with a particular time-window, which helps in maintaining the smaller trajectory radius. The present study evaluates the station-keeping performance of two kinds of balloon systems namely, dual-balloon (DB) and balloon–stratosail (BS), for a wide range of realistic wind conditions. The former system uses a secondary spherical balloon as a control device, while the latter deploys a stratosail [7]. In this study, the drift velocity of the balloon system is computed by considering the dynamic equilibrium of the drag forces acting on the balloon and the control device. Further, the drag coefficients required for computing the aerodynamic forces on the stratosail for various orientations (yaw and roll) is obtained from computational fluid dynamic (CFD) simulations. The present work is different from that of Nock et al. [6] which studies long duration flights of a balloon–stratosail system along constant latitude. Furthermore, their study assumes the balloon flight at a fixed altitude of 35 km, and the BGS wing assembly (stratosail) at a 20 km altitude. On the other hand, the present study simulates balloon flights with reasonable altitude variations (<500 m), based on an altitude control algorithm, and uses wind speed values predicted by a reduced order model.

For a realistic projection of the balloon system's flight path, the input wind conditions are obtained from a reduced order model which enables a compact representation of a large weather dataset. In the present study, we use such a model based on the proper orthogonal decomposition (POD) method. The details of the POD model are presented in reference [18], and is based on weather dataset obtained from Singapore meteorological station for a period spanning from January 2012 to May 2015 (i.e. 3 years and 5 months). This period was sufficient to cover one complete cycle of the quasi-biennial oscillation phenomenon (QBO), and enabled the development of a Fourier prediction model for the stratospheric winds. For further details on the POD based Fourier prediction model, readers are referred to [18].

Having obtained the realistic wind parameters using an appropriate model, the objective is to compare two kinds of trajectory control devices as mentioned earlier, and bring out the best range of operating altitudes and wind conditions for a given time-window of the flight. These results will assist in real-time trajectory simulations, or preliminary design of trajectory control devices. In view of the objectives, the manuscript has been organized into six sections including the introductory section. Section 2 presents a brief description of the two kinds of balloon systems, and the method for evaluating the force coefficients associated with each balloon-system. Section 3 presents the simplified model used for simulating the trajectory of the balloon systems. Section 4 discusses the methodology used to obtain the optimal orientation of stratosail with respect to the relative wind, which results in minimum drift velocity of the balloon system. Several numerical cases are presented in Section 5 to demonstrate the performances of the two systems for different wind conditions, followed by Sec-

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