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Simulation and control of serviceable stratospheric balloons traversing a region via transport phenomena and PID

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A B S T R A C T

Balloon systems can be used as alternatives to communication satellites for a number of applications. Launching, flight and safe landing of zero pressure high altitude stratospheric balloons were simulated in 3-D using transport phenomena, process control techniques and a flight gas Compress–Release-system. A model developed was numerically solved and the results were validated using NASA test flight data. The effect of PID control on Compress–Release mechanism is discussed in detail. It was found that with this model it is possible to place the balloons at target altitudes, extend flight time, ensure their horizontal flights over desired coordinates and interfere with the balloon system whenever needed for technical service without using ballast under varying environmental conditions. The simulation was applied to a set of balloons following several routes in Turkey using actual wind data. The results would be helpful for the design, operation and control of safe, reliable and serviceable high altitude stratospheric balloons.

1. Introduction

The ability to fly balloons for extended durations of months to years, at high altitudes of 18 km or higher has been an elusive goal. High altitude flight provides a unique vantage point for scientific exploration as well as observation and surveillance. For civilian applications, high altitude airships present a low cost alternative to a geostationary satellite. For the military, it presents a versatile platform that can be positioned over key areas of interest quickly and provides continuous wide area coverage for extended periods of time [1].

A terrestrial radio link faces a great deal of obstacles in a path: Hence, the electromagnetic wave cannot travel great distances, while a satellite link features an extremely long transmission path, which weakens the wave and demands additional cost, although less obstacles obstruct the signal. Thus, the current focus is on the use of an undeveloped space, the stratosphere that is located between the terrestrial and the satellite domains. The idea has existed for some time of an airship, a balloon, or the like which would be kept in the stratosphere, where the airstream is relatively steady and used for telecommunication systems relay purposes [2].

On the other hand, the demand for an economical "broadband" wireless access system is increasing, due to rapid popularization of mobile communication (such as mobile phones) and internet. It is expected that the stratospheric platform may be the infrastructure that will allow these services to be offered economically to business users as well as personal users [2–5].

Maintenance and repair of satellites cannot be provided without special rockets that are extraordinarily expensive. Stratospheric balloons, as ideal and low cost platforms, can carry heavy loads to near space environment and operate for various applications. Having their lift by buoyancy force, these vehicles require much less power than traditional aircraft and satellites [6].

The high altitude airship is a thermal vehicle. It is in a mostly radiant thermal balance considering many heat sources influencing it. When warm, the balloon gas expands and either pressurizes the gas envelope or is vented out. If venting takes place with zero pressure balloons, night time cooling makes ballast dropping necessary [7]. However, up to now there was no balloon control model available that could carry large payloads at constant altitude without using ballast. We have developed a model of stratospheric balloon using transport phenomena and a Gas-Compress–Release system to keep it at constant altitude for a long time such as 485 days [8].

Some investigations have been published on high altitude balloons. Stefan [9] studied the thermal effects on high altitude balloons. Saito et al. [10] developed a high altitude balloon with ultra-thin polyethylene films. Kenya et al. [11] made an experimental

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Nomenclature

A_p	projected area of the balloon .... m^2
C_d	drag coefficient
C_{ib}, C_{out}	inside and outside concentrations of the lift gas .... $kmol/m^3$
C_1, C_2	lift gas concentrations at the inside and outside balloon surfaces .... $kmol/m^3$
D_{ABre}	real effective diffusion coefficient .... m/s^2
D_b	diameter of the balloon .... m
e	error
Fi	Flight route. $F1$: Erzurum to Antalya, $F2$: Antalya to Izmir, $F3$: Samsun to Antalya, $F4$: Istanbul to Izmir
g	gravitational acceleration .... m/s^2
H	altitude of the balloon .... m
H_d	desired altitude of the balloon .... m
h_{ci}, h_{co}	convective heat transfer coefficients inside and outside balloon surfaces .... $W/(m^2\,K)$
k_{ci}, k_{co}	convective mass transfer coefficients at the inside and outside balloon surfaces .... m/s
k_f	thermal conductivity for gases and the balloon wall, $W/(m\,K)$
k_p, k_i, k_d	proportion, integral, derivative coefficients
M	total weight of the balloon and the auxiliary equipment .... kg
M_{gain}	amount of the compress and release lifting gas .... kg
M_{hel}, M_{store}	weight of lift and stored gas (helium) .... kg
N_A	lift gas flux through balloon wall .... $kmol/(m^2\,s)$
P	pressure .... Pa
PID	proportional, integral, derivative controller
$q_{e,\infty}, q_{i,\infty}$	external and internal infrared radiation density .... W/m^2
q_T, q_{rad}	total heat flux for the lift-gas and solar radiation flux .... W/m^2
$t, \Delta t$	time and its step .... s, min or h
T_1, T_2	temperatures of the lift gas at the inside and outside balloon surfaces .... K
T_a, T_{ib}	atmospheric and bulk temperatures of the lift gas .. K
V	volume of the balloon .... m^3
v_x, v_y, v_z	velocity of the balloon in x, y, z directions ..... m/s
v_{wx}, v_{wy}, v_{wz}	velocity components of wind in x, y, z directions .... m/s
v_{rx}, v_{ry}, v_{rz}	relative velocity in x, y, z directions .... m/s
v_r	velocity of the balloon relative to the air .... m/s
Δx	balloon wall thickness .... m
α	solar absorptivity of the balloon film
ε	porosity of the balloon wall material
ρ_{air}, ρ_b	density of air and balloon system .... kg/m^3
τ	tortuosity

study of thermal modeling for stratospheric platform airships. Xia et al. [12] developed a three dimensional transient thermal model to predict the thermal behavior of spherical stratospheric balloons. Xiong et al. [13] had simplified analytical model for predicting temperature of balloon at high altitudes. Liu et al. [14] studied a comprehensive numerical model investigating thermal-dynamic performance of a scientific balloon. However, these studies have focused on the geometry, thermal designs, selection of a suitable material to go to higher altitudes and flight trajectory not for the whole flight but only ascension phase. In all these studies, ballast drop was used which is conventional method to control the altitude. The gas-compress-release mechanism that we developed is novel and useful [8]. The wind driven effect on the balloon movement traversing a region and descent control have not been studied. In this paper, novel gas compress–release system has been studied with not only heat transfer but also mass and momentum transfer in order to examine the whole transport phenomena aspects along the travel. The process was controlled with PID controller in order to examine whole flight trajectory. Also, not less importantly, the effect of wind was included on the high-altitude-balloon control.

To design a balloon, besides the physical properties of balloon material it is essential to predict not only the temperature, pressure and altitude; it is also vital to include and predict aspects such as mass transport mechanisms and relevant variables, and flight phases of ascent, floating and descent processes. Up to now, there is no study on landing the balloons anytime maintenance, repair or resupplying the lift gas is needed. There has been no study about descent control and safe landing to the ground either. Safe and controlled landing is important to keep the equipment from any damage and predict the coordinates of balloon landing site [15].

The atmosphere of our planet is a very dynamic environment with great fluctuations in temperature, pressure, density, wind speeds and solar intensity [1]. Atmospheric conditions around the balloon are significantly important for the design of the stratospheric balloons.

The objective of this study is to combine heat, mass and momentum equations, use a Gas-Compress–Release system and PID control in order to track the balloons, keep them at target altitudes for longer periods and interfere with them anytime needed. This approach has been applied to a set of balloons traversing a country starting from various geographic locations and using real wind data. The study given below includes not only vertical movement but also horizontal movement of the serviceable stratospheric balloons due to wind velocity. Therefore, performance of balloons was simulated in a real environment. These results show that it is possible to provide movement of balloons over Turkey or any other country by wind and Gas-Compress–Release system to accomplish desired purposes and land them safely to the ground. Additionally, results would be helpful for the design of safe, reliable serviceable movable high altitude balloons that operate for civilian and military missions such as telecommunication, observation etc.

2. Balloon and transport phenomena: heat, momentum and mass transfer

For the stratospheric balloons, a model was developed based on balloon dynamics, and heat and mass transfer aspects before [8]. The system we consider in this study is shown in Fig. 1. It has a control mechanism and a 3-D velocity. For the sake of completeness three of the major equations are reproduced below from the previous work:

Balloon velocity in vertical direction is obtained from integration of the following equation:

$$\frac{d\boldsymbol{v_z}}{dt} = -\frac{\boldsymbol{v}}{\|\boldsymbol{v}\|} C_d \frac{1}{2M} \rho_{air} v_z^2 A_p + \frac{\rho_b - \rho_{air}}{\rho_b} \boldsymbol{g} \tag{1}$$

Lift gas leaks out by passing through the balloon material. The differential leakage amount of lift gas can be calculated From Eq. (2), the gas flux equation, given below.

$$N_A = k_{ci}(C_{ib} - C_1) = D_{ABre} \frac{(C_1 - C_2)}{\Delta x} = k_{co}(C_2 - C_{out}) \tag{2}$$