Flight Simulation for a Two-Balloon High-Altitude System

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Abstract

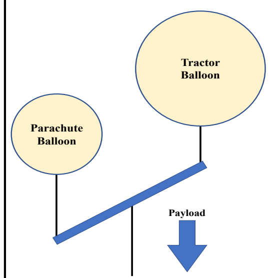
A typical high-altitude balloon system consists of a single balloon for lift and a parachute to return the payload. Since a parachute has a fixed area and the drag force depends on the air density, the initial descent speed can be extremely large, resulting in chaotic motion. This project explores using two balloons to lift the payload and a single balloon to return it. The advantage of using a balloon for the return instead of a parachute is that the area of the balloon scales with the density producing a more controlled descent. A simple, one-dimensional flight simulator was previously developed for the proposed two-balloon system. The simulator uses Euler's method to calculate position and velocity and a realistic model for drag. This work has expanded on this by making the simulator three-dimensional, adding crosswinds, translating the simulation coordinate system to latitude and longitude, and adding real-time weather information.

Introduction

A high-altitude balloon will be used to observe solar eclipses in 2023 and 2024. Normally a single balloon is used for the ascent and a parachute is used for the descent of the payload, but this results in large initial descent speeds that can cause twisting and fouling of the payload lines. This happens because a parachute has a fixed area, so the drag force it experiences at high altitude is very small due to the low air density. A system that uses two balloons for ascent and a single balloon instead of a parachute for the descent should provide a constant speed as the area of the balloon scales with the air density and pressure. It is important to predict the flight path of a balloon system to aid in the recovery of the payload, and online simulations do exist for one-balloon systems but not for the proposed two-balloon system. So, a simple two-balloon simulation was developed to predict the flight path. This initial simulation is one-dimensional, does not include crosswinds, and is independent of geographic location. The goal of this project was to improve this simulation by adding these features.

Discussion

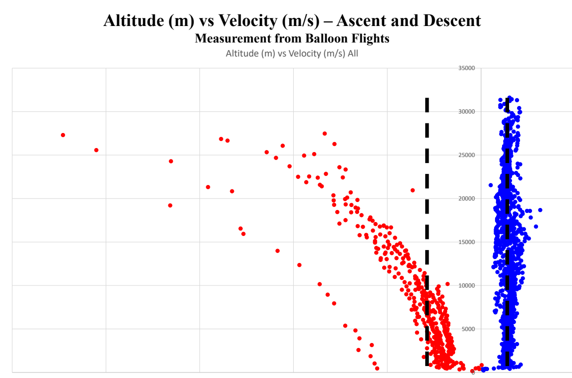
The initial two-balloon simulation used for this project is a zero-pressure model in which the temperature and pressure inside the balloons is equal to that of the surrounding air. It uses the standard atmospheric model for temperature and pressure as function of altitude. It also has an empirically derived function for the coefficient of drag based on the observation of a constant ascent terminal velocity in previous test flights. The position and velocity of the balloon system is updated in small time steps using Euler's method.



$$F_{net} = F_d + F_b + F_{cw} + F_w = m_{total}a$$
$$F_b = buoyant\ force$$
$$F_w = gravitational\ force$$
$$F_d = drag\ force = -\frac{1}{2}c_d\rho_A {v_z}^2$$
$$F_{cw} = cross\ wind\ force = \frac{1}{2}c_d\rho_A(v_{wind} - v)^2$$

Euler Method for Determining Velocity and Position

$$v_{n+1} = v_n + a\Delta t$$
$$z_{n+1} = z_n + v_{n+1}\Delta t$$



The initial simulation is one-dimensional, meaning that the balloon system could only go up or down (z-direction). The first step in improving it was to add the horizontal coordinates (x and y-directions). The second step was to introduce crosswinds as a drag force based on the relative velocity between the balloon system and the winds in the horizontal (x-y) plane.

Since this simulation will be used to predict the landing site for the balloon payload, the next step was to translate the simulation coordinates to latitude and longitude using the Universal Mercator (UTM) coordinates. UTM divides the Earth into 60 zones and assigns x-y coordinates to locations within each zone. The Allegheny Observatory was used to determine the initial zone because this is where the test flights will launch, but this may be adjusted as needed. It is possible for the balloon system to cross into other zones during its flight, so translation between zones was also included.

The final step to improving the simulation was to incorporate real weather data from ncei.noaa.gov. This database of radio sonde measurements from stations around the world is updated daily and includes wind speed and direction at various altitudes. Data from this site will be used to determine the crosswinds over the flight path of the balloon system.

Conclusion

A simple simulation for a high-altitude, two-balloon system was modified to include a three-dimensional coordinate system that can be translated to geophysical coordinates, the effects of crosswinds, and real time weather data. Future improvements to the simulation may include using weather forecasts instead of archived data, including the effects of solar heating on the balloons, estimating the maximum altitude based on the burst diameter, and improving the empirical model for the coefficient of drag. Data collected from future test flights will also be used to test and improve the simulation.

References

[1] András Sóbester, et. al. *High-Altitude Gas Balloon Trajectory Prediction: A Monte Carlo Model.* AIAA journal, 2014-04, Vol.52 (4), p.832-842
[2] Mark Denny, *Weather Balloon Ascent Rate.* Phys. Teach. 54, 268 (2016)
[3] https://predict.habhub.org/
[4] http://astra-planner.soton.ac.uk/
[5] https://www.ncei.noaa.gov/pub/data/igra/

Acknowledgements

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