A Survey of Current Balloon Trajectory Prediction Technology

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High-altitude scientific balloons allow for very little control over their trajectories. Although systems exist to influence the burst altitude of the balloons, their horizontal motion is dictated solely by the vagrancies of the wind. The accurate prediction of balloon trajectories is thus a topic of great importance to flight operations personnel, since launch/no-launch decisions must be made based on the likelihood of the balloon landing in some undesirable location. Such concerns are particularly acute in areas with high population densities or significant areas of restricted airspace, both of which are prevalent in the Mid-Atlantic region. This paper presents an overview of the present state of balloon trajectory prediction. The mathematical fundamentals of balloon trajectory prediction are discussed, as are the major available software implementations.

I. Introduction

High-altitude ballooning is an exciting activity that presents numerous opportunities for both scientific research and education, but it is not without risk. In particular, balloons can pose a collision hazard to air traffic, and descending balloons raise the possibility of hitting something on landing. The obligation of engineers to "hold paramount the safety, health, and welfare of the public in the performance of their duties" [1] requires that balloon operators pay attention to mitigating these concerns. In the United States, Federal Aviation Administration (FAA) regulations provide some specific guidance. They codify the obligation to avoid posing a hazard to persons or property on the ground [2], and they delineate areas in which balloons may not operate [3]. At best, balloon operators have only very limited control over the trajectories of their balloons once released. Some balloons, particularly larger zero-pressure ones, have venting and ballast systems that allow for altitude control. These systems, however, provide no facility for direct control of the balloon's lateral motion. The smaller latex balloons flown by the National Weather Service and many university research groups are typically completely unguided. Thus, range safety considerations must be addressed primarily, if not entirely, through *a priori* knowledge that the balloon's trajectory is not likely to be hazardous. Such knowledge is typically based on numerical forecasts of the balloon's trajectory.

This paper aims to present an overview of balloon trajectory prediction technology. Section II discusses the forces on a balloon in flight and derives the equations of motion. Section III examines the thermodynamic considerations involved in modeling the balloon's canopy. Section IV considers existing prediction systems that implement these principles, while section V identifies outstanding issues in the field.

II. Balloon Flight Dynamics

Balloon flights occur in two distinct flight regimes: the canopy regime, in which the balloon is held aloft by the buoyant force of the lifting gas, and the parachute regime, in which the payload train falls to earth under parachute after the balloon canopy has burst or been detached. In order to create sound trajectory forecasts, the vertical and horizontal motion of the balloon must be modeled to generate the equations of motion, and transitions between regimes must be identified.

A. Forces on the Balloon

In modeling the flight dynamics of the balloon, there are three forces that are of interest: gravity, buoyancy, and drag.

The buoyant force F_b is caused by the displacement of air by the canopy of the balloon. Since lifting gases are by definition less dense than air, the buoyant force exceeds the force of gravity on the lifting gas inside the canopy, generating the lift that propels the balloon upward. The buoyant force, which acts in the $\hat{z}$ direction, is given by [4] as

$$\vec{F}_b(z) = V(z)\rho_{air}(z)g\hat{z} \tag{1}$$

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It must be noted that V, ρ_{air}, and ρ_{gas} are all strongly dependent on altitude. Latex balloons in particular can expand to a multiple of their launch site diameter at apogee, and the density of the atmosphere at typical burst and float altitudes can approach 1% of sea-level density [5].

The buoyant force is opposed by the downward force of gravity on the balloon,

$$\vec{F}_g = -m_{sys}g\hat{z} \tag{2}$$

One concern sometimes overlooked is that m_{sys} represents the total mass of the entire balloon-payload system, which includes the mass of the lifting gas inside the canopy.

The final force acting on the balloon is that of drag, which acts to oppose the balloon's velocity relative to the surrounding air, $\vec{V}_{rel} = \vec{V} - \vec{V}_{wind}$. It is given by [4, 6] as

$$\vec{F}_d(z, \vec{V}_{rel}) = -\frac{1}{2}\rho_{air}(z)C_D A(z)|\vec{V}_{rel}|\vec{V}_{rel} \tag{3}$$

This is equation is applicable to both the canopy regime and the parachute regime. Because of its quadratic dependence on velocity and tendency to act in all three directions, drag plays a major role in determining the trajectory of the balloon in all regimes of flight.

B. Equations of Motion

Equations of motion for the balloon are obtained by applying Newton's Second Law, $\Sigma\vec{F} = m\vec{a}$, to the sum of the forces. However, the mass in question is not identically the mass of the balloon. Since the balloon is a body moving through a fluid, it tends to drag some of the fluid along with it. The mass of this dragged air is termed 'added mass', m_a, while the total mass of the system and added mass is the 'virtual mass', m_v, and it is m_v that must be used in Newton's Second Law. This is because the forces acting on the balloon must act against not only the balloon's mass, but also the added mass of the air [7, 8]. The added mass is typically expressed as a multiple on the lifting gas mass. Based on methods from hydrodynamics and naval architecture, where added mass is a major design consideration, it is possible to determine added mass coefficients using computational techniques. For latex balloons, which are modeled as nearly spherical, the added mass is typically taken as 50% of the mass of air displaced by the lifting gas. More complicated expressions are required for zero- and super-pressure balloons, and these expressions vary depending on whether the lateral or vertical motion of the balloon is being considered [7].

Applying Newton's Second Law, equations of motion for a balloon system in the canopy regime are given by Lee [4] as

$$m_v\ddot{x} = \vec{F}_d \cdot \hat{x} \tag{4a}$$

$$m_v\ddot{y} = \vec{F}_d \cdot \hat{y} \tag{4b}$$

$$m_v\ddot{z} = (\vec{F}_d + \vec{F}_g + \vec{F}_b) \cdot \hat{z} \tag{4c}$$

Equations 4a and 4b reveal that the balloon's horizontal motion is dictated solely by drag. Under these conditions, the balloon's horizontal velocity will rapidly (within tens of seconds) converge to the ambient wind velocity from rest. It is therefore a reasonable simplifying assumption to ignore transient effects and treat the balloon's horizontal velocity as identically equal to that of the surrounding air [9].

Expanding the z equation of motion under the assumption that there is no vertical wind, equation 4c becomes

$$m_v\ddot{z} = -\frac{1}{2}\rho_{air}(z)C_D A(z)\dot{z}\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2} - m_{sys}g + V(z)\rho_{air}(z)g \tag{5}$$

The solution of this equation at a particular altitude is asymptotic to some value of $\dot{z}$. This means that, after transient effects have settled, the balloon's ascent velocity over a relatively small change in altitude is effectively constant. However, the expansion of the balloon and changes in ambient atmospheric conditions over larger changes in altitude can cause the ascent velocity to vary significantly over the course of the flight.

The equations of motion in the parachute regime are identical to the canopy regime except for the lack of a buoyancy term in equation 4c, although the numerical values C_D, A, and m_v change. In computing the change in m_v, it is important to consider that the lifting gas is no longer part of the system, and, for latex balloons, neither is much of the canopy. The amount of the canopy that remains attached to a latex balloon after burst is a poorly understood problem, but 50% is a reasonable average [9].

C. Solving for Trajectory

The equations of motion are tightly coupled with the ambient atmospheric conditions. Although standard atmosphere models do exist that contain analytic relations for atmospheric state as a function of altitude, these are of little use for practical trajectory prediction. They generally supply a uniform set of relations for anywhere on the earth, ignoring local weather conditions. More importantly, standard atmospheres do not supply wind data, which is the most significant factor in determining the balloon's ground track. As a result, the equations of motion must be solved by numerical integration, using forecast data from large-scale weather models from meteorological organizations. Since weather models output forecasts for a grid of points, forecast atmospheric conditions for a particular point are typically obtained by interpolating from the nearest grid points.

Only a few papers in the balloon trajectory prediction literature discuss the specific numerical solution methods used. Dai [6] reports using a fourth-order Runge-Kutta (RK4) method, which is standard for trajectory predictions in satellite flight dynamics applications. The new Cambridge University Space Flight (CUSF) predictor (Tawhiri) also uses RK4. Sóbester [9] uses the LSODA software package, which automatically chooses between linear multistep (Adams) and backwards differentiation methods based on the stiffness of the problem [10].

III. Canopy Modeling

As a balloon rises, the gas inside expands due to the lower ambient pressure. Modeling the corresponding expansion of the balloon canopy as a function of altitude is a critical task in trajectory prediction, since the canopy size factors in to several aspects of the prediction. The ascent velocity is directly dependent on the canopy size, since drag is proportional to cross-sectional area. Perhaps more importantly, latex balloon canopies burst when they reach a certain size, and burst location can dramatically influence the overall shape of the balloon trajectory.

A. Canopy Thermal Modeling

The volume of the canopy is governed by the Ideal Gas Law,

$$P_{gas}V = m_{gas}RT_{gas} \qquad (6)$$

where the gas subscript denotes the properties of the lifting gas, rather than the ambient conditions. Thus, assuming the mass of the gas is known from inflation procedures, knowledge of pressure and temperature is sufficient to determine the volume of the canopy. For latex and zero-pressure balloons, lifting gas pressure is typically taken to be the same as ambient pressure. While this is accurate for true zero-pressure balloons, it is only an approximation for latex balloons, since latex balloons are elastic and require an interior pressure to hold them at their inflated size. This pressure difference is on the order of 1% of ambient pressure at ground level, and a few percent at higher altitudes [11, 12]. In view of the other uncertainties inherent in balloon trajectory prediction, this is a reasonable approximation.

The temperature of the lifting gas, however, is a somewhat more difficult problem. Some models treat the temperature of the lifting gas as identical to the ambient temperature [9]. While this is not a particularly good approximation, since differences on the order of tens of Kelvin have been observed even in latex balloons, it does greatly simplify the calculations[12]. For higher-fidelity models, the typical approach is to try to identify the sources of heat flux on the canopy and assume convective transfer to the lifting gas [4, 6]. Modeling these heat fluxes is the subject of various papers in the literature, most focusing on zero- and super-pressure ballooning, but Farley [13] presents a representative list. He identifies radiative heating from the Earth's surface and the sun (both direct and reflective/albedo) as the principal heat fluxes into the canopy, and convective losses to the atmosphere as the principal heat flux out. Since radiative heat transfer is dependent on the cross-sectional area of the balloon, balloon canopy geometry is of considerable importance for high-fidelity thermal models. Determining this area is straightforward for nearly-spherical latex balloons, but larger zero- and super-pressure balloons have much more complicated geometries, which can be modeled as a tessellation of triangles [6].

For models using the heat flux approach, solving for the temperature of the lifting gas becomes an initial value problem governed by the following equations from Lee[4]:

$$\frac{\mathrm{d}T_{gas}}{\mathrm{d}t} = \frac{Q_{gas-canopy}}{c_v m_{gas}} + (\gamma - 1)\frac{T_{gas}}{\rho_{gas}}\frac{\mathrm{d}\rho_{gas}}{\mathrm{d}t} \qquad (7)$$

$$\frac{\mathrm{d}T_{film}}{\mathrm{d}t} = \frac{Q_{canopy}}{c_{canopy}m_{canopy}} \qquad (8)$$

In these equations, $Q_{gas-canopy}$ denotes the convective heat transfer from the canopy to the gas, Q_{canopy} denotes the net heat flux into the canopy, c_v denotes the specific heat of the lifting gas at constant volume, and c_{canopy} denotes the specific heat of the canopy. Because Q_{canopy} depends on the balloon's position and the ambient conditions, these equations become coupled with the balloon's equation of motions and must be solved numerically.

B. Canopy Burst Modeling

While zero- and super-pressure balloons are terminated with control systems, latex balloons rely on the natural expansion and eventual bursting of the canopy to transition from the canopy to the parachute regime. Accurate models of the the canopy burst diameter are thus critical to accurate trajectory forecasts. Most manufacturers publish a nominal burst diameter for their balloons, but this is subject to a considerable amount of random variation. Furthermore, most manufacturer's data is quoted for low payload mass flights intended for atmospheric soundings, while some research flights fly with considerably heavier payloads, potentially putting the canopy under more stress and affecting the burst diameter. Sóbester et al. [9] present a model of burst diameter uncertainty based on a large dataset of NOAA 700 g sounding balloon flights. They determined that the dataset is approximated by a Weibull distribution and proposed to scale their results to other balloon sizes based on nominal balloon burst diameter. While such scaling seems reasonable, there have been no published studies to empirically establish burst diameter probability distributions of larger balloons.

IV. Major Implementations

There are a number of publicly available software packages that use the principles described above to predict balloon trajectories. This section compares and contrasts some of those implementations.

A. Cambridge University Space Flight Predictor

One of the most commonly used predictors is a web-based predictor developed by Cambridge University Space Flight (CUSF) and hosted by the U.K. High Altitude Society [14]. It is strictly a flight dynamics model; it makes no attempt to model the expansion of the canopy as the balloon ascends. Ascent rate, burst altitude, and sea-level descent rate are given as input parameters; ascent rate is treated as constant, while the descent rate is computed by assuming terminal velocity in a standard atmosphere. It also contains no provision for flights with floating, such as is encountered with zero-pressure balloons. The simulation uses wind data from NOAA's Global Forecasting System (GFS) model.

The main advantages of the the CUSF predictor are its intuitive user interface and clear trajectory maps. Since it takes ascent and descent rates and burst altitude as the input parameters, rather than information about the canopy and lifting gas mass, the system is easy to use for more approximate predictions and by those with limited knowledge of balloon canopy modeling. It also generates maps (figure 1) and KML files directly from the predictor, allowing for easy visualization of the predicted trajectory. Its principal drawbacks are its use of a constant ascent rate and computing density using a standard atmosphere.
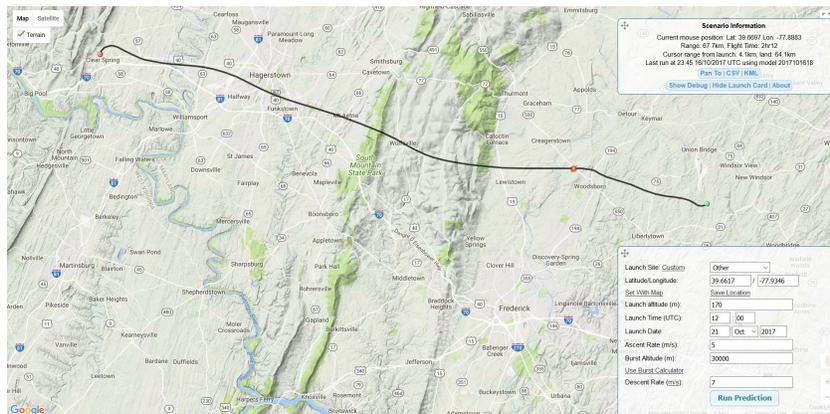

**Fig. 1   CUSF-predicted [14] ground track for typical latex balloon launch**

B. ASTRA Predictor

Another web-based predictor with excellent visualization capabilities is the ASTRA predictor run by the University of Southampton [15]. The predictor was written by Niccolò Zapponi based on modeling by Sóbester et al. [9]. The ASTRA predictor is optimized for latex balloons, and includes thermal modeling of the canopy during ascent and descent. It employs Monte Carlo techniques to randomly vary parameters of the flight, including wind and canopy burst diameter in order to develop a probabilistic estimate of balloon landing location. Figure 2 shows representative output from ASTRA.

ASTRA's most significant feature is its detailed, peer-reviewed probabilistic model of latex balloon behavior. Other features include its excellent visualization features, including the ability to produce a landing site heatmap, support for floating flights, and KML export capability. Its principal drawbacks are that it takes longer to run than CUSF, though this is to be expected, since it computes multiple trajectories, and the fact it does not allow the user to enter a custom parachute or balloon canopy size.
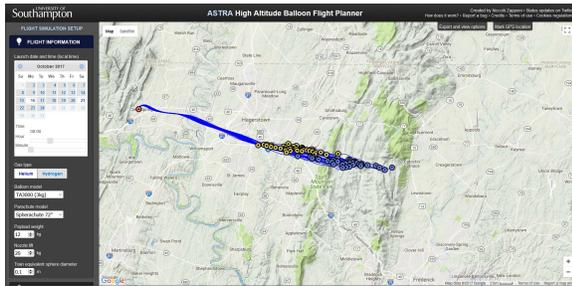
(a) A set of ASTRA-predicted[15] tracks for a typical latex balloon launch. These tracks are from the same input conditions, but the parameters have been randomly varied by ASTRA's Monte Carlo algorithm.
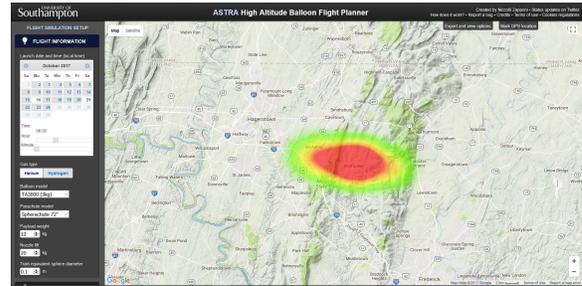
(b) The landing site heatmap generated by ASTRA [15] for the same tracks.

Fig. 2   Representative ASTRA [15] output

C. University of Wyoming Predictor

The University of Wyoming Department of Atmospheric Science maintains an online balloon trajectory prediction system [16]. Although it does not include integrated graphics functionality, it does support exporting to KML for visualization in Google Earth (figure 3). It has significant limitations, including a much coarser temporal resolution than other predictors and no facility to input ascent velocity parameters. However, it does allow for the direct input of parachute size and coefficient of drag for descent velocity calculation, and its text output provides atmospheric state information, interpolated from the GFS data, as well as position information relative to the launch site.

V. Future Work

Although the general physical phenomena underlying balloon trajectory prediction are fairly well understood, many details are open questions. Sóbester et al. [9] identify uncertainties related to latex balloon burst behavior, including the burst diameter of balloons larger than 700 g and the degree to which a burst canopy remains attached to the balloon as significant unresolved questions. Several papers exist in the literature concerning the thermal behavior of zero- and super-pressure balloons, but comparable research about latex balloons is lacking [4, 6].

In terms of available software packages, there is not a publicly available predictor that supports both thermal modeling of the canopy and the specification of arbitrary canopy and parachute parameters. Such a predictor would be a significant improvement over the ASTRA predictor, which, while otherwise feature-rich, requires users to select their canopy and parachute from a list [15]. Other predictor features that could be useful would be the ability to run simulations based on historical wind data to aid in post-flight analysis and the option to use higher spatial resolution weather forecasts where available (e.g., the North American Mesoscale (NAM) model instead of the GFS in North America). Neither of these features is available in any of the predictors discussed in section IV.
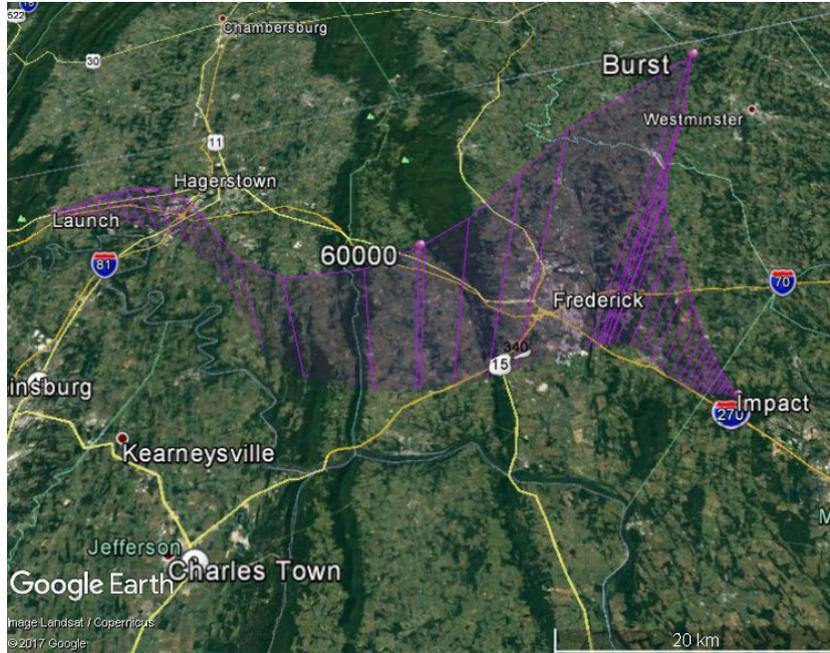
Fig. 3   University of Wyoming-predicted [16] ground track for typical latex balloon launch, visualized in Google Earth

VI. Conclusion

The major kinematic modeling concerns for high-altitude balloons have been discussed, equations of motion have been derived, and simplifications to the solutions have been identified based on transient behavior that does not contribute significantly to the overall trajectory solution. Thermal modeling concerns for the balloon canopy have likewise been explored, including the heat flux on the canopy during ascent. The prediction of latex balloon burst diameter has been discussed, with the understanding that significant uncertainties remain in this area. Major publicly-available prediction software packages have been reviewed, with an emphasis on identifying features relevant to individuals conducting flight operations. Suggestions for future improvement on these packages have been presented.

High-altitude scientific ballooning is an important tool for research, education, and outreach, and accurate trajectory prediction systems ensure that ballooning remains a safe activity accepted by airspace regulators and the general public. Continued improvement in balloon trajectory prediction systems increases the usefulness of balloon flights as a scientific endeavor and makes the activity more accessible to new participants.

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