Re-entry predictions of space objects and impact on air traffic

Franco Bernelli-Zazzera[1,a*], Camilla Colombo[1,b], Mattia Recchia[1,c]

[1] Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, 20156 Milano, Italy

[a] franco.bernelli@polimi.it, [b] camilla.colombo@polimi.it, [c] mattia.recchia@mail.polimi.it

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Abstract. This work focuses on predicting the re-entry of an uncontrolled re-entry vehicle (RV) and how this affects air traffic. It includes the propagation of the nominal trajectory and that of the fragments resulting from the breakup of the object. The breakup does not occur at a fixed altitude but is a consequence of the thermal and dynamic loads acting on the RV as it re-enters the atmosphere. The purpose of the analysis is to identify a dangerous area at specific heights (flight levels) to be evacuated in time for air traffic. The hazard area is defined as that which includes all the impact points of the fragments at this altitude taking into account the additional safety margins. The study also considers the presence of uncertainties affecting the initial state of the vehicle. Accordingly, a Monte Carlo analysis is performed to predict the worst-case scenario and to better estimate the hazard area. Once the area has been defined, an evacuation algorithm calculates, for each aircraft, the trajectory changes necessary to clear or avoid the zone over time.

Introduction

When a spacecraft, usually at the end of its life, leaves its nominal operating orbit, either due to some planned maneuver or natural decay caused by disturbances, and begins to approach increasingly dense atmospheric layers, it is said to be re-entering the Earth. Some reentry vehicles are designed to survive in Earth's atmosphere and be recovered, so they may have additional capabilities, such as the ability to develop lift forces to perform a soft landing [1]. Other vehicles, on the other hand, are not designed to withstand aerodynamic and thermal loads during the final phase of the trajectory and can suffer partial or total fragmentation. This case is called destructive reentry [2].

In this research, starting from the state of the vehicle at an altitude of 120 km, in which the reentry is supposed to start, the trajectory is propagated until the breakup conditions are met, thus defining the breakup point. At this altitude, the reentry vehicle (RV) is assumed to experience complete fragmentation caused by the high dynamic and thermal loads to which it is subjected. Therefore, a debris cloud is generated at the breakup point, composed of fragments each characterized by different parameters. Once the cloud of debris is generated, all fragments fall until they reach the level of interest (Flight Level) at which their dispersion is evaluated.

Since reentries are subject to many uncertainties, a Monte Carlo (MC) analysis is performed to account for some errors that may be present in the initial state of the vehicle and to evaluate how they affect the expected impact location. All fragment trajectories resulting from the MC analysis are then used to define the Hazard Area (HA) which includes all predicted debris locations and represents the area posing a risk to local air traffic. Once the danger zone has been defined, the affected aircraft must be redirected to evacuate or avoid the zone.

The procedures explained are applied to a simulated re-entry event in which real-traffic data are used to simulate a realistic scenario.

Methodology

The analysis starts by assigning the RV initial conditions, typically referring to the beginning of the reentry, arbitrary set at an altitude of 120 km [2]. The nominal trajectory, corresponding to the initial re-entry vehicle state, is propagated in time. At each propagation step, it is verified if the breakup conditions are satisfied. When the conditions are met, the RV breakups and the debris cloud is formed. For the cloud generation, it is assumed that the object experiences a complete fragmentation at a single altitude and all the fragments are generated at the same time. Once the debris are generated, for each one of them the new initial conditions are computed taking into account both the pre-breakup state and the velocity increment with the proper direction. At this point, all the fragments are considered as single independent entities and their trajectory is evaluated until they reach the altitude of interest, that could be ground level or an altitude corresponding to a particular Flight Level. Finally, the fragments dispersion is evaluated, in terms of longitude and latitude, at the altitude of interest. This debris distribution will be useful for the following study analyzing the effects on the air traffic.

Breakup Models. Two fragmentation methods are implemented in this work, both providing very similar results.

The first implemented model is based on the NASA Standard Breakup Model [3] and for this reason is called the NASA-Based Breakup Model (NBBM). The NASA Standard Breakup Model derives from the analyses of the fragmentation, due to both explosions and collisions, of spacecraft and rocket bodies in Low Earth Orbit (LEO) and it aims at defining each fragment with three different parameters: the characteristic length (L_c), the Area-to-Mass ratio (AM) and the velocity variation imparted (ΔV). All these features are described in terms of probability distributions. The models used in this research assume that the RV breakup occurs as a consequence of a fictitious collision with air. For this reason, the implemented power law distribution that provides the number of fragments of a given size and larger (N_{Lc}) is the one used in the NASA Breakup Model for collision events.

The second model proposed in this work is called Independent-Based Breakup Model (IBBM). This method tries to merge some features of the NASA Standard Breakup Model [3] with others implemented in the Independent discrete fragmentation model [4], which is applied mainly for asteroid entry analyses. Specifically, the IBBM implements the same distributions of the NASA Breakup Model for the computation of the fragment's characteristic length and Area-to-Mass ratio. The main difference between the IBBM and the NBBM is in the computation of the velocity variation.

In this work, both the dynamic and thermal loads are supposed to be able to cause the RV's breakup. In particular, the complete fragmentation is triggered whether the dynamic pressure acting on the vehicle exceed its ultimate tensile strength or if the temperature reaches the melting point of the material composing the RV. For this purpose, the RV is assumed to be made entirely of aluminum and a relation linking the aluminum ultimate tensile strength to the material temperature is implemented.

Dynamics. The nominal trajectory and the post-breakup fragments trajectories are evaluated adopting the following assumptions. The RV is a non-lifting object, not capable of generating any lift force ($L = 0$). The motion is over a spherical, non-rotating Earth ($\omega_E = 0$). A ballistic entry is assumed, with no thrust force ($T = 0$) and no propellant mass flow ($\dot{m} = 0$). The mass ablation of both the RV and the related fragments is neglected.

With the assumptions just mentioned, the equations of motion become the following set of six first order ordinary differential equations (ODEs) [1]:

$$\begin{cases} \dot{h} = v \sin\gamma \\ \dot{\lambda} = \frac{v\cos\gamma \sin\psi}{r\cos\varphi} \\ \dot{\varphi} = \frac{v}{r}\cos\gamma\cos\psi \\ \dot{v} = -\frac{D}{m} - g\sin\gamma \\ \dot{\gamma} = -\left(g - \frac{v^2}{r}\right)\frac{\cos\gamma}{v} \\ \dot{\psi} = \frac{v}{r}\cos\gamma\sin\psi\tan\varphi \end{cases} \tag{1}$$

where D is the drag force and the state x = $\{h; \lambda; \varphi; v; \gamma; \psi\}$, is composed, respectively, by the altitude, longitude, latitude, velocity, climb angle and heading angle.

Monte Carlo Analysis. Earth re-entries are affected by lots of uncertainties that could have non negligible effects on the prediction of the hazard area that poses risk to the air traffic. To statistically predict that area, a Monte Carlo (MC) analysis is performed. Each sample generated for the MC analysis represents a set of new initial conditions at the nominal altitude of 120 km. The re-entry simulation is therefore repeated for each sample and the resulting debris dispersion at Flight Level 400 (FL400) are recorded. Once the MC simulation is completed, an area enclosing all the fragments footprints at FL400 can be defined. The final Hazard Area is then retrieved by adding some additional safety margin. Figure 1 shows both the pre and post-breakup trajectories, while Figure 2 reports both the fragments dispersion at the altitude of interest and the computed Hazard Area.

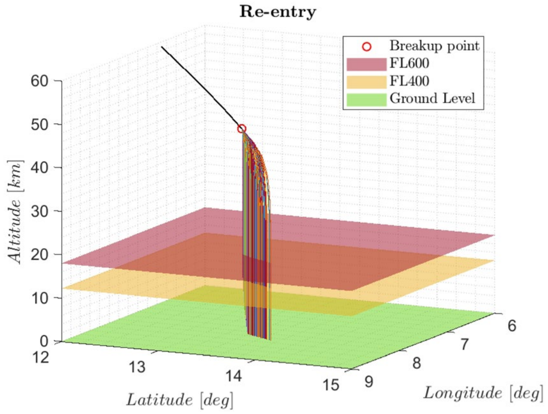

Figure 1: Re-entry trajectories.

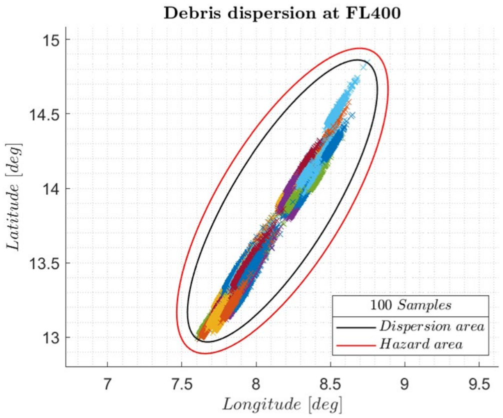

Figure 2: Hazard area and debris dispersion.

Air Traffic management. Two different actions, inferred from [5], are proposed for the management of the air traffic in presence of an hazard area.

The first algorithm is used to evacuate aircraft that are within the hazard area at the time it is computed. The algorithm's logic is to find the required changes in the aircraft heading which allow the shortest evacuation time. The following assumptions are made: 1) the aircraft are assumed to move with constant velocity during all the operations; 2) after completing the required turns, the aircraft move on a straight trajectory; 3) it is assumed that aircraft can only perform horizontal maneuvers.

The second algorithm is applied to an aircraft which is outside the hazard area at the moment it is computed but it is expected to enter it. The following assumptions are made: 1) the aircraft are assumed to move with constant velocity throughout the path; 2) the nominal path is assumed to be aligned in the same direction of the initial velocity vector; 3) turn maneuvers are not considered in the computation of the alternative path and aircraft are supposed to be able to turn instantaneously; 4) only horizontal maneuvers are taken into account. The algorithm then computes an alternative flight path that allows the aircraft to avoid the hazard area.

Figures 3 and 4 show examples of the evacuation and avoidance procedures.

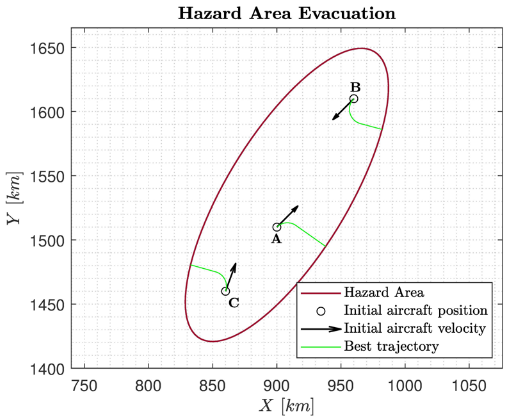

Figure 3: evacuation procedures.

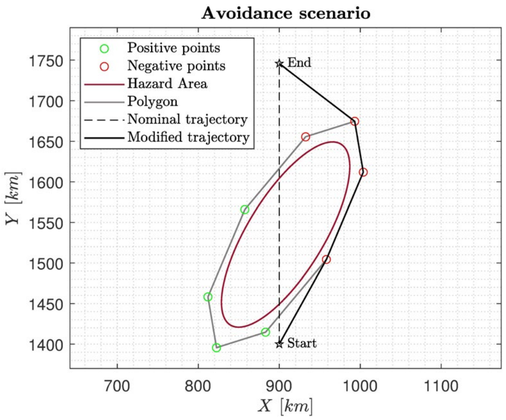

Figure 4: hazard area avoidance procedure.

Real Scenario

A generic reentry event is analyzed, leading to the definition of a Hazard Area. Then, to assess the re-entry impact on the local air traffic, real traffic data are retrieved from Flightradar24 [6] filtering only the flights at the altitude corresponding to the FL400 (40000 ft) and at a particular time instant. Finally, the algorithms discussed are used to manage the air traffic according to the aircraft positions. The simulated path are shown in Figure 5 in which stars represent the aircraft initial positions while dots the final ones.

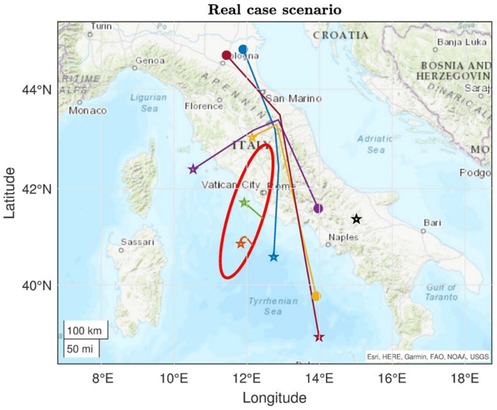

Figure 5: Evacuation and avoidance simulated paths.

Conclusions

This work has shown a preliminary assessment of the impacts Earth's re-entries have on the air traffic. Some future developments can be easily integrated while keeping the overall structure intact. Particularly, improvements in the breakup models with the introduction of new distribution functions that better describe the atmosphere's fragmentation can be integrated. Also the air traffic management algorithms could be upgraded with new procedures that ensure minimization of the impact on the routes while still avoiding collisions.

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