ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2016) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Sensitivity analysis and probabilistic re-entry modeling for debris using high dimensional model representation based uncertainty treatment

Piyush M. Mehta *, Martin Kubicek, Edmondo Minisci, Massimiliano Vasile

Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, UK

Received 15 October 2015; received in revised form 29 July 2016; accepted 24 August 2016

Abstract

Well-known tools developed for satellite and debris re-entry perform break-up and trajectory simulations in a deterministic sense and do not perform any uncertainty treatment. The treatment of uncertainties associated with the re-entry of a space object requires a probabilistic approach. A Monte Carlo campaign is the intuitive approach to performing a probabilistic analysis, however, it is computationally very expensive. In this work, we use a recently developed approach based on a new derivation of the high dimensional model representation method for implementing a computationally efficient probabilistic analysis approach for re-entry. Both aleatoric and epistemic uncertainties that affect aerodynamic trajectory and ground impact location are considered. The method is applicable to both controlled and un-controlled re-entry scenarios. The resulting ground impact distributions are far from the typically used Gaussian or ellipsoid distributions.

Keywords: Debris; Re-entry; Ground-impact; Probabilistic-distribution; Modeling

1. Introduction

Space Situational Awareness (SSA) is quickly becoming imperative for nations around the world, especially those with space capabilities and assets. As the low Earth orbit (LEO) debris and spacecraft population that have exceeded their operational lifetime rises each year, the rate at which objects re-enter the Earth's atmosphere will also steadily rise. Most of these objects will probably not reach the ground for impact; however, parts of large objects like rocket bodies and satellites or resident space objects (RSOs) with mass greater than a ton have a high probability of surviving the harsh re-entry environment. The surviving parts can be hazardous (e.g. fuel tanks with unused hydrazine or radioactive components) and can cause damage and casualties within a populated area.

The National Aeronautics and Space Administration (NASA-STD-8719.14, 2012) and the European Space Agency (Requirements on Space Debris Mitigation for ESA Projects, 2008) guidelines require that any RSO re-entering the atmosphere (1) fully demise in the atmosphere, or (2) impact with an energy of no more than 15 Joules with an associated casualty risk of less than 1 in 10000. Complying with these guidelines require an end-of-life analysis for all future planned missions. The impact location of an object re-entering the atmosphere is affected by uncertainties in initial conditions, atmospheric characteristics, and object properties, as well as break-up/fragmentation events. Therefore, it is important to have an accurate estimate of not just the deterministic impact location but also the statistical distribution due to the uncertainties involved. Existing

* Corresponding author.
E-mail address: piyushmukeshmehta@gmail.com (P.M. Mehta).

http://dx.doi.org/10.1016/j.asr.2016.08.032
0273-1177/

Please cite this article in press as: Mehta, P.M., et al. Sensitivity analysis and probabilistic re-entry modeling for debris using high dimensional model representation based uncertainty treatment. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.08.032

re-entry modeling tools used by space agencies are either deterministic, proprietary, non-open source, and/or are not freely available to the research community (Rochelle et al., 1999; Koppenwallner et al., 2005; Martin et al., 2005).

All the existing tools have five basic building blocks: (i) Aerodynamics, (ii) Aerothermodynamics, (iii) Flight Dynamics, (iv) Structural analysis, and (v) Thermal analysis, and can be classified as either spacecraft- or object-oriented. Spacecraft-oriented tools perform the analysis with higher fidelity compared to object-oriented tools (for e.g. 6DoF vs 3DoF dynamics or detailed thermal analysis vs lumped mass approach), however they are harder to use and computationally expensive because spacecraft-oriented tools constantly share data between the building blocks whereas object-oriented tools use the blocks independently. Therefore, a logical approach would ideally involve using an object-oriented tool for the preliminary analysis, followed by a more concentrated campaign with a spacecraft-oriented tool based on the preliminary results from the object-oriented tool. The only spacecraft-oriented tool known to exist is SCARAB (Spacecraft Atmospheric Re-entry and Aero-thermal Break-up) developed by HTG under a contract from ESA (Koppenwallner et al., 2005).

The object-oriented approach uses a simplified representation of the re-entering object made up of primitive shapes such as sphere, cylinder, cone, etc. The approach assumes or calculates a demise altitude following which the object is assumed to break-up into multiple objects, represented by the individual primitive geometries (Rochelle et al., 1999; Martin et al., 2005; Parigini et al., 2015). Fig. 1 shows the idea behind an object-oriented tool.

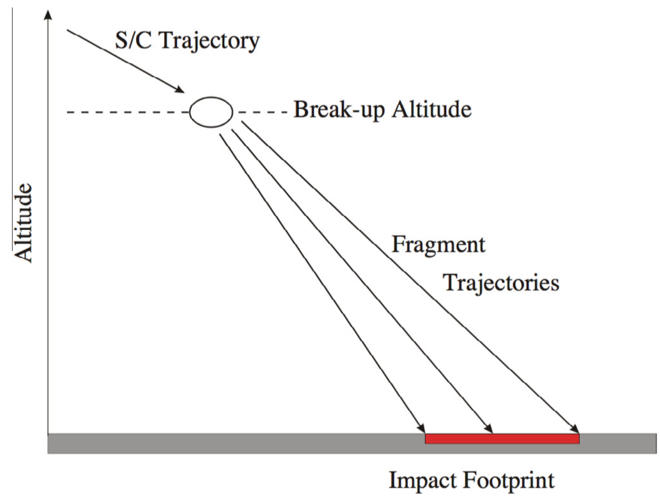

Fig. 1. Concept behind an object-oriented tool (Lips and Fritsche, 2005).

As previously mentioned, an accurate end-of-life analysis involves a probabilistic approach due to the uncertainties involved. A Monte Carlo (MC) campaign is the most intuitive approach available for uncertainty quantification and propagation. Fig. 2 shows an example of a MC campaign run using Deimos' proprietary object-oriented tool DEBRIS (Parigini et al., 2015).[1] The trajectories in blue show a limiting case representative of shallow uncontrolled re-entry, cyan represents a 'normal' controlled re-entry while the orange color represents a limiting case of controlled re-entry at a highly steep flight path angle (not realistic). DEBRIS is one of a very few, if not the only, new-age re-entry tool that performs uncertainty-treatment albeit expensively.

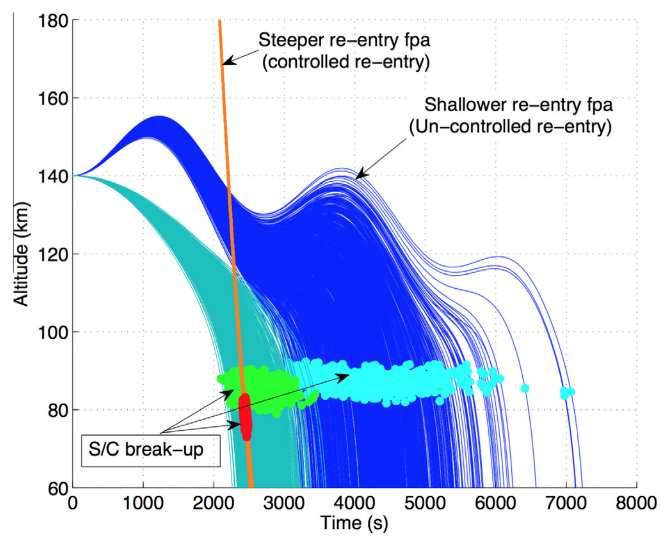

Fig. 2. Monte Carlo analysis and the concept behind an object-oriented tool (Parigini et al., 2015). fpa = flight path angle.

The MC approach can provide a realistic distribution for the output of interest ($F(\mathbf{x})$) due to the uncertainties in the input parameters, however, it does so with a very high computational cost. Moreover, a sensitivity study that can provide qualitative and quantitative insights into the effects of uncertainties in input parameters on the output and influence engineering design decisions is typically not feasible. Even though MC based methods are among the most popular used for sensitivity studies, they require a large amount of sampling of the stochastic input domains and expensive function evaluations to estimate the statistical properties of the given model. The model code is typically assumed to be a black-box and will henceforth be refereed to as the black-box model (BBM) in this paper.

The well known Sobol sensitivity method (Saltelli et al., 2004, 2008) is also based on the MC approach and decomposes the variance of $F(\mathbf{x})$ for the given BBM into parts attributable to input variables. Let's assume we have n uncertain input parameters; a sensitivity study accounting for only first order effects would require $n+1$ MC campaigns, each coming at a very high cost. The outcome of the method is the quantification of the influence of each variable in the given BBM. Scatter plots can be used to gain insights into the BBM, visualize the influence of a variable, and estimate the behavior of $F(\mathbf{x})$ in a given domain

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

Please cite this article in press as: Mehta, P.M., et al. Sensitivity analysis and probabilistic re-entry modeling for debris using high dimensional model representation based uncertainty treatment. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.08.032