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Satellite vulnerability to space debris – an improved 3D risk assessment methodology

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ABSTRACT

The work described in the present paper, performed as a part of the P^2 project, presents an enhanced method to evaluate satellite vulnerability to micrometeoroids and orbital debris (MMOD), using the ESABASE2/Debris tool (developed under ESA contract). Starting from the estimation of induced failures on spacecraft (S/C) components and from the computation of lethal impacts (with an energy leading to the loss of the satellite), and considering the equipment redundancies and interactions between components, the debris-induced S/C functional impairment is assessed.

The developed methodology, illustrated through its application to a case study satellite, includes the capability to estimate the number of failures on internal components, overcoming the limitations of current tools which do not allow propagating the debris cloud inside the S/C. The ballistic limit of internal equipment behind a sandwich panel structure is evaluated through the implementation of the Schäfer Ryan Lambert (SRL) Ballistic Limit Equation (BLE).

The analysis conducted on the case study satellite shows the S/C vulnerability index to be in the range of about 4% over the complete mission, with a significant reduction with respect to the results typically obtained with the traditional analysis, which considers as a failure the structural penetration of the satellite structural panels.

The methodology has then been applied to select design strategies (additional local shielding, relocation of components) to improve S/C protection with respect to MMOD. The results of the analyses conducted on the improved design show a reduction of the vulnerability index of about 18%.

Abbreviations: BAU, Business as Usual; BLE, Ballistic Limit Equation; CFRP, Carbon Fiber Reinforced Plastic; FTA, Fault Tree Analysis; GEO, Geostationary Orbit; HC, Honeycomb; LEO, Low Earth Orbit; MEO, Medium Earth Orbit; MLI, Multi Layer Insulation; MMOD, Micrometeoroid and orbital debris; MTG, Meteosat Third Generation; P^2, Prediction, Protection & Reduction of Orbital Exposure to Collision Threats; SAR, Synthetic Aperture Radar; SAW, Solar array Wing; SRL, Schäfer Ryan Lambert; S/C, Spacecraft; S/S, Sub-System; S-1, Sentinel-1

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1. Introduction

With the continuous growth of the space debris population occurred in the last decade, the need for an improvement over the traditional way of computing the risk induced by micrometeoroids and orbital debris (MMOD) to orbiting spacecrafts, from the early design phases to mission operations, strongly emerged.

The traditional approach to space mission vulnerability with respect to MMOD impacts, typically evaluates the probability of structural penetration. This approach, developed to deal with manned mission, is not well suited to evaluate satellite vulnerability: penetration of a satellite structural panel does not necessarily lead to the loss of the satellite or the loss of a component (as demonstrated by the SRL HVI test campaign [1,3,4,5]).

The 30-month project P^2–ROTECT (Prediction, Protection & Reduction of Orbital Exposure to Collision Threats), funded by the European Commission via the Framework Program 7 under Contract no. 262820, was initiated in February 2011 to develop improved methodologies and tools to evaluate the vulnerability of space missions, for both trackable and untrackable space debris. A more precise and realistic estimation of the risk induced by on-orbit impacts (i.e. a vulnerability index) allows the comparison of different future scenarios and the evaluation of the effectiveness of protection, mitigation and remediation actions to reduce the space debris threat.

This paper is focused on the risk induced by untrackable debris and micrometeoroids to space missions and it presents an enhanced methodology to evaluate satellite vulnerability with respect to the traditional approach.

2. Methodology

The enhanced methodology developed to evaluate the spacecraft (S/C) vulnerability using the ESABASE2/Debris tool is illustrated in Fig. 1. Inputs and outputs are shown in blue, computational tools are shown in green. This methodology avoids overestimating the S/C vulnerability through the adoption of the Schäfer Ryan Lambert (SRL) Ballistic Limit Equation (BLE) to evaluate failures on internal components and the inclusion of a functional analysis of the S/C accounting for the redundancies and the interactions between components.

A similar approach to the S/C vulnerability with respect to MMOD impacts, that evaluates damage on internal components and takes into account their functional dependencies, is presented in [6].

The first inputs come from the analysis of the S/C system (orbital and mission parameters, physical architecture, and functional analysis). Starting from these inputs, two ESABASE2/Debris geometrical models are derived: an “External Model”, including all the S/C external components and appendages (SAR antenna and Solar Array) and the main BUS structure, and an “Internal Model”, encompassing all the internal components, without the external panel. The latter also includes all the external items and appendages (see Section 2.5)

Other inputs required by the computational tool ESABASE2 are the MMOD environment models (see Section 2.2) and the Ballistic Limit Equations (BLEs) (see Section 2.4).

Finally, a lethal threshold (see Section 2.3) that allows discriminating between impacts that lead to component failure and impacts that impair the whole S/C causing the loss of the mission is defined.

All these elements are used as inputs for the ESABASE2 simulations to evaluate the number of failures caused by MMOD impacts on internal and external components, as well as the number of lethal impacts. Component failures and lethal impact probabilities are determined based on failure and impact rates by using the Poisson distribution equation (Eq. (1)) derived from the discrete probability

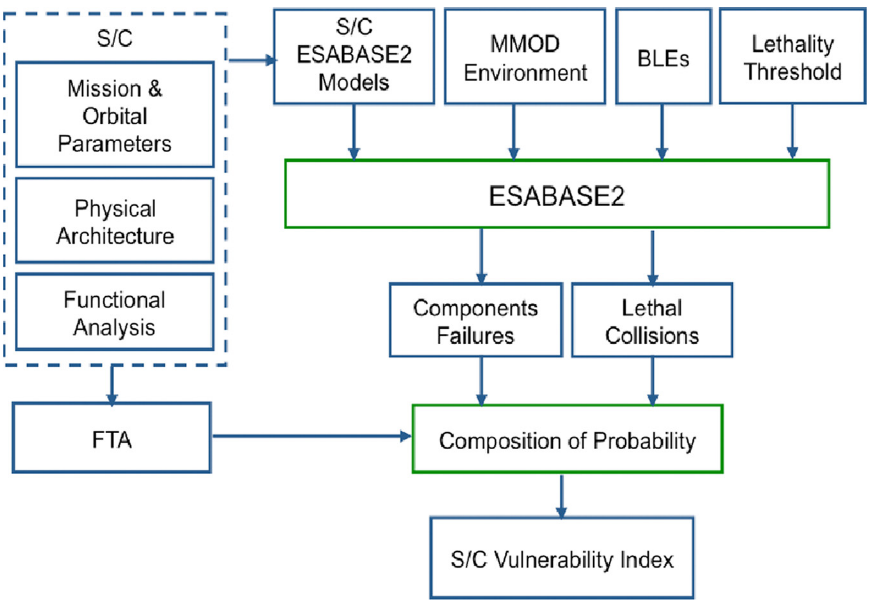

Fig. 1. Vulnerability methodology flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)