Design for Demise: Systems-level techniques to reduce re-entry casualty risk

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ABSTRACT

“Design for Demise” are solutions at different design levels to meeting the space debris mitigation requirement to minimise the risk to human population following uncontrolled re-entry of spacecraft. We have identified, analysed and evaluated through detailed numerical simulations a set of techniques that will yield a design able to reduce the re-entry casualty risk of any element of a satellite.

We developed a number of changes which could be made at systems level via a Concurrent Engineering Facility study to the depth of a mission Phase A, considering application to the CarbonSat mission. A multi-disciplinary assessment of their advantages and disadvantages was performed, including spacecraft-oriented modelling using the SCARAB tool. The particular techniques considered included designing a spacecraft without some or all of its outer panels, using strategically-placed openings or break-out patches in the structural panels for early influx of airflow, moving critical components outside of the main spacecraft structure, and containment of hard-to-demise components.

1 INTRODUCTION

Over recent years, the rising population of space debris has been increasingly recognised as a serious issue for the space-faring community. Mitigation is required, either by moving satellites to a safe long-term orbit at the end of their active life, or by disposing of them by re-entering the Earth’s atmosphere. For energetic reasons, the former option is preferred for spacecraft in MEO or GEO, and the latter from LEO. The side effect of re-entry is the risk to human population from surviving objects [1].

To minimise the risk, a requirement is imposed on spacecraft whose planned disposal method is re-entering the Earth’s atmosphere that the risk of casualties must be below 10^{-4}. Compliance with this requirement can be achieved by a controlled de-orbit, where the safety concern is not the survivability of elements but the size of the footprint in order to fit it into a safe area, usually the open ocean. However, the impact in mass and cost of a controlled re-entry can be prohibitive, and hence the alternative is to ensure passive and safe re-entry within a 25-year timeframe. As uncontrolled re-entry is fully passive, it does not rely on the satellite still functioning correctly at end of life, and so maximises the useful life by avoiding the need to de-orbit a still-functioning satellite.

“Design for Demise” is the solution at system design level proposed to ensure compliance with the risk requirement using uncontrolled re-entry. This paper presents results from the Multi-Disciplinary Assessment of Design for Demise Techniques project, which was led by Deimos Space UK with subcontractors OHB, HTG and EPFL. The objective of the project was to identify, analyse and evaluate through detailed numerical simulations a set of techniques that will yield a design able to reduce the re-entry casualty risk of any element of a satellite.

The approach consists of several steps:

- To identify those elements of a satellite that are critical from a re-entry point of view based on literature review and dedicated simulations
- To identify design-for-demise techniques applicable to those critical elements
- To assess the implementation of the identified techniques from a multidisciplinary point of view
- To validate the proposed techniques in representative mission scenarios making use of state-of-the-art simulation tools at different levels of fidelity
- For the most promising techniques, to identify the required technology developments to allow their use in future missions, creating a technology roadmap for a proper and timely development

The project considered LEO spacecraft in the 800 kg to 4 tonne class. Larger spacecraft cannot generally reduce the risk adequately for uncontrolled entries, and must therefore be designed to have a controlled entry landing in the ocean. Smaller satellites can be assumed to demise fully on entry without any changes being needed. In between, there are satellites which may have a casualty risk above 10^{-4}, but low enough that the risk

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could potentially be reduced below this level by design changes. LEO spacecraft are relevant because natural orbital decay can bring them back into the Earth's atmosphere within 25 years.

2 MODELLING APPROACH

The destruction of a re-entering object is a highly stochastic problem involving complex and coupled phenomena. The dynamics of the entry is coupled with the aerothermodynamics and the thermo-mechanical loads evaluation to manage with melting, deformation and fragmentation processes.

During re-entry, each spacecraft component is exposed to the convective heating and radiative heating of surrounded gas. The component demises if the net heat (heat input less heat lost by radiative cooling) exceeds the heat of ablation (the sum of the heat to raise the component to the melting point and the heat of fusion). Thus materials with a high melting temperature tend to survive the re-entry.

Modelling approaches can be divided into two sub-categories: spacecraft-oriented and object-oriented.

A spacecraft-oriented approach is characterized by a detailed modelling of all the processes and objects involved (aero-thermal interactions, thermo-mechanical loads, melting and deformations). The output represents a very detailed assessment but it requires significant effort to build the spacecraft model and high computational loads. Hence it is clear this approach is suitable for verification of a limited set of well-defined cases, but not to run fast assessments considering a wide range of possible cases. HTG's SCARAB (Spacecraft Atmospheric Re-Entry and Aerothermal Break-up) tool is currently the only commercial spacecraft-oriented modelling software.

An object-oriented approach, on the other hand, uses simpler models of a spacecraft and its components, together with trajectory and aerothermodynamics calculations to model the demise. The common idea of an object-oriented approach is to model break-up of a spacecraft as a single event: at a certain point of the entry trajectory the level of loads acting on the spacecraft results such that the structure collapses. After the main breakup, trajectory propagation and thermal analysis are performed for each fragment independently. The elements composing an entering object are usually known and therefore the analysis can be centred on the elements which are most likely to reach the ground. This is a very important feature when fast analysis involving several mission scenarios and spacecraft configurations are required.

In this project, the DEBRIS tool was used for object-oriented modelling [2]. DEBRIS is part of DEIMOS's proprietary Planetary Entry ToolBox [3]. It has been used to support debris analyses at system level from phases A to D. This tool provides the capability to cope with uncertainties in environment (atmosphere), state (position and attitude) and vehicle characteristics (aerodynamics, mass properties) for the derivation of ground footprint, survivability and risk analysis. It is an object-oriented code, which allows the rapid execution of different demise scenarios.

Object- and spacecraft-oriented approaches therefore have complementary strengths, trading off fast evaluation of a wide range of possible designs against more detailed analysis of a specific design. During the development of an individual spacecraft, an object-oriented approach may be preferred in early phases when different designs are being considered, before a final design is analysed in detail with a spacecraft-oriented approach. The object-oriented tools allow us to run fast and extensive parametric and statistical analyses. In this frame, uncertainties have an important role, because they compensate the poor knowledge or large variability of the environmental, object and mission parameters and also add robustness to the assessment results. Additionally, only a rough level of detail of the system elements and configuration is required to set up a simulation.

In this project, a large number of Nominal, Monte Carlo and parametric analyses have been run in DEBRIS, followed by SCARAB simulations using a smaller number of different initial conditions.

3 IDENTIFICATION OF CRITICAL ELEMENTS

The critical elements of a satellite were identified using a combination of literature review and simulation. The re-entry casualty risk metric as defined in [4] was used, which takes into account for each item of debris predicted to survive to the ground the casualty area given by the collision cross-section between a piece of debris and the human body, and the casualty risk resulting from multiplying this area by the population density appropriate to the re-entry epoch and orbital inclination. For example, a casualty area of 8 m² caused by an uncontrolled re-entry from a sun-synchronous orbit in the year 2050 (population density 13 persons/km²) corresponds to a casualty probability of 1:9,615.

The total casualty area and risk is strongly driven by the number of surviving fragments. Therefore, all design for demise technologies that will be analysed in this study have to focus on the reduction of the number of surviving fragments.

Typical components of satellites in the reference mission class were modelled to determine their likelihood of survival to the ground and contribution to the casualty area. The elements which contributed most to the casualty risk were found to be:

- Propellant tanks, which are usually made of titanium alloys
- Reaction wheels, specifically, the steel flywheels
- Optical benches
- Balance masses
- Magnetic torquers (specifically, iron cores)
- Other objects made of critical materials such as star tracker barrels and coolers.

The main factors which make an object critical include:

- The material it is made of: materials such as titanium, silicon carbide and steel, which have a high melting point and high heat capacity, are particularly difficult to demise.
- Its size and mass: large objects have more material to ablate and are more likely to survive.
- Whether it is located on the edge of the spacecraft or protected within the structure.

4 IDENTIFICATION OF DESIGN FOR DEMISE TECHNIQUES

The objective of this project is to identify design-for-demise techniques which are applicable to the critical elements identified above, to assess the benefits they will bring, to develop further the most promising techniques, and to validate them using detailed simulations. The process is therefore to come up with a large number of potentially useful techniques, and to shortlist them based on:

Demisability: How big a reduction in casualty area can be achieved?

Applicability: Can a technique be applied to many classes of satellites, or only a few?

TRL: How close is the technique to being used? How likely is it that it will be successfully developed?

Development cost: How expensive would it be to develop?

Recurring cost: How much will it increase the cost of a mission, considering parts and design effort?

Systems impact and trade-offs: Will a proposed technique lead to disadvantages such as a higher mass, lower reliability or shorter lifetime? Will big changes in satellite design be needed?

In this section, we list techniques and preliminarily assess the benefits they might provide in terms of the overall casualty area of a satellite, their potential use and applicability to different mission scenarios, and the impact that any such changes will have at systems level. Where appropriate this assessment uses results from DEBRIS simulations.

At top level, techniques can be categorised by whether they affect the entire spacecraft, or whether they are intended to reduce the risk from one specific subsystem or component. They can also be categorised by how they are intended to improve demisability:

Minimise required heat: Techniques which minimise the energy required for demise, including materials changes to use materials which are easier to demise, or minimising the mass of critical materials.

Maximise available heat: Techniques which increase the energy available to demise components, including changes to the shape and mass distribution of the spacecraft, which in turn can affect the ballistic coefficient or attitude during entry.

Optimise heat transfer: Techniques which make best use of the available energy to cause demise, for example using layering or open structures to get the heat in to the components which most need it.

Minimise casualty area: Techniques to reduce the total casualty area of a satellite, generally by ensuring that surviving debris lands as one piece not several.

4.1 Systems-level techniques

This section considers different techniques that could be performed at system level to reduce the overall casualty risk or encourage the demise of specific components.

Putting critical components at the edge: Moving the most difficult to demise components to regions of the satellite where they will encounter airflow from the start of entry means they will get the most effect of the available heat. DEBRIS simulations show that such techniques can make a difference to components on the edge of criticality such as MTQ, although they are not adequate for the most difficult to demise components: titanium fuel tanks do not demise even if they are fully exposed throughout entry.

Stronger attachment of the solar arrays: Causing the solar arrays to remain attached for longer changes the trajectory, as they act as aerodynamic drag devices. However, simulations show that changing the altitude at which the solar arrays break off has relatively little effect on the altitude where the spacecraft breaks up, and hence on component demise.

Exploding the spacecraft or ejecting components: It would be possible to separate components before re-entry, potentially increasing demisability by maximising exposure. However, it would be necessary to carry out any active steps at end of life, potentially 25 years before re-entry, and so such an approach would create multiple pieces of debris for many years. This option is thus rejected as being likely to worsen the overall debris problem, as well as violating the space debris mitigation guidelines.

Promoting early breakup by weakening the structure: Instead of actually breaking the satellite apart, it is possible to weaken the structure at end of life (or, indeed, earlier) by using explosive shape charges or thermal straps. However, such a development would require a large qualification effort to ensure that it would work successfully but not detonate too early. In general, satellite operators have indicated an unwillingness to have a “self-destruct” measure on board. Alternatively, weakening can be triggered by the entry itself, for example by using heat-activated frangibolts or thermal straps. These techniques are preferred as they cannot be triggered accidentally, though there are still concerns about reliability.

Getting the airflow inside the satellite: Openings in the outer structure can allow the hot air behind the hypersonic shock in to the spacecraft, promoting an earlier break-up and an earlier demise of the inner components. Among the solutions which can be considered are burst discs (circular bulkheads made of a demisable material such as aluminium), ram air devices, or using easily-separated outer panels. All of these are relatively straight-forward to implement, being inexpensive and having low impact at system level. The openings would all be underneath the multi-layer insulation to avoid causing problems with thermal regulation during life, but this is expected to be quickly removed very early in entry.

Containment of debris: Unlike other techniques, containment does not seek to encourage components to demise, but instead to reduce the total casualty area due to undemised components. For some satellites, the casualty requirement can be met if all the debris lands as one item rather than several separate ones. Although implementation would not be easy, as rearranging the components to keep the critical ones together will affect the mass properties and thermal engineering, doing so could significantly reduce the total casualty area.

4.2 Sub-systems-level techniques

This section considers different techniques that could be performed at sub-system and component level to reduce the casualty risk due to that component of the spacecraft. Techniques are considered for different critical components separately.

Propellant tanks: Titanium tanks are essentially undemisable; only using a different material can reduce their contribution to casualty risk. Finding a demisable material which can survive the challenging chemical and pressure requirements is not simple. Various materials have been considered in the literature including steel and aluminium tanks, and composite overwrapped pressure vessels (COPV) which have a metal liner wrapped in carbon fibre containing materials. However, simulations suggest that neither steel tanks nor titanium or steel liners of COPV tanks demise, so the materials selection is limited. The most promising approach is changing to a more demisable material: aluminium-lined COPV tanks are currently being developed by Cobham, and tanks made from aluminium lithium alloy being studied by ESA.

Reaction wheels: The most promising options for reaction wheels is to replace the steel flywheel with a demisable material such as aluminium, either completely or at least partially (e.g. a steel structure and demisable counterweights). Changing the design of the wheels (radius, thickness or adding holes or spokes) could also be considered. Other ways to increase the exposure, such as locating the wheels at the outside of the spacecraft or removing the casing could make a marginal difference at best, while more radical solutions like using more, smaller wheels would have a significant systems-level effect, increasing the mass and making the AOCS more complex.

Balance masses: Depending on the constraints on the balance mass, the simplest approach is to use a demisable material such as aluminium rather than steel. However, being less dense this might take up too much space, and so an alternative option is to break up a single mass into multiple smaller masses held together with an easily demisable connection.

Payload elements: The payload of a satellite can be the most challenging for D4D, not least because payloads are highly variable between different missions, and because payloads often have some of the most challenging requirements, leading to them being made of some of the least demisable materials. Where it is possible to replace a critical material with a more benign one, this should be considered. Otherwise, containment of debris can be the best option, firstly ensuring that the entire payload lands as one item, and potentially also keeping it attached to other critical elements such as the tank.

5 DETAILED DESIGN AND EVALUATION OF TECHNIQUES

Detailed design, to the level of a Phase A assessment study, was done for the most promising D4D techniques, allowing us to assess the implementation from a multidisciplinary point of view, evaluating their impact at system level. Four of these techniques were selected for validation by applying them to a real mission, CarbonSat, initially through a Concurrent Engineering Facility study, followed by detailed design and modelling.

5.1 Containment tether

The most successful technique applied to CarbonSat was a tether to contain the bipod "feet" together all the way to the ground [5]. These titanium feet are part of the isostatic mounting between CarbonSat's platform and payload "boxes", and are the biggest contributor to the casualty risk. Keeping them together during entry doesn't promote their demise, but reduces the on-ground risk by ensuring that they land as one object rather than 9 individual pieces.

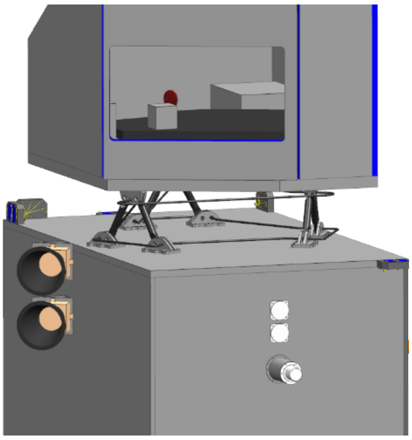

Figure 1. Tether concept as applied to CarbonSat

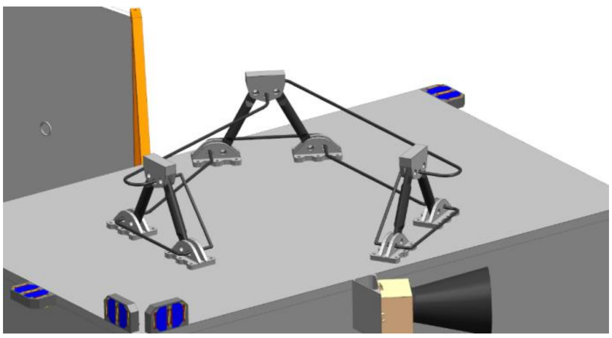

Figure 2. Tethered feet, payload not shown for clarity

5.2 Break-out patches

Break-out patches were designed into the side panels, aiming to expose components on the inside to the aerodynamic flow earlier, and thereby promote demise. For CarbonSat, the aim was particularly to target the reaction wheels. Various system impacts and challenges were recognised, such as the need for thermal, radiation and micrometeoroid and orbital debris protection, but solutions were found for all of them. The extra mass needed for protection was larger than the reduction from the panel material removed, leading to a mass penalty of 4.5 kg overall. However, the additional exposure does not reduce the casualty area; the same critical components all survive to the ground.

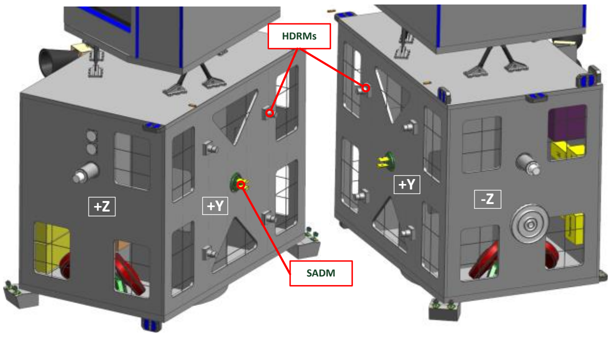

Figure 3. CarbonSat design with break-out patches in three panels

5.3 Closure panel-free design

Taking the idea of opening up the satellite further, a design where entire closure panels were removed was considered. Although the systems impacts were generally larger from removing more of the panels, viable solutions were found to each of the challenges, requiring additional internal structure to prevent undesired vibrations as well as shielding for sensitive components. Unfortunately the extra exposure resulting from these changes was still found to be insufficient to demise any additional critical components.

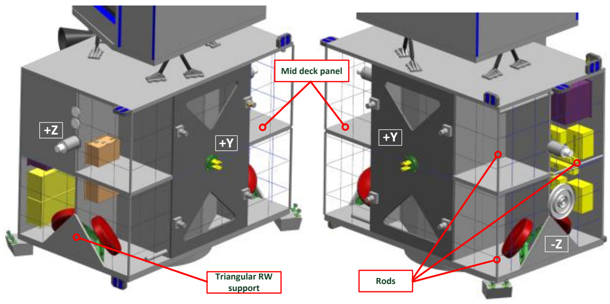

Figure 4. Closure panel-free CarbonSat design

5.4 Reaction wheels outside

Putting the Reaction Wheels outside of the main spacecraft structure was expected to maximise their exposure and promote their demise. As this concept had been studied in parallel activities, it was decided to investigate whether accommodating them inside the launch vehicle adaptor (LVA) ring is feasible. No significant difficulties were found with implementing this technique, although it was necessary to select wheels with separate electronics. The mass penalty for this technique is 20 kg, which is quite significant at over 2% of the spacecraft dry mass. However, the SCARAB results show that the demisability of the wheels is not increased by external mounting in this configuration, as they now shield each other.

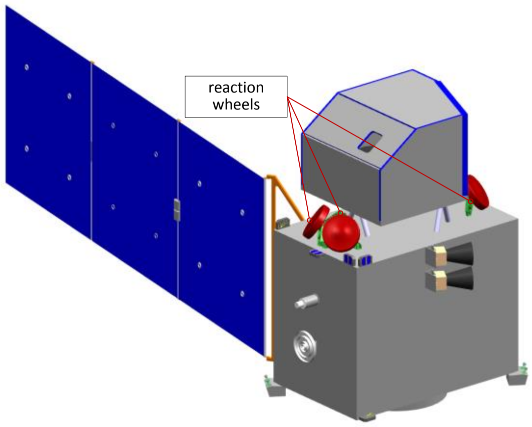

Figure 5. Reaction wheels outside of the main structure

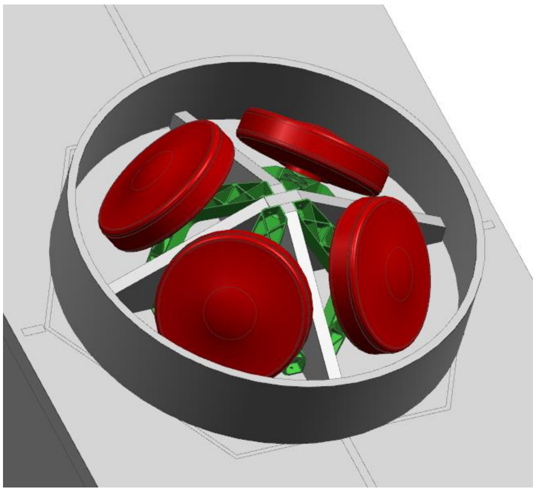

Figure 6. Reaction wheels outside design tested on CarbonSat, with the wheels in the LVA

5.5 Other techniques

An additional technique, replacing the titanium propellant tank with one made from an aluminium-lithium alloy, was also tested in the simulations, finding that such a tank would demise in almost all cases.

Other D4D techniques which were considered but not shortlisted include:

- Putting other components outside of the main structure, such as the magnetorquers
- Removing all of the outer panels, i.e. taking the closure panel-free design even further
- Using demisable structural joints so that the spacecraft breaks apart earlier in entry, or modifying the panels so that they are removed earlier in entry
- Other methods for containing the hard-to-demise components including a non-demisable box or bracket, or a net.

6 REVIEW OF RESULTS AND CONCLUSIONS

Overall, the most successful techniques were direct substitution of a non-demisable material with a one with a much lower melting point, and containment of separate critical elements to reduce the casualty area. None of the three techniques which aim to demise critical components by increasing their exposure during entry succeeded for the CarbonSat study case. This result gives a clear direction for future work: away from the systems-level changes that previously were considered to be some of the most promising, and towards component-level changes such as replacement materials and containment.

A detailed development roadmap was produced for the most promising technique, the containment tether, including a ROM costing and timeline. The developments needed in related tools and techniques to allow the D4D process to be applied in the future by satellite design teams were also mapped out. Guidelines were also produced to help these teams to identify critical components early in the process, and to understand D4D approaches that they should consider.

7 REFERENCES

1. ESA Space Debris Mitigation Handbook, 2nd edition, (2003).

2. C. Parigini *et al.* (2017). "DEBRIS: An object-oriented code for footprint survivability and risk analysis", *7th European Conference on Space Debris*.

3. D. Bonetti *et al.* (2016). "PETbox: Flight qualified tools for atmospheric flight", *6th ICATT conference*.

4. H. Klinkrad (2006) "Space Debris: Models and Risk Analysis", Springer.

5. J.-C. Meyer et al. (2017). "Containment tether – concept study of an efficient solution to reduce the casualty area of spacecraft components", *7th European Conference on Space Debris*.