Materials Research Proceedings 42 (2024) 113-116 https://doi.org/10.21741/9781644903193-25

Feedback control of a density-based space debris model to support the definition of efficient mitigation and remediation strategies

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Keywords: Space Debris, Feedback Control, Sustainability, Density Propagation

Abstract. Space can be seen as an extension of our planet's biosphere, and as happens with Earth's ecosystem, humanity's utilisation of it is not sustainable. The number of in-orbit debris is dramatically growing and the current guidelines for limiting their proliferation are less adequate to face nowadays situation. The research proposes to develop a systematic way to investigate the effectiveness of the different mitigation and remediation measures. This is done integrating a density-based model for in-orbit objects propagation with a feedback controller on the environment, mimicking human actions in space, to reach a target scenario. The tool will be a valuable support to the definition of a new strategy for the sustainable future utilisation of space.

Introduction

Life on Earth dramatically relies on space assets, but future access to orbit is threatened by the uncontrolled exploitation of space. When scientist Donald Kessler in the '70s proposed his theory on the proliferation of debris in space, less than 5000 objects were tracked orbiting Earth. In the following decades that number has grown exponentially and today hundreds of thousands of debris as little as 1 mm are estimated to pollute our planet's orbital space [1]. In 2002 the Inter-Agency Debris Committee (IADC) formulated guidelines to limit the proliferation of debris [2], that focussed on disposal of spent bodies, reduction of explosions risk and collisions prevention. However, recently, miniaturisation of technologies and a more affordable access to orbit fuelled a new concept of space economy and the consequent increase in launch traffic [3]. According to the future predictions of the European Space Agency's (ESA) Annual Environment Report the current utilisation of space is not sustainable [1]. Therefore, it is now mandatory to define new and updated guidelines suited to face the fast-evolving situation, such as the recent ESA's Zero Debris Policy to limit creation of debris in ESA's future missions [4]. There is broad agreement in this context that it is required to synergistically combine wider adoption of mitigation measures and innovative remediation techniques [1][5]. As of today, simulators for space objects evolution have been used to investigate the effect of specific counteractions. ESA's DELTA software was exploited in [6] to characterise the possible future debris scenarios by manually changing the requirements of IADC guidelines, and in [3] the effect of different static levels of Post-Mission Disposal (PMD) adherence were analysed. However, there is still no consensus on how to efficiently combine these elements in a suitable strategy towards a sustainable space utilisation. A fast and systematic approach is necessary to investigate the predicted effectiveness of the many possible debris mitigation actions.

To address this need, the research proposes the integration of an evolutionary model of the space population with an active feedback controller. Mitigation and remediation measures enter the system as control inputs, mimicking human actions in space and on mission design, as shown in Fig. 1. The control logic tunes the selected inputs in time acting on the objects' distribution in space to reach a target scenario. The approach allows for fast and versatile analyses of the many possible futures predicted by the model under the effect of diversified rules.

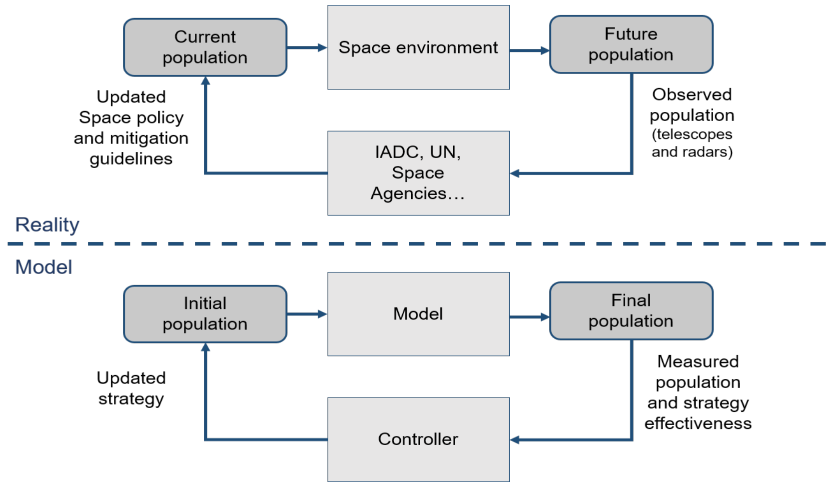


Fig. 1. Schematic of the model (bottom) compared to the real-world interactions it aims to represent (top). The figure is inspired from the one in [10].

Methodology

Fig. 1 shows the main blocks of the tool that is being developed within the research. The space objects' propagator exploits the approach of describing the clouds of debris as a flow with continuous properties. Leveraging on previous works, such as [7][8][9], the dynamic is defined by enforcing mass conservation through Eq. (1), in which the time evolution of the density n is affected by the dynamics $\boldsymbol{f}$ and the deposition and removal rates $\dot{n}^+$, $\dot{n}^-$.

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{f}) = \dot{n}^+ - \dot{n}^- \tag{1}$$

The applicability and effectiveness of such density-based methods have been extensively proven in the literature and advanced multi-dimensional tools for debris environment propagation through continuum mechanics have been developed in recent years, such as the Starling and COMETA suites [9][10]. However, a simplified one-dimensional model is first considered, to privilege rapidity of the analyses on accuracy in this preliminary development phase. Referring to the work in [7][8], Eq. (1) is formulated in terms of orbital radius only. The spatial domain is divided in spherical shells and the evolution of the objects' density is captured through the finite volume method, adapting the analysis in [9] to the one-dimensional case. Eq. (2) shows the system of equations resulting by applying the divergence theorem to Eq. (1) of each i^{th} shell within its limiting radii $r_{i_{lower}}$, $r_{i_{upper}}$, in which the dynamic term v_r considers only the natural effect of atmospheric drag, exploiting the simplified exponential model for air density in [7].

$$\begin{cases} \dot{n}_i = \frac{1}{V_i}\left(-\left(4\pi n_{i+1} v_{r_{i+1}} {r_{i_{upper}}}^2 - 4\pi n_i v_{r_i} {r_{i_{lower}}}^2\right) + \int_V ({\dot{n}_i}^+ - {\dot{n}_i}^-) dV\right) \\ \vdots \end{cases} \tag{2}$$

Expanding the work in [8], source and sink mechanisms included in $\dot{n}$ account for new launches, objects moved through PMD and active debris removals. Each of them is modelled as a continuous contribution in time and space to the density rate. These functions can take any shape to mimic real behaviours, such as historical profiles, or to investigate alternatives in space utilisation. Additionally, in-orbit fragmentations will be included based on the collision and explosion probabilities of the objects. The first feedback control logic analysed is the quadratic proportional one proposed in [11] for its simple definition and physical interpretation. It is reported in Eq. (3), in which the gain proportional to the squared error e^2 is the ratio of maximum control allowed $u_{\max}$ with the squared maximum error $e^2_{\max}$ between the shell's density n_i with respect to a reference value n_{ref}, above which the control is saturated. For the preliminary results shown in the following the error is defined as in Eq. (3).

$$u = \frac{u_{\max}}{e_{\max}^2} e^2 \qquad \text{where} \qquad e = n_{ref} - n_i \tag{3}$$

In future works, more complex definitions will be considered, such as PID or linear quadratic controllers, and robustness will be analysed accounting for uncertainty. Any source or sink term in Eq. (1) can be considered, in principle, as a control input. Up to now, both launches and PMD models have been included in the propagator and the feedback controller can act on the objects' distribution in space and time by changing the launches deposition rate $\dot{n}_{launches}$ or the compliance factor λ that scales the PMD contribution as $\lambda \dot{n}_{PMD}$ to reach a predefined target.

The tool will benefit from its extreme versatility to characterise many future scenarios aiming at the most promising strategies to reach sustainability of the environment. Combinations of the control inputs will be considered and diversified rules analysed in time for different species of objects and different orbital regions.

Preliminary results

Since the research is still in its preliminary phase, the results of a simple example are provided in the following considering a scenario that is not a realistic representation of the debris environment but has the sole purpose of validating the control technique. Taking as a reference the work by McInnes in [7], here a similar Gaussian initial distribution profile is considered, and the target is defined in terms of uniform final density n_{ref} for all the shells. The feedback proportional control logic of Eq. (3), with the inputs in Table 1, acts on the deposition rate $\dot{n}_{launches}$, tuning the launch profile in time and space based on the local density of each region.

Table 1. Controller inputs of Eq. (3).

u_{Max}	e_{Max}	n_{ref}
$2e-7$ [$\#/sm^3$]	0.5 [$\#/m^3$]	1 [$\#/m^3$]

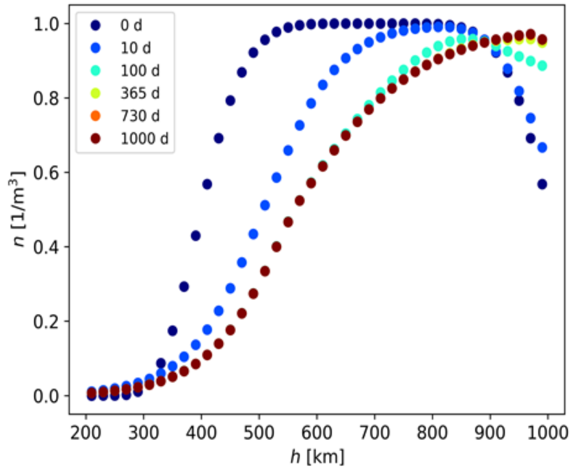
In Fig. 2a it is clearly visible the feedback effect in time to bring the density profile to the target one. The controlled launch rate is provided in Fig. 2b, and as expected the deposition rate is close to zero at high altitudes where the initial density is close to one and the absence of a relevant sink mechanism causes accumulation of objects. Differently, it is visible that with the constraints given in Table 1, the control action is not capable of overcoming the strong drag effect at low altitudes, even with the maximum allowed source rate, and after 100 days the profile reaches a limiting scenario. The results obtained agree with the analytically derived ones in [7].

This simple example paves the way to model more complex and realistic scenarios. All the contributions to Eq. (2) previously described will be modelled and many cases investigated, in terms of different inputs combinations, different sinks and sources profiles and different targets.

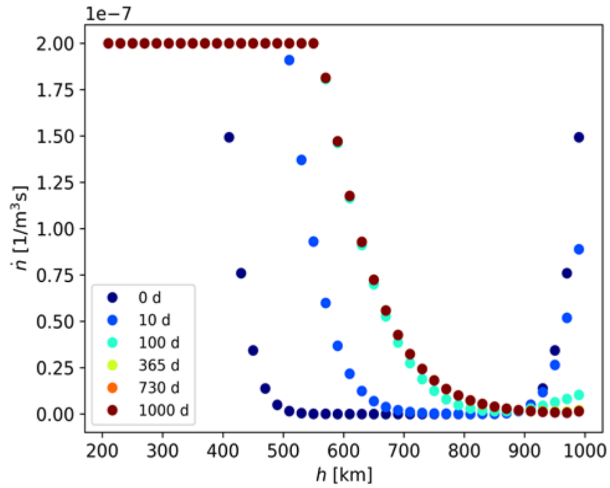
The proposed research responds to the need of a systematic way for analysing efficient strategies to face the debris proliferation problem. The approach is versatile, and the simplicity of this preliminary dynamical model allows for fast analyses. The tool will support the redefinition of regulations and standards for a sustainable utilisation of the space environment.

Acknowledgements

The research received funding from the European Research Council (ERC) under the European Union's Horizon Europe research and innovation program as part of the GREEN SPECIES project (Grant agreement No 101089265) and was partially supported by the ICSC—Centro Nazionale di Ricerca in High Performance Computing, Big Data, and Quantum Computing funded by European Union—NextGenerationEU.



(a) Density profile evolution captured at different time snapshots.



(b) Controlled deposition term evolution captured at different time snapshots.

Fig. 2. Time evolution of the density and density rate profiles in altitude. Each point represents the value of one orbital shell. Snapshots are taken at 0, 10, 100, 365, 730 and 1000 days.

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