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Author: Mr. Joseph Ivarson
Auburn University, United States

Mr. Luke Scharck
Auburn University, United States
Ms. Ana Barona-Mejía
Auburn University, United States
Mr. Luis Manuel Postigo
Auburn University, United States
Mr. Laith Bader
Auburn University, United States
Ms. Kate Handel
Auburn University, United States
Prof. Allan David
Auburn University, United States
Prof. Davide Guzzetti
Auburn University, United States

OPERATIONAL ENVELOPE ANALYSIS AND CONOPS COMPARISONS FOR SMALL DEBRIS REMEDIATION USING PROGRAMMABLE DUST

Abstract

Micron-sized dust deployment across a selected orbital swath is being considered as one option to remediate small, lethal debris (1mm - 1 cm) that are elusive to tracking, with few or no competing technology alternatives documented. Debris flying through the swath collides with dust grains and experience a resultant artificial drag. In this enhanced drag environment, debris descends to lower altitudes faster than its natural decay rate, with a substantial increase in descent speed above 800 km. One main limitation of current dust-based solution is that inert, homogenous dust grains tend to decay (and possibly spread) much faster than the target debris population, losing their ability to effectively operate at the target altitude. However, through the careful tuning of dust grain properties, a designer can passively harness environmental stimuli to gain control on the collective dust swath dynamics, broaden the overall design space, and regain efficacy. In previous work, we identified the key design parameters, performance metrics, and outcomes for thermochromic dust grains, which achieve passive control through the induction of asymmetric solar radiation pressure over the orbit cycle. The functioning principles has been verified via the work-energy principle and extensive multi-physics numerical simulations. The current work extends the analysis to include mission-level performance models and metrics for programmable dust solutions. This new analysis includes comprehensive trade studies examining key mission parameters and their effects on debris remediation efficacy. Such key mission parameters encompass design traits like the density and shape of the dust swath, the total mass of particles required, particle-to-debris impact characteristics, and orbital configurations. This study highlights the interdependencies among mission parameters, emphasizing the need to balance these factors for an optimal concept of operations. It also demonstrates a significant improvement in remediation efficacy when passive control of swath dynamics is implemented. In one case study, we show that programmable dust removed over 3.5 times more debris mass compared

to inert particles for the same total dust mass to orbit. Additional discussion on the behavior expected by the ideal dust grain properties is provided with the hope of soliciting insight from the broader aerospace materials community. Previous and current research on programmable dust continues to suggest strong potential for the concept to become a viable solution for small debris remediation.