# Multidisciplinary and Multiscale Modeling of Aerodynamic Decelerator Systems

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## ABSTRACT

Current technology for decelerating a spacecraft from the supersonic speed of atmospheric entry to the final stages of landing on Mars is based on parachute systems. An early attempt at the simplified stress analysis of such a system which failed during a flight test conducted by NASA in 1972 revealed that the maximum stresses occur during the opening of the parachute [1]. During this attempt, it was noted that the majority of the related studies deal with inflated canopy shapes and apply static equilibrium conditions during intermediate stages of the inflation process. It was also concluded that such approaches underpredict the stress levels experienced by a parachute, and therefore cannot account for observed canopy failures. Despite this and the fact that the many canopy failures observed in flight tests during the past four decades occurred during inflation, the majority of parachute studies continue to deal today with inflated canopy shape and with static equilibrium conditions during assumed intermediate stages of the inflation process. Furthermore, most related computational efforts have focused so far on developing CFD and Fluid-Structure Interaction (FSI) parachute models for the easier to simulate post-inflation regime. This, because the development of a high-fidelity, multidisciplinary, multiscale computational model for parachute inflation dynamics is a formidable challenge.

During the last two years, the authors and their collaborators at the NASA Jet Propulsion Laboratory (JPL) rose to the challenge and developed an Eulerian computational framework for the predictive simulation of flexible fluid-structure interfaces evolving in high-speed turbulent flows. This framework is built around an Eulerian computational model for highly nonlinear FSI problems that has proven itself for the failure analysis of submerged structures subjected to explosions and implosions [2,3], and for the prediction of turbulent viscous flows past highly flexible flapping wings [4,5]. Its key computational ingredients include: a robust embedded boundary method for CFD and FSI that is numerically stable, capable of second-order accuracy in the vicinity of material interfaces, and is robust against spurious spatial [6] and temporal oscillations due to ill-conditioning and discrete events, respectively; a homogenization method for supersonic, turbulent flow computations past porous membranes; a fast algorithm for computing the distance to the wall based on a distance error estimation [7]; a direct approach for accounting for cable-driven FSI interactions [8]; a computationally tractable multiscale approach for modeling membrane structures based on model hyperreduction [9] and machine learning; an innovative approach for modeling parachute deployment based on space filling curves [8]; and an adaptive mesh refinement approach for tracking boundary layers and flow features that is driven by an error indicator based on the distance to the wall and the curvature of the computed solution [10].

This lecture will present the multidisciplinary, multiscale computational approach outlined above, and illustrate it with the detailed discussion of several high-fidelity simulations of aerodynamic decelerator systems. It will also report on its validation using data from the Mars landing of NASA's rover Curiosity.

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