Multifidelity modeling for the design of re-entry capsules

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The design and optimization of space systems presents many challenges associated with the variety of physical domains involved and their coupling. A practical example is the case of satellites and space vehicles designed to re-enter the atmosphere upon completion of their mission [1]. For these systems, aerodynamics and thermodynamics phenomena are strongly coupled and relate to structural dynamics and vibrations, chemical non equilibrium phenomena that characterize the atmosphere, specific re-entry trajectory, and geometrical shape of the body. Blunt bodies are common geometric configurations used in planetary re-entry (e.g. Apollo Command Module, Mars Viking probe, etc.). These geometries permit to obtain high aerodynamic resistance to decelerate the vehicle from orbital speeds along with contained aerodynamic lift for trajectory control. The large radius-of-curvature of the bodies' nose allows to reduce the heat flux determined by the high temperature effects behind the shock wave. The design and optimization of these bodies would largely benefit from accurate analyses of the re-entry flow field through high-fidelity representations of the aerodynamic and aerothermodynamic phenomena. However, those high-fidelity representations are usually in the form of computer models for the numerical solutions of PDEs (e.g. Navier-Stokes equations, heat equations, etc.) which require significant computational effort and are commonly excluded from preliminary multidisciplinary design and trade-off analysis.

This work addresses the integration of high-fidelity computer-based simulations for the multidisciplinary design of space systems conceived for controlled re-entry in the atmosphere. In particular, we discuss the use of multifidelity methods to obtain efficient aerothermodynamic models of the re-entering vehicles. Multifidelity approaches allow to accelerate the exploration and evaluation of design alternatives through the use of different representations of a physical system/process, each characterized by a different level of fidelity and associated computational expense [2, 3]. By efficiently combining less-expensive information from low-fidelity models with a principled selection of few expensive simulations, multifidelity methods allow to incorporate high-fidelity costly information for multidisciplinary design analysis and optimization [4–7]. This presentation proposes a multifidelity Bayesian optimization framework leveraging surrogate models in the form of gaussian processes, which are progressively updated through acquisition functions based on expected improvement. We introduce a novel formulation of the multifideltiy expected improvement including both data-driven and physics-informed utility functions, specifically implemented for the case of the design optimization of an Orion-like atmospheric re-entry vehicle.

The results show that the proposed formulation gives better optimization results (lower minimum) than single fidelity Bayesian optimization based on low-fidelity simulations only. The outcome suggests that the multifidelity expected improvement algorithm effectively enriches the information content with the high-fidelity data. Moreover, the computational cost associated with 100 iterations of our multifidelity strategy is sensitively lower than the computational burden of 6 iterations of a single fidelity framework invoking the high-fidelity model.

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