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ENHANCING THERMAL PROTECTION SYSTEM ANALYSIS FOR SPACECRAFT RE-ENTRY THROUGH MACHINE LEARNING-AUGMENTED INVERSE HEAT CONDUCTION PROBLEMS

Abstract

In the context of space exploration, the entry of spacecraft into a planet's atmosphere at high velocities subjects the Thermal Protection System (TPS) to extreme temperatures and heat fluxes. Stable thermal data collection is thus feasible only through the resolution of a specific kind of ill-posed problem, namely the Boundary Inverse Problems of Heat Conduction (IPHC), which are grounded in Partial Differential Equations.Although this problem was successfully resolved decades ago, obtaining the necessary data to determine the thermal status of the TPS or spacecraft currently requires the installation of numerous thermal sensors on the TPS. This not only complicates the preparation for ground thermal tests but also reduces the payload capacity for future flights.To address this issue, we propose integrating machine learning techniques, alongside IPHC applications, as supplementary tools. Specifically, this research employs a machine learning algorithm known as Gappy Proper Orthogonal Decomposition (Gappy POD) to aid in constructing the thermal physical field for reusable TPS.In essence, our approach unfolds in two phases. Initially, we apply traditional IPHC using sparse thermal sensors distributed across various TPS tiles. Subsequently, leveraging this data, we construct a comprehensive thermal physical representation of the TPS during entry within the Gappy POD framework.Our findings reveal that, by integrating machine learning techniques and conducting comparisons between the Gappy POD results and those from multiple IPHC solutions with extensive sensor arrays, followed by spline-surface post-processing, we can achieve the required thermal identification accuracy at a significantly reduced sensor weight. This reduction primarily stems from the decreased need for numerous sensors.