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Nuclear Systems Safety Analysis by Artificial Intelligence, Meta-Modeling and Adaptive Simulation

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Abstract

For the safety analysis of nuclear systems, the response under different perturbed conditions must be studied. This can be done by means of mathematical models, implemented in corresponding Best-Estimate (BE) computer codes for numerical simulation. Given the uncertainties in the operational conditions and in the models and parameters, the analysis entails repeated system response simulations under different conditions and parameters settings to identify unsafe states of operation. The feasibility of the analysis is challenged by the fact BE codes are: i) computationally demanding; ii) high-dimensional; iii) somewhat black-box; iv) dynamic; and v) affected by uncertainties. In this work, *different* computational methods are suggested for efficiently tackling the corresponding computational issues. In nuclear safety analyses, it is often necessary to identify the combinations of inputs values (system design and/or operational parameters), which lead the system to failure (e.g., to the fuel peak cladding temperature exceeding a regulatory threshold): these configurations define the so-called Critical Region (CR). The computational burden associated to such thorough exploration can be efficiently tackled by a synergistic action of two approaches: (i) fast running *meta-models* (implemented to mimic the behavior of the long-running code at a largely reduced computational time); and (ii) *adaptive sampling strategies* to *intelligently* trace the CR boundary and update the meta-model training set *only* around the (interesting) failure regions. A suitable *learning function* is used by the authors to iteratively refine Kriging (Gaussian Process) meta-models to accurately discriminate between the safe and failure domains of a nuclear passive safety system designed for decay heat removal after reactor shut-down due to a station black-out accident. A reduction of three-four orders of magnitude in the computational cost is obtained with respect to using the BE code (RELAP-3D) at the expense of a relatively small error (2.24%) in the estimation of the output (i.e., the energy exchanged in the passive system). It is worth noting that the above methods rely on the assessment of the *uncertainty* in the models of the phenomena related to the operation of the nuclear systems of interest. Such assessment typically consists in: (1) the identification of the uncertain input parameters and hypotheses that characterize the phenomena that may occur in the system, (2) the quantification of such uncertainties. Such *integration* requires *Inverse Uncertainty Quantification (IUQ)* approaches to find the characterization of the input uncertainty that is most consistent with the experimental data available, with the lowest computational burden. The authors propose a structured Bayesian methodology to calibrate the model of a natural circulation-based passive decay heat removal system by means of *functional (time-dependent) data* coming from a real, full-scale experimental facility. The approach combines: (i) Kriging meta-models; (ii) time series filtering (to increase meta-modeling performance); (iii) transient *dimensionality reduction* by Sparse Staked AutoEncoders; (iv) nonparametric (Markov Chain Monte Carlo) sampling of the model output posterior distribution. The method is shown to give consistent results also in case of very scarce experimental data available (i.e., one single time series measurement).

Keywords: Nuclear safety; Simulation; Artificial intelligence; Adaptive simulation; Uncertainty quantification