Multi-output excursion set estimation applied to the calibration of a wind turbine numerical model

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Many industrial challenges involve excursion set estimation, which can be defined as identifying a set of feasible input values for black-box models. These input values must satisfy a constraint on the model's output, such as remaining below a specified threshold (e.g., [1]). A widely used approach to address this problem involves modeling the expensive black-box function as a realization of a Gaussian Process (GP). This surrogate model is constructed through a sequential Design of Experiments, with points selected in the design space $\mathbb{X} \subset \mathbb{R}^d$ based on the optimization of an acquisition criterion (see [2] for more details). The Bichon criterion [3] is a classical approach to excursion set estimation that offers a balanced trade-off between exploring the design space and exploiting known regions around the boundary of the excursion set.

In this work, we focus on the pre-calibration of a numerical model for wind turbines. The simulator, treated as a black-box model, takes system parameters (such as stiffness coefficients of various materials) as inputs and returns vibration frequencies and deformation eigenmodes as outputs in response to wind loads. The inputs are denoted by Θ, and the outputs by $\lambda_i(\Theta)$ for frequencies and $\mathrm{Mod}_i(\Theta)$ for modes, where $i \in 1, \ldots, p$, and p is the number of modes.

Our goal is to estimate the set of feasible input parameters that ensure the simulator's outputs match the experimentally observed data. More precisely, we aim to pre-calibrate the numerical model (Figure 1) by determining a set of feasible input parameters Θ for the simulator. These parameters must ensure that the vibration frequencies $\lambda_i(\Theta)$ and deformation modes $\mathrm{Mod}_i(\Theta)$ computed by the simulator are sufficiently close, within predefined thresholds, to the observed frequencies $\lambda_i^\star$ and modes $\mathrm{Mod}_i^\star$, derived from experimental data based on Operational Modal Analysis (OMA) (e.g., [3]).

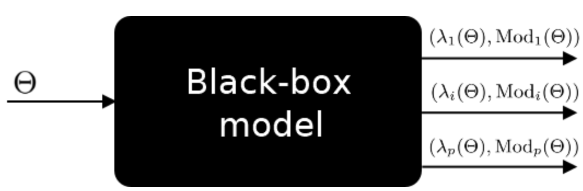

Figure 1: Schematic diagram of the wind turbine simulator.

Mathematically, we focus on black-box models with vector-valued outputs $\boldsymbol{G} := (G_1, \ldots, G_p)$. The partial excursion sets are defined as follows:

$$\forall\, i \in \{1, \ldots, p\},\ \Gamma_i^\star := \{\mathbf{x} \in \mathbb{X}, G_i(\mathbf{x}) \leq T_i\}. \tag{1}$$

In [5], a criterion is proposed for estimating the intersection of partial excursion sets. In the context of our pre-calibration problem, knowing the input values that are feasible for all output components is insufficient. Therefore, this work aims to estimate the partial excursion sets for each output component simultaneously. This allows us to determine, for any given point in the design space, which output component exceeds its respective threshold.

We propose two natural extensions of the Bichon criterion: (1) Alternating Scal, which alternates optimization between components, and (2) Pareto Scal, which leverages Pareto solutions from the bi-objective optimization of the Bichon criteria. These two approaches use separate GP models for each output component. We also introduce a vector extension (Vect) of the Bichon criterion, based on minimizing the distances between each component of the GP and its respective threshold. This extension relies on a multi-output GP model that incorporates correlations between outputs (see [6]) and requires the computation of orthant probabilities in multivariate normal distributions.

The methodologies introduced above are compared across several analytical examples, considering 2 and 4 input components, and 2 output components. Subsequently, these methodologies are applied to the pre-calibration stage of the wind turbine simulation, exploring two different problem formulations based on two dissimilarity measures. The first focuses on the two primary deformation modes, while the second considers all deformation modes and all vibration frequencies.

Our results on both analytical examples and the wind turbine simulator pre-calibration demonstrate the effectiveness of our proposed strategies for estimating partial excursion sets. However, limitations associated with the covariance structure of the multi-output GP model suggest areas for future refinement.

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