Proceedings of the 11th North American International Conference on Industrial Engineering and Operations Management, Milwaukee, Wisconsin, USA, June 9-11, 2026

Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA11.20260385
Published: June 9, 2026

Calibrating Digital Twins in Rapidly Changing Systems

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Abstract

Digital twins support real time decision making by synchronizing virtual models with real world physical systems. However, when real world systems change rapidly and a digital twin is built on a high fidelity simulation model, conventional calibration methods may require substantial computational effort and become sensitive to noisy observations. In this dissertation, we develop fast and robust calibration methods for digital twins in such environments. First, we reformulate calibration as a root finding problem that uses the sign of the discrepancy between simulated and observed outputs to guide the search more efficiently than standard minimization. We embed this framework in Bayesian optimization with new acquisition functions and a search space reduction strategy. Unlike standard minimization based Bayesian optimization approaches that treat calibration as minimizing a nonnegative discrepancy objective, this formulation preserves directional residual information and uses it to guide sampling more efficiently. Second, we extend the approach to rootless and stochastic settings, improving reliability when an exact root is unavailable or observations are noisy. Third, we propose a robust predictive calibration framework for nonstationary systems, where calibration must account for uncertain future evolving system dynamics. We demonstrate our contributions through a wind farm operations case study, where calibrated digital twins are used to support wake steering decisions under uncertain and changing wind conditions.

Keywords
Digital Twins, Changing Systems, Virtual models