Koi-utils: a Framework for Uncertainty Quantification in Cardiac Simulation

Eli Child, Asher Merrill, Matthias AF Gsell, Anton J Prassl, Gernot Plank, Akil Narayan, Karli Gillette

Department of Biomedical Engineering, University of Utah,
Salt Lake City, Utah, USA

Introduction: Cardiac digital twins of electrophysiology show promise for patient-specific therapy for cardiac arrhythmias but require rigorous uncertainty quantification (UQ) to increase clinical confidence. However, expanding parameter spaces and disconnected digital twinning pipelines make UQ difficult to automate, reproduce, and scale.
Aim: We aim to create a framework for reproducible, flexible, and streamlined UQ in cardiac digital twinning pipelines.
Methods: We created *Koi-utils*, a modular framework for large-scale UQ built on the openCARP ecosystem and UncertainSCI. This framework consists of six primary stages fundamental to UQ: sampling, screening, simulation, extraction of quantities of interest, data-driven modeling, and analysis. Each stage is automated and has reproducible inputs and outputs. We demonstrated the *Koi-utils* framework end-to-end in a small-scale yet physiologically complex sheet model of in silico pace mapping within the ventricles, deploying a Gaussian Process Emulator (GPE) to predict arrhythmic reentry with uncertainty estimates under variation in conduction velocity and pacing protocol.
Results: Our framework implementation achieved fully automated execution of all UQ-related stages. The trained GPE on the cardiac sheet model achieved an AUC of 0.80 when predicting arrhythmic reentry on validation data.
Conclusion: *Koi-utils* enables streamlined, reproducible, end-to-end UQ in cardiac electrophysiology simulations. This advances cardiac digital twinning toward scalable and reliable clinical deployment.

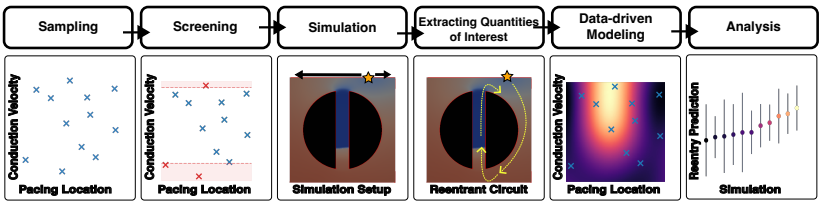

Figure 1. Example of the six-primary stages of *Koi-utils* within a re-entrant slab model with insilico pacing.