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Adaptive importance sampling for reliability assessment of an industrial system modeled by a piecewise deterministic Markov process.

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Abstract:

For safety reasons, EDF needs to assess the reliability of industrial systems involved in the operation of nuclear and hydroelectric power plants. These systems are considered to have failed when one or more continuous physical variables (temperature, pressure, level of liquid in a tank, etc.) exceed a critical threshold. Such threshold can only be reached after the malfunction of certain combinations of components. The physical variables of the system evolve according to deterministic differential equations that depend on the status of the system's components (active, inactive, broken), and this status is modified as a result of random and/or deterministic discrete events (failures, repairs, control mechanisms, etc.).

The estimation of the probability of failure of the system relies on the simulation of piecewise deterministic Markov processes (PDMP) modeling the hybrid operation of the system [1]. These systems are highly reliable because of the many control mechanisms and components present in redundancy; the typical probability of failure is therefore low (in our case about 10^{-6}). Since simulating these systems is numerically expensive, it is not possible to estimate the probability of failure using a standard Monte-Carlo approach. Instead, we propose an importance sampling (IS) method.

It is known from [2] that the optimal instrumental distribution of a PDMP to estimate the probability of a rare event by importance sampling relies on the knowledge of the committor function of the process. This committor function represents the probability that a PDMP trajectory realizes the rare event of interest knowing its current state. Unfortunately this function is never explicitly known.

We will present the two main aspects of our importance sampling method:

1. The construction of a family of approximations of the committor function that are faithful in the framework of PDMP modeling multi-component systems with complex interactions. For this purpose we used the reliability concept of minimal path sets of the system [3], which are the smallest sets of components ensuring the functioning of the system. The approximations of the committor function are then increasing functions of the number of minimal path sets having at least one broken component.
2. The implementation of an efficient algorithm with good statistical properties to both sequentially refine the instrumental distribution used for importance sampling and to estimate the probability of the rare event without wasting samples. The sequential strategy is a cross-entropy procedure [4] coupled with a recycling scheme for past samples inspired by [5] for which we have proved convergence and asymptotic normality.

Our method and its performances are illustrated on a test case from the nuclear industry: the spent fuel pool (whose operation is described in [1]).

References

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Short biography – After a master's degree in statistics at Sorbonne University, Guillaume Chennetier did his internship at EDF R&D Saclay in rare event simulation and sensitivity analysis for piecewise deterministic Markov processes in order to access the reliability of hybrid multi-component systems involved in the operation of nuclear and hydraulic power plants. He is now pursuing this work in a PhD thesis with Ecole Polytechnique and still with EDF R&D Saclay.