The interacting particle system estimation method with piecewise deterministic Markovian processes

T. Galtier, H.Chraibi, A. Dutfoy, J. Garnier
Laboratoire de Probabilités et Modèles Aléatoire (LPMA), University Paris Diderot
EDF R&D, Département management des risques industriels

Supervisor(s): Prof. J. Garnier (Ecole Polytechnique), H.Chraibi and A.Dutfoy (EDF R&D)

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Adress: EDF R&D, 7 Boulevard Gaspard Monge, 91120, Palaiseau, France

Email: tgaltier@gmail.com

Abstract: For both safety and regulation issues, the reliability of power generation systems has to be assessed. The considered systems (dams or nuclear plants for instance) are often complex dynamic hybrid systems. Therefore only simulations methods can be reasonably considered to assess their reliability. As the systems are highly reliable, their failure is a rare event. In this context it is well-known that the naive Monte-Carlo simulation method is time-consuming, so we want to use a variance reduction method to accelerate reliability assessment for our dynamic hybrid systems.

A failure of a dynamic hybrid system often corresponds to a physical variable of the system (temperature, pressure, water level) entering a critical region. The simulation of such a system requires an accurate model of the physical variables' trajectory. These physical variables are often determined by simple differential equations but those equations depend on the status of the multiple components of the systems (on, off, or out-of-order). Thus the model should incorporate the dynamics of the statuses of the components, which rely on deterministic feedback mechanisms and on random failures and repairs. To encounter for this hybrid interplay between the discrete process of components' statuses and the continuous evolution of the physical variables EDF has recently developed the PyCATSHOO tool [2], which allows the modeling of dynamic hybrid systems. PyCATSHOO bases this modeling on piecewise deterministic Markov processes [3]. It evaluates the dependability criteria of the studied systems by Monte Carlo simulation. The objective of our work is to set up new algorithms to accelerate this simulation.

Several acceleration methods for variance reduction can be proposed: importance sampling methods and particle filter methods. In a variance reduction method, we generally need to increase the probability of simulating a failing trajectory by altering the simulation process, and then correct the induced bias by an appropriate weighting of each simulation.
The importance sampling method consists for instance in simulating from a weakened system before re-weighting simulations with a likelihood ratio. It can theoretically be very effective and is applicable to PDMP [1], but in order to reach a good efficiency with this method we need have a good approximation of the probability that the system would fail before the observation duration knowing its current state. Such approximation is rarely available with complex system, so we chose to focus on particles filters which require less information about the system.
Unlike in importance sampling, in a particle filter method, we keep simulating according to the original system. The difference is that we do not simulate directly the trajectories on the entire observation duration, but we simulate piece by piece by alternating between an exploration and a selection step. During the exploration step we simulate the trajectories on a small time interval, therefore exploring the most probable trajectories on a short horizon of time. Then we apply a selection on these trajectories, we replicate the trajectories which seem close to failure and give up the less "promising" trajectories. At the next exploration, only replicated trajectories are continued, before the next selection, and the next exploration, and so on... This way the effort

of simulation is concentrated on trajectories which have higher chance of becoming a failing trajectory before the end of the observation duration. In the end we get more failing trajectories to fuel our estimation. Here we take interest in the interacting particles system method (IPS) [6] which uses the particle filters to estimate the probability of rare events, our goal is to adapt it to PDMPs.

When we try to apply the IPS method to reliable complex hybrid systems we run into an issue. With reliable components and slow repairs there is a high probability that no component failure or repair occur during the short exploration time, and with PDMP it means that the trajectories are likely to follow a deterministic path. So when we explore the trajectory space most simulated trajectories end up being the same one, hence limiting our exploration of the trajectory space. To avoid this pitfall, a particular filter was proposed in [7] that enhances the occurrence of random jumps (failure or repairs) or modifies the occurrence time of the last jump. However the proposed method is limited to a special case of PDMP which does not allow to model automatic control mechanisms in components. We propose another approach using the memorization method developed in [4]. The idea is to start the exploration by finding the most likely trajectories continuing each batch of replicated trajectories and to condition the rest of the exploration to avoid these trajectories hence simulating more different trajectories. The estimate of the reliability obtained with our modified version of the IPS algorithm is still strongly consistent and satisfies a CLT. We have proven that the variance of the CLT is always smaller with our version of the IPS method. A simulation study on a small system confirms a significant improvement in terms of variance reduction. We also give estimate of for variance of the CLT which is adapted from one of the estimates developed in [5].

References

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Short biography – I got my master degree in statistics at the "École nationale de la statistique et de l'analyse de l'information" (ENSAI) in Rennes in 2014 . I am currently doing a PhD at the Industrial risk management departement of EDF R&D and the university Paris 7. This PhD is funded by EDF R&D, its goals are to speed-up the reliability assessment of dynamic hybrid systems, and to implement them in the "PyCATSHOO" simulation tool developed by EDF.