PhD proposal

Verification of dynamic properties for a family of hybrid models. Application to epidemic control.

Advisors : Benoît Delahaye et Morgan Magnin – benoit.delahaye@ls2n.fr, morgan.magnin@ls2n.fr
Supervisor : Guillaume Cantin – guillaume.cantin@ls2n.fr
Teams MéForBio & VELO – Laboratoire des Sciences du Numérique de Nantes UMR 6004

Context

In an international context marked by a steady increase in major epidemic events, scientific research is in great demand, to provide institutional players with decision-making support in a climate of urgency and uncertainty [Mor20]. Anticipating and controlling the spread of these emerging epidemics are two crucial issues, that concern many scientific communities.

A great deal of progress has recently been made in modelling the propagation dynamics of these events. To study the effect of human behaviour and the decisions of institutional players on bio-logical dynamics, we know how to build hybrid models, by coupling discrete probabilistic modelling tools such as Markov chains, derived from computer science, with continuous deterministic modelling tools such as differential equations, derived from mathematics [CSB22].

Methods for verifying the properties of Markov chains are well known [BK08], as are methods for analysing the dynamics of differential equations [Per13]. But the verification of the properties of these hybrid models obtained by coupling the two formalisms is a poorly explored area, which today represents an essential area of research, with equally promising applications in other fields (study of the dynamic properties of biological systems).

Objectives

The primary objective of this thesis is to construct a new formalism for defining and studying a class of hybrid models. These hybrid models will be obtained by coupling a deterministic continuous process with a probabilistic discrete process. The chosen framework will have to be sufficiently broad to cover several application domains, and will have to go beyond existing work [JCD22, SFM22, Hen00], in particular with in-depth reflection on time scales. This class of models will also have to be equipped with a logical structure enabling models to be compared and refined.

The second objective of this thesis will be to extend or redefine property verification methods for these new models. In addition to the usual properties such as accessibility and invariance, we will be particularly interested in dynamic properties such as stability and periodicity. The verification methods may be numerical and based on statistical processing, or symbolic and associated with an algorithmic procedure.

One case study will focus on epidemic propagation and control. These phenomena are characterised by the juxtaposition of a continuous viral dynamic with a human dynamic aimed at reducing their impact. The generality of the hybrid formalism designed in this way will be illustrated by a complementary biological case study focusing on the resilience of a simplified model of the circadian clock in the face of events that disrupt it (jet lag, disruption of the day/night mechanism, etc.) [AMI16].

This research will be carried out in the context of two projects currently being funded: (1) the CoSysM3 project, led by Cristiana J. Silva (University of Lisbon, Portugal), funded for 4 years by the Portuguese Science Foundation, which focuses on the control of epidemics, and (2) the VERHYDYN project, led by Guillaume Cantin (Nantes University), funded by INS2I for 2023 and 2024, which focuses on the verification of dynamic hybrid systems. These research projects will make it possible for the doctoral student to spend periods of scientific collaboration between the Universities of Nantes and Lisbon.

Candidate profile

To carry out this thesis work, the candidate should have a sound knowledge of theoretical computer science, formal model verification methods, and a keen interest in applied mathematics. Experience of studying epidemiological models would be highly appreciated.

Références

[AMI16] Alexander Andreychenko, Morgan Magnin, and Katsumi Inoue. Analyzing resilience properties in oscillatory biological systems using parametric model checking. *Biosystems*, 149:50–58, 2016.

[BK08] Christel Baier and Joost-Pieter Katoen. *Principles of model checking*. MIT press, 2008.

[CSB22] Guillaume Cantin, Cristiana J Silva, and Arnaud Banos. Mathematical analysis of a hybrid model: Impacts of individual behaviors on the spreading of an epidemic. *Networks & Heterogeneous Media*, 2022.

[Hen00] Thomas A Henzinger. The theory of hybrid automata. In *Verification of digital and hybrid systems*, pages 265–292. Springer, 2000.

[JCD22] David Julien, Guillaume Cantin, and Benoît Delahaye. End-to-end statistical model checking for parametric ODE models. In *International Conference on Quantitative Evaluation of Systems*, pages 85–106. Springer, 2022.

[Mor20] Serge Morand. Emerging diseases, livestock expansion and biodiversity loss are positively related at global scale. *Biological Conservation*, 248:108707, 2020.

[Per13] Lawrence Perko. *Differential equations and dynamical systems*, volume 7. Springer Science & Business Media, 2013.

[SFM22] Honglu Sun, Maxime Folschette, and Morgan Magnin. Limit cycle analysis of a class of hybrid gene regulatory networks. In *Computational Methods in Systems Biology: 20th International Conference, CMSB 2022, Bucharest, Romania, September 14–16, 2022, Proceedings*, pages 217–236. Springer, 2022.