Research Internship - M2 SIF

Transient analysis of transport networks.

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Abstract : The objective of this internship is to define a transient analysis framework for models of transport networks. This internship will first define an appropriate notion of symbolic run for networks populated by fleets of vehicles with simple dynamics. It will then consider verification of a timed quantitative properties (e.g. written with the Signal LTL logic) for these symbolic runs.

The practical application of the techniques developed during this internship is to improve efficiency of urban transport networks.

Keywords : Transport networks, transient analysis, symbolic analysis, online verification.

Detailed description:

Improvement of urban transport networks is a major challenge for the next coming decades. Increasing the transport offers is a way to reduce greenhouse gas emissions, and to facilitate the life of growing populations commuting every day in large cities. The problems to address are to improve efficiency of existing transport backbones, in terms of consumed energy, persons transported per hour, and resilience to unexpected delays caused by failures or passengers misbehaviors. These challenges have to be addressed at the level of a single line/transport means, but also at a global level of a complete interurban network connecting several transport means (trains, metros, busses, and even new mobility solutions such as electric bikes and trolley fleets).

A transport network can be seen as a graph, in which some vertices represent access points for passengers, edges represent connections between these points, where moving objects (buses, metros,…) transit. Vehicles can have a very complex dynamics, but several assumptions (for instance that security headways are perfectly respected in a metro network) allow for a simplification of their physical models [Kecir19].

An efficient way to improve a network is to follow advices given by so-called **regulation techniques**. These advices suggest speeds and dwell times of vehicles to ensure regularity of departures from all access points, to reinject kinetic energy during braking at the most appropriate moment in a tram system…. A possible way to perform regulation in transport network is to see is as an optimal control problem: regulation is then an additional mechanisms computed once for all to take the best decision from **every possible state** of the system. Though this approach is theoretically appropriate, the size of the systems considered (several million of states and transitions) prevent from computing optimal controllers. Yet, designers of traffic management systems include controllers in their architectures. These controllers are often very ad hoc rules (e.g. ”when a train is late, reduce its dwell time”). Ad-hoc controllers give a priori no guarantee on the efficiency of the controller system. Further, rules that seem to be common sense sometimes are sometimes inefficient. It is hence necessary to analyze the behavior of transport systems with regulation to get a sufficient confidence in the rules implemented by the controller.

Again, this analysis faces the **state space explosion** problem. Usual model-checking techniques can address only small networks [Bertrand19]. A way to circumvent this problem and handle larger networks is to rely on **statistical model checking**. Rather that computing the whole state space of a system to verify a property φ, statistical model checking (SMC) performs **random runs** of the system to approximates empirically the **probability that φ is satisfied**, and an error margin. Statistical model checking allows to increase the size of models that can be verified, because one needs not compute explicitly the whole state space of a system to simulate a run. SMC nevertheless has limits: the number of random runs sampled that is required to compute a trustable estimation of $P[\varphi]$ can be very high. A possible solution is to perform transient analysis on quotient systems [Horvath12]. Roughly speaking, considering a system with *n* variables $x_1,\ldots x_n$, a small difference in the value of some x_i may not impact the overall behavior of the whole system. Then, states of a system can be grouped into equivalence classes, also called **state classes**. Addressing properties of timed systems via their state classes is a standard approach for models such as Petri nets [Berthomieu91, Lime06] or timed automata [Alur91] , where classes are called regions. Classes are usually defined as constraints on values of variables, and on sojourn time in each class. If the number of classes is finite, standard model checking techniques can be used to verify φ on a finite quotient state space. Otherwise, one can perform random simulation to get symbolic runs, that sample successively classes of states rather than concrete states, to compute transient probabilities, and analyze probabilities of symbolic runs satisfying φ. For both techniques, verification is done on an **abstract model**, i.e. a quotient transition system which states are state classes.

There are several difficulties to achieve this objective on transport network models. One of them is to ensure that the models used to represent transport networks allows for an effective analysis. In practice, this means that one can effectively **sample a successor class** from a given state class, and associate a probability to this symbolic transition. In general, when modeling cyber-physical systems with noise, one cannot guarantee that the abstract model is finitely branching, nor that the time for the occurrence of a particular event (e.g. $x_i > 200$) yields a finite set of constraints. We have designed simplified models for metro networks [Kecir19] that guarantee effectiveness of the successor relation among state classes. The internship will first build on this model, but will also investigate other physical models of vehicles allowing for an effective successor relation. The objective here is to find classes that are stable by computation of a successor, and for which this calculus can be performed in polynomial time, to keep good performance of SMC.

A second difficulty is the evaluation of the truth of a property. On a concrete run, one can use a formula written for instance with a **quantitative logic** such as Signal LTL [Maler08] to verify both timed and quantitative properties of runs. **Signal LTL** is particularly well adapted to talk about properties of cyber-physical systems, because its formula can address at the same time values of variables and time. Runs are seen as maps associating real valuation of variables to every time point. It has been shown that verifying Signal LTL properties of runs with real values can be brought back to online verification of runs with Boolean signals (see [Maler08] for a complete and intuitive explanation).

Now addressing quantitative properties of symbolic runs is a new challenge. First of all, the notion of class in well adapted to group concrete states, but symbolic runs define (infinite) sets of concrete runs. Evaluation of the probability $P[\varphi]$ calls for refinement of state classes so that

1) the truth value of a property is invariant on the whole symbolic run, and

2) one can compute a probability measure for the set of concrete runs represented by a symbolic run.

In this internship, we will address symbolic online verification of models for transport networks. The internship will start with simple models for metro, where the dynamics of trains is defined as affine functions representing remaining distances of trains to the next station. A simulator for these systems already exists [Mochy20], and statistical model checking of signal LTL for these models with concrete runs sampling is under development. The next step is then to define symbolic runs for these models, that is identify the appropriate set of constraints that allow for the representation of a state class, and define a successor relation on state classes. Last, depending on the obtained results, the internship will address symbolic verification techniques for transport networks, starting with simple reachability properties, and progressing towards a complete bounded verification framework for signal LTL.

Bibliography:

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Requires & appreciated skills:

The candidate should have a strong interest in formal methods, and the ability to read papers with some mathematical material (see [Maler 00] and [Lime 06]) to get an idea of the type of maths & logics that will be used during the internship. Former experience in verification, model checking will be appreciated.