SUBJECT FOR THE INSA-UT PHD PROGRAM OF THE CHINA SCHOLARSHIP COUNCIL

SESSION 2020

Institution: Laboratoire Connaissance et Intelligence Artificielle Distribuées (CIAD), Université de Technologie de Belfort-Montbéliard, France

Title of the subject:

How to simulate large-scale cyber-physical systems with an agent-oriented approach – Application to Smart Cities.

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1. Description of the PhD Subject

1.1 General Context

Microscopic simulation of traffic and crowd behaviors remains a major challenge. In the last decade, many works have been devoted to the study of collective behaviors and their inherent emergent properties such as spontaneous organizations of pedestrians into lines, oscillations at gates, etc. Agent-Based Simulation (ABS) is one of the approaches to support microscopic simulation. Agent-based modeling allows complex behaviors of various interacting entities to emerge from a set of simple individual rules. Phenomena such as flocks of birds, schools of fish, and complex biological systems of cells are good examples of how systems with simple goals can demonstrate complex emergent behaviors as a result of interactions between neighboring agents (local to global). MABS can therefore be regarded as an appropriate approach for pedestrian simulation and the study of associated emergent phenomena.

However, as soon as we consider a microscopic simulation of several individuals and their relationships, the complexity of the system and associated computational costs increase. We are therefore faced a dilemma common in the field of simulation: to manage a compromise between performance and accuracy. Our goal consists in designing a generic agent-based simulation model and a tool that are able to accurately represent phenomenon such as traffic in a time regarded as acceptable for an end-user (on a standard computer) in applications' field such as the smart cities. The main goal is to dynamically adapt the accuracy of the simulation according to the volume of available computational resources.

Solving this issue is not just a problem related to the implementation of the model or the design of the associated simulator. The entire design chain of the simulation is thereby impacted. Before further describing the approach we propose to address this problem, it is necessary to remind some fundamentals on the computer simulation and ABS.

According to Fishwick, computer simulation may be defined as follows: "*Computer simulation is the discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer, and analyzing the execution output*" [Fishwick, 1997]. This definition considers the simulation as an experimental process with three fundamentals phases (see also [Shannon, 1977]). This first approach was then refined by Zeigler et al. in the *Theory of Modeling and Simulation* [Zeigler et al., 2000] which presents the key component of a simulation experiment:

1. The **source system**: the real or virtual environment that we are interested in modeling.
2. The **experimental frame**/context: the conditions under which the system is observed or experimented with.
3. The **model**: a system specification. A set of instructions, rules, equations or constraints for generating system behavior.
4. The **simulator**: computation system capable of executing a model to generate its behavior.
5. The **modeling relation**: relation between a model, a system and an experimental frame. It defines the validity of the model, its ability to faithfully capture the system behavior within the extent demanded by the objective of the simulation study.
6. The **simulation relation**: relation between a simulator and a model. It defines the correctness of the simulator, its ability to correctly simulate the model, to faithfully generate the model's output trajectory given its initial state and its input trajectory.

In the remainder of this document the terms; system or source system, model and simulator will be heard in the sense defined above.

Zeigler's approach raises the fundamentals of the simulation in general. It must be specialized to study specific issues related to MABS. Fabien Michel, in his thesis [Michel, 2004], adopts a multi-view perspective to describe the four fundamental aspects of a MABS:

- **Behaviors**: includes the modeling of the agent's deliberative processes ("*agent mind*").
- **Environment**: defines various physical objects in the simulated world (the situated environment, its structure and the "*bodies*" of the agents) and the endogenous dynamics of the environment (environmental laws).
- **Scheduling**: deals with the modeling of the passage of time and the definition of scheduling rules and policies.
- **Interaction**: concerns the modeling of the result of the actions and interactions at a time t, management of simultaneous actions.

This first description was then extended by Stéphane Galland and Nicolas Gaud to manage issues related to the multilevel agent-based simulation [Galland et al., 2009, Gaud, 2007; Gaud et al., 2007, 2008].

Let's now return to our initial goal: simulate large scale systems in term of partial environment and size of the simulated population. To tackle this problem, we adopt a multilevel perspective transversally to the whole simulation design process: from the source system analysis to the execution of the corresponding model within the appropriate simulator. Indeed, adjusting the complexity of a simulation requires a model that integrates different levels of abstraction and complexity, and that defines transitions between these levels. However, within ABS the model is decomposed into at least three distinct models: Behaviors and Interaction, Environment, Scheduling. Designing a multilevel ABS thus requires the integration of the multilevel perspective within these three kinds of models.

The multilevel approach also impacts the analysis process of the source system. These aspects require a methodology to assist the analysis of the system to extract its different levels of abstraction, and the design of the model. It also requires a collection of adapted concepts to describe a multilevel model. Moreover, the simulator must be capable of executing a multilevel model and adapt dynamically the complexity of this model according to the volume of available computational resources and simulation criteria to focus on.

Providing an effective solution to the described problem therefore requires an integrated approach covering the methodological aspects, the modeling approach and the associated concepts (meta-model), the design of an adapted simulator and finally the deployment and execution of the model on this simulator.

1.2 Aim of the PhD works

This project aims at designing an integrated approach covering the entire design process of a simulation and enabling the creation of a simulation tool able to large scale cyber-physical systems. This tool will then be used to accurately and efficiently simulate large ground and aerial traffic in virtual urban environments and improving the understanding of related spatial dynamics (emergent phenomena).

To address this problem, we propose an approach combining three research axes:

- *Meta-model, models and algorithms*: first, provide a full set of abstractions to analyze a source system and design multilevel models whose accuracy/complexity can be dynamically adjusted according to dynamic constraints. Then, using this meta-model, design multilevel pedestrian, car unmanned aerial vehicle behaviors and understand the laws which govern the interactions between them, and with their virtual environment.
- *Methodology*: develop a specific methodology for analyzing a source system, designing multilevel agent-oriented models and assisting the deployment of these models on the proposed simulator.
- *Deployment and Execution*: design a multi-agent simulator able to execute the previously proposed multilevel models without introducing bias while providing optimal performance. Then optimize this simulator to reduce the computational cost of simulation. On this point, we may exploit the agent-oriented programming language SARL (http://www.sarl.io) and its associated platform (http://www.janusproject.io), and adapt the platform to be runnable on the new computation plat-form (cluster, etc.).

These three axes will lead us to develop a prototype of multilevel multi-agent simulator on which we will deploy examples of ground and aerial traffic simulation in virtual environments. This application will provide support for the validation and a pragmatic evaluation of the simulator and the associated multilevel model of unmanned vehicles such as autonomous vehicles and areal vehicles.
An agent-based model (ABM) is a class of computational models for simulating the actions and interactions of autonomous agents with a view to assessing their effects on the systems as a whole. ABM is now widely used for modeling increasingly complex systems. Application of ABM is not only limited to the computer science domain. Currently, many research areas such as transportation behavior modeling need to analyze and understand the complex phenomenon of interactions between different entities. While traditional modeling tools in transport science may have difficulties to catch

the complexity, ABM can do it through modeling the interaction of autonomous agents and deducing the rules for such a system. We, therefore in this PhD subject, propose to use an agent-based model for simulating traffic on a large area.

2. Scientific Context

2.1 Position of the PhD subject in the works of research team

This thesis is positioned on the research theme of the laboratory CIAD, and their current national and international collaborations. It lays in the continuity of the works in the project RBFC UrbanFly on the simulation of swarms of unmanned aerial vehicles. Moreover, it perfectly fits in our collaboration with the Institute for Research on Transportation (IMOB) of the University of Hasselt in Belgium. Both projects allow us to have a favorable context to undertake the research proposed in this subject.

The integration of this thesis, and its candidate in this context provides strong scientific background directly related with experts from different underlying scientific disciplines: analysis and control of traffic simulation in a virtual environment, planning...

2.4 International Collaborations

- **Transportation Research Institute (IMOB) - Hasselt University.** Wetenschapspark 5 bus 6, 3590 Diepenbeek, Belgium. http://www.uhasselt.be/imob-en
- **Royal Melbourne Institute of Technology** (Australia).

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