Integrated modeling and control platform for urban traffic networks

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Abstract—The paper presents respectively a modeling and a control approach of urban traffic networks, integrated into a software application. These approaches are based on an agent-oriented methodology and have as a goal the possibility of simulating, evaluating and optimizing the traffic in crowded areas, as large cities, using both off line scenario policies and fine tuning scenario control.

Keywords—traffic network, agent, activation profile, congestion

I. INTRODUCTION

One of the most acute problems of large urban agglomerations is the efficient management of their traffic infrastructure. Due to the socio-economical dynamics, it is a fact that the number of cars is increasing at a far greater rate than the road infrastructure, resulting, especially at peak-hours, in traffic congestions that affect the quality of life, in terms of stress, noise, safety and pollution.

These problems can be solved, at a certain level, by political measures and public education, but they also need a technical approach related to the adaptation of urban traffic functioning at real context. More specifically, traffic congestion can and should be avoided, in certain circumstances, by adapting the duration of traffic lights to vehicle flows, this being an approach that necessitates the lowest investments in infrastructure modifications.

Larger investments and different approaches can be justified when the problem becomes insolvable by traffic light control. Literature provides a series of works on modeling ([2] and [8]), simulation ([14]), traffic management, optimisation and control, as well as traffic forecasting ([4]).

Given this context, a primary objective of the research studies presented in this paper is designing methods for adapting phases durations to the traffic conditions in order to prevent congestive traffic states. To test and validate the methods proposed, a simulation software that runs a model of a traffic network has been implemented. The modeling approach chosen is described in section two. Section three presents the simulation software platform, describing its structure and functionality. Section four is dedicated to the traffic light control strategy, together with a case study to test and validate it. Finally, section five synthesizes conclusions and further research directions.

II. THE AGENT-ORIENTED MODELING APPROACH

A. Multi-Agent Modeling Approach

From a systemic perspective, traffic can be seen as that is both complex – large scale, dynamic, nonlinear, time-dependent, with irregular topology, and open – extendable, modularized.

On one hand, designing a management and control solution for such a system requires an open, flexible and versatile architecture that can be easily extended towards a complex solution that integrates multiple dedicated sub-systems such as public transportation priority systems, environment protection management systems, dynamic route guidance systems, etc. On the other hand, it is very difficult, if not impossible, to analyze and control the overall system behavior by exclusively global and formal mathematical models. The complexity and diversity of the traffic related problems impose the necessity of modularity, while the challenging design objectives require integrating intelligence and decisional capabilities within the software solutions towards achieving autonomy and adaptability.

There is a natural way of decomposing a traffic network into two kinds of parts: active elements, as crossroads, that have a definite role in regulating the car flow, and passive elements, as the road segments that are linking active elements and that are only physical parameters of the system. Based on this decomposition it can be easily imagined an agent oriented modeling & control approach based on networking control agents that are managing active elements. Such an agent can control the duration and the succession of traffic lights, which it has to calculate and adapt to the car flow on input roads of the crossroad.

This paper presents an agent-oriented modeling approach that is based on the concept of activation profile of the light phases for a given crossroad, as detailed in [1]. Using this agent-based virtualization a distributed traffic control scheme can be built, which is both scalable and flexible.

Modular models of crossroads can be easily encapsulated into collaborating software agents that will reproduce the metropolitan network at the level of the communication paths established among them. Such agents are enabled with a certain degree of intelligence and cooperate in order to reach an optimum traffic state.
We have chosen a dual modelling approach for the crossroads – using both Hybrid Petri Nets and continuous equations as two equivalent types of models. A library of such models has been designed containing various types of crossroads in the traffic network which can be used within the internal representation of the world by junction agents. The extensive description of these models can be seen in [14].

Every crossroad can be modeled broadly by a structural part and by a parametric one.

The structural part, almost completely unchangeable, is linked to the number and configuration of input/output roads, their respective capacity (in terms of standard vehicles) and the structure of light phases – this last one being usually established for long term and changed only if proven necessary – which reflects the order in which lights are synchronized.

The parametric part consists in the (measured) input car flow and in the durations of light phases and respectively of a whole light cycle. Durations of light phases are actually controlled by crossroad agents, so as to be adapted to the car flow and to avoid congestions and traffic jams. “Congestion” is a term that defines the situation in which the capacity of a road is overflowed due to a red light to its output and a green one to its input, thus blocking the functioning of a crossroad (Fig. 1).

Figure 1. Illustration of a congested crossroad

Figure 2 represents an activation profile for a crossroad of five phases (i.e. five lights) and total light cycle duration of 130 seconds. Green light corresponds to a value of 1, while red corresponds to a value of 0 (yellow light is considered to be included in the green light time).

For every input and/or output segment of a crossroad are defined their maximal capacities, based on the physical structure of the roads. The state of such a segment is defining basically three working regimes for a crossroad agent (Fig. 3):

- **Safe zone regime**: the length of the car queue does not exceed a pre-defined (lower) warning limit when red light at the segment output; then the agent will not change its control parameters;

- **Warning zone regime**: if the car queue length is between the lower and the higher warning limits, then the agent will try to modify the parameters of its functioning scenario (fine tuning) with respect to the duration of light phases. The activation profile will not be changed, and the durations will be changed only between pre-defined limits. It is considered that an “acceptable” evolution is obtained, if the trend of the car queue length is changed.

- **Critical zone regime**: if car queue length exceeds the higher warning limit, another functioning scenario is directly selected – the activation profile is changed; sometimes even from the point of view of light phase number.

It is easy to remark that every agent is concentrated on its own objective – avoiding congestion for “its own” crossroad, so as the functioning of such a system could not allow even to define optimization criteria.

This is the reason for traffic management and control architecture that will be presented in the following will have several control layers.

**B. The Proposed Traffic Management and Control Architecture**

Figure 4 presents the overall structure of the proposed traffic management and control architecture, with three multi-agent layers.

The bottom layer is composed by junction agents, whose functioning and implementation is based on the considerations previously described. They will use offline, simulation-based, predefined control scenarios, as described before, and will communicate horizontally with pair agents that are controlling physically adjacent crossroads. This layer is able to ensure the
Figure 4. Architecture of the traffic management and control system

proper functioning for safe zone and warning zone regimes described above and also, in the case on vertical communication break-downs, a degraded functioning for the critical zone regime.

The vertical communication is with another type of agents – the zone supervisors. A zone supervisor is an agent that coordinates the functioning of a physical traffic sub-network, mediating the conflicts between junction agents and furnishing them with appropriate basic scenarios for the warning zone regime and for the critical zone regime.

They can ensure an optimal functioning regime in terms of maximal car flow in their supervised area, basically using Genetic Algorithms and fuzzy control approaches, as it will be described in section IV.

The horizontal communication that takes place between junction agents, respectively zonal supervisors aims towards proper functioning of the structure and prevention of the cases when the optimum functioning regime of an entity leads to congestion in another region.

Finally, a higher level supervisory agent is coordinating zone supervisors, basically establishing, for critical functioning regimes that cannot be solved otherwise, degraded functioning regimes with preferential routes.

Zone supervisors are also dealing with priority vehicles, as the higher level supervisor will solve problems related to grave accidents or infrastructure modifications.

III. THE SOFTWARE PLATFORM: STRUCTURE AND FUNCTIONALITY

A software platform has been implemented to test the multi-agent approach under the hierarchical architecture proposed in Section 2. The simulation platform allows the simulation and analysis of the behavior of a region in the urban traffic infrastructure, where crossroads are managed and controlled by lower level agents coordinated by zonal supervisors.

The simulator was implemented in Java using agent programming concepts combined with classical object programming. The multi-agent system was created using the JADE infrastructure which offers specific facilities for agent creation and agent interaction. The concepts of Junction, Input, Output, LightPhase, etc. were modeled as OOP classes, which are integrated within the agent’s world model.

The traffic region is transposed into a community of agents, of which several junction agents each monitoring and controlling a junction and a supervisor that runs optimization algorithms and coordinates the lower level agents. Initial values of the attributes are supplied by the user via the graphical interface, or derived by simple calculus for available data.

The graphical user interface allows the user to select the type of junction from a library of junction models and guides him/her through the application flow, from data acquisition to running the simulation and visualizing results.

The user defined junction connections are automatically replicated within the agent system as connection between the corresponding junction agents. Figure 5 presents a snapshot of the junctions in a traffic region defined in the simulation platform, while Figure 6 presents a plot for visualizing the variation of the waiting queues of a junction against time during while the simulation is running.

Preliminary studies of urban traffic regions simulations using the simulation platform confirm the adequacy of the multi-agent approach for the modeling and simulation of
complex, large scale systems. The implicit modularity obtained by the multi-agent implementation allows a functional decomposition leading to a reduction of complexity without loss of generality. The autonomous functioning of each unit combined with communication among working units results in a complex, emergent behavior of the overall system which could have hardly been modeled otherwise.

IV. TRAFFIC MANAGEMENT AND CONTROL

Urban traffic control in large cities is still an open problem for the research community. Because of the time-variability, non-linearity and uncertainties characterizing the traffic system it is difficult to design high performance control solutions using traditional methods. A constrained optimization problem over a city-wide traffic network is very difficult to solve and may not have a solution.

Given the complexity and the particularities of urban traffic control and optimization problems, the latest research efforts in the area of traffic control are directed towards the use of artificial intelligence methods. Intelligent techniques approaches have been successfully applied to traffic control problems, such as rule-based systems for predefined plan selection ([6]), fuzzy rules control systems ([3]), neural networks ([7],[11]), or neuro-fuzzy systems ([15]), cellular automata modeling and evolutionary algorithms optimization ([9],[10] and [13]).

The decentralized approach presented in Section 2 transforms the congestion prevention problem into a green light timings optimization problem decomposed in multiple sub-problems which can be solved at each layer in the hierarchy of control.

Local congestion prevention mechanisms implemented by junction agents may ensure satisfactory performance when the traffic load is not critical. They also provide a reasonable alternative when the bottom layer becomes disconnected from superior command in the event of whatever system or communication failure.

The junction agents on the bottom layer work in the timeframe of the real traffic environment, therefore their congestion prevention mechanisms must be based on fast response, direct methods derived from current measurements only.

However, such local congestion prevention mechanism does not guarantee globality due to lack of spatial and temporal perspective. Therefore, to optimize for global performances, the implementation of a supervisor level is needed which will monitor, synchronize and coordinate a group of junction agents in a given subregion.

The zonal supervisor works on a larger timescale, implementing strategies to serve two main objectives:

- regional statistic estimation and prediction planning for zonal optimization;
- conflict resolution if mutual agreement on green light timings ([11]) fails between any two junction agents on the bottom layer.

We have chosen genetic optimization in order to achieve zonal congestion prevention taking into account multiple (or all) junctions in the area of interest. The optimization variables are the green phase timing lengths for all junctions of interest. The total light phase duration is also an optimization variable, aiming towards a balanced traffic flow across the region.

The optimality of a solution is evaluated in terms of minimizing the weighted average of the waiting queue lengths on all road segments entering the junctions.

Considering that queue lengths ($N_{ik}$ in vehicles) are given by equation (1) for each of the inputs of the junction, the fitness of an individual is inversely proportional to the weighted average of all $N_{ik}$ where the optimizing variables are $t_{phl}$ and $T_{tot}$ under inequality restriction (2).

\[ N_{ik} = N_{ik} + \sum_{l=1}^{p} \sum_{j=1}^{m} ph_j(t_{ph}) \cdot w\cdot \Delta t, k = \frac{1}{n} \]

\[ N_{ik} \leq 0.01 \cdot c^\text{warning} \cdot c_k, k = \frac{1}{n} \]

where:

- $I = \{ i_k \mid k = \frac{1}{n} \}$, $n = \text{Card}(I)$ is the set of junction inputs (entry road segment);
- $vph = \{ ph_j = f(t) \mid l = \frac{1}{n}, p; f : [0, T_{tot} ] \rightarrow \{0,1\} \}$ is the set of light phases characterized by an activation profile (as presented in Figure 2) over the total duration $T_{tot}$ of a light cycle;
- $w_{ik}$ is the vehicle passing rate in [veh./min.] associated to the direction $i_k \rightarrow output_j$ for $j=1,m$
- $\Delta t$ is the time step of the simulation.
- $c^\text{warning}$ is a “warning zone” limit indicator expressed as percent of the input link capacity, $c_{ls}$, both attributes of $i_k$

Communication between the layer of junction agents and the zonal supervisors layer is bidirectional. The best solution obtained by the zonal supervisor running the GA is communicated to the bottom layer junction agents and applied in traffic, while data acquired from traffic is sent to upper layers to be used for prediction and planning.

In this case we implemented prediction and planning by using real traffic data received from the junction agents and stored as traffic history over a period of one month (data used was from October 1st to October 31st of 2009). These data are preprocessed in order to be used as model inputs for simulating over one hour in the future to obtain a forecast of the network behavior. Preprocessing implies various statistic operations on the data in order to derive the most relevant inputs according to the time of day and day of the week. These data manipulations ensure that our simulations take into account traffic load variations such as daytime vs. nighttime traffic, work shifts:
morning time vs. evening, working days vs. weekends and holidays.

As a case study, we have chosen an urban area of three interconnected junctions located in the center of Bucharest, as depicted in Figure 7. Under current traffic conditions and green light phase timings this small area is prone to developing congestive traffic states.

The genetic algorithm was run with the following options:

- the default type double for chromosomes, within a certain lower bound and upper bound \([lb, ub]\) derived from the time limits imposed on each phase;
- population size of 15 chromozomes;
- a maximum number of 15 generations as a stopping criterion or a maximum of 7 stall generations;
- stochastic uniform selection function;
- adaptive feasible mutation, which randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation.

Simulation results over the time-span of an hour are presented in Figures 8 a, b, and c. As can be seen, all input queues remain consistently below a certain threshold considered as a percentual limit of the total road segment capacity (marked by a red horizontal line in all Figures).

The computational and temporal requirements to reaching a solution by genetic algorithms need also to be taken into consideration to verify the feasibility of the implementation in the real traffic environment. The simulations presented above were done on a machine with an Intel Core2 Duo CPU at 2.6GHz. The total runtime time was slightly below the timespan of the simulations with possible overhead due to other Windows processes running. Also, further code optimization may be possible.

V. CONCLUSIONS AND FUTURE RESEARCH

In the case of junction agents, fuzzy logic is a powerful tool for processing nondeterministic and non-linear problems, such as that of adjusting green light timings according to the conditions of traffic observed at any given moment. Traffic control is generally expressed by rules, which makes fuzzy
rule-based signal control a plausible choice for exploring in the near future.

Membership functions are defined for crossroad lane queue lengths using fuzzy terms such as “long-queue”, “short-queue”. More green time is allocated for a lane if there are many vehicles arriving in, and less green time otherwise.

A second research objective is to study methods for reducing the runtime of the genetic algorithm in finding a solution, since time is a critical issue for the problem of congestion prevention. The most time consuming element in running a genetic algorithm optimization, is evaluating the fitness function at each step. One possible means towards achieving this objective is adopting a hybrid solution in conjunction with artificial neural networks (ANNs) ([5]). The next step in our research is the offline training of a neural network model for the urban area under consideration which will then be used in evaluating the chromosomes produced by the GA. To ensure more accuracy for the ANN model of a traffic area a library of such models may be built to take into consideration traffic load variations.

We also intend to use in the future the NCIT-Cluster, a high performance computing cluster infrastructure available at the Politehnica University of Bucharest to test the distributed implementation presented above.

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