POLITEHNICA UNIVERISTY OF BUCHAREST

PHD THESIS SUMMARY

Intelligent transport systems for the efficency of urban mobility

Celestin Domițian DRĂGĂNESCU

PhD supervisor: Prof.dr.ing. Aurelian Mihai STĂNESCU

BUCHAREST

2023

The doctoral thesis makes contributions in a field in permanent evolution and improvement, that of Intelligent Transport Systems (SIT), with direct application in the area of urban car traffic. In this sense, it was considered that traffic efficiency depends on the interaction of three factors: the human factor, who is the decision-maker, and who benefits from the assistance of a decision support system, the environmental factor, which is expressed through a context-sensitive system in which priority is given by sensory information and the pragmatic factor of effective vehicle driving and traffic optimization. The doctoral thesis has a chapter dedicated to the analysis of each of the 3 factors, bringing to the fore both the materials used in the analysis (the modeling/simulation framework, user interface elements) and the methods proposed to achieve the objectives. The main original results are: the construction of a framework model for an adaptive SIT that is context sensitive; the solution for embedding vehicular networks (RV) in the structure of hierarchical information networks through the Internet of Vehicles (IoV), which includes a procedure for minimizing the average response delay to service requests in the RV; development of a dedicated framework for the management of context-sensitive generic intelligent transport systems, customized by a context-aware communication procedure for collision avoidance; design and implementation of a decision support system for solving communication problems associated with traffic management in RVs with autonomous vehicles (VA); developing an agent-oriented model for predicting location and waiting times for an urban bus route; implementation of a platform that enables the provision of smartphone-based travel services, leveraging the fusion of two data sets: the user's GPS trajectories and geo-spatial context data obtained through OpenStreetMap (OSM). All these results have been verified and validated through case studies,

Chapter 1, dedicated to the analysis of the current state of the research, offers a selective analysis of some recent works that highlighted specific problems and dedicated tools that could be compared with the solutions adopted by me in the elaboration of the thesis, with a clear indication of the similarities and differences between these solutions and of course the new elements introduced in the thesis. When I chose to use a solution, I specified to what extent my approach brought something new, if not necessarily an improvement, at least as a way of working. The analyzed papers were grouped into two categories: i) Theoretical and methodological approaches, where the emphasis was placed on papers presenting new directions in modeling and simulation, and ii) Specific applications based on SIT, where the emphasis was placed on papers regarding the management of vehicle networks.

Chapter 2, corresponding to the title: Design and development methodological framework for SIT, is dedicated to the creation of a design/development environment that allows the modeling of data acquisition and processing processes and the design of modules with distinct functionalities that ensure the combination of the three essential components of the systems transport: road infrastructure, vehicles and users (human factor). The essential objective of operating in this framework was to ensure the SIT's ability to react (by adaptation) to unforeseen changes that occur in the environment, through what we called adaptability to context changes. This objective – sensitive (or conscious) adaptation to the context – was a leit-motif in the elaboration of the thesis, every solution, method, procedure or device representing the author's contributions having a direct relation to this concept. As such, the main novelty of this chapter lies in the construction of a framework model for an adaptive SIT that is context-sensitive, i.e. we have developed constructive solutions whereby the basic framework model has been adjusted to fit the particular case of context-aware adaptation. context. The adaptive framework was designed to plan the system tasks from the beginning, so that if the existing resources allow, the system will allocate predefined adaptive tasks, with the mention that the newly arrived tasks, adjusted along the way, will have lower priorities than the functionally defined ones initial. The basic framework model was then populated with specific behavioral models as follows: i) Road network generation model; ii) Traffic generation model; iii) The driving model (piloting) with keeping the safety distance; iv) Intersection coordination model; v) Visualization model (video frames); vi) Communication model (Vehicle to Vehicle V2V and Vehicle to Any V2X); vii) Braking pattern. All these models were validated by simulation, and the results were disseminated through two papers, the first published during the thesis development stage: [Dra17] and [Tun17]

A second original approach in this chapter was to adjust the basic framework so that it can be configured as an interactive development framework for intelligent cyber-physical transportation systems (SITCF). The purpose of this approach was to allow the introduction of the human factor as an active element of the decision-making process, capable of carrying out real-time interactions, in which all the hardware and software components that cooperate to achieve the objectives are involved. Such systems can be said to be Cooperative Intelligent Transport Systems (SIT-C) that allow vehicles to interact with each other, road infrastructure and users through wireless (digital) connectivity technology. Specifically, components with specific functionalities were designed, among which I mention: i) the user component; ii) traffic flow management component; iii) the leadership management component and iv) the interaction component. In order to validate the solutions proposed for the SITCF design, it would have been necessary to develop a functional model, which unfortunately was not realized. However, based on the design principles of cyber-physical components, a method of using interoperability to avoid conflicts between information obtained from different digital maps has been developed and validated. More precisely, the method allows the correction of errors due to semantic heterogeneity, i.e. differences in the meaning of the information contained in the model. The results regarding the validation of the method were published in [Dra19]..

Chapter 3 deals with how to improve the management of a mixed population of vehicles equipped with different levels of automation, which constitute a heterogeneous network with moving nodes, called a vehicular network (RV). Vehicular networks represent the future in road transport, being the only way to take over the technological advance imposed by Information and Communication Technology and Artificial Intelligence. My contributions in this field have been rather modest, primarily due to lack of communication training. I decided to focus on two directions. The first concerns the integration of practical solutions based on existing standards, which can be associated with the concept of context awareness, very rarely described in the literature, but, as I said before, a line of strength of my research for the thesis. The second refers to the signaling of developments for the future, which can exploit the evolution of new emerging technologies.

The original solutions in the first category relate directly to that distinct subdivision of the IoT called the Internet of Vehicles (IoV), and have been validated by simulation on the adaptive framework model developed by me and described in Chapter 2. In this sense I have presented both potential solutions (already validated or in the process of validation) of embedding the RV in the structure of hierarchical information networks, but also a vision of improving the management and operation performance of the SIT through the prism of integration in the IoV. The main contribution was a method for optimizing message dissemination, which we called the cashing broadcast strategy. Caching strategies have been used in VR, so the original part of the research refers to an improvement of an optimization solution proposed in [Hua21], through which we introduced the concept of delay-aware content and we have developed an algorithm that simultaneously streamlines the transmission of V2V and V2I messages. The improvement proposed in the thesis considers the decomposition of the optimization problem into two suboptimal problems, namely the optimization of vehicle associations and the optimization of content caching decisions [Dra21b]. Based on these considerations, an optimization algorithm for the cache storage procedure is proposed, hereafter referred to as the Cache Optimization Algorithm

(AOC), which solves two objectives: the optimization of the delay-sensitive association of vehicles and the optimization of caching decisions according to content.

The second significant contribution of this section aims at improving the efficiency in the control of vehicular networks by associating the new concept of Edge Intelligence with the way of describing vehicular networks through distributed dynamic network models. Then, these elements are used to develop a procedure for optimizing the provision of services in vehicular networks, the result of which is to minimize the delay of the response to the service request made by a component vehicle of the RV by jointly optimizing the caching of the service, the scheduling requests and resource allocation. I mention that the analysis of vehicular networks as dynamic distributed networks was a task undertaken by participating in a research collective in the Department of Automation and Industrial Informatics, and my goal was to demonstrate how RV can be formalized as a dynamic distributed network (RDD) , and then the validity of the solution will be exemplified by concrete applications carried out with the help of Edge Intelligence techniques. The obtained results were materialized by the development of a consensus-based algorithm for establishing the decision in RDD, which I can consider my main theoretical contribution (if not the only one) to this thesis. The novelty lies in the fact that we used the idea of distributed consensus with an essential change, in the sense that the network nodes were considered as agents of a multi-agent system operating in the intervals in which the decision to insert or remove a node has to be made, and then configure the network topology for the new instance. Such constraints can be encoded in the consensus dynamics by saturating the values that an agent transmits to neighboring nodes.

I wanted to integrate the results of my research into a multi-objective optimization program that simultaneously targets three targets: service cache (through the AOC algorithm), service request scheduling, and resource allocation strategies. For the last two problems, decisions were to be made by consensus according to the algorithm described in the previous section, hereafter called the Management Optimization Algorithm (AOM). The results of this approach were synthesized in a Procedure for Minimizing the Average Response Delay to Service Requests in a Vehicular Network, but the solution was not published because it is not complete, because: i) it does not include mobility aspects of vehicles; ii) optimization algorithms were treated separately, there is no (not tested) global algorithm to solve a multi-objective optimization problem. However, the delay minimization procedure was implemented in the application that is the subject of case study 6.1.

Regarding the contributions in the second category, those aimed at compatibility with the short-term evolution of some emerging technologies, we started from the current situation in which the evolution of IoV, both from the point of view of dimensional development and the way in which it keeps pace with technological progress, the evolution of IoT will follow in full, primarily of its relation to the Edge Computing (EC) and Fog Computing (FC) paradigms. In response to the huge volume of data transferred over networks, EC and FC have emerged as distinct information layers in a hierarchical network structure where the lower layer is IoT and the upper layer is Cloud Computing (CC), which enable the distribution of computing and storage to the edge of the network to migrate some of the processing power from centralized cloud servers to distributed LAN resources. As such, we have studied how the IoV will expand on the support provided by Big Data technology, starting from the theoretical and methodological foundation of exploratory data analysis, defined by the acronym BDA (Big Data Analytics). There are many arguments that support such an evolution, but of these two seem essential to me. First of all, the volume of data transferred in vehicular networks will continue to increase, as the number of fully autonomous vehicles will reach values unimaginable today. Second, the fact that BDA technology is evolving at the pace in which Artificial Intelligence techniques are developing, thus strengthening its status as the dominant technology of the future. Based on this study, we considered the future development of an IoV variant called cognitive IoV and proposed a pervasive middleware architecture for independent SIT integration that can solve all EC-level interaction problems within three sub-networks in RV, namely the network the intra-vehicle, the inter-vehicle network and the beyond-vehicle network, after which we proposed the development of a dedicated framework for the management of generic Context-Aware Intelligent Transport (CAIT) systems, which we made known through publication of the work [Dra19].

Chapter 4, titled Uncertainty and Risk Management in SIT, is oriented towards finding solutions for situations that go beyond the current state of SIT, being intended to deal with the conditions in which road traffic will develop in the future, mainly with autonomous vehicles. And this chapter has two sections, one dedicated to risk, the other to uncertainties. The first section is based on different risk management models, which can be integrated and described in a wider unifying framework of global risk analysis, for which the main objective is to design a decision support system capable of dealing with complex situations that they have a fast-changing and hard-to-predict dynamic. The complexity of decision-making for a large system like IoV requires new tools and methodologies for modeling and decision-making, which is why I decided to use agent-oriented modeling (MOA) as a recommended solution for distributed dynamic systems, which also allows leveraging some techniques of IA. The experimental results demonstrated the applicability of the MOA approach for road traffic screening and coordination in vehicular networks with IoV communication support. The main advantage is that MOA provides the means to model each agent and its relationships within the system and in addition, the model is scalable, i.e. it can be extended to situations with heavy urban traffic. The flexibility of the MOA approach allows for a seamless reconfiguration of the network and indicates adaptability for changes imposed by RV evolution.

The model we proposed has a number of limitations, because in the desire to test a simple model, we neglected a number of factors that normally affect the behavior of the system (not using a high-performance communication protocol adapted to high transmission speeds , limiting the number of sources of interference, lack of a mechanism for managing old (historical) information However, the algorithm we proposed for Intersection Control based on an Agent Oriented Model (CI_MOA) proved its efficiency in the case of the application implemented for Case Study 6.2 (but only validated by simulation), called Context-Aware Communication for Collision Avoidance This application manages how to send and receive messages announcing a possible collision so that the vehicle has enough time to come to a complete stop before reaching the point of possible collision The purpose of application requirement definition is to control in communication parameters accordingly, so that drivers/vehicles are alerted in time if a risk of collision is detected. Obviously, the application must first recognize the presence of other vehicles, and therefore the application requirement must be defined only based on the vehicle's own information and environmental information. If we assume that the collision avoidance application works in a vehicular network with V2V communication, we will first need to model the PC collision probability of a vehicle approaching an intersection. So that PC can be exploited directly by the communication system, I proposed that it be converted into a performance indicator specific to the communication system, which I chose to be the minimum packet delivery ratio (Packet Delivery Ratio - PDR).

The second section of this chapter is called Decision Making under Uncertainty and is dedicated to solutions designed to combat the effects of unexpected and uncontrolled changes that may occur in the environment. The main objective was to design and implement a decision support system that provides support for solving communication problems associated with road traffic management for RVs where the connected vehicles are considered to be autonomous vehicles (VA) with a driver, which are interconnected through IoV in a network of autonomous agents that interact with each other and at the same time are able to receive information from a complex environment. The proposed solution is based on a relatively new principle regarding the treatment of uncertainties, that of antifragility, taken from the materials made available within the already mentioned research group in the Department of Automation and Industrial Informatics, of which I was a part during the thesis development. My contribution consisted in the antifragile design of a context-aware adaptive control system capable of improving its performance under adverse and stressful conditions, i.e. having the property of self-improving and therefore named Antifragile Self-Improving System (ASIS). The proposed design methodology shows how an ASIS can be integrated into the structure of a SIT and how it contributes to increasing performance. To validate the solution we used an original test procedure based on the injection of corrupted and false data to introduce faults into the steering system during real-time vehicle operation. The test was carried out in a completely virtual environment that allows the simulation of the behavior of the active safety system in traffic based on a virtual adaptive model (in the MATLAB environment) with a predictive control structure (MPC) - Model Predictive Control). As such, we developed an adaptive MPC model to simulate the longitudinal and lateral motion of the vehicle.

The final contribution presented in this chapter is a solution to Coping with Uncertainties in Public Transport Planning, which was used in the application presented in Case Study 6.1, called Developing an Agent-Oriented Model for Predicting Location and Waiting Times for a Route of bus (MOA_BUS). I briefly summarize the ideas that were the basis of the implementation of MOA-BUS: i) Based on measurements carried out along a route in different traffic, hour, or weather conditions, a hypothetical model is generated, preferably as close as possible to reality, which we call BUSi; ii) This model stores part of the data acquired in previous scenarios (called historical data), but it is able to supplement it with synthetic data acquired during the bus movement on the current route; iii) Based on a calibration procedure, all synthetic data allow the development of a real-time updated model, called BUSc. This calibrated model is a static pattern (that is, it has a fixed number of states that are unchanged over time), but which allow configuration by assimilating new data both deterministically and randomly (stochastically).

It can be stated that we have achieved an integrated framework to reduce the uncertainty in running a MOA model when making real-time predictions by combining parameter calibration and data assimilation. Numerical experiments have shown that this framework provides more accurate predictions than a baseline scenario (without parameter calibration) than a scenario with parameter calibration but without data assimilation. In its current form, the framework can provide real-time information systems regarding a bus's location and arrival times at passenger stations. A model-based prediction of bus location and arrival time allows bus operators the ability to assess and update their transport infrastructures in real time. Although the simulation model is relatively simple it is able to recreate some of the important features of the bus system, such as scheduling, bus crowding and responses to dynamic passenger demand.

Chapter 5 was designed as an opening to the future of using SIT in conjunction with various emerging technologies. This time the focus is on the exploitation of some results (model, algorithm, method) described in the previous chapters, but not as definitive solutions, but rather as suggestions for use in the most judicious way. These "perspective" contributions did not have the chance to be published - both because they were formulated in the last stage of writing the thesis, and because they did not have enough consistency, but most of them were the basis of implementations highlighted in the two studies of case.

In the following I will review the ones that I am sure can find use in concrete applications in the not too distant future. However, I emphasize that I have selected those that are directly related to the two essential characteristics of SIT that I had in mind in the thesis, namely highlighting the ability to be aware of the context and, respectively, the way to integrate the human factor in management automated mixed urban traffic, with an emphasis on capitalizing on the pilot's experience in establishing the optimal ratio between human and automatic control.

1. Integration of the human factor in the automated driving of mixed urban traffic

Both through regulatory instruments and through the results of recent research, recommendations and principles of conduct have been formulated to ensure a collaborative activity regarding mixed road traffic, known under the acronym CAD (Cooperative and Automated Driving). My contribution to this field is also a suite of recommendations in applying a concept I have called Human Factor Intervention (IFU) to explicitly include human intentions and motives in addressing control problems that have been partially or even deviated entirely from a human driver to a technological system. These recommendations have been put into practice through an example of IFU integration in a control application. The use case considers the interaction between a vehicle with at least level 4 automation and a bicyclist traveling in the same direction on a two-way urban road. The example demonstrated that the IFU can be a first mathematical basis of how the essential components of the control system can be operationalized for analysis and design in real cases. I believe that the most important contribution of IFU lies in the extension of the classical type of control for a wider traffic environment, including the consideration of the essential entities: the driver, the vehicle, the infrastructure and the traffic environment, human behavior and reported moral standards to traffic safety. Second, IFU provides expertise for solving critical situations due to unpredictable events, because each solved situation is recorded and increases the accumulated knowledge. Finally, the IFU has the capacity for self-improvement, ensured not only by increasing the quality of reasoning through successive iterations, but also by the fact that human values are explicitly taken into account within the intelligent control system.

2. Capitalizing on the logistic support of IoT in the optimization of urban traffic

In order to make the most of all the facilities offered by IoT in intelligent traffic management, we proposed a structure of the dispatching system that includes: the integrated management of traffic information, the control system of warning signals and traffic lights, the communication system with the traffic police and public transport service system. Integrated traffic information management is the level of real-time use of data collected from traffic, and is realized by providing reasonable travel suggestions for travelers in combination with theoretical traffic planning models. The signal control system takes data from the road infrastructure and information about traffic congestion and provides indications and warnings aimed at bringing traffic flow to a reasonable level. The information communicated by the police headquarters refers to traffic emergencies, unforeseen events and untimely changes on certain road sections and takes appropriate measures to reduce the impact caused by these traffic events. The public transport service system allows travelers to determine the travel route, choose the most convenient mode of transport and thus optimize their travel activities.

3. Designing a cyber-physical-social system for intelligent transport

We started from the observation that most research related to the use of CPS in various industrial fields still focuses on the complexity of the engineering elements and ignores the social complexity of CPS. To compensate for this deficiency, we proposed a complex structure called a cyber-physical-social system (CPSS) which is constituted by a physical (material) system and a social system (which includes the human factor), and a cyber system that connects them on both. We validated this self-designed structure through a case study (proof of concept) regarding the use of CPSS in an IoV-based application. The application leverages V2V, V2I and V2X communication technologies to improve traffic safety and efficiency in vehicular networks by accessing transportation cloud services with CPSS extensions so that the intelligent driving system can include a wide range of new applications that express people's transportation needs and other social information simultaneously with improving the vehicle's level of autonomy. The human factor is represented by behavioral analysis (especially personal travel style) and how to obtain information from mobile navigation devices.

4. Use of Digital Twin for routing in software-defined vehicle networks

In some recent papers (2021) I came across the concept of Software-Defined Vehicular Network (SDVN) in relation to the relationship of RV with the environment (context), and I thought I could propose SDVN for the construction and application of new context-sensitive network schemes that provide advantages in data collection, prediction, verification and validation operations, but at the same time can validate these operations prior to actual execution in the physical environment based on a simulation in the environment Digital Twin (DT). In this way I tried to use the knowledge gained by participating in the CIDSACTEH complex project, and to propose a solution of SDVN type, on a simple example of intelligent choice of vehicle routes. Specifically, the SDVN application can be run in the DT simulated environment before being launched into real-time processing, and the procedure that allows the combination of the two technologies has been named DT-SDVN. The example (also a proof of concept) consisted of comparing a conventional variant of a temporal graph-based routing algorithm with the new variant using DT, to show the improvement in RV quality as a result of the recursive interaction between the physical component and the virtual of DT-SDVN.5. Servicii de transport inteligent bazate pe smartphones.

The starting point was the implementation of an SBTS platform, which allows the provision of Smartphone-based Travel Surveys (SBTS). Technology (or more correctly technologies) related to smartphones represents the most dynamic area of ICT development. It is difficult to say if and when the evolution in the field of smartphone technology will stop, but it can be said with certainty that the applications considered at the level of 2020, focused on the exploitation of an SBTS platform, are already outdated in complexity at this moment. Access to huge databases brings new challenges in terms of speeding up calculations, optimizing storage space, extending communications. I explained that I succeeded, by integrating the knowledge gained in the "collaborative" research of a group of PhD students, a particular original application that ensures the fusion of GPS and GIS with a multidimensional tensor, which I then put into practice in the Case Study 6.2. The fusion procedure is based on two data sets: the user's GPS trajectories and the geo-spatial context data obtained through OpenStreetMap (OSM). It is important that the two data sets cover the same interval both spatially and temporally, and the solution we proposed ensures the description of the spatial context by the OSM data in the same time interval in which the users generated their trajectories.

6. Optimizing intelligent urban traffic management systems using artificial intelligence

Some considerations regarding the use of AI techniques are presented in some directions where these techniques can be exploited with maximum efficiency, especially I had the intention to use them in Case Study 6.2, in case I would have transposed the application validated by simulation into a case of real traffic. Briefly, these directions are: i) Integrating BDA into a road traffic management system; ii) AI techniques for data aggregation in simulation environments; iii) AI techniques for developing and using predictive models.