Autonomic Systems

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Autonomic Road Transport Support Systems

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Autonomic Road Transport Support Systems: An Introduction

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1 Motivation and Challenges

One of the most persistent problems that plague modern-day road transport facilities is the quality of service provided. Especially during rush hours, this expensive infrastructure does not operate at capacity nor does it provide the level of service required by its users. Congestion has become a problem with severe economic and environmental repercussions. Hence, efficient road traffic management is more important than ever.

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Despite the fact that a lot of research has been conducted in this field and, more importantly, huge amounts of money have been invested in hardware, communication and software systems, the average traffic conditions are still far from the desired level. In fact, a paradox can be observed: Although very good and well-designed methods are reported in the academic literature, a persistent theory-practice gap appears [1]. Methods that are reported to perform well in simulated environments do not often translate to a realistic deployment, thereby limiting benefits to the potential and not the actual.

There are many reasons for this situation. Administrative inertia and institutional conflicts is one, but as the need for more and more efficient systems increases so does the pressure on network operators to become more efficient.

The theory-practice gap, however, is mainly due to the complex nature of the traffic phenomena and the associated decision-making problems road operators are faced with. The traffic flow complexity can be attributed to the erratic nature of the collective outcome of thousands of individual driving decisions and the random occurrence of capacity-reducing events. For network operators, this is compounded by the rules, regulations and policies they are bounded to and by the complex methods/tools used to support decision-making within a Traffic Control Centre (TCC).

TCC operators receive copious information from a diverse set of resources, and therefore it is not an understatement to claim that they suffer from information overload. The decision-making problems encountered when viewed in their totality are beyond the human capability to solve efficiently. Even if highly efficient (at least in simulation) methods are applied, the operators still face a problem of understanding them. Highly efficient algorithms come at the cost of design and development sophistication, which is beyond the reach of the normal operator. This effect is compounded by the deployment of vehicle automation systems that are becoming available. From various on-board devices to driverless vehicles, a new type of driver-vehicle-infrastructure system emerges.

The background that these developments are based on is the communication network capability of various agents involved in the traffic flow process. As communication technology becomes more advanced and higher channel capacity and bandwidth become available, traffic management system architectures can be realised in an ever-increasing variety of centralised/de-centralised notions. This allows the design and development of systems with a high degree of intelligence embedded within them capable of displaying highly sophisticated behaviour.

Hence, there is a *need* for intelligent, automated assistance to deal with the complexity of traffic management, while at the same time the technical platform *exists* to support such a capability. But what form should this assistance take? This leads us to the notion of autonomic computing as introduced in the following and from there to the field of *Autonomic Road Transport Support* (ARTS) Systems, which are the topic of this volume.

2 Autonomic Computing

A system that carries out a process by itself, without human intervention, can be said to be automatic. Generally humans create the automatic process to achieve certain goals, though the system is not usually explicitly aware of what its goals are. For example, a thermometer informs people of the room temperature automatically (it happily performs this process over time without anyone intervening), but it has no explicit knowledge of what it is doing.

Nowadays, we have systems that can interact with the outside world and carry out a process involving situations where the system makes decisions itself, based on sense data from a dynamic and unpredictable environment. In other words, the system can sense, interpret the sensed data and use that interpretation to control how the system affects the outside world. We call these systems *autonomous*, and current examples in the transport area are driverless cars and so-called "managed motorway" systems. Generally humans create the autonomous process to achieve certain goals, though the system itself need not be aware of what its goals are or what they mean.

For more intelligent management assistance, it would be desirable if the system embodied some understanding of its own functions. Human operators could then communicate service expectations to the system (such as to keep to certain limits of road congestion or emissions of pollutants), and in response the system would assess its performance against expectations, derive outstanding goals to achieve from this self-assessment, and plan how to act in order to achieve its goals while protecting its currently achieved goals. We also require that the system be able to carry out and monitor the execution of those plans and learn and adapt from its experience. We call a system that displays these kinds of self-management properties "autonomic".

Whereas we are concerned with transportation systems that are constituted with hardware and software, autonomicity as a separate and distinctive system feature was originally put forward as an important system design objective in the context of computer software systems. Such desirable system features had been discussed by other researchers, e.g. [2, 3], but in an effort to characterise system automation that goes beyond the traditional notions of automatic control, it was IBM through the Autonomic Systems vision who characterised the properties of such systems in [4] and subsequent initiatives[1] that promoted autonomics and supported their development in the computer systems domain.

In [4] general definitions of "self-∗" properties that characterise autonomicity were given and a discourse started which, just few years later, had already resulted in a large body of literature. Different self-∗ properties have been defined for addressing the needs of various functionalities, such as self-healing, self-configuration,

[1]In fact, IBM launched the Tivoli Systems division to specifically implement autonomic properties into their computer systems.

self-optimisation, self-protecting, which may be considered as falling under the general term of self-management for the computer systems domain.

Many self-∗ properties have been introduced by design at different levels of hierarchy within computer systems (e.g. software application level, hardware management level, etc.) in the literature, resulting to autonomic system behaviour at the component level. Different methodological approaches have been used for enabling systems to possess them, including optimisation, control theory, machine learning and artificial intelligence. The outcome of this design effort are systems with increased resilience in the presence of uncertainty, improved levels of service and learning capabilities.

Furthermore, autonomic systems interact with users at a higher policy and requirements level rather than at a lower operational level. Hiding complexity from a user is important, in order to minimise potential concern about a potentially large number of micro-actions that may need to be orchestrated/executed. Hence, the information overload, e.g. of system administrators, is avoided and interactions with the computing system are performed at a higher policy level.

3 Autonomics Applied to Transport Systems

The vast majority of the published literature on autonomics has been concerned with the design of autonomic computer systems. This is natural since the core design concepts that have been applied in autonomics stem from this domain area. Gradually other domains have found their way towards designing autonomic systems by developing systems with some self-∗ properties. Examples are financial markets [5], household energy management [6], telecommunication networks [7], spacecraft operations [8] and transportation systems [9].

There are two main views regarding the use of autonomics in the traffic management context. The first one adopts the narrow perspective of the use of autonomic computing and communication systems for supporting centralised or decentralised traffic operations. There is an increased demand for computing power, monitoring and control application information and data exchange in real time for any real-world network. Autonomics can be the computing and communications systems technology leading to the required level of service for components installed inside a TCC, over the road network infrastructure and in the vehicles themselves.

A more general view, which can be adopted beyond the computing and communications technologies, is that of designing systems explicitly having a range of self-∗ properties. This is a far more complicated task holding a higher promise. It requires a fundamental approach enabling to consider phenomena of bottom-up emergence of component and system behaviour. This exceeds the mere analysis of (completely designed) systems, but instead covers all stages of design, operation and optimisation, e.g. based on appropriate simulation models and tools. It is no coincidence that simulation technologies play an important role in quite a few chapters of this book.

In addition, different technologies and methodologies can be used for system design purposes, such as optimisation, scheduling, feedback and model predictive control, machine learning and automated planning. These methods in conjunction with technological advancements in the form of vehicle automation create a fertile ground for the design of autonomic systems at different operational levels, from the TCC general policy implementation to vehicle-to-vehicle coordination.

4 Overview of This Volume

This volume covers a broad range of views—theory, models, architectures (including platforms and development methods) and applications, showcasing autonomic concepts and features in autonomic road transport support systems. It blends into, extends and generalises the emerging discussion on the use of autonomic concepts in the domain of road traffic flow management.

This discussion is relatively new and has taken place along different dimensions of related research covering the full range of traffic operations, including modelling, control, surveillance, scheduling and routing behaviour. As such, this volume aspires to become one of the first texts in the literature where the notion of systems supporting traffic management operations with self-$*$ properties is discussed. The scope of the individual contributions covers different aspects of traffic management with an explicit effort dedicated to the selection and interpretation of self-$*$ properties.

The volume's chapters focus on methods that are used for designing, developing and implementing systems that demonstrate an autonomic property in their operation. Every chapter explains how autonomic properties can be developed and used in the context of the particular problem considered. The definition of autonomic behaviour is given within the context of the specific problem and target application. A whole range of applications related to the traffic management operations are considered. More specifically, routing control is considered in chapters "A Game Theory Model for Self-adapting Traffic Flows with Autonomous Navigation" and "TIMIPLAN: A Tool for Transportation Tasks"; signalised junction control in chapters "Self-management in Urban Traffic Control: An Automated Planning Perspective", "An Experimental Review of Reinforcement Learning Algorithms for Adaptive Traffic Signal Control", "Learning-Based Control Algorithm for Ramp Metering" and "Traffic Signal Control with Autonomic Features"; simulation verification in chapters "Simulation Testbed for Autonomic Demand-Responsive Mobility Systems" and "Multi-Agent Traffic Simulation for Development and Validation of Autonomic Car-to-Car Systems"; traffic flow model validation in chapters "Autonomic Systems Design for ITS Applications Modelling and Route Guidance" and "Performance Maintenance of ARTS Systems"; integrated control in chapters "A Multiagent Approach to Modeling Autonomic Road Transport Support Systems", "A Self-optimization Traffic Model by Multilevel Formalism", "An Organic Computing Approach to Resilient Traffic Management", "An Autonomic

Methodology for Embedding Self-tuning Competence in Online Traffic Control Systems” and “Applying the PAUSETA Protocol in Traffic Management Plans”; and electric vehicle management in chapter “Electric Vehicles in Road Transport and Electric Power Networks”.

In order to design and eventually deploy these systems, we can distinguish two broad approaches that have been followed. Artificial Intelligence (AI) and Multi-Agent Systems (MAS) methods form the core of the first approach, whereas control methods are at the heart of the second. Both computer science and engineering are represented as disciplines. This book presents their confluence on the broader subject of traffic management. In order to facilitate the presentation and coverage of the subject’s wide range, the volume is divided into three parts.

4.1 Part I: Models, Concepts, Architecture and Theories of ARTS

The first part of the book contains a collection of state-of-the-art research concerned with models, concepts, architectures and theories that provide a foundation for use in the development of autonomic traffic management systems.

In the first chapter of this part (chapter “A Game Theory Model for Self-adapting Traffic Flows with Autonomous Navigation”), Varga presents an application of game theory for modelling and analysing the self-organisation of routing behaviour. Routing games are used for modelling autonomous self-adaptive navigation providing in this way an interesting theoretical foundation for autonomic routing systems. Game-theoretic modelling of the interaction among self-interested entities enables the study of the resulting collective autonomic phenomena.

The second contribution by Jimoh and McCluskey (chapter “Self-management in Urban Traffic Control: An Automated Planning Perspective”) is concerned with urban junction signal control using Automatic Planning (AP) and how to develop a system with self-management properties. It is argued that in order to create such self-awareness functionality the traffic management system (or a suitably defined subsystem) needs to be situation-aware and have knowledge of its components, its environment and the reasoning between them. Hence, autonomic systems must be deliberative with respect to their actions in real time in order to apply control.

Within such a framework the system can respond on its own, without external guidance, during unforeseeable situations. One of the tools that can be used for enabling such capability is AP. In order to use this technology, a specific application domain requires its formal description using a suitable language and the subsequent use of heuristics for dynamically finding plans and schedules that aim to satisfy a set of objectives. The domain in this case is the urban road junction equipped with traffic lights and the vehicle volume that needs to be served. The chapter elaborates on the architecture of a self-managing system based on AP.

A different approach towards control of signalised intersections is discussed in chapter "An Experimental Review of Reinforcement Learning Algorithms for Adaptive Traffic Signal Control" by Mannion, Howley and Duggan. In this contribution, a Traffic Signal Control regime based on Reinforcement Learning (RL-TSC) is presented. A wide overview of RL is provided, and its importance as a method supporting the evolution of learning of a system is highlighted. RL is described as a Markov decision process where the reward function, the set of states, the set of actions and the state transition function are defined for the signalised intersection. It is argued that RL can be used for developing systems with autonomic properties because it enables system adaptability, learning capability and self-optimisation through flexible goal orientation based on online learning.

In chapter "A Multiagent Approach to Modeling Autonomic Road Transport Support Systems", Fiosins, Friedrich, Görmer, Mattfeld, Müller and Tchouankem provide a conceptual agent-based model of a traffic system comprised of drivers and traffic control centres as participants. Drivers are modelled as locally autonomous agents, which act to optimise their operational and tactical decisions, such as their route choice. Traffic management centres act as agents influencing the traffic flow process according to dynamically selected policies.

Two autonomic features emerging from the local decisions and actions of traffic participants are considered: (1) autonomic routing, whereby vehicle agents individually adapt routing decisions based on local learning capabilities and traffic information, and (2) vehicle grouping, i.e. collective decision-making of vehicles, which dynamically form and operate groups to drive in a convoy, thus aiming at higher speed and increased throughput. In this framework, autonomicity is studied as a property emerging from the decentralised agents' interactions.

The final contribution of the first part is chapter "Self-optimization Traffic Model by Multilevel Formalism" by Stoilov and Stoilova. In this work, the authors propose to use a bi-level optimisation formalism for developing an urban junction signal control strategy with a self-optimising behaviour. The self-optimisation aspect of a complex system is implemented by simultaneous solutions of interconnected local optimisation problems which are part of a hierarchical structure. An example of this approach is given for urban junction signal control where the green splits of a cycle are determined in one level and the cycle duration on the other.

4.2 Part II: Platforms and Methods for Engineering ARTS

This part of the volume presents software platforms, methods and other tools that can be used for further studying and developing ways of designing autonomic traffic management applications.

The first contribution of this part, chapter "An Organic Computing Approach to Resilient Traffic Management", by Sommer, Tomforde and Hähner, explores the application of organic computing to the management of decentralised junction signal and vehicle routing control systems. The organic traffic control system described provides a self-organised and self-adaptive solution combining the principles of autonomic and organic computing. A basic requirement behind this approach to system design is for parts of the design-time process tasks to be transferred to the system's responsibility at runtime showing at the same time robustness and flexibility. Based on the discussion of these two properties, the chapter discusses resilience of a traffic management system, i.e. proactive robustness.

In chapter "Autonomic Systems Design for ITS Applications Modelling and Route Guidance", Kotsialos and Poole provide a general methodology for system design based on the autonomic nervous system. Autonomics is put forward as a more general system design approach where self-$*$ properties are considered design requirements, and tools from control theory and optimisation are used for endowing feedback control loops with autonomic properties. A distinction between sympathetic and parasympathetic system functionalities is drawn as two partially competing but mostly complementary components of an autonomic system.

The authors evaluate their approach through an application of macroscopic traffic flow model validation METANET. Optimisation is used for calibrating and verifying the model in such a way that the spatial distribution of fundamental diagram capacities is automatically detected, without the need for expert engineering judgement. At a higher level of policy determination and expression, the requirements for an autonomic route guidance application are discussed.

In the third chapter of this part (chapter "Simulation Testbed for Autonomic Demand-Responsive Mobility Systems"), Čertický, Jakob and Píbil present an open-source simulation testbed for emerging autonomic mobility systems, in which transport vehicles and other resources are automatically managed to serve a dynamically changing transport demand. The contribution acknowledges the need of providing usable frameworks and platforms that enable the controlled experimentation with autonomic systems. This will help accelerate the development of control mechanisms for autonomic mobility systems and to facilitate their mutual comparison using well-defined benchmark scenarios.

In their contribution (chapter "Multi-Agent Traffic Simulation for Development and Validation of Autonomic Car-to-Car Systems"), Vokrinek, Schaefer, Pinotti and Tango propose another simulation testbed. They apply the multi-agent paradigm to the study of decentralised coordination strategies applied in cooperative car-to-car systems, such as an Autonomic Lane Change Assistant. The focus of their work differs from the previous chapter in that it acknowledges and takes into account the role of the human user (in their case the driver) in an autonomic system. Thus, the chapter provides a methodological basis to study a number of interesting phenomena that occur when advanced driver assistance systems meet autonomic features aiming at increasing safety and efficiency.

In chapter "Performance Maintenance of ARTS Systems", Schumann focuses on the problem of analysing the performance of autonomic systems. The chapter points out that the performance of an autonomic, self-managing system not only depends on characteristics of the environment but also on the adaptation history of the system. The chapter further stresses the important role of experimental, empirical validation for these systems. The main contribution of this chapter is that