Towards a decentralized intelligent traffic management system

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***Abstract*—Growing cities and the increasing number of inhabitants lead to a higher volume of traffic in urban road networks. As space is limited and the extension of existing road infrastructure is expensive, the construction of new roads is not always an option. Therefore, it is necessary to optimise the existing urban road network to reduce the negative effects of traffic, e.g. pollution emission and fuel consumption. Urban road networks are characterised by their great number of signalised intersections. Until now, the optimisation of these signalisations is done by hand through traffic engineers. As urban traffic demands tend to constantly change, it is almost impossible to foresee every situation upfront. Hence, a new approach is needed, that is able to react adaptively at run-time to optimize signalisations of intersections according to the current situation. The Organic Traffic Control (OTC) system offers a decentralised approach with communicating intersections, which are able to adapt their signalisation dynamically at run-time and establish progressive signal systems to optimize traffic flows and the number of stops per vehicle.**

I. Introduction

Urban road networks are characterised by their great number of signalised intersections. Traffic engineers try to use the existing road network efficiently by optimising signal plans followed by an improved coordination of traffic flows in order to reduce negative impacts of traffic like pollution emissions. The problem here is, that even the optimisation of a single signalised intersection is a very difficult task due to its mathematical complexity.
The increasing mobility and rising traffic demands cause serious problems in urban road networks. An additional difficulty arises from the fact that traffic demands in urban road networks are constantly changing, so that the signalisation has to be continuously adapted to new situations. Under the assumption that these changes would appear at frequent intervals it would be possible to handle them with time-dependent switching of predefined signal plans. As there are irregular traffic demands due to events like sport events or the beginning or ending of holidays or even completely blocked roads due to incidents, road works or bad weather conditions, which are difficult or even impossible to be foreseen, it is necessary to shift the signal plan optimisation from design-time to run-time in order to be able to immediately adapt the signalisations of intersections. Therefore, learning intersections are needed that can communicate among each other and adapt their signalisation autonomously to changes in the environment.

A. Related work

Approaches to reduce the negative impacts of traffic include an improved control of traffic lights and the introduction of dynamic traffic guidance systems that take current conditions into account. The *Split, Cycle, and Offset Optimisation Technique* (SCOOT, [1]) is one of the first adaptive network control systems that was successfully applied in the field. It responds automatically to fluctuations in the traffic flow and offers other techniques like the priorisation of busses. The *Sydney Coordinated Adaptive Traffic System* (SCATS, [2]) is a computerised area wide traffic management system started in 1970 and continually being improved. It is able to control traffic intersections and mid-block pedestrian crossings. Further projects dealing with new approaches for the management of traffic are *OPAC* (Optimisation Policies for Adaptive Control, [3]), *BALANCE* (Balancing Adaptive Network Control Method, [4]) and *MOTION* (Method for the Optimisation of Traffic Signals in Online-Controlled Networks, [5]).
Another solution for the former aspect is Organic Traffic Control (OTC) which provides a self-organised and self-adaptive system founding on the principles of Organic Computing (OC, [6]). The design principle behind this architecture is to transfer characteristics like *local responsibility*, *self-organisation*, *robustness*, *adaptivity*, and *capability of learning* to systems of different application domains. The current status of the OTC system is mainly based on dissertations of [7] and [8]. Based on these works, intersection controllers got the ability to self-adapt to changing traffic conditions by adapting their signalisation. Furthermore, the system is able to establish a coordinated operation of nearby intersections to enable so-called green waves. In contrast to the formerly presented approaches, OTC relies on a decentralised structure which eliminates the problem of a single point of failure and the bottleneck between the central traffic management unit and the other components in the system.

B. Working plan

Future work will further improve the OTC system by enhancing the framework with several techniques. An intelligent traffic management system has to provide features like traffic flow prediction, methods for congestion avoidance and congestion detection. These abilities will improve the system to be able to deal with complex road traffic situations. These features will reduce the average travel time through the network as well as the number of stops. Additionally, public transport will be included in the optimisation process of the signalisation, allowing the system to give priorisation to buses or trams. These goals will be presented in the following.

II. Objectives and Approach

A. State of the art

The OTC system consists of a self-organising observer/controller framework for signal control. As shown in Fig. 1, the OTC architecture extends the intersection controller within an existing road network, the System under Observation and Control (SuOC), by adding several layers on top. Current installations in cities worldwide often rely on so-called fixed-time controllers. These controllers follow pre-defined phases in which different turnings receive the right to switch to green. Additionally, so-called interphases are defined, in which all traffic lights of an intersection are switched to red light to avoid accidents.

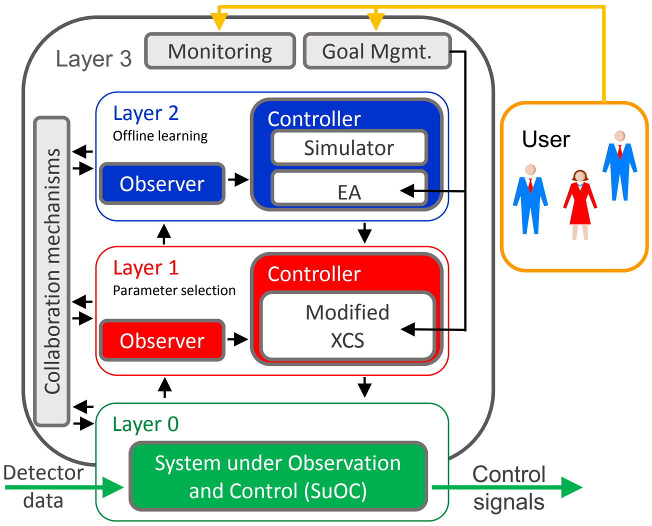

Fig. 1. Organic Traffic Control Architecture

Therefore, the traffic light controller follows a simple time-dependent algorithm. Fig. 2 depicts a simple intersection with 12 turnings and detectors. These detectors are typically implemented as induction loops in the surface and measure traffic flows for every turning.

The recorded traffic flows are passed to the observer on Layer 1. This Layer 1 contains a modified learning classifier system (based on Wilson's XCS [9]) where parameter sets for the signalization, based on the observed traffic flow data, are selected. In case of a new situation (no parameter set is known), the offline learning component on Layer 2, represented by an evolutionary algorithm, creates new classifiers and passes these back to Layer 1, where the new parameter set is applied. Simultaneously, Layer 1 reacts with the best possible action while Layer 2 searches for a new solution. Here, AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks [10]) is used to evaluate

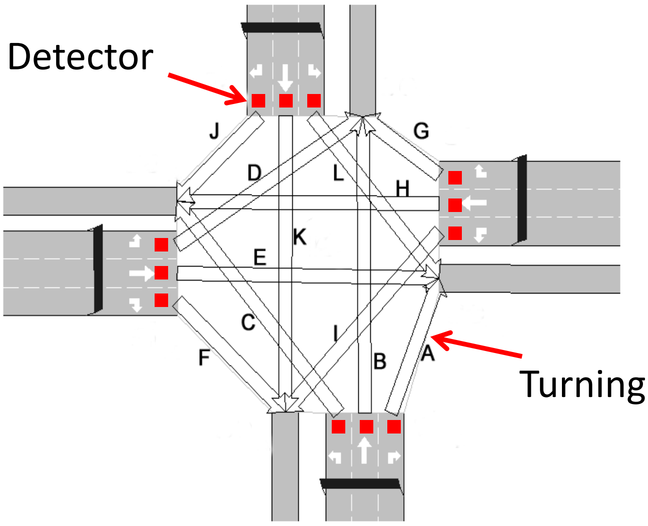

Fig. 2. An exemplary intersection with detectors and turnings

the quality of the created parameter sets. Mechanisms for a decentralized collaboration between intersections enable these to communicate and exchange data. This allows the network to coordinate signalisations of traffic lights in response to changing traffic demands. The system is able to reduce the number of stops per vehicle to reduce pollution emission, fuel consumption and travel time, while maximizing the flow through the road network. As several intersections of an urban road network can be located in close vicinity, their coordinated signalisation is essential for implementing so-called green waves to increase the traffic flow. By identifying the strongest traffic streams, the system is able to minimise the network-wide number of stops by establishing green waves for these streams.

B. Future work

As the traffic management system gets the ability to self-adapt, mechanisms must be introduced for ensuring the correctness of the system's behavior and the applied actions. Therefore the road network evolves to an robust intelligent decentralised traffic management system, which can autonomously adapt within defined borders and reliable offer advantages for traffic participants. By further introducing techniques like traffic forecasting and early congestion detection, the system transforms from a reactive to a proactive traffic management system.

1) Predicting future traffic situations: The existing OTC system [7] is able to react to changes in the traffic flow, but it lacks the ability to proactively establish mechanisms to prevent the traffic network of traffic jams or traffic bottlenecks. Forecasting the upcoming traffic flow may help the system to prevent decreases in traffic flow caused by road constructions or bad weather conditions. As [11] states, artificial neural networks (ANN) were already successfully explored for the prediction of traffic flows up to 15 minutes ahead. This approach has shown to be able to deal with complex nonlinear predictions [12], which lets ANNs appear as appropriate for the traffic domain. A multitask learning (MTL) model for ANNs will be used as presented in [13] and [14], as MTL may offer improvements to the generalization performance of the ANN by integrating field-specific training information contained by the extra tasks. The most considered task is the so-called main task, while the others are called extra tasks. The introduced prediction techniques will be integrated into the observer on Layer 1, so every intersection controller has a prediction component for each turning. Furthermore the raised data should be integrated in the components responsible for the routing algorithm and signalisation of the traffic flow. As the simulation of new classifiers on Layer 2 needs some time, the situation passed to Layer 2 could be the predicted one, instead of the current one. With a sophisticated prediction, this approach might lead to a faster reaction time and a better matching set of classifiers especially in the startup phase of the system.

2) Dealing with congestions: By an early detection of possible capacity shortages, the system should be able to adapt the routing of vehicles to avoid congestions. But even with a sophisticated forecasting technique, situations which can not be foreseen may exist. Accidents are not predictable and may have severe influences on the traffic situation. An accident may not only lead to a drastic decrease in traffic flow in the particular location, but may also cause a tailback that blocks other routes that are not overloaded [15]. This phenomenon especially occurs in busy areas with a large number of road intersections. The OTC system has therefore to be equipped with two new features. The first is a detection mechanism for congestions which may be achieved by analysing the data passed by detectors and the resulting traffic flow data. Several papers were written about this topic. Approaches include vehicle-to-vehicle communication [16], stationary video cameras [17] or cellular system technology [18]. In the OTC system, data from detectors in the street surface should be incorporated in the congestion detection mechanism. In case of a detected traffic shortage, the second mechanism then adapts the system in the way that the traffic flow takes other paths through the system, in the way that the negative effect of the accident is minimized. This may be achieved by adapting green times of traffic lights and an extended route guidance through variable message signs. The signalising should therefore consider (dynamic) link capacities. The OTC system is already equipped with a decentralised routing component, that is able to determine the best routes to prominent destinations in the network for unaffected traffic flows [7]. This component should now be extended by the described mechanisms. An interesting effect might be observed, when all or most traffic participants follow the alternative route proposal. By choosing the alternative route, this might lead to new traffic jams on the alternative routeing. Therefore, a (distributed) detection of the emergent effect of cascading link failures should be established. In addition, an intelligent algorithm is needed, to distribute the traffic participants adequately on alternative paths through the road network.

3) Public transport: Until now, the OTC system only considers individual traffic. By introducing new vehicle classes for public transport like buses or trams, the consideration of these traffic participants will also be part of the signalisation optimisation process. Therefore, the system will be able to give priority to public transport by extending corresponding green times or shortening conflicting phases to allow unaffected passing by the vehicle. This may lead to decreased waiting times and number of stops for public transport, with possible negative effects for other traffic participants.

4) Optimising phase sequences: A further improvement should by achievable by incorporating all basic signalisation parameters into the optimisation process. Currently, only the phase durations, the cycle time - and in the coordinated case - the offset of signalised intersection have been considered. By establishing a predefined set of allowed phase transitions, the phase sequence can be incorporated as additional parameter. This leads to decreased waiting times as costly phase transitions might be skipped.

III. Conclusion

The realisation of the presented ideas enhances the existing OTC system to convert it from a reactive to a robust proactive traffic management system which is able to predict upcoming traffic shortages and drops in traffic flow and, in addition, has the ability to react autonomously and to adapt the traffic flow to solve the presented problems. By including public transport into the optimisation process of the network, the system is able to handle these prioritised. Therefore, the OTC system gets the ability to detect traffic anomalies and is assigned with the feature of self-organised resilience.

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