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An intelligent control system for traffic lights with simulation-based evaluation

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ABSTRACT

This paper introduces an intelligent control system for traffic signal applications, called Fuzzy Intelligent Traffic Signal (FITS) control. It provides a convenient and economic approach to improve existing traffic light infrastructure. The control system is programmed on an intermediate hardware device capable of receiving messages from signal controller hardware as well as overriding traffic light indications during real-time operations. Signal control and optimization toolboxes are integrated into the embedded software in the FITS hardware device. A fuzzy logic based control has been implemented in FITS. In order to evaluate the effects of FITS system, this study attempts to develop a computational framework to evaluate FITS system using microscopic traffic simulation. A case study is carried out, comparing different commonly used signal control strategies with the FITS control approach. The simulation results show that the control system has the potential to improve traffic mobility, compared to all of the tested signal control strategies, due to its ability in generating flexible phase structures and making intelligent timing decisions. In addition, the effects of detector malfunction are also investigated in this study. The experiment results show that FITS exhibits superior performance than several other controllers when a few detectors are out-of-order due to its self-diagnostics feature.

1. Introduction

In urban traffic management and operations, signal control systems play a crucial role in mitigating congestion and traffic impact issues. The control scheme can be classified into non-adaptive and adaptive control approaches. The major difference between these two approaches is whether signal parameters can be adjusted in real-time with regard to detected traffic conditions. For both non-adaptive and adaptive systems, on-street detectors, such as in-pavement loop detectors, are deployed for the purpose of improving the performance of signal control systems.

Vehicle actuated (VA) control system is one of the most popular non-adaptive system with the aid of loop detectors. They are commonly seen in European countries. In the Nordic countries, LHOVRA (see Appendix A) and MOVA (Microprocessor Optimized Vehicle Actuation) belong to the earliest VA-based signal control systems initiated in the 1980s (Vincent & Peirce, 1988; Peterson, Bergh, & Steen, 1986). They are still widely used in Sweden, Finland, Denmark, etc. Both LHOVRA and MOVA make extension decision based on time gaps between vehicles reported by detectors. Therefore, the signal timings vary continuously according to the latest traffic condition. In the US, actuated signal controllers, either in a stage-based or dual-ring manner, are widely deployed based on National Electrical Manufacturers Association (NEMA) standards (Tarnoff & Ordonez, 2004).

In the past decades, many transport planning agencies and researchers have attempted to improve the signal systems deployed through tuning control parameters. One of the most widely used methods in engineering application is to apply a simulation-based optimization approach with respect to the pre-determined strategies and policies. For example, Ma, Jin, and Lei (2014) applied a stochastic optimization approach (mainly genetic algorithm) to determine signal control parameters for the purpose of improving traffic mobility efficiency, enhancing energy and reducing vehicle wait-time as well as emissions exhausted by vehicles. However, the optimal signal parameters normally correspond to a certain level of traffic demand. Due to the system uncertainties and variation of demand levels, the tuning process for signal parameters should be continuously executed in operations. In practice, control parameters are required to be predefined in the controller hardware. It would be hard to frequently change control parameters under the existing architecture of traffic signal system in order to be in accordance with live traffic conditions.

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In parallel to continuous development of non-adaptive signal control system, adaptive control strategies have attracted increasing research interests. For example, SCOOT (Split Cycle Offset Optimization Technique) and SCATS (Sydney Coordinated Adaptive Traffic System) are among the earliest adaptive signal control systems respectively developed by Hunt, Robertson, Bretherton, and Royle (1982) and Sims and Dobinson (1980). The ideas behind the two systems are similar: selecting the most appropriate signal plan from a look-up table according to the traffic condition detected. Alternatively, a number of other adaptive control approaches were, together with the development of vehicle detection methods, proposed by Gartner (1983), Henry, Farges, and Tuffal (1984), Luyanda et al. (2003), and Boillot, Midenet, and Pierrelée (2006).

Along with the evolution of traffic signal system, applications of adaptive control methods have shown to be a promising direction for future traffic management. In the mean time, emerging information and communication technology has offered great opportunities for developing more efficient signal control systems. Recently, more innovative approaches, especially from computer science and machine learning, have been applied for the development of adaptive signal control. For example, Cai, Wong, and Heydecker (2009) formulate signal control as a sequential decision-making problem and solve it using the approximate dynamic programming approach. El-Tantawy, Abdulhai, and Abdelgawad (2013) apply reinforcement learning approaches and equip signal system with the intelligence to carry out learning for control parameters. Nevertheless, most adaptive signal control systems focus on managing traffic at the network level using simplified fixed-time (FT) control logic to represent local operation.

In reality, signal systems often apply more advanced detecting and corresponding control technologies, and so there is great need to develop new approaches changing the parameters of the controller adaptively according to traffic conditions. The MOTION signal control system is a recent example, which optimizes the timing plans at the network level and applies vehicle actuated control at the local operation (Brilon & Wietholt, 2013). In addition, Jin and Ma (2015) developed an adaptive control approach based on the existing group-based traffic signal infrastructure. The approach has been evaluated in a microscopic traffic simulation environment. The study reveals that the current signal control system can be significantly improved, in terms of mobility, if control parameters can continuously adapt to real traffic conditions.

In practice, there are policy and economic barriers for deploying completely new traffic signal systems and control strategies. It is therefore convenient and more economic to develop an intermediate system capable of collaborating with current infrastructure and appending new functionalities including new control methods. Such a system should be able to communicate and work together with an already installed controller, receiving detection information and providing traffic light indications. Optimization algorithms and new control strategies should be implemented as software and embedded into the system. Fuzzy Intelligent Traffic Signal Control (FITS) is such an intermediate system dedicated for traffic signal control at urban intersections. It is implemented on an ARM single board computer capable of communicating with real signal controllers (such as LHORVA, MOVA and NEMA) as well as receiving detector information from the existing infrastructure.

Fig.1 shows the hardware on which the FITS control system has been implemented. FITS applies real-time traffic simulation to predict live traffic states at the intersection being controlled. The simulation software embedded in the device determines traffic conditions using detecting data. The controller can take over the signal control tasks and apply its own control logic. Indeed, a fuzzy group-based signal control approach has been adopted in the control program. The pioneer development of the Fuzzy Control algorithm showed many advantages over conventional group-based signal controller in the FUSICO (FUzzy SIgnal COntrol) project (Niittymäki & Pursula, 2000). Currently, the control algorithm has been enhanced and implemented as embedded software in the new single board computing device with new functionalities such as automated signal optimization. The system has also been commercialized for real applications in several cities in the US and Europe.

This paper aims to introduce the basic principles of FITS system. Moreover, the effectiveness of FITS system is evaluated by using an integrated simulation framework in a laboratory environment, the so-called FITS-in-the-loop simulation. The rest of the paper is organized as follows. Section 2 describes the basic principles of FITS signal control system. The following section illustrates the evaluation approach using FITS-in-the-loop simulation. A case study is then carried out using the SUMO microscopic traffic model and the results are presented in Section 4. Section 5 concludes the paper with summary and future work.

2. FITS system

2.1. Fuzzy control for signal timing

The original idea of the FITS controller was to mimic human policeman in controlling traffic lights at an intersection. Signal timing is generated by understanding the prevailing traffic situations using the detection information obtained. Here, vehicle detecting information has to be processed for representing the current state of the traffic system. Fuzzy Logic is therefore applied to approximate the reasonings of human mind while modeling uncertainty of the traffic conditions perceived. Indeed, a variational implementation of a microscopic traffic simulation model (Kosonen, 1999) is embedded as software in the controller to predict the states of the traffic system.

The microscopic model represents the states and interactions among vehicles as well as the status of signal controllers. The interaction between vehicles is modeled using a rule-based system. The speed and lane change of a vehicle are determined by a set of rules that are executed every time step. In addition, after receiving detection information, the simulation model has the capacity to adapt its prediction based on the current state. Simultaneously, it is also possible to derive from the simulation model some useful measures indicating, for example, the average delays, queues, stops, emission, etc. In fact, these refined indicators can be used as inputs for the reasoning process in the controller. The sensors within this paper are limited to stationary vehicle detectors, although other types of sensory information are also adopted to FITS in real applications.

Since real-time simulation may predict the state of traffic system and effects at intersections, different types of traffic inputs and derivable measures can be applied in the fuzzy rules. In the current implementation, the fuzzy inference process is encapsulated into its own generic object in the object-oriented framework. In general, the standard Mamdani fuzzy inference system has been applied in the rule-based reasoning in FITS. It is based on the controller developed as part of the FUSICO project with modifications to the rule set. This section illustrates the basic principles of the fuzzy signal controller but more technical aspects are presented in the publication of the FUSICO study (Niittymäki & Pursula, 2000).

For the inference system, fuzzy membership functions and rules are the essential components. The input variables of FITS are mapped by sets of membership functions, converting them into fuzzy truth values between 0 and 1. Since group-based phasing and vehicle detecting information are applied for signal control, the inputs of traffic volume, occupancy, queue length and waiting time for certain signal group are inferred when making control decisions. Although a general membership function is defined in the system, simple triangle membership functions are currently adopted for all input variables.

For instance, queue length can be modeled by a number of fuzzy sets including “zero”, “a few”, “medium” and “long”. The membership functions of the fuzzy sets can be described as follows: