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Type-2 fuzzy multi-intersection traffic signal control with differential evolution optimization

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A B S T R A C T

This paper proposes a multi-agent type-2 fuzzy logic control (FLC) method optimized by differential evolution (DE) for multi-intersection traffic signal control. Type-2 fuzzy sets can deal with models' uncertainties efficiently because of its three-dimensional membership functions, but selecting suitable parameters of membership functions and rule base is not easy. DE is adopted to decide the parameters in the type-2 fuzzy system, as it is easy to understand, simple to implement and possesses low space complexity. In order to avoid the computational complexity, the expert rule base and the parameters of membership functions (MF) are optimized by turns. An eleven-intersection traffic network is studied in which each intersection is governed by the proposed controller. A secondary layer controller is set in every intersection to select the proper phase sequence. Furthermore, the communication among the adjacent intersections is implemented using multi-agent system. Simulation experiments are designed to compare communicative type-2 FLC optimized by DE with type-1 FLC, fixed-time signal control, etc. Experimental results indicate that our proposed method can enhance the vehicular throughput rate and reduce delay, queue length and parking rate efficiently.

1. Introduction

Traffic jam has been a common problem due to the rapid growth of vehicles in the cities, particularly in the rush hours. Developing new infrastructure is a kind of method to alleviate this phenomenon. However, the rate at which the vehicles are increasing is much faster than the speed of the constructing infrastructure. Moreover, the city layout has usually been settled down, which limits the space for building roads in urban construction. This necessitates the optimum usage of the existing infrastructure instead of constructing new roads. It is well known that the congestion aroused by intersections is a major factor of traffic jam. So research on traffic signal control has become an emerging field to reduce the average delay experienced by vehicles inside the traffic network.

Transportation system is a large complex nonlinear system. It is very hard to establish a precise mathematical model for calculating the green time of an intersection based on traffic condition due to the nonstationary characteristics of traffic flow at intersections. Moreover, the traffic flow is a kind of pseudorandom behavior, because the platoons are formed by the signals in neighboring intersections (Balaji & Srinivasan, 2010). It limits the usage of stochastic control models. Generally speaking, the development of traffic signal control varies from fixed-time signal control to adaptive signal control. A strategy for the optimal cycle length and green split with an objective to reduce the delay which was used as the standard of the fixed-time control was proposed in Webster (1958). Fixed-time signal control used historical data to determine the green time without capability of responding to short-term traffic demand and pattern changes. Actuated control could partially solve this problem by extending green response to real-time traffic arrivals. However, such controllers only considered the situation of the green phase until it reached the pre-set maximal green time, even though the queues of the red phases were very long at that time. To overcome the limitations of actuated controllers, adaptive traffic control methods emerged based on the present and past information utilizing artificial intelligence techniques such as neural networks, fuzzy logic or an evolutionary process (Zhao, Dai, & Zhang, 2012).

Since traffic flow is usually controlled by rules, a rule-based inference system capable of dealing with uncertainties associated with input and output variables would be more suitable for the design of traffic signal control system. Fuzzy logic control (FLC)

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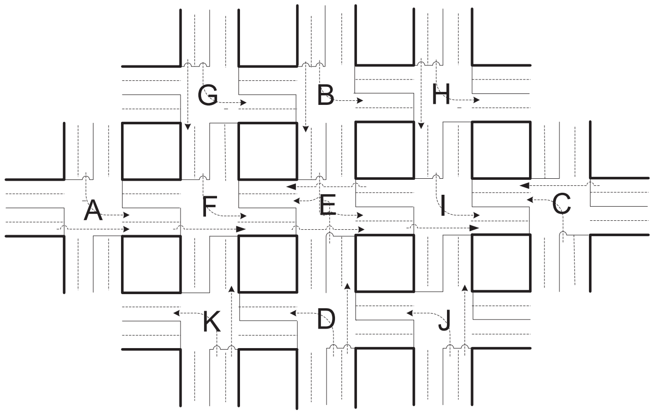

Fig. 1. An eleven-intersection traffic network.

provides such a solution that has the capability to mimic human thinking and translate the expert knowledge into computable numerical data without the necessity to setup a precise mathematical model or define an exact relationship between input and output variables. We have witnessed a rapidly growing interest in fuzzy control in application to the field of traffic signal control (Pappis and Mamdani,1977; Chiu & Chand, 1993; Chou & Teng, 2002; Murat & Gedizlioglu, 2005; Rahman & Ratrout, 2009; Trabia, Kaseko, & Ande, 1999; Zaied & Othman, 2011). Although these proposed methods had shown better performance compared with fixed-time control and actuated control, recent research has shown the limitations of traditional type-1 fuzzy logic theory in treating large uncertainty factors and unexpected disturbances (Liang & Mendel, 2000; Mendel, John, & Liu, 2006).

There exist more uncertainties in traffic signal control system. The traffic data like queue length collected from the loop detectors have nonstationary noise associated with it. The noise is influenced by various factors such as the vehicle length, the environmental condition, the driver selection behavior, etc. But type-1 fuzzy set only assigns a crisp value to the membership function discounting the uncertainties, which cannot meet the demand in transportation system. Comparatively speaking, type-2 fuzzy sets have better capability to handle models' uncertainties efficiently because of its three-dimensional membership functions (Melin, Mendoza, & Castillo, 2010; Wu & Tan, 2006; Zarandi, Rezaee, Turksen, & Neshat, 2009). So recently some research scholars began to focus on the application of type-2 FLC to traffic signal control (Balaji & Srinivasan, 2011; Balaji, Srinivasan, & Tham, 2008; Sabetghadam, Shabaninia, Vaziri, & Vadhava, 2012). Type-2 FLC exhibited better performance than type-1 FLC. However, the quality of expert knowledge determined the performance of FLC, and it was extremely important and difficult to select the optimal parameters for MF and the rule base.

In order to solve the above problem, intelligent algorithms like GA, PSO were employed to optimize the parameters of MF and the rule base of FLC (Castillo, Martinez-Marroquin, Melin, Valdez, & Soria, 2012; Castillo & Melin, 2012; Castillo, Melin, Alanis, Montiel, & Sepulveda, 2011; Cazarez-Castro, Aguilar, & Castillo, 2010; Hidalgo, Melin, & Castillo, 2012; Oh, Jang, & Pedrycz, 2011; Shill, Akhand, & Murase, 2011). In these works, parameters of FLC were adjusted and the corresponding simulation results demonstrated that type-2 FLC had better performance than the conventional type-1 FLC. As one of the most efficient and powerful stochastic real-parameter optimization algorithms (Storn & Price, 1997), DE has been shown better performance with good convergence than GA and PSO (Vesterstrom & Thomsen, 2004) and successfully applied to diverse domains (Das & Suganthan, 2011; Liu & Xu, 2012; Price, Storn, & Lampinen, 2005). DE was much more simple and straightforward to implement compared to other evolutionary algorithms. And the feature that the space complexity of DE is low helped in extending DE for handling large scale and expensive optimization problems (Das & Suganthan, 2011). This feature made DE more suitable for the optimization of type-2 FLC.

Usually, most of research about traffic signal control mainly focused on isolated intersection or two-way intersections, as it is the basic element of a traffic network and can be modeled easily. However, the assumption of isolated intersection simplifies the network optimization problem and ignores the influence among the adjacent intersections. And it is not realistic to suppose the two-way intersections due to the existence of turning vehicles. In addition, the selection of phase sequence also influents the efficiency of green time assignment. Moreover, aiming at traffic network, the employment of multi-agent system can reduce the complexity of handling interactive information among the adjacent intersections. Based on the above analysis, a multi-agent type-2 fuzzy logic controller optimized by DE is designed for a four-phase intersection incorporating turning vehicles in this paper. Then it is applied in an eleven-intersection traffic network. Each intersection's phase time and phase sequence are decided by its own and adjacent intersections' traffic volumes. In order to avoid the increasing exponentially of the computational complexity due to evolving the membership function and the rule base simultaneously, the expert rule bases and the parameters of the membership function are fine-tuned by turns in this paper.

The rest of this paper is organized as follows: Section 2 describes the traffic network we studied and the approach to evaluate traffic volumes. A type-2 fuzzy logic controller for a four-phase signal control is designed in Section 3. A simple introduction about DE and optimized process of type-2 FLC using DE are detailed in Section 4. Simulation experiments are set to compare with the benchmarks in Section 5. The discussion and conclusion are summarized in the last section.

2. Traffic network

The traffic network we studied is illustrated in Fig. 1. The intersections at the middle E, F and I are labeled as the central intersections, while the other eight intersections are referred to as outbound intersections. Every intersection is four-phase intersection which is the most common intersection in real life. No vehicle exists in the traffic network before simulation is supposed in this paper. At the beginning of each simulation, new vehicles are generated from the outside of the outbound intersections.

Every direction of each intersection has two groups of traffic loop detectors. One group is used to detect straight vehicles, while the other one detects left-turning vehicles. Each group consists of two sensors, one at the downstream stop line for recording the departure vehicles, and the other at the corresponding intersection's upstream for estimating the arrived vehicles. The queue length of each approach can be measured easily based on the detection.

Here, we select the most common four phase situation, that are, "west–east straight phase", "west–east left turning phase", "north–south straight phase", "north–south left turning phase". They are shown in Fig. 2. Suppose that the distance between the two adjacent intersections is 500 m, moving average speed is 40 km/h and the parking distance between two neighboring vehicles is 8 m, then each lane can queue at most 62 vehicles. The time to reach the next intersection should be calculated according to not only the moving average speed but also the queue length of the next intersection.