Expert Systems with Applications 42 (2015) 5403–5415

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

A novel approach for dynamic traffic lights management based on Wireless Sensor Networks and multiple fuzzy logic controllers

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ARTICLE INFO

Article history:
Available online 6 March 2015

Keywords:
Road-traffic management
Dynamic management of traffic lights
Fuzzy logic controllers

ABSTRACT

This paper proposes a novel approach to dynamically manage the traffic lights cycles and phases in an isolated intersection. The target of the work is a system that, comparing with previous solutions, offers improved performance, is flexible and can be implemented on off-the-shelf components. The challenge here is to find an effective design that achieves the target while avoiding complex and computationally expensive solutions, which would not be appropriate for the problem at hand and would impair the practical applicability of the approach in real scenarios. The proposed solution is a traffic lights dynamic control system that combines an IEEE 802.15.4 Wireless Sensor Network (WSN) for real-time traffic monitoring with multiple fuzzy logic controllers, one for each phase, that work in parallel. Each fuzzy controller addresses vehicles turning movements and dynamically manages both the phase and the green time of traffic lights. The proposed system combines the advantages of the WSN, such as easy deployment and maintenance, flexibility, low cost, noninvasiveness, and scalability, with the benefits of using four parallel fuzzy controllers, i.e., better performance, fault-tolerance, and support for phase-specific management. Simulation results show that the proposed system outperforms other solutions in the literature, significantly reducing the vehicles waiting times. A proof-of-concept implementation on an off-the-shelf device proves that the proposed controller does not require powerful hardware and can be easily implemented on a low-cost device, thus paving the way for extensive usage in practice.

1. Introduction

One of the main goals of Intelligent Transportation Systems (ITSs) is to ensure road efficiency, especially where traffic jams are very likely to occur, for instance, in traffic lights junctions. The main aspects to be considered in traffic lights control are both the cycles and the phases of the traffic lights. A traffic light cycle is the sequence of traffic lights signals (e.g., green, yellow, red) at the end of which the same signals configuration that occurred at the beginning of the sequence itself restarts. A traffic light phase is the time period during which it is possible, for a given set of lanes, to proceed in the direction that is allowed. In case of more than two phases it is necessary to determine the activation sequence of the individual phases, also known as phase sequence.

Looking at the current state of practice, most of the traffic lights today feature fixed cycles, therefore the green time duration of each traffic light phase is very likely to be inappropriate and unbalanced, as it is determined without taking into account either the actual traffic flows or the actual queue lengths. Fixed-time control methods based on a predefined time-plan are suitable for managing stable and regular traffic flows, but are not able to efficiently cope with dynamically varying traffic conditions.

In some cases the green light duration varies based on the vehicles density assessed, for instance, by means of ring detectors installed under the road. However, there is still some limitation in these solutions. First, inductive loop detectors are highly intrusive and entail service disruption during installation and maintenance. As a result, reliable and cost-effective alternative solutions, which can provide traffic data with the same accuracy as inductive loop systems, while allowing flexibility and disruption time minimization are in high demand. Second, in many cases the green signal is granted to each phase following a static phase sequence. As a consequence, it may happen that, at a given moment, instead of executing a phase characterized by longer queues, another one, less critical, is selected. To overcome the limitations of state-of-practice solutions, the traffic lights phase sequence should not be static, but dynamically determined based on the real-time assessment of the queue lengths.

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http://dx.doi.org/10.1016/j.eswa.2015.02.011
0957-4174/

This paper addresses the dynamic control of traffic lights in an isolated intersection, i.e., an intersection whose incoming vehicle flows are not affected by the effects of upstream traffic lights. The main performance target here addressed is the reduction of the vehicle average waiting times in the queues. To achieve this goal, the paper proposes a traffic lights dynamic control system that combines an IEEE 802.15.4 Wireless Sensor Network (WSN) for real-time traffic monitoring with multiple fuzzy logic controllers, one for each traffic light phase, for dynamically determining the green time duration of each phase. The challenge here is to design a flexible, scalable and effective system that avoids complex and computationally expensive solutions, which would not be appropriate for the problem at hand and would impair the practical applicability of the approach in real scenarios.

The proposed system works in two steps. In the first step (real-time traffic data acquisition and processing) the number of queued vehicles estimated by the nodes of a WSN deployed nearby the traffic lights is sent to the WSN base station (coordinator). Here, data processing is performed, with a twofold aim. Firstly, to sort the traffic lights phases according to a priority that depends on the number of queued vehicles. Secondly, to select the phase to be executed first. In the second step (Green time duration dynamic calculation) the green time duration of each selected phase is determined by the relevant fuzzy logic controller, that exploits the information about the number of queued vehicles of the selected phase.

Our approach represents a novel and effective solution that overcomes some limitations of previous approaches. In fact, several traffic-responsive control approaches were proposed in the literature over the years. Some of these approaches, such as the ones in Dion and Hellinga (2002) and Comert (2013), select phases and extend the phase durations based on predefined logic rules. Moreover, many traffic control systems in the literature, such as Abbas, Karsiti, Napiah, Samir, and Al-Jemeli (2015) and Sun, Jiang, and Wang (2010), take into account the traffic of the current phase only, without considering the length of the queues in the other phases. Conversely, the approach proposed in this paper is able to dynamically select the phase to handle thanks to the detection of the number of vehicles in the queue on the roadway.

Some other approaches proposed in more recent years, such as Zhou, Cao, Zeng, and Wu (2010) and Zhou, Cao, and Wu (2011), introduce *adaptive* algorithms for traffic lights control that adjust both the traffic lights sequence and duration according to the traffic conditions assessed in real-time through a WSN. The proposed algorithms consider several traffic factors (e.g., traffic volume, waiting times, vehicle density) in order to determine the optimal duration for the green light. The algorithms select the phase with the highest execution priority through a simple IF-THEN construct and calculate the green time duration as a "crisp" value. Although the algorithms proposed in Zhou et al. (2010, 2011) are interesting and present good simulation results, these works do not address the practical implementation of their approaches and the relevant design issues, as the wireless communication protocol is not specified and there is no indication about the computational cost of the presented algorithms. Moreover, in the works in Zhou et al. (2010, 2011) traffic flows are controlled by simple rules. Conversely, a rule-based inference system, such as that proposed in our paper, is more suitable for the design of traffic signal control system, thanks to its capability of dealing with uncertainties associated with input and output variables (e.g., the number of vehicles in the queue, the phase to handle and the green time of traffic lights).

Traffic signal control systems are large complex nonlinear stochastic systems and, as a consequence, it is hard to find optimal traffic signal settings. For this reason, other works in the literature propose traffic lights control systems based on Computational Intelligence (CI). Among CI techniques, fuzzy logic controllers are particularly suitable for traffic lights management, because they are based on human reasoning. This means that they take decisions on the basis of human direct experience of the considered environment, expressed through specific inference rules that embed the human feelings about the traffic lights system and reflect the human reaction to the system behavior.

A fuzzy controller for a single two-phase intersection which is able to dynamically manage the green time of traffic lights was presented in the seminal work of Pappis and Mamdani (1977). In such a work fuzzy rules were developed for deciding about extending the current green phase of an isolated traffic intersection featuring simple one-way East–West/North–South traffic control. Unfortunately, the work in Pappis and Mamdani (1977) does not address either turning movements or the dynamic management of the phases cycle. Conversely, the approach proposed in this paper addresses both aspects. Another limitation of Pappis and Mamdani (1977) is that it does not consider four phases, that represent a typical scenario in traffic light junctions. Conversely, our system deals with four phases.

Other approaches introduce a two-stage fuzzy logic control method, i.e., (Trabia, Kaseko, & Ande, 1999; Murat & Gedizlioglu, 2005), in which a first fuzzy controller is used to determine the phase to be handled, while a second one deals with the traffic lights green time management. The main contribution of these works compared to the work from Pappis and Mamdani (1977) is the dynamic selection of the traffic light phases. The two approaches in Trabia et al. (1999) and Murat and Gedizlioglu (2005), differ in the fuzzy controllers used, i.e., in the type of membership functions and in the number of inference rules.

Both the approaches in Trabia et al. (1999) and Murat and Gedizlioglu (2005) need two-stage fuzzy logic control because they use inductive loops or video cameras to estimate the amount of vehicles queued at the traffic lights and, for this reason, they need a fuzzy controller to determine the phase of the traffic light junction that has to be managed. Then, they also need the second controller to dynamically manage the green time increase/decrease. Conversely, our system does not need a fuzzy controller to determine which phase has to be managed, as the WSN located near the traffic light junction already provides the exact number of queued vehicles.

Nowadays, video monitoring and surveillance systems are used in many traffic management applications to assess traffic conditions. For instance, video monitoring systems are used in Kanungo, Sharma, and Singla (2014), Calderoni, Maio, and Rovis (2014), Qi, Zhou, and Ding (2013) for traffic density estimation and vehicle classification, while in other works (Diaz-Cabrera, Cerri, & Medici, 2015; Gomez, Alencar, Prado, Osorio, & Wolf, 2014) they are used for traffic lights detection and distance estimation. However, these solutions rely on expensive cameras and require hardware capable of performing image processing. While the use of video cameras and video monitoring systems is justified for more complex traffic management applications, it represents an overshooting for traffic lights management of isolated intersections, in which cost/benefit assessments lean towards simpler, low-cost but effective systems, like the one proposed in this work.

Similarly, sophisticated solutions based on complex fuzzy controllers, i.e., type-2 (Bi, Srinivasan, Lu, Sun, & Zeng, 2014) ones, that are more computationally demanding, are justified in the case of multiple intersections, but for the case like the one addressed in this paper are not required.

The strength of the traffic lights control system here proposed is that it combines the advantages of the WSN with the benefits of multiple fuzzy logic controllers.

Wireless Sensor Networks (WSNs) are very appealing candidates for the problem at hand, as they are easy to deploy and manage. The WSN accuracy proved to be comparable with (or even