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Multi-agent immune networks to control interrupted flow at signalized intersections

Saber Darmoul [a,*], Sabeur Elkosantini [a], Ali Louati [b,c], Lamjed Ben Said [c]

[a] Industrial Engineering Department, King Saud University, P.O. Box 800, 11421 Riyadh, Saudi Arabia
[b] Raytheon Chair for Systems Engineering, Advanced Manufacturing Institute, King Saud University, P.O. Box 800, 11421 Riyadh, Saudi Arabia
[c] University of Tunis, ISG, SMART Lab, 41, Avenue de la Liberté, Bouchoucha, Le Bardo, 2000 Tunis, Tunisia

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ABSTRACT

Urban traffic is subject to disturbances that cause long queues and extended waiting times at signalized intersections. Although Multi-Agent Systems (MAS) were considered to control traffic at signalized intersections in a distributed way, their generic conceptual framework and lack of built-in adaptation mechanisms prevent them from achieving specific disturbance management capabilities. The traffic signal control problem is still a challenging open-ended problem for which learning and adaptation mechanisms need to be developed to deal with disturbances in an intelligent way. In this article, we rely on concepts and mechanisms inspired by biological immunity to design a distributed, intelligent and adaptive traffic signal control system. We suggest a heterarchical multi-agent architecture, where each agent represents a traffic signal controller assigned to a signalized intersection. Each agent communicates and coordinates with neighboring agents, and achieves learning and adaptation to disturbances based on an artificial immune network. The suggested Immune Network Algorithm based Multi-Agent System (INAMAS) provides intelligent mechanisms that capture disturbance-related knowledge explicitly and take advantage of previous successes and failures in dealing with disturbances through an adaptation of the reinforcement principle. To demonstrate the efficiency of the suggested control architecture, we assess its performance against two control strategies from literature, namely fixed-time control and a distributed adaptation of the Longest Queue First – Maximal Weight Matching (LQF-MWM) algorithm. Agents are developed using SPADE platform and used to control a network of signalized intersections simulated with VISSIM, a state-of-the-art traffic simulation software. The results show that INAMAS is able to handle different traffic scenarios with competitive performance (in terms of vehicle queue lengths and waiting times), and that it is particularly more successful than the other controllers in dealing with extreme situations involving blocked approaches and high traffic volumes.

1. Introduction

According to the US Federal Highway Administration (FHWA, 2011), 5–10% of traffic delays are due to inefficient control of traffic signals. A more efficient and effective control of traffic signals contributes to improve urban traffic fluidity, safety, and sustainability. In literature, numerous fixed-time and adaptive Traffic Signal Control Systems (TSCS) were developed to

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[*] Corresponding author.

E-mail addresses: sdarmoul@ksu.edu.sa, darmoulsaber@gmail.com (S. Darmoul), selkosantini@ksu.edu.sa (S. Elkosantini), alouati@ksu.edu.sa, ali.louati@hotmail.com (A. Louati), lamjed.bensaid@isg.rnu.tn, bensaid_lamjed@yahoo.fr (L. Ben Said).

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control signalized intersections. In fixed-time control strategies, the cycle time is fixed in terms of both phase duration and sequencing, which are usually determined based on historical traffic data (Jovanović et al., 2017). Unfortunately, such control strategies are applicable only in case of low traffic volumes (Tettamanti, 2013). Moreover, fixed-time controllers are not able to adapt to variations of traffic conditions, especially in cases of disturbances, such as congestion, accidents, or crossing of emergency vehicles (ambulances, firefighters, security vehicles, etc.) (Truong et al., 2017). Therefore, adaptive controllers were developed to dynamically adapt cycle times to traffic conditions by changing either phase durations, or sequencing, or both. Many adaptive strategies were developed in the literature (Araghi et al., 2015; Tahilyani et al., 2013). The most recent research effort focuses on developing distributed approaches using multi-agent technology (Bazzan and Klügl, 2013; Chen and Cheng, 2010).

The main reasons for considering multi-agent systems (MAS) are to enable complex problem modeling and resolution, and to achieve distributed control. However, due to their generic conceptual framework and lack of built-in adaptation mechanisms, the MAS paradigm alone is not able to achieve capabilities specifically dedicated to disturbance management. Consequently, a variety of computational intelligence techniques were combined with MAS, and integrated in agents to achieve reactive and adaptive control of traffic signals (Doniec et al., 2008; Tahilyani et al., 2013). Despite their success and popularity, these approaches still face some limitations, including explicit knowledge representation, learning, capitalization of knowledge stemming from repeated exposure to, and control of disturbances, and assessment of performance on real, or at least realistic, situations (Marsetič et al., 2014).

More recently, some authors investigated the potential of biological immunity to provide concepts and mechanisms for disturbance management in transportation engineering (Darmoul and Elkosantini, 2014). Biological immunity is a natural system that relies on a limited but efficient and effective set of concepts and mechanisms to deal with a great variety of disease causing elements disturbing the integrity and normal behavior of the host organism. From a computational intelligence point of view, biological immunity offers several appealing features, such as distributed control, pattern recognition, optimization, adaptation, and learning, to state a few. In traffic control, only a few works investigated the use of immunity features to control traffic signals (Moalla et al., 2013; Trabelsi et al., 2012; Masmoudi et al., 2012; Negi, 2006). These works are rather proofs of concepts that consider a limited number of intersections (at most one or two) and provide limited numerical assessment of performance. To the best of the authors' knowledge, no work integrates immune features within a multi-agent system architecture to control traffic and achieve disturbance management at multiple signalized intersections.

In this article, we design a distributed, intelligent and adaptive traffic signal control system based on concepts and mechanisms inspired by biological immunity. We suggest a heterarchical multi-agent architecture, where each agent represents a traffic signal controller assigned to a signalized intersection. Each agent communicates and coordinates with neighboring agents, and achieves learning and adaptation to disturbances based on an artificial immune network algorithm. We particularly focus on explicit disturbance-related knowledge representation, and on knowledge capitalization to take advantage of previous successes and failures in dealing with disturbances.

Therefore, the article is organized as follows: ection 2 analyzes existing works on MAS for traffic signal control. Section 3 introduces the main concepts and mechanisms of biological immunity. Section 4 introduces our MAS architecture. Section 5 details our modeling in terms of immune concepts and mechanisms adapted for traffic signal control. Section 6 details the suggested learning and control algorithms embedded within agents. Section 7 describes our experimental framework for performance assessment. Section 8 provides experimental results. Section 9 provides a discussion of the advantages, limitations and future possible extensions of the suggested architecture. Finally, ection 10 concludes the paper with future possible research directions.

2. Multi-agent systems for traffic signal control

In the last decade, several distributed architectures were suggested to control signalized intersections (Bazzan and Klügl, 2013; Chen and Cheng, 2010; Davidsson et al., 2005). They offer different disturbance management and adaptation capabilities, which are succinctly discussed in the following subsections.

2.1. Distributed control architectures

Multi-agent systems distribute information processing and decentralize decision-making capabilities on several autonomous and intelligent entities, called agents, which interact with each other to solve complex problems. Distribution/decentralization rely on a (logical and/or physical) task decomposition and responsibility assignment that result in different control architectures. The most commonly used architectures are hierarchical and heterarchical (Chen and Cheng, 2010). Hernández et al. (2002) evaluated the potentials and drawbacks of a hierarchical versus heterarchical architecture and drew some conclusions with respect to the general applicability of multiagent architectures for intelligent traffic management.

Hierarchical architectures use some kind of organizational structure, where a hierarchy of authority exists (Bazzan and Klügl, 2013). Such architectures were suggested for example in (Abdoos et al., 2013; Hernández et al., 2002; Srinivasan et al., 2006; Choy et al., 2003; Roozemond, 2001). Authority both solves conflicts and insures global performance. However, the design choice by which hierarchically superior decisions are made and lower level agents just implement them, reduces the autonomy of lower level agents and may even compromise local performances. Thus, more flexible coordination mechanisms need to be investigated (Bazzan and Klügl, 2013).