A Distributed Least-Squares Algorithm in Wireless Sensor Networks With Unknown and Limited Communications

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ABSTRACT

In this article, the authors propose a new distributed least-squares algorithm to address the sensor fusion problem in using wireless sensor networks (WSN) to monitor the behaviors of large-scale multiagent systems. Under a mild assumption on network observability, that is, each sensor can take the measurements of a limited number of agents but the complete multiagent systems are covered under the union of all sensors in the network, the proposed algorithm achieves the estimation consensus if local information exchange can be performed among sensors. The proposed distributed least-squares algorithm can handle the directed communication network by explicitly estimating the left eigenvector corresponding to the largest eigenvalue of the sensing/communication matrix. The convergence of the proposed algorithm is analyzed, and simulation results are provided to further illustrate its effectiveness.

KEYWORDS
Distributed Estimation, Least-Squares, Local Communication, Sensor Network

INTRODUCTION

With the rapid development of computing, communication and sensing technology, recent years have seen an ever-increasing research interests in applying wireless sensor networks (WSNs) to monitor the operation of large-scale multiagent systems, such as electric power systems, water management systems, gas-pipeline systems, weather forecast systems, and to name but a few (Kar & Moura, 2009; Khan & Moura, 2008; Li & Guo, 2015; “Distributed kalman filtering for sensor networks”, 2007; Scutari & Barbarossa, 2008; Wang, Ahn, Lu, & Staskevich).

For such types of large-scale multiagent systems, it is normal that individual sensors may only cover a limited number of agents due to their physical limitations. Thus, to detect the overall behavior of multiagent systems, sensor fusion problem has to be addressed so that the measurements by individual

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sensor components can be effectively processed and utilized. The standard solution is to employ a centralized fusion center for information collection and processing. However, such a solution lacks scalability, fault tolerance, and robustness to limited communication. In this paper, we propose a new distributed least-squares estimation algorithm for sensor fusion in WSNs with limited communication.

The proposed solution in this paper follows the line of research on cooperative control and distributed estimation problems in multiagent systems (Francis & Maggiore, 2016; Qu, 2009; Qu, Wang & Hull, 2008; Saber, Fax & Murray, 2007; Wang, 2016; Wang et al., 2013). Plenty of results are available in this regard (Lewis et al., 2014). For instance, the consensus control was solved for first-order linear systems in (Lin, Broucke & Francis, 2004; Saber & Murray, 2004), for second-order linear systems in Tanner, Jadabaie and Pappas (2007), for high-order linear systems (Qu, Wang & Hull, 2008; Wang et al., 2006), and for nonlinear systems (Dong et al., 2016; Li, Rang & Xiao, 2016; Lin, Francis & Maggiore, 2007; Moreau, 2005; Wang, 2016). There are also many results solving the distributed estimation problems. For example, average consensus algorithm was designed in Spanos, Olfati-Saber and Murray (2005) to find the average of stationary signals. Distributed Kalman filtering algorithms were proposed in (Kar & Moura, 2009; Khan & Moura, 2008; Olfati-Saber, 2005; Scutari & Barbarossa, 2008). Two dynamic average consensus algorithms, a proportional algorithm and a proportional-integral algorithm, were proposed to solve the distributed estimation problem in Freeman, Yang, and Lynch (2006). Distributed Kalman filtering algorithm was used in Lynch et al., (2008) for environmental modeling. The nonlinear protocol for consensus estimation was proposed in Nosrat, Shafiee, and Menhaj (2012), and it was proved that the tracking errors were upper bounded.

In this paper, motivated by the distributed consensus algorithms in (Lewis et al., 2014; Saber, Fax & Murray, 2007), we propose a new distributed least-squares estimation algorithm to detect the behaviors of the multiagent systems. We assume that the sensor network satisfies a general kind of network observability condition, that is, each sensor can take the measurements of a limited number of agents but the complete multiagent systems are covered under the union of all sensors in the network. In addition, we consider the limited communication among sensors and assume the communication topology among sensors is strongly connected (Lewis et al., 2014). Each sensor is endowed with a distributed least-squares estimator. Through local information exchange with its communication neighbors, the estimation consensus can be reached for all sensors, and the state vector of all agents can be recovered by any individual sensors. Compared with the existing results such as those in Kar and Moura (2008), Khan and Moura (2008), Olfati-Saber (2007), Wang et al., (2007) and Scutari and Barbarossa (2008), the proposed distributed least-squares algorithms can handle the directed communication network by explicitly estimating the left eigenvector corresponding to the largest eigenvalue of the system matrix. In addition, by introducing an elegantly structured observation matrix for each sensor, the possible singularity problem can be avoided even the number of sensors are significantly smaller than that of agents. The convergence of the proposed algorithm is analyzed, and simulation results are provided to further illustrate its effectiveness. A preliminary version of the paper was presented in Wang et al., (2013). This paper makes an extension of the results in Wang et al. (2013) by designing an improved algorithm to deal with unknown communication topologies. In addition, thorough simulations are provided to further validate the proposed algorithm.

PROBLEM STATEMENT

Consider the sensor fusion problem of using N sensors to monitor the behaviors of a network of q agents. We assume that the number of sensors is far more less that of agents in the network, that is, \( N \ll q \). For each agent, its behavior can be described by a feature variable \( x_i, i = 1, \cdots, q \). In the development below, we assume that \( x_i \) is a scalar and time-invariant. The vector case can be treated similarly. For the case of \( x_i \) being slowly time-varying, the proposed algorithm works as well by simply introducing a discounting factor.
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