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Review article

Distributed state estimation for discrete-time linear time invariant systems: A survey

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ABSTRACT

Motivated by the increasing availability and quality of miniaturized sensors, computers, and wireless communication devices and given their enormous potential, the use of wireless sensor networks (WSN) has become widespread. Because in many applications of WSNs one is required to estimate at each local sensor unit the state of a system given the measurements acquired by multiple sensors, there has been a flurry of activity related to the theory of distributed state estimation. This article contains a literature survey of distributed state estimation for discrete-time linear time invariant systems. In order to obtain the proper historical context, we review the state of the art in this field and summarize previous work. To provide the mathematical intuition behind some of the methods, this survey paper reproduces some of the main results given in the literature. It also provides a critical appraisal of the state of the art and affords the reader a comprehensive presentation of the most relevant results published so far.

Contents

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1. Introduction

Given a dynamical system, a number of sensors with computing capabilities, and a communication network connecting the sensors, viewed as nodes of the network, the problem of *distributed state estimation* consists of estimating the global state of the system at every node without the need for a central coordination unit. This problem arises when the measurements of other sensors are required to compute the state estimate at an individual node, but the computation is spread over the group of nodes. The simpler case where the state estimate can be computed without the knowledge of the measurements of other sensors and the sensors are not required to communicate, is known as the problem of *decentralized state estimation*. Another particular case where all nodes can route the information to one central computational entity and the state estimate is computed and possibly sent to every node, leads to the problem of *centralized state estimation*. This type of classification of the architectures of multiple systems, which will be followed throughout this survey, can be found in many references on distributed control systems such as Lunze (1992) and Zamani and Aguiar (2015). However, other classifications are found in the literature, depending on the field of study.

The problem of distributed state estimation arises mostly in situations where the sensors are relatively distant from each other and communications are scarce. In these situations decentralized state estimation is often not possible since the sensors are unable to observe individually the whole state of the system and communication limitations prevent the use of centralized approaches. Distributed state estimation has been considered in a wide range of applications where the above conditions hold, from network localization to environmental monitoring, surveillance, object tracking, collaborative information processing, and traffic monitoring (see Aberer et al., 2010; Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002; Bahr, Leonard, & Fallon, 2009; Bethke, Valenti, & How, 2007; Dong et al., 2017; Ghabcheloo et al., 2009; Mesbahi & Egerstedt, 2010; Prathap, Shenoy, Venugopal, & Patnaik, 2012; Rawat, Singh, Chaouchi, & Bonnin, 2014; Smith & Hadaegh, 2007; Soares, Xavier, & Gomes, 2015a; Soares, Aguiar, Pascoal, & Martinoli, 2013; Soares, Aguiar, Pascoal, & Martinoli, 2015b; Wang & Ren, 2017; Xu, 2002; Zavlanos, 2008; Zhang, Wang, Liu, Ding, & Alsaadi, 2017 and the references therein for an introduction to these topics). In what follows we give a survey of the state of the art in distributed estimation. Some of the main theoretical issues will be discussed in detail, with special emphasis on consensus based estimation and linear time-invariant (LTI) systems.

In the literature, one can find many references that give an overview of the field of distributed state estimation and have influenced the organization of this article. See for example the book by Hall and Llinas (2001) for an early overview of the problem of distributed sensor fusion and Wah and Rong (2003) for a comparison and a technical summary of some of the most relevant methods of distributed estimation. An overview of many aspects related to data fusion applied to target tracking is given in Zhao, Shin, and Reich (2002) and Smith and Singh (2006). Two surveys of several techniques and problems associated with information fusion for sensor networks are presented in Makarenko and Durrant-Whyte (2004) and Nakamura, Loureiro, and Frery (2007). More recently, Mahmoud and Khalid (2013) and Li et al. (2015b) give extensive literature surveys of the state of the art in distributed state estimation and Garin and Schenato (2010) offers an overview of the technical details associated with consensus-based distributed estimation.

Most of the work referenced in Mahmoud and Khalid (2013) and Li et al. (2015b) deals with the general problem of distributed estimation for linear time varying systems and even nonlinear systems. However, a number of methods for distributed estimation have recently been described for the specific case of LTI systems that are competitive in terms of performance and bandwidth requirements, when compared with methods suitable for general time-variant or nonlinear systems. For this reason, and given the fast pace of the advancements in the area of distributed estimation, in contrast with Mahmoud and Khalid (2013) and Li et al. (2015b) this survey focuses on recent results tailored for linear time invariant discrete-time systems and outlines the underlying principles of some of the main results in the field.

1.1. Outline

The paper is organized as follows. Section 2 introduces the mathematical background necessary for the exposition that follows. Section 3 gives a formal definition of the problem of distributed state estimation. Sections 4–7 are the core of this survey and present in detail different methods of distributed estimation. Section 8 summarizes methods that are designed to

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