Automatica 66 (2016) 185–194

Contents lists available at ScienceDirect

Automatica

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

Brief paper

Simultaneous fault detection and consensus control design for a network of multi-agent systems ☆

Mohammadreza Davoodi [a], Nader Meskin [a], Khashayar Khorasani [b]

[a] Department of Electrical Engineering, Qatar University, Doha, Qatar

[b] Department of Electrical and Computer Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada

ARTICLE INFO

Article history:
Received 6 May 2014
Received in revised form
23 September 2015
Accepted 6 December 2015

Keywords:
Simultaneous fault detection and consensus control
Multi-agent systems
Linear matrix inequality (LMI)
Autonomous underwater vehicles

ABSTRACT

The problem of simultaneous fault detection and consensus control (SFDCC) of linear continuous-time multi-agent systems is addressed in this paper. A mixed H_∞/H_- formulation of the SFDCC problem is presented and distributed detection filters are designed using only relative output information among the agents. With our proposed methodology, all agents reach either a state consensus or a model reference consensus while simultaneously collaborate with one another to detect the occurrence of faults in the team. Indeed, each agent not only can detect its own fault but also is capable of detecting its neighbor's faults. It is shown that through a decomposition approach the computational complexity of solving the distributed problem is significantly reduced as compared to an optimal centralized solution. The extended linear matrix inequalities (LMIs) are used to reduce the conservativeness of the SFDCC results by introducing additional matrix variables to eliminate the couplings of Lyapunov matrices with the system matrices. It is shown that under a special condition on the network topology the faulty agent can be isolated in the team. Simulation results corresponding to a team of autonomous unmanned underwater vehicles (AUVs) demonstrate and illustrate the effectiveness and capabilities of our proposed design methodology.

1. Introduction

Multi-agent systems have recently received considerable attention in the control system community due to their potential applications in many areas, such as formation control of unmanned aerial and underwater vehicles, flocking of mobile vehicles, distributed optimization of multiple mobile robotic systems, and scheduling of automated highway systems (Olfati-Saber, 2006). On the other hand, automatic detection of system faults is of growing importance as the size and complexity of systems rapidly increase. A great deal of attention has recently been devoted to the problem of detection filters design to accomplish fault detection and isolation (FDI) tasks (Ding, 2008).

Most of the available literatures on FDI of multi-agent systems are based on centralized fault diagnosis architectures (Shames, Teixeira, Sandberg, & Johansson, 2011). In practice, it is quite challenging to address the problem of FDI in a network of multi-agent systems with a centralized architecture due to the stringent computational resources and communication bandwidth limitations (Zhang, 2010). The simplest approach to overcome these drawbacks is to use a decentralized architecture. However, in a decentralized implementation since FDI modules only receive local information, they will inevitably be unable to take into account in their solution the information corresponding to the neighboring agents (Ferrari, 2009). Consequently, the only viable and feasible architecture is a distributed one that is more suitable than a centralized architecture due to its lower complexity and use of fewer network resources. Distributed architecture is more effective than a decentralized solution due to taking into account information exchanges among the neighboring agents.

However, despite the critical necessity for distributed FDI solutions for a network of multi-agent systems, there exist only a few contributions in the literature on design of distributed FDI

☆ This publication was made possible by NPRP Grant No. NPRP 5-045-2-017 from the Qatar National Research Fund (a member of Qatar Foundation). The material in this paper was partially presented at the 13th European Control Conference, June 24–27, 2014, Strasbourg, France. This paper was recommended for publication in revised form by Associate Editor Michéle Basseville under the direction of Editor Torsten Söderström. The statements made herein are solely the responsibility of the authors.

E-mail addresses: davoodi.mr@qu.edu.qa (M. Davoodi), nader.meskin@qu.edu.qa (N. Meskin), kash@ece.concordia.ca (K. Khorasani).

http://dx.doi.org/10.1016/j.automatica.2015.12.027
0005-1098/

filters (Meskin & Khorasani, 2009, 2011; Meskin, Khorasani, & Rabbath, 2010; Shames et al., 2011). The problem of distributed FDI in a network of multi-agent systems having double integrator dynamics is considered in Shames et al. (2011). In Meskin and Khorasani (2009), development, design and analysis of actuator fault detection and isolation filters for a network of unmanned vehicles are investigated. Recently the problem of distributed FDI in a network of *heterogeneous* multi-agent systems having different dynamics and order from one another is also considered in Davoodi, Khorasani, Talebi, and Momeni (2014). In Davoodi, Khorasani, Talebi, and Momeni (2013), a robust semi-decentralized fault detection (FD) strategy for a network of *homogeneous* multi-agent systems is presented and applied to a team of micro-air vehicles.

On the other hand, cooperative control of multi-agent systems has recently received significant attention from various scientific communities. One critical issue arising from cooperative control of multi-agent systems is determining how to develop distributed control policies that are based on local information and enable all agents to reach an agreement on certain quantities of interest. This problem is known as the consensus problem (Li, Duan, & Huang, 2009). Consensus problem has a long-standing tradition in computer science. In the context of multi-agent systems, recent years have witnessed dramatic advances of various distributed strategies that achieve agreements. Model reference consensus (Li, Duan, Chen, & Huang, 2010) is another basic concept in cooperative control of multi-agent systems. Here the objective is not only to achieve consensus, but also to make the agents follow a reference system or a virtual leader.

According to the above literature review, many of the robust model-based approaches in multi-agent systems research can be classified as belonging to one of the following two categories. *First*, there are robust model-based approaches for achieving cooperative control and *second*, there are robust model-based approaches with the objective of fault detection and isolation capabilities. Notwithstanding the above, there are scenarios where it is possible and more importantly, desirable to consider an integrated design of the feedback controllers and the FD filters. This simultaneous design unifies both the control and the detection modules into a single framework. Hence, it is conceivable and expected that a simultaneous fault detection and control (SFDC) design should lead to a far less overall complexity as compared to an approach where two modules are designed separately (Alavi & Saif, 2012; Khosrowjerdi, Nikoukhah, & Safari-Shad, 2004). It should be pointed out that the SFDC design has other advantages in comparison with the separate design. The reader can refer to Ding (2009), Alavi and Saif (2012) for more details on these advantages.

According to the proposed classification in Ding (2009), the existing SFDC techniques are divided into two categories: (1) without embedded residual generator (ERG) (Jacobson & Nett, 1991), and (2) with the ERG (Henry & Zolghadri, 2005). In the SFDC with the ERG (which will be used in the structure of this paper), the controller output is fed back for designing the FD. This leads to loss of some robustness in comparison with the SFDC without the ERG where the controller output is not employed for design of the FD. However, the proposed SFDC framework without the ERG depends on reference signals that have been shown to deteriorate the FD performance. Moreover, additional design degrees of freedom are considered in the proposed SFDC without the ERG which increases the computational complexity of the problem.

The problem of simultaneous fault detection and control design has attracted significant attention in the past two decades, both in the research and in the application domains (Davoodi, Golabi, Talebi, & Momeni, 2012, 2013; Davoodi, Talebi, & Momeni, 2012; Wang & Yang, 2009). In Davoodi et al. (2012), the authors addressed the problem of SFDC by using dynamic observers for linear continuous-time systems. In Davoodi et al. (2013), the authors proposed an H_∞ formulation of the SFDC problem by using dynamic observer detector/state feedback controller and an average dwell time analysis for continuous-time switched linear systems. A preliminary version of this paper has already been presented in Davoodi, Meskin, and Khorasani (2014) in which the problem of simultaneous fault detection and model reference consensus design is considered by using distributed detection filters for a network of linear multi-agent systems. In this paper, the case of consensus problem is also investigated which requires a new derivation of the model transformation and a new design methodology.

The contributions of this paper can therefore be summarized as follows:

(1) For the first time in the literature, an LMI based approach for the mixed H_∞/H_- *distributed* simultaneous fault detection and consensus control (SFDCC) design of continuous-time linear multi-agent systems using relative output information is proposed. A set of distributed modules are designed that generate two signals, namely the residual and the control signals. Using the residual signal not only each agent's faults but also faults of its neighbors can be detected. Using the control signal all the agents can either achieve (i) a state consensus or (ii) a model reference consensus. The SFDCC modules are designed such that the effects of disturbances and faults on the residual signals are minimized and maximized, respectively (for accomplishing the fault detection task), while the effects of disturbances and faults on the specified control outputs are minimized (for accomplishing the state consensus or model reference consensus problems).

(2) Motivated by Li et al. (2010), Massioni and Verhaegen (2009), a decomposition technique is employed in the SFDCC design procedure that allows the system to be partitioned into a set of lower order subsystems for reducing the computational complexity of the design as well as for specifying the SFDCC modules with a distributed architecture. The decomposition approach that is used in Li et al. (2010), Zhang, Lewis, and Das (2011) leads to conservativeness in the solution since one needs to equate the Lyapunov variables between all the conditions. To overcome this difficulty, the authors in Massioni and Verhaegen (2009) applied the extended LMI formulations for a class of discrete-time systems to avoid common Lyapunov variables and solved the problem of designing distributed controllers with H_∞ and H_2 performance indices. However, continuous-time systems were not addressed and solved in Massioni and Verhaegen (2009). It should be pointed out that it is not possible to relate the results in the continuous-time and the discrete-time domains by simple transformations since the underlying control objective involves H_∞ and H_2 performances that are distinctly and separately formulated for their respective controller designs. In this paper, motivated by Pipeleers, Demeulenaere, Swevers, and Vandenberghe (2009), the extended LMI formulation for solving our proposed H_∞/H_- distributed SFDCC problem for a network of continuous-time multi-agent systems is used to avoid the use of common Lyapunov variables.

(3) A required sufficient condition on the network topology and residual signals for guaranteeing isolation of the faulty agent in the team is obtained. This distributed strategy is based on flags that are generated corresponding to the residual signals of the team agents.

Finally, it should be noted that in this paper we consider a completely different problem from the one proposed in Davoodi et al. (2014). Indeed, in Davoodi et al. (2014) the problem of *FDI* design for a network of *heterogeneous* multi-agent systems is solved by designing a set of detection *filters* for a set of *virtual* systems whose orders are equal to the *sum* of the order of each agent and its nearest neighbor agents. However, in this paper the