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Research article

Distributed reconfigurable control strategies for switching topology networked multi-agent systems

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ABSTRACT

In this paper, distributed control reconfiguration strategies for directed switching topology networked multi-agent systems are developed and investigated. The proposed control strategies are invoked when the agents are subject to actuator faults and while the available fault detection and isolation (FDI) modules provide inaccurate and unreliable information on the estimation of faults severities. Our proposed strategies will ensure that the agents reach a consensus while an upper bound on the team performance index is ensured and satisfied. Three types of actuator faults are considered, namely: the loss of effectiveness fault, the outage fault, and the stuck fault. By utilizing quadratic and convex hull (composite) Lyapunov functions, two cooperative and distributed recovery strategies are designed and provided to select the gains of the proposed control laws such that the team objectives are guaranteed. Our proposed reconfigurable control laws are applied to a team of autonomous underwater vehicles (AUVs) under directed switching topologies and subject to simultaneous actuator faults. Simulation results demonstrate the effectiveness of our proposed distributed reconfiguration control laws in compensating for the effects of sudden actuator faults and subject to fault diagnosis module uncertainties and unreliabilities.

1. Introduction

The areas of cooperative control and multi-agent systems have received extensive attention in the past few years due to their applications in areas where either human involvement is dangerous or impossible. The works in [48,10,49,51] consider the problem of multi-agent systems from various control related perspectives. During any cooperative task, agents' actuators, sensors, or their physical components may become faulty that can prevent the team from reaching its objectives or increase the cost of the agents cooperation. In safety critical missions, the vehicles should have the capability to cope with unexpected events and avoid catastrophic failure. For instance, the crash of the Boeing freighter in 1992 could have been avoided if its control laws were reconfigured to manage it land safely [29]. Motivated by the above, the fault recovery and control reconfiguration problems have been extensively studied in the literature as in [46,47,28], to name a few.

In this paper, we consider the control reconfiguration problem of multi-agent systems subject to these types of actuator faults and under switching network topologies. This problem is distinct from the control design problem of healthy multi-agent systems as studied in [48,10,49,51,41] and [18]. In [9], a comprehensive literature review on consensus control of multi-agents was conducted for healthy systems. Our considered problem challenges here are different from the previous works in the literature in the sense that our problem should be practically solved on-line and by using only local information. This is due to fact that faults occur at unknown times, have unknown patterns, and the FDI information are also available locally, while the healthy consensus control problems can be solved off-line and by potentially using the entire team information. Moreover, due to the information sharing structure of multi-agent systems, the fault-tolerant control approaches that have been proposed in the literature for single agent systems [46,47,28] cannot and are not suited and applicable to multi-agent systems.

The problem of fault recovery and control reconfiguration in multi-agent systems is more challenging as compared to that of a single agent, and has been studied only in recent years. In [39,1,50,7,43,42,13,14], the control reconfiguration problem in networks with fixed topology is considered. In [39,1], a high-level supervisor was proposed to address the formation flight problem in multi-agent networks subject to loss of effectiveness faults

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(LOE). In [50,7,43,42] adaptive control strategies were employed to ensure that agents reach a consensus even when the agents are subject to actuator faults that do not cause rank deficiency in the input channel matrix. In [13,14], a network with undirected fixed topology network was considered and distributed reconfiguration strategies are presented to stabilize the consensus errors of a single faulty agent subject to LOE fault without destabilizing the consensus errors of the agents in the neighboring set of the faulty agent. In [32,35], the control reconfiguration problem in switched topology networks was studied. In [32], a reconfigurable control strategy was proposed to guarantee state synchronization in a team of Euler-Lagrange systems, whereas in [35] a team of LTI systems subject to LOE actuator faults was studied and a two-level, i.e. the agent-level and the team-level reconfiguration strategies are presented. Some recent results have also appeared in [31] dealing with fault-tolerant and adaptive control strategies for multi-agent systems. In this work, the results of the works [13,14] are extended to a multi-agent network with directed switching topologies subject to LOE as well as stuck and outage faults.

In this work, a reconfigurable control law is proposed to ensure that all the agents can follow the leader (that is directly in communication with *only a very small* number of agents), and minimize the team performance upper bound in a faulty team under directed switching network topology. The loss of effectiveness (LOE), outage and stuck faults in the agents actuators are considered. The proposed approach is **(a)** fully distributed, **(b)** does not require sharing any global information, and **(c)** has the capability to compensate for the outage fault that cause rank deficiency in the input channel matrix, unlike the works in [39,1,13,14,50,7,43,42,32,35] that either consider only the LOE fault or assume that the rank of the input channel matrix remains unchanged after the fault occurrence. When the network topology switches, an agent's neighboring set becomes time-varying that makes the approaches that are proposed for fixed topology networks mostly ineffective, and the reconfiguration problem more challenging.

This paper is an extension of the work that has appeared in [16,15] in the following perspectives. First, in [16], the network topology is assumed to be fixed and undirected, whereas in the current paper we consider directed and switching network topologies. Second, [16] does not consider the possibility of simultaneous faults in multiple agents, whereas in this work we do consider and manage the team under this scenario. Third, in this work we provide an upper bound on the entire team cost, whereas in [16] the control recovery cost is designed to only ensure that the local cost is minimized. Finally, in [15] the stuck fault case is not considered and it only uses the quadratic Lyapunov function approach and not the convex hull function methodology. More detailed and comprehensive simulation scenarios are considered here as well as formal mathematical proofs and derivations are included in the current work.

To tackle the problems that were identified above, in this paper, first a control reconfiguration problem is defined and then transformed into *two* optimization problems in which one is subject to a time-invariant dynamical system and the other is subject to a linear discontinuous system. It is well-known that the existence of a quadratic Lyapunov condition is the necessary and sufficient condition for stability of an LTI system, however, when the system is not LTI that statement does not necessarily hold anymore. This motivates that one uses non-quadratic Lyapunov functions, e.g. Polynomial Lyapunov functions, Polytopic Lyapunov functions, and piecewise quadratic Lyapunov functions to ensure derivation of less conservative results. The main advantage of non-quadratic functions is that they all provide necessary and sufficient conditions for stability, however in [21] it was shown that the degree of the required polynomial even for a system with a moderate low order may be exceedingly very large.

In [22,23], convex hull Lyapunov functions were introduced to study stability and convergence rates of linear differential inclusion (LDI) systems through matrix inequalities. The provided conditions using convex hull functions are sufficient but do provide significant performance improvements over those of quadratic Lyapunov functions. In the work in [6], the composite Lyapunov functions are employed to design consensus in a team of healthy agents and under undirected network topology and in [5] an optimization algorithm for selecting the optimal gains is proposed. In [27,36] the authors have also considered Lyapunov functions for developing consensus control of multi-agent systems. Motivated by the above, in this work we employ quadratic as well as convex hull (composite) Lyapunov functions to select the recovery control gains for a team of agents subject to directed network topology and actuator faults. Our main motivation for using convex hull functions is to improve and minimize the overall cost of reaching the consensus in the faulty multi-agent team.

Based on the above discussion and to summarize, the main *contributions* of this work can be stated as follows:

1) Distributed reconfigurable control laws for a team of multi-agent systems with directed switching topology networks are proposed. The developed strategies do not require sharing any global information and guarantee that agents simultaneously follow the leader states, while a specified team performance index bound is minimized.
2) The proposed distributed reconfiguration control strategies are capable of simultaneously recovering from a single fault as well as concurrent faults that are injected into the multi-agents actuators.
3) Our proposed recovery control laws are capable of managing three types of actuator faults, namely the LOE, the outage, and the stuck faults, subject to uncertainties, inaccuracies, and unreliabilities that are present in the FDI module detection and estimation information.

The remainder of this work is organized as follows. The required background material and problem formulation are provided in Section 2. In Section 3, our proposed cooperative control recovery approach is developed and presented. In Section 4, our proposed approach is applied to a team of autonomous underwater vehicles (AUVs) and simulation results are presented. Finally, Section 5 concludes the paper.

2. Background and problem formulation

2.1. Graph Theory

The communication network among $N+1$ agents can be represented by a graph. A directed graph $\mathcal{G}(t) = (V, E(t))$ consists of a nonempty finite set of vertices $V = \{v_0, v_1, \ldots, v_N\}$ and a finite set of arcs $E(t) \subset V \times V$. The i-th vertex represents the i-th agent and the directed edge from i to j is denoted as the ordered pair $(i, j) \in E(t)$, which implies that at time t the agent j receives information from the agent i. The neighboring set of the i-th agent in the network is denoted by $\mathcal{N}_i(t) = \{j | (j, i) \in E(t)\}$. The adjacency matrix of the graph $\mathcal{G}(t)$ is given by $G(t) = [g_{ij}(t)] \in \mathbb{R}^{(N+1)\times(N+1)}$, where $g_{ij}(t) = 1$ if $j \in \mathcal{N}_i(t)$, otherwise $g_{ij}(t) = 0$. The Laplacian matrix for the graph $\mathcal{G}(t)$ is defined as $L(t) = D(t) - G(t)$, where $D(t) = \text{diag}\{d_i(t)\}$ and $d_i(t) = \sum_{j=0}^{N} g_{ij}(t)$.