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Cooperative adaptive output feedback control for nonlinear multi-agent systems with actuator failures

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This paper considers the cooperative adaptive output feedback control problem for nonlinear multi-agent systems with actuator failures. By constructing local filters to estimate the unmeasurable states, an effective cooperative adaptive fault-tolerant controller is developed. Furthermore, by introducing additional local estimators to estimate the unknown parameters involved in its neighbor's dynamics, the extra transmissions of online parameter estimators among the linked subsystems are avoided. In addition, it is proved that the proposed control protocol guarantees the consensus output tracking errors converge to an adjustable neighborhood of the origin and all signals in the closed-loop systems are bounded. Finally, a simulation example is given to illustrate the effectiveness of the proposed control scheme.

1. Introduction

In recent years, tremendous interest has been drawn to the distributed cooperative control of multi-agent systems (MAS) due to the broad applications in mobile robot networks, distributed sensor networks and unmanned air vehicles, etc [1–4]. Consensus is a significance issue in cooperative control. The main work of consensus is to design controller with the neighbors' information such that all agents reach an agreement. Generally, the consensus can be broadly classified into leaderless consensus [5–10] and leader-following consensus [11–14]. The objective of leaderless consensus is to design distributed controllers for the MAS such that all agents converge to a common trajectory. If the trajectory is formed by a dynamic which is called the leader, this problem is the corresponding leader-following consensus.

However, many practical systems in engineering are inherently nonlinear. Therefore, the consensus for nonlinear MAS has recently received increasing attentions [15–23]. The results [15] and [16] solved the consensus for first-order nonlinear MAS. This result is extended to the consensus for second-order nonlinear MAS with uncertainty in [17]. Cooperative tracking control for higher-order nonlinear MAS with matched uncertainty is developed in [18]. Wang et al. [19] used the backstepping technique to solve the consensus for a class of nonlinear MAS with mismatched unknown parameters. To deal with "explosion of complexity" problem in backstepping technique, the results [20] and [21] proposed the dynamic surface approach and command filtered technique respectively to solve the consensus for nonlinear MAS with unmatched uncertainty in strict-feedback form. Although the literatures have made some efforts, they all assume that the state information is measurable. However, in many practical applications, some state information cannot be available. So it is significant to develop an output feedback controller for nonlinear MAS. The work [22] considered the synchronized tracking control for nonlinear MAS with matched uncertainty by using state and output information. The result [23] addressed the output feedback consensus linear MAS with matched nonlinear functions. However, the consensus for nonlinear MAS with unmatched nonlinear functions cannot be considered.

On the other hand, actuator failures may lead to performance deterioration or even instability of this system. Although the fault-tolerant control (FTC) has been extensively studied [24–28] during the past two decades, it is only in recent years that the FTC for MAS receive attention from references [29–34]. The work [31] studied the performance of a team of unmanned vehicles (agents) that are subject to some actuator faults in forms of loss of effectiveness and lock-in-place. The fault-tolerant consensus was further considered in [32] for linear MAS with actuator faults. In [33], a cooperative fault-tolerant controller scheme was proposed to ensure that all agents synchronize to the leader in spite of actuator

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bias faults. Although these efforts, there are still no result on the cooperative output feedback control for nonlinear MAS with actuator failures.

Inspired by the previous works, this paper considers the cooperative adaptive output feedback control problem for nonlinear MAS with actuator failures and unmatched nonlinear. It is assumed that the leader signal y_0 and its derivative up to the second-order are continuous and bounded. Under this assumption, the dynamic surface technique is extended to solve the "explosion of complexity" problem in standard backstepping method. Furthermore, the Kreisselmeier filters are proposed to estimate the unmeasurable states for the system with unknown parameters. In addition, it is proved that the consensus output tracking errors converge to an adjustable neighborhood of the origin and all signals in the closed-loop system are semi-globally uniformly ultimately bounded. Finally, an example is given to illustrate the effectiveness of the designed control scheme. Compared with the existing works, the main contributions of this paper are the following aspects:

1. This paper is the first trial to consider the cooperative adaptive output feedback control problem for nonlinear MAS with actuator failures. Compared with the state feedback consensus in the references [20–22] and [32,33], the partial state information is unavailable. In order to solve this problem, the Kreisselmeier filters are used to estimate the unmeasurable states.
2. For the standard backstepping approach [19,35] and [36] in nonlinear system with actuator failure, it requires the repeated differentiations of the virtual controllers. Therefore, the complexity of the controller will be dependent on the number of agents and the relative degree. As the number of agents and the relative order increase, the complexity of the distributed controller will increase accordingly, which will lead to unacceptable computational burden and will be a restriction for real-time implementation. In order to reduce the complexity, first-order filters are proposed to avoid the repeated differentiations of the virtual controllers. So this method is less complicated.
3. By introducing additional local estimators to estimate the unknown parameters involved in its neighbor's dynamics, the extra transmissions of online parameter estimators among the linked subsystems are avoided.
4. By using adaptive mechanism, which is driven by the consensus errors, the controller parameters are adjusted online, and then the influence of actuator faults is compensated automatically.

Notation: The norm of a vector $\bullet$ is defined as $\|\bullet\|$. $R^{p\times q}$ represents the set of real matrices with the dimensional $p\times q$. I denotes the identity matrix with appropriate dimensions. The transpose of matrix M is denoted as M^T. The Kronecker product of matrices A and B is symbolized by $A\otimes B$. The symmetric positive definite matrix P is denoted as $P>0$. In addition, $col\{c_1,\dots,c_n\}=[c_1^T,\dots,c_n^T]^T$ with $c_i\in R^{n_i}$.

2. Preliminaries and problem statement

2.1. Basic graph theory

Let $\mathcal{G}=(\mathcal{V},\mathcal{E})$ be a graph consists of nodes $\mathcal{V}=\{v_1,v_2,\dots,v_N\}$ and edges $\mathcal{E}\subseteq\mathcal{V}\otimes\mathcal{V}$. An edge e_{ij} in $\mathcal{G}$ is denoted by the ordered pair of vertices (v_j,v_i), where v_j and v_i are called parent and child vertices, respectively. The node i is called a neighbor of node j, if $e_{ij}\in\mathcal{E}\Longleftrightarrow a_{ij}>0$ which means that node i can obtain information from node j. The set of neighbors for node i is defined as $\mathcal{N}_i=\{v_i\in\mathcal{V}:e_{ij}\in\mathcal{E},j\neq i\}$. The directed path in a directed graph $\mathcal{G}$ is composed of a series of edges. The directed graph $\mathcal{G}$ has a directed spanning tree if there exists at least one node that has directed paths to all other nodes. The adjacency matrix $\mathcal{A}$ of the digraph $\mathcal{G}$ has the following elements $a_{ij}=0$, if $e_{ij}\notin\mathcal{E}$ and $a_{ij}=1$ if $e_{ij}\in\mathcal{E}$. The Laplacian matrix $\mathcal{L}$ has the following elements $\mathcal{L}_{ij}=-a_{ij}$ if $i\neq j$ and $\mathcal{L}_{ii}=\sum_{j\neq i}a_{ij}$. This paper considers the digraph $\mathcal{G}$ with the Laplacian matrix $\mathcal{L}$.

2.2. Nodes dynamics and fault model

Consider the MAS consisting of N followers, labeled as $1,\dots,N$. The dynamics of the followers can be expressed as follows [35,36,38]:

$$\begin{cases}\dot{x}_{i,j}=x_{i,j+1}+\varphi_{i,j}(y_i), j=1,\dots,\rho-1\\ \dot{x}_{i,\rho}=x_{i,\rho+1}+\varphi_{i,\rho}(y_i)+\sum_{j=1}^{m}b^i_{n-\rho,j}\beta^i_j(y_i)u_{ij}\\ \vdots\\ \dot{x}_{i,n-1}=x_{in}+\varphi_{i,n-1}(y_i)+\sum_{j=1}^{m}b^i_{1,j}\beta^i_j(y_i)u_{ij}\\ \dot{x}_{in}=\varphi_{i,n}(y_i)+\sum_{j=1}^{m}b^i_{0,j}\beta^i_j(y_i)u_{ij}\\ y_i=x_{i1}\end{cases}\tag{1}$$

where $x_i=[x_{i1},\dots,x_{in}]^T\in R^n$, $y_i\in R$, $u_{ij}\in R$ are the state, output and input vector with $i=1,\dots,N$, $j=1,\dots,m$, respectively, ρ is the relative degree, b^i_{rj} are unknown parameters and $\varphi_i(y_i)=col\{\varphi_{i1},\dots,\varphi_{in}\}$ are known smooth nonlinear functions, where $j=1,\dots,m$, $r=1,\dots,n-\rho$ and $\beta^i_j(y_i)\neq 0$, for any $y_i\in R$. The signal of the leader node (labeled 0) is y_0.

Assumption 1. The directed graph $\mathcal{G}$ contains a spanning tree with the leader as the root node.

Lemma 1 (*Zhang and Lewis [18], Qu [37]*). *If Assumption 1 holds, the matrix $\mathcal{L}+\mathcal{B}$ is nonsingular. Where $\mathcal{B}=diag\{a_{10},\dots,a_{N0}\}$ and $a_{i0}=1$ denotes that the i-th subsystem can obtain information from the leader, otherwise $a_{i0}=0$.*

Remark 1. Similar to references [19,20], Assumption 1 is a necessary condition for networks connectivity of digraph.

2.3. The actuator failures model

This paper considers the actuator failures containing stuck, outage and loss of effectiveness. As described in references [10,35,36,38], the actuator failures are defined as

$$u_{ij}(t)=\overline{u}_{ij}(t)+\overline{d}_{ij}(t),\quad t\geq t_j,\ j\in\{1,\dots,m\}\tag{2}$$

where failure index j, failure time instant t_j and failure value $\overline{u}_{ij}$ are unknown and

$$\overline{d}_{ij}(t)=\sum_{l=1}^{h}\overline{d}_{ij,l}(t)f_{ij,l}\tag{3}$$

for some known bounded scalar signals $f_{ij,l}$ and some unknown scalar constants $\overline{d}_{ij,l}$ with $l\in\{1,\dots,h\}$ and $j\in\{1,\dots,m\}$.

Suppose p_k actuators failing at t_k, i.e., for $t_k\leq t\leq t_{k+1}$, there are $p=\sum_{i=1}^{k}p_i$ failed actuators with $k=1,\dots,q$, $t_0<t_1<\cdots<t_q<\infty$ and $t_{q+1}=\infty$; For the jth actuator of follower i, $v_{ij}(t)$ and $u_{ij}(t)$ represent the input and the output that has failed under the faulty, respectively. Then, the actuator fault is defined as