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Research article

Synchronization of multiple 3-DOF helicopters under actuator faults and saturations with prescribed performance

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ABSTRACT

The distributed cooperative control strategy is proposed to make the networked nonlinear 3-DOF helicopters achieve the attitude synchronization in the presence of actuator faults and saturations. Based on robust adaptive control, the proposed control method can both compensate the uncertain partial loss of control effectiveness and deal with the system uncertainties. To address actuator saturation problem, the control scheme is designed to ensure that the saturation constraint on the actuation will not be violated during the operation in spite of the actuator faults. It is shown that with the proposed control strategy, both the tracking errors of the leading helicopter and the attitude synchronization errors of each following helicopter are bounded in the existence of faulty actuators and actuator saturations. Moreover, the state responses of the entire group would not exceed the predesigned performance functions which are totally independent from the underlaying interaction topology. Simulation results illustrate the effectiveness of the proposed control scheme.

1. Introduction

Research on cooperative multiple unmanned aerial vehicle (UAV) systems has drawn increasing attention for their promising potential in a variety of applications due to their advantages such as flexibility, task allocation and cost effectiveness [1].

For multi-UAV systems, attitude synchronization is used to describe the same attitudinal behavior of each UAV. [2,3] explore position synchronization for multiple robot systems. [4] addresses a synchronized rotation strategy for multiple spacecraft formation flying.

In order to achieve the synchronization for the multi-UAV system, the UAV group should exhibit a fault-tolerance capability if one or more individuals suffer from faults. Due to the state information sharing between UAVs which may also lead to the propagation of the information of the faulty UAVs, the entire system must react cooperatively to minimize the fault effect on the stability and performance. Therefore, a fault tolerant cooperative control should be well designed to deal with this issue.

Fault tolerant cooperative control for multi-agent systems with actuator faults still has not been fully investigated in the literature. For linear multi-agent systems, a hierarchical framework subject to the loss of control effectiveness which can solve the cooperative fault accommodation problem in formation flight of multiple unmanned vehicles is proposed in Refs. [5–7]. Semi-decentralized optimal control strategy [8], fault compensation based on fault diagnosis or estimation [9–14] and fault tolerance based on topology reconfiguration [15] are several other methodologies to deal with the same problem. For nonlinear multi-agent systems, the problem of stochastic consensus in nonlinear agents with state-dependent noise perturbations and repairable actuator failures is investigated in Ref. [16]. The consensus problem for the nonlinear multi-agent systems with the actuation faults can be solved by utilizing a robust fault-tolerant control scheme [17].

Actuator saturation is another critical issue that needs to be tackled in fault tolerant control design [18]. In real applications, the output of UAV actuator always has the saturation limit. When actuator faults occur, in order to maintain the maneuvering performance, the required control effort may quickly saturate the actuators. Thus, further control effort would not result in any variation in the actuator output after the saturation. Consequently, the system may become unstable. Robust output feedback attitude stabilizer [19,20], modified fault tolerant controllers based on adaptive control [21,22] or sliding mode control [23,24] are several specific methodologies to design the fault tolerant control laws

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under the constraint of actuator saturation for spacecraft. Barrier Lyapunov function based adaptive cooperative control methods are proposed in Refs. [25,26] to deal with the input saturations for multi-agent systems with actuator faults.

Although some methods (such as [27,28] have been developed to solve the prescribed performance control problem for single systems, few procedures exist to make the transient behavior of multi-agent systems bounded by some prescribed performance functions which are always highly affected by the graph topology. For multi-agent systems with high order, the system transient can be bounded by *a priori* defined time-dependent constraints in Ref. [29], following the same problem for multi-agent systems with single order [30]. However, to our best knowledge, there are no work involving the prescribed performance control problem for multi-agent systems in the presence of actuator faults.

In this paper, a fault tolerant cooperative control scheme is proposed for multiple 3-DOF helicopter systems to maintain their attitude synchronization and tracking performance in spite of actuator faults and saturations. Additionally, the system transience of the entire group is bounded by a set of prescribed performance functions. The main contributions of this work can be summarized as three points. First, with the proposed distributed cooperative control method based on robust adaptive control, both the tracking errors of the leading helicopter and the attitude synchronization errors of each following helicopter are bounded regardless of the actuator faults. The second contribution is the ability of the proposed design methodology to prevent the distributed controllers from actuator saturation during the operation in spite of the actuator faults. Furthermore, the state response (both transient and steady performance) would not violate the requirement of the prescribed performance which are fully independent from the underlying interaction topology and the severity of the faults. Simulations are conducted to make a comparison with the control protocols reported in Ref. [17] to point out the better performance properties of the proposed control methodology.

The rest of this paper is organized as follows: Section 2 presents the problem formulation, Section 3 gives the details of both fault tolerant cooperative control design and the stability analysis. Section 4 shows the simulation results, and Section 5 gives the conclusions.

2. Problem formulation

Consider a group of homogenous 3-DOF helicopters, and each 3-DOF helicopter is the attitude system of a twin-rotor UAV (see Fig. 1).

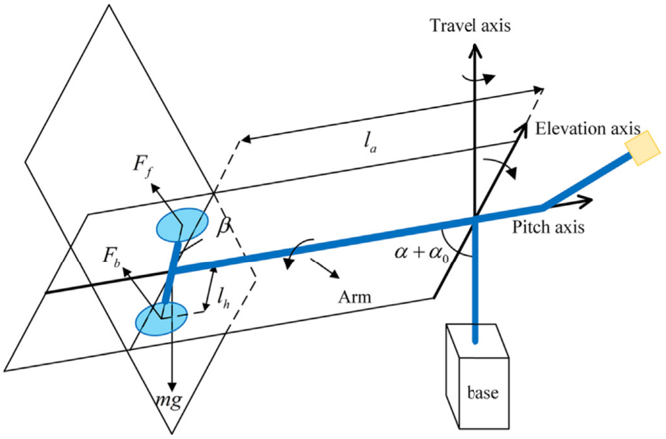

Fig. 1. The schematic diagram of 3-DOF helicopter.

2.1. The dynamics of 3-DOF helicopter

The dynamics of three angular motions of one helicopter are shown as follows [31,32].

$$\begin{cases} J_e\ddot{\alpha}=K_f l_a\cos\beta\left(V_f+V_b\right)-mgl_a\sin(\alpha+\alpha_0) \\ J_p\ddot{\beta}=K_f l_h\left(V_f-V_b\right) \\ J_t\ddot{\gamma}=K_f l_a\sin\beta\sin(\alpha+\alpha_0)\left(V_f+V_b\right)+K_f l_h\cos(\alpha+\alpha_0)\left(V_f-V_b\right) \end{cases} \tag{1}$$

where $\alpha,\ \beta,\ \gamma$ denote the elevation, pitch and travel angles, respectively. α_0 denotes the initial angle between the helicopter and base. $J_e,\ J_p,\ J_t$ are the moments of inertia with the respect to the elevation, pitch and travel axes, respectively. K_f is the force coefficient of the propeller, l_a is the distance from the travel axis to helicopter body, l_h is the distance from pitch axis to each rotor, m is the effective mass, g is the gravity. $V_f,\ V_b$ are the respective voltages applied to the front and back motors.

Because travel motion is fully determined by the other two motions, we only consider elevation and pitch motions of the system in this work. This consideration is well accepted in the literature such as [31,32].

2.2. Graph theory

The undirected graph can always describe the connections among a multi-helicopter system. Given an undirected graph $\mathscr{G}\triangleq(\mathscr{V},\mathscr{E})$, it consists of nodes $\mathscr{V}=\{1,2,\dots,n\}$ and undirected arcs $\mathscr{E}=\{\mathscr{E}^1,\dots,\mathscr{E}^m\}$. Each undirected arc is a pair of nodes as $(i,\ j)\in\mathscr{E}$, which implies that node i and j can exchange information. The neighbor set of node i is denoted by $N_i\triangleq\{j\in\mathscr{V}|(j,i)\in\mathscr{E}\}$. The weighted adjacency matrix of graph $\mathscr{G}$ is defined as $\boldsymbol{A}=[a_{ij}]^T$, where $a_{ij}>0$ if $(i,\ j)\in\mathscr{E}$, otherwise, $a_{ij}=0$, moreover, a_{ii} equals to 0 for all $i\in\mathscr{V}$. The Laplacian matrix is defined as $\boldsymbol{L}=\boldsymbol{D}-\boldsymbol{A}$ with $\boldsymbol{D}=diag\{d_i\}$, where $d_i=\sum_{j\in N_i}a_{ij}$. Define a path from node 1 to node k in $\mathscr{G}$ as a sequence of arcs $(1,\ 2),\ (2,\ 3),\dots,(k-1,\ k)$, where node $m\in\mathscr{V}$ and arc $(m,\ m+1)\in\mathscr{E}$, $m=1,\dots,k-1$, and $\mathscr{G}$ is connected if there is a path from every node to each other node. If the external reference signals are only available to a certain node (called as the leading node and labeled as 1) of the undirected graph, and the access to the reference signals can be described by a diagonal matrix $\boldsymbol{B}\triangleq diag\{b_i\}$ with $b_1=1$ and $b_i=0,\ \forall i\in\{\mathscr{V}-1\}$.

Based on the definitions, the following Assumption and Lemma exist.

Assumption 1. *The topology of the considered multi-helicopter system is an undirected graph with a node having the access to the external reference signals (called as the leading node).*

Lemma 1. [29] *For a connected undirected graph $\mathscr{G}$, if a node (labeled as 1) has the access to the external reference signals, then the matrix $\boldsymbol{L}+\boldsymbol{B}$ is a nonsingular $\mathscr{M}$-matrix.*[1]

2.3. Nonlinear state equations of the multi-helicopter system under actuator faults and saturations

Loss of control effectiveness is one typical type of actuator faults, which has been discussed in Refs. [33,34] for single UAV. This

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[1] An $\mathscr{M}$ -matrix is a square matrix with non-positive off-diagonal entries and positive principal minors.

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