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Robust distributed attitude synchronization of multiple three-DOF experimental helicopters

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ABSTRACT

Multiple experimental three-degrees-of-freedom (three-DOF) helicopters that are equipped with active disturbance systems constitute an attractive platform to validate robust control strategies. In this paper, a distributed synchronization controller is developed for such a platform, where each helicopter is subjected to unknown model uncertainties and external disturbances, and the desired trajectories are generated online, communicated through a network and not accessible by all helicopters. The controller is composed of a continuous tracker and a continuous uncertainty and disturbance estimator (UDE). The tracker makes the nominal closed-loop system globally asymptotically stable, and the UDE output is used to reject total uncertainties. The conditions that ensure zero-error tracking for each helicopter are identified; for the case with nonzero error, explicit relationship inequalities between the involved design parameters and the ultimate bound of error are revealed. Experimental results of four cases demonstrate improved tracking and synchronization accuracy of using the UDE with small parameters.

1. Introduction

Modern aerial applications require higher system reliability and/or mission performance. This demand has triggered the rapidly growing research interest in networks of multiple aerial vehicles, which have great potential in both military and civil aerial missions such as coordinated monitoring, surveillance, search and rescue. In the cooperative control research of multiple aerial vehicles, it is challenging to address the nonlinear and coupling dynamics and treat unknown uncertainties and external disturbances (Danapalasingam, Leth, la Cour-Harbo, & Bisgaard, 2010; Gadewadikar, Lewis, Subbarao, & Chen, 2008; Hoffmann, Huang, Waslander, & Tomlin, 2011; Mahony & Hamel, 2004; Marconi & Naldi, 2007; Shim, Koo, Hoffmann, & Sastry, 1998). Furthermore, experimental studies are rarely used to investigate this topic.

To build an economical and practical testbed to implement the control techniques, Quanser Consulting Inc. developed a laboratory three-degrees-of-freedom (three-DOF) helicopter, as shown in Fig. 1. Although this helicopter has a simpler model than an industrial helicopter, it retains some features of an industrial helicopter and is now widely used in control education and research (3DOF helicopter system, Kutay, Calise, Idan, & Hovakimyan, 2002; Kiefer, Graichen, & Kugi, 2005; Liu, Lu, & Zhong, 2010; de Loza, Rs, & Rosales, 2013; Rios, Rosales, Ferreira, & Davilay, 2012; Rios et al., 2010). In particular, with the so-called active disturbance system (ADS), it is a promising platform to verify various robust control strategies as shown in Rios et al. (2010), de Loza et al. (2012) and Liu et al. (2013). However, these existing results appear to focus on the robust control of a single three-DOF helicopter. For cooperative control of multiple-vehicle systems (MVSs), one often encounters situations where some state trajectories of vehicles must be synchronized. For example, the attitude angles of vehicles often must be asymptotically equal in formation control problems (Ghommam, Mehrjerdi, & Saad, 2013; Liu, Shan, & Sun, 2007; Ren, 2010; Sarlette, Sepulchre, & Leonard, 2009). These facts motivate this study on the robust attitude synchronization problem of multiple three-DOF helicopters.

The trajectories of synchronized MVSs to the desired trajectories can be achieved using distributed control algorithms. Some solutions of this problem of linear systems can be found in Ren (2008), Li, Duan, and Chen (2010), Xi, Yao, and Zhong (2013) and the references therein. Several solutions for nonlinear systems were also reported in the literature (e.g., Kladis, Menon, & Edwards, 2011a, 2011b; Kladis, 2014; Menon & Edwards, 2009). In particular, to address the input disturbance and unmodeled plant dynamics, sliding-mode-control (or switching-control) approaches and adaptive-control approaches have been investigated (Das & Lewis, 2010; Hu, 2012; Khoo, Xie, & Man, 2009; Wang, Huang, Wen, & Fan, 2014; Zhang, Wang, & Guo, 2010 for examples).

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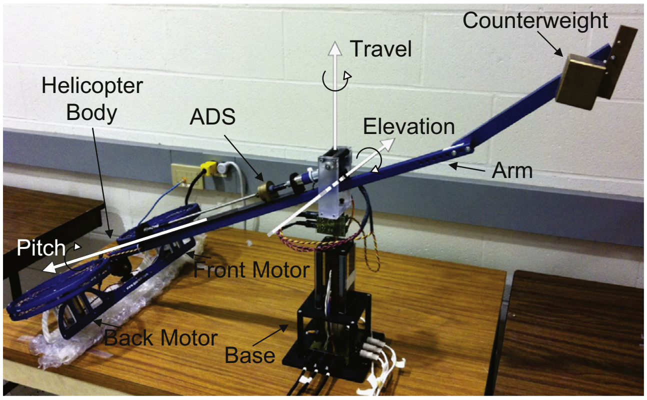

Fig. 1. Three-DOF helicopter with ADS.

Fig. 2. The four three-DOF helicopter setup at UTIAS.

In this paper, a robust distributed tracking control scheme is developed for multiple three-DOF helicopters to achieve attitude synchronization in elevation and pitch channels. In addition to a theoretical proof of its effectiveness, the scheme is also implemented and experimentally verified on the "four three-DOF helicopters" platform in Fig. 2. It is important to note that the considered helicopter model is nonlinear and subject to the unknown time-varying disturbances. More specifically, the main contributions of this work are two-fold, which are summarized as follows.

First, we propose a continuous control solution to a group of n experimental three-DOF helicopters. In the control design, lumped uncertainties and disturbances (LUDs) involved in system dynamics are systematically considered, and linear disturbance estimators are designed to generate control signals to compensate the effect of LUDs (in this work, "linear" indicates that the actual LUDs and estimator outputs satisfy a linear filter relationship). To the best knowledge of the authors, the idea to design these disturbance estimators has only been well studied for *a single disturbed vehicle* in Zhong and Rees (2004), Zheng, Chen, and Gao (2009), Talolea et al. (2010) and Liu, Chen, and Andrews (2012). With this work and our recent work (Zhu, Li, Liu, & Gao, 2014), we extend the design to MVSs. It is also important to note that this solution, which also serves as an alternative to the robust consensus tracking problem of linear second-order systems, is clearly different from the aforementioned sliding-mode-control-based or adaptive-control-based solutions.

Second, the proposed solution is experimentally implemented and verified. By designing four experimental scenarios, the benefits of using the disturbance estimator and the effect of estimator parameters on the tracking and synchronization accuracy are demonstrated. It is worth mentioning that although various strategies for distributed tracking or motion synchronization have been studied in the literature, few have been systematically verified on experimental platforms (particularly on a multiple-helicopter platform). This solution improves our previous solution (Shan, Liu, & Nowotny, 2005) by considering the disturbance compensation and allowing the desired trajectory information to be available to only partial helicopters in the group. The experimental verifications in this paper are also clearly different from these in Kutay et al. (2005), Kiefer et al. (2010), Rios et al. (2010), de Loza et al. (2012) and Liu et al. (2013), where only a single three-DOF helicopter was considered.

The remainder of the paper is organized as follows. In Section 2, some concepts about graph theory are described, and the problem is formulated. The input transformations and two supporting lemmas are presented in Section 3. The controller design and analysis results are provided in Section 4. Experimental results are presented and compared in Section 5. Concluding remarks are drawn in Section 6.

Notations: For a matrix A, A^{-1} denotes its inversion and $rank(A)$ denotes its rank. I_n refers to the $n\times n$ identity matrix. For a vector $X\in R^{n\times 1}$ and a matrix $C=[c_{ij}]\in R^{m\times n}$, $\|X\|_2=(\sum_{i=1}^{n}|x_i|^2)^{1/2}$, $\|X\|_\infty=\max_{1\le i\le n}|x_i|$, $\|C\|_\infty=\max_{1\le i\le m}\sum_{j=1}^{n}|c_{ij}|$ and $\|C\|_2=(\lambda_{max}(C^T C))^{1/2}$, where $\lambda_{max}(\cdot)=\max_i|\lambda_i|$ and λ_i are the eigenvalues. $\mathbf{0}_n$ refers to the n-dimensional column vector with all 0 elements, and $|a|$ denotes the absolute value (modulus) of a real number a.

The notations related to the i-th three-DOF helicopter, $i\in\mathcal{I}=:\{1,\ldots,n\}$, are listed as follows. α_i is the elevation angle, $\dot{\alpha}_i$ is the elevation rate, β_i is the pitch angle, $\dot{\beta}_i$ is the pitch rate, $J_{ei}>0$ and $J_{pi}>0$ are the moments of inertia about the elevation axis and the pitch axis, respectively, K_{fi} is the force constant of the motor-propeller combination, l_{ai} is the distance from the elevation axis to the center of helicopter body, l_{hi} is the distance from the pitch axis to either motor, m_i is the effective mass of the helicopter body, g is the gravitational acceleration constant, $f_{\alpha i}(t)$ and $f_{\beta i}(t)$ denote the LUDs acting on the elevation channel and the pitch channel, respectively, V_{fi} and V_{bi} are the voltages applied to the front and back motors, respectively, and V_{si} and V_{di} denote the sum and difference of V_{fi} and V_{bi}, respectively.

2. Preliminaries

2.1. Preliminaries on graph theory

The information exchange among n helicopters is modeled with a directed graph $\mathcal{G}$. The graph $\mathcal{G}$ consists of a pair $(\mathcal{V},\mathcal{E})$, where $\mathcal{V}=\{\upsilon_1,\upsilon_2,\ldots,\upsilon_n\}$ and $\mathcal{E}\subset\mathcal{V}\times\mathcal{V}$ denote the set of nodes and the set of edges, respectively. Here, node υ_i $(i=1,\ldots,n)$ represents the i-th helicopter, and an edge $(\upsilon_j,\upsilon_i)\in\mathcal{E}$ indicates that the i-th helicopter can obtain information from the j-th helicopter, i.e., node υ_j is a neighbor of node υ_i. Use N_i to denote the subset of $\mathcal{V}$ of all neighbors of υ_i. A path from υ_i to υ_j is a sequence of edges $(\upsilon_i,\upsilon_{i_1}),(\upsilon_{i_1},\upsilon_{i_2}),\ldots,(\upsilon_{i_l},\upsilon_j)$, with distinct nodes υ_{i_k}, $k=1,2,\ldots,l$, and υ_i is said to have a directed path to υ_j. If there is a node with a directed path to each of the other nodes, this node is called the root node, and $\mathcal{G}$ has a directed spanning tree.

The weighted adjacency matrix of $\mathcal{G}$, which is denoted by $A_n=[a_{ij}]\in R^{n\times n}$, is a non-negative matrix, where $a_{ii}=0$ and $a_{ij}>0$ $(i,j\in\mathcal{I}$ and $j\neq i)$ iff $(\upsilon_j,\upsilon_i)\in\mathcal{E}$. The Laplacian matrix of $\mathcal{G}$ is denoted by $L=[l_{ij}]\in R^{n\times n}$, where $l_{ij}=-a_{ij}$ if $i\neq j$, and $l_{ii}=\sum_{j\in N_i}a_{ij}$. A constant matrix $\overline{B}=diag(b_1,\ldots,b_n)\in R^{n\times n}$ is defined as: $b_i>0$ if node υ_i can access the desired trajectory information; otherwise, $b_i=0$. In this study, it is allowed that there is some $i\in\mathcal{I}$ such that $b_i=0$, i.e., the desired trajectory information is not accessible to some helicopters (as shown in Fig. 5, three of the four helicopters in the experiments cannot access the desired trajectory information). Using the previously defined matrices L and $\overline{B}$, it is easy to