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An innovative tri-rotor drone and associated distributed aerial drone swarm control

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HIGHLIGHTS

- A novel unmanned aerial vehicle platform based on a three tilted-rotor configuration is presented.
- Robust feedback linearization controller is developed to deal with the highly coupled and nonlinear dynamics.
- Distributed formation control tracking protocol is proposed to control a swarm of tri-rotor UAVs.

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ABSTRACT

This paper presents a novel unmanned aerial vehicle platform based on a three rotor configuration, which can achieve the highest level of maneuverability in all 6 dimensions (i.e. 3D position and 3D attitude). The three propellers can be tilted independently to obtain full force and torque vectoring authority, such that this new aerial robotic platform can overcome the limitations of a classic quadrotor UAV that cannot change its attitude while hovering at a stationary position. A robust feedback linearization controller is developed to deal with this highly coupled and nonlinear dynamics of the proposed tri-rotor UAV, which linearizes the dynamics globally using geometric transformations to produce a linear model that matches the Jacobi linearization of the nonlinear dynamics at the operating point of interest. A distributed formation control tracking protocol is then proposed to control a swarm of tri-rotor UAVs. The 3D position and 3D attitude of each vehicle can be controlled independently to follow a desired time-varying formation. The effectiveness of the designed control strategy is illustrated in a realistic virtual reality simulation environment based on real hardware parameters from a physical construction.

1. Introduction

In recent years, cooperative control of multi-rotor Unmanned Aerial Vehicles (UAVs) have received significant attention from both the practical engineering and academic communities due to their broad prospect in applications [1]. When working together, they are able to perform complex tasks with excellent efficiency and reliability, such as search and rescue [2], crop and weed management in agriculture [3], oil pipeline surveillance [4], etc. Aiming at more efficient configurations in terms of size, autonomy, flight range, payload capacity and other factors, some innovative vehicle platforms are developed by researchers [5]. One of such aerial robotic platforms that holds new and significant properties is the tri-rotor UAV, which is cost effective with more flexibility and agility [6,7].

The proposed tri-rotor UAV has three rotors arranged in an equilateral triangular configuration and each rotor is attached to a servo motor that can independently change the rotating direction of the propeller. Thus, complete 3D thrust and 3D torque vectoring authority is achieved, which means that the vehicle does not have a nominally upright flying orientation: it can fly in any orientation chosen by the user. Any time-dependent 3D position trajectory can be tracked at the same time as tracking any time-dependent 3D attitude trajectory. This configuration guarantees the UAV a high level of flexibility and maneuverability for attitude control and position movement. Compared to the quadrotor, this innovative configuration also requires less hover power and hence provides longer flight time [8], which makes it ideal for deployment in various missions.

To the best of the authors' knowledge, no prior literature has studied a tri-rotor UAV configuration with completely independent tilted-rotor capability on all three rotors. The tri-rotor UAV introduced in [9] only has one servo motor that is installed on the arm, which cannot hold different attitudes while hovering. A triangular quadrotor is proposed in [8], which contains a single

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large rotor fixed on the main body. This configuration requires more power to hover and causes uncompensated gyroscopic drift.

In contrast to a quadrotor UAV, which has zero angular momentum in hover, a tri-rotor UAV has persistent angular moment, and hence also gyroscopic dynamics due to the asymmetric configuration of the system which poses significant control systems complexities. Furthermore, independent attitude and trajectory tracking can and should be considered simultaneously. However, the control algorithm in [10] only considers attitude stabilization (as opposed to simultaneous independent attitude and trajectory tracking) and the control design proposed in [11] only focus on the static hovering. In this paper, both these two objectives (i.e. simultaneous independent 3D attitude and 3D trajectory tracking) are considered for the tri-rotor UAV in order to overcome the limitation of quadrotors and thus create more possibilities when performing special tasks through aerial robotic platforms.

Furthermore, swarm robotics is a field of multi-robotics where a group of robots are controlled in a distributed way to perform complex tasks in a more efficient way than using a single robot [12]. As a key control technique in swarm robotics, distributed cooperative control of multi-agent systems has also experienced a rapid growth in the research efforts from the international robotics community, which includes consensus control [13,14], rendezvous control [15], obstacle avoidance [16], formation control [17,18], etc. Formation control of multi-agent systems is hence a key active area of research which shows broad applications [19]. In applications where the goal cannot be accomplished by a single robot or a single aerial robotic vehicle due to physical limitations in its capability, formation control has been flagged as an important underpinning methodology. It can be applied to a variety of areas, such as cooperative surveillance [20], target enclosing [21], load transport [22], etc. Based on a consensus strategy, [23] proved that leader–follower, virtual structure and behavior-based formation control approaches can be unified in the framework of consensus problems. [24] discussed the formation stability problems for general high-order swarm systems, but the question how to achieve desired formation was not considered. Static formation experiments on quadrotor swarm systems based on consensus approaches is achieved in [25], while time-varying formation control of aerial swarm systems is still a vigorously active research topic with much progress still needed.

Motivated by the challenges stated above, the combination of time-varying formation control and the proposed innovative tri-rotor drone is developed and investigated in this paper. The formation control protocol for the designed aerial swarm is fully distributed. The communication topology of the network is modeled using graph theory. Robust feedback linearization [26] is used to handle the tri-rotor drone's highly coupled and nonlinear dynamics. It provides a systematic multi-input/multi-output (MIMO) method which linearizes nonlinear dynamics geometrically to match the Jacobi linearization of the nonlinear system at the operating point of interest. In contrast to classic feedback linearization which does full nonlinear dynamic inversion to produce a linear system which is simply a chain of integrators, robust feedback linearization preserves the system information at the operating point of interest. It has been successfully demonstrated [27] to provide significant robustness to both model uncertainty and external dynamics. An output feedback formation control protocol is also applied to the networked tri-rotor UAV swarm, which consists of an optimal state observer and an optimal (Linear Quadratic Regulator—LQR) distributed state feedback formation protocol. It is shown that LQR based optimal design provides a straightforward way to construct fully distributed controllers and observers that ensure stabilization and synchronization of the swarm [28].

The paper is organized as follows. Notation and preliminaries on algebraic graph theory are presented in Section 2. The nonlinear dynamical model of the tri-rotor drone is described in Section 3. Robust feedback linearization of a single tri-rotor drone is first given in Section 4 and then an optimal distributed formation controller is designed at the end of Section 4 to control a swarm of tri-rotor drones. Section 5 is devoted to the presentation of simulation results when the proposed control architecture is applied to the aerial swarm of tri-rotor drones. Conclusions are given in Section 6.

2. Preliminaries

In this section, notation, definitions and basic concepts on graph theory are introduced.

2.1. Notation and definitions

Let $\boldsymbol{I}_n \in \mathbb{R}^{n\times n}$ denote the identity matrix of dimension n and $\mathbf{1}_N \in \mathbb{R}^n$ be the vector with all entries equal to one. diag$\{a_i\}$ represents a diagonal matrix with diagonal entries a_i. The Kronecker product is denoted by $\otimes$. We use the superscript T and $*$ to denote the transpose and complex conjugate transpose of a matrix respectively. For $\lambda \in \mathbb{C}$, Re(λ) is the real part of λ.

2.2. Graph theory

Consider a weighted and directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ with a nonempty set of N nodes $\mathcal{V} = \{1, 2, \ldots, N\}$, a set of edges $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$, and associated adjacency matrix $\mathcal{A} = \left[a_{ij}\right] \in \mathbb{R}^{N\times N}$. An edge rooted at node i and ended at node j is denoted by (i, j), which means information can flow from node i to node j. a_{ij} is the weight of edge (i, j) and $a_{ij} > 0$ if $(i, j) \in \mathcal{E}$. Assume that there are no repeated edges and no self loops. Node j is called a neighbor of node i if $(i, j) \in \mathcal{E}$. Define the in-degree matrix as $\boldsymbol{D} = \text{diag}\{d_i\} \in \mathbb{R}^{N\times N}$ with $d_i = \sum_{j=1}^{N} a_{ij}$. The Laplacian matrix $\boldsymbol{L} \in \mathbb{R}^{N\times N}$ of $\mathcal{G}$ is defined as $\boldsymbol{L} = \boldsymbol{D} - \mathcal{A}$. A directed graph has or contains a directed spanning tree if there exists a node, called the root, such that there exists a directed path from this node to every other nodes.

Lemma 1 (*[29]*)**.** *If $\mathcal{G}$ contains a spanning tree, then zero is a simple eigenvalue of $\boldsymbol{L}$ with associated right eigenvector $\mathbf{1}_N$, and all the other $N - 1$ eigenvalues have nonnegative real parts.*

The following assumption of graph topology holds throughout this paper.

Assumption 1. The directed graph $\mathcal{G}$ contains a spanning tree and the root node i can obtain information from the leader node.

3. Mathematical modeling

In this section, we dynamically modeling the proposed tri-rotor UAV.

3.1. System description

The configuration of the tri-rotor UAV is illustrated in Fig. 1, which was first proposed in our earlier work [6]. The UAV has a triangular structure with three arms and a force generating unit plus a revolute joint at the end of each arm. All three arms have identical length l. Each force generating unit includes a fixed pitch propeller driven by a brushless DC motor to provide thrust. The motors can be powered by a single battery pack located at the center of mass or by three separate battery packs located at an equal distance from the center of mass and each other. The propeller-motor assembly is attached to the body arm via a servo motor that can rotate in a vertical plane to tilt the propeller-motor assembly with an angle