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Integral sliding mode formation control of fixed-wing unmanned aircraft using seeker as a relative measurement system

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ABSTRACT

This paper deals with three dimensional leader–follower formation control of unmanned aircraft systems. The main contribution of the paper is kinematic formulation of the leader–follower formation based on seeker measurements which omit the need for communication networks. Considering uncertainties in measurement of followers speeds, a robust controller is employed. Then, by proposing an integrated controller–estimator consisting of the robust controller and a disturbance compensator, keeping the formation while the leader is maneuvering is guaranteed. Simulation results verify the accuracy of the integrated controller–estimator system.

1. Introduction

In the last few years, cooperative control of unmanned vehicles progressively has been developed for a wide range of practical applications in both civil and military areas. One of basic problems in cooperative control of unmanned vehicles is formation flight of unmanned aerial systems applicable in variety of missions such as reconnaissance and surveillance, search and rescue, remote sensing, and communication relay service.

Although many successful results in this research area have been reported, the problem of leader–follower formation flight in which the follower aircraft is equipped with only onboard sensors to track the leader aircraft is an open challenging topic. Most approaches for solving autonomous formation flight assumed an active communication link between the vehicles [1–4]. The main problem of these approaches is that failures in transmitting/receiving system lead to missions failures. Hence, recently, the assumption of limited measurements for formation control of unmanned vehicles is considered in [5–7]. Furthermore, many researches have focused on vision based formation control in mobile robots [8–12]. Vision based formation flight from navigation and guidance point of view is also an actively studied topic in the literature. For instance, two-dimensional formation guidance laws for formation flight using only line of sight angles information with respect to two nearby vehicles were introduced in [13]. In [14], a pursuit guidance algorithm is proposed for formation control of unmanned aerial vehicles. In these papers, a simple model is used and leader maneuvers are not considered. However, in [15], a three dimensional formation flight simulation is proposed in which an adaptive acceleration based guidance law is designed for the purpose of tracking a maneuvering leader aircraft. Moreover, in [16], a combination of adaptive output feedback and backstepping techniques is used for a line of sight based formation flight configuration of a leader and a follower aircraft. In [17], the preliminary design of a vision based sensory system for application to autonomous aerial refueling is proposed. Moreover, in [18,19], by fusion of the information of relative vision observations with the measurements of navigation sensors and global positioning system, a vision-based relative navigation framework for autonomous tight formation flight is presented.

In this paper, a formation flight strategy based on the leader–follower structure is proposed in which a team of followers track a leader trajectory in a desired geometric pattern. Application of this approach for formation flight control is common in the literature (see [20–22] for instance). However, in this work, by using airborne seekers as practical measurement systems, it is supposed that only relative measurements with respect to the leader are available for the followers. The line of sight (LOS) angles and LOS rate angles with respect to the leader are information provided by seekers [23]. In general, seekers are sorted in two classes namely: three axes seeker and two axes seeker [24]. In this paper, elevate-azimuth seekers which have two axes and can provide relative measurements in elevation and azimuth axes are considered.

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Since in the proposed control strategy in addition to the seeker measurements, speed of the follower is needed, a pressure meter is used to measure the follower speed with respect to the atmosphere which is prone to uncertainties. Therefore, an important issue for a practical control design is robustness to uncertainties. Robustness in nonlinear control can be effectively accomplished using sliding mode control. In this work, to guarantee robustness, we have used the integral sliding mode control strategy basically introduced in [25]. The main idea of this approach is considering an integral term in the sliding surface such that the system trajectories start on the sliding surface for any desired trajectory, and therefore the surface converge to zero with no transient phase [26].

Integral sliding mode controller (ISMC) is used in a broad area of robotics and aerospace researches. For example, in [27], the integral sliding mode protocols are developed to achieve accurate finite-time consensus in multi-agent systems in spite of the disturbances. In [28], ISMC is addressed as a design technique for accommodating nonlinear disturbances in multi-quadrotor autonomous control. Moreover, in [29–31], ISMC is used to control manipulator robots. In [32], station keeping, reconfiguration and precision formation control of spacecraft are performed via the use of the nonlinear integral sliding mode method. [33] is focused on problem of the leader–follower formation control of nonholonomic mobile robots with mismatched uncertainties via ISMC. However, a fundamental distinction of this work with respect to the existing studies is our different nonlinear model of the leader–follower system which results in a different stability analysis approach.

The main contributions of the paper compared with the existing results in the literature devoted to leader–follower formation flight problem can be studied in two points of view:

1. The proposed formation flight strategy is based on the seeker and speed measurement system which present a communication free formation control method which to the best of the authors' knowledge is not studied so far. To achieve this goal, a three dimensional multiinput–multioutput nonlinear state-space model for the leader–follower system is addressed which is applicable for formation flight with usual control structure.
2. In the presence of the leader maneuvering and measurement uncertainties in the followers, an integrated robust controller–estimator is designed, and the stability of the closed-loop system is theoretically proved by the Lyapunov stability criterion.

The following notations are considered in this paper. × is the cross product operator. By defining A and B as two coordination frames and Q as a vector, ${}^{A}Q$ denotes vector Q with respect to the frame A. ${}^{B}_{A}C$ shows the rotation matrix of B with respect to A and $\mathbf{D}_A Q$ indicates the derivative of vector Q expressed in term of the frame A. Note that this is a common notation in the literature [34,35].

The rest of the paper is organized as follows. In Section 2, the leader–follower relative kinematics are derived together with a representation of the state-space model of the system. In Section 3, we present an analytical formulation of the formation control strategy and the nonlinear disturbance compensator. Section 4 is devoted to numerical evaluating of the proposed strategy via an example. Finally, in Section 5, we draw conclusions and suggest future work.

2. Problem formulation

The three dimensional formation can be considered as regulation of the relative distance and relative angles of a follower with respect to a leader. These relative quantities are depicted in Fig. 1

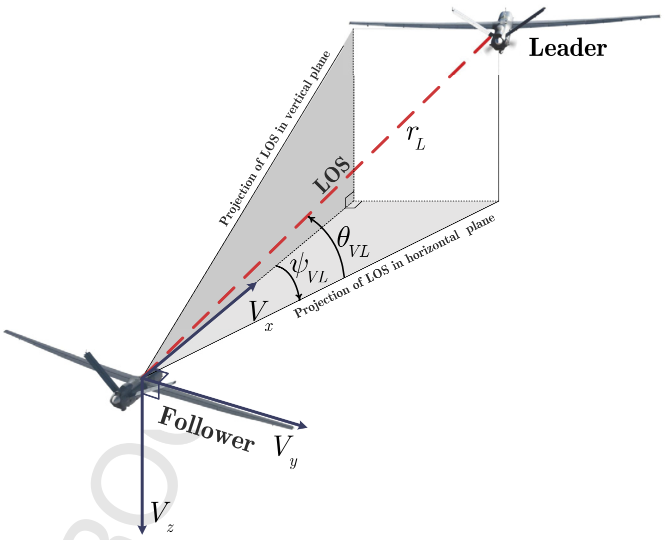

Fig. 1. The leader–follower relative kinematics.

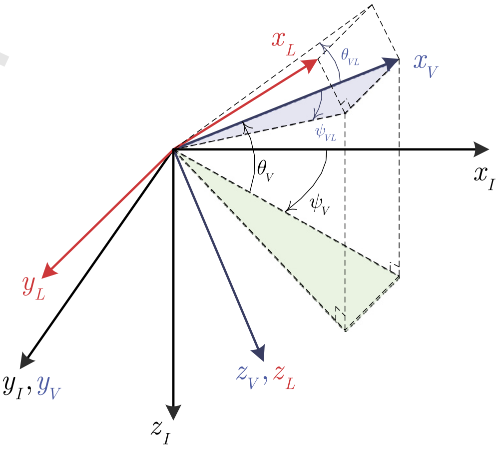

Fig. 2. Coordinate frames.

where r_L is the relative distance, and θ_{VL} and ψ_{VL} are the relative pitch and yaw angles, respectively. Accordingly, at first, a kinematic formulation for the above-mentioned problem is derived; then, the state-space representation of the problem is expressed.

2.1. Mathematical modeling

The kinematic formulation of the leader–follower structure is expressed in this subsection. At first, let us introduce three coordinate frames I, V and L as the inertial reference frame, the follower velocity frame, and the line of sight frame, respectively. The related scheme for these coordinate frames is depicted in Fig. 2.

By considering ${}^{V}V_F = \begin{bmatrix} v_F & 0 & 0 \end{bmatrix}^\top$ as the follower velocity vector with respect to the frame V, we have

$$ {}^{I}V_F = {}^{I}_{V}C\,{}^{V}V_F = \begin{bmatrix} v_F\cos\theta_V\cos\psi_V \\ v_F\cos\theta_V\sin\psi_V \\ -v_F\sin\theta_V \end{bmatrix} \tag{1} $$

where ${}^{I}_{V}C$ is the rotation matrix of I with respect to V, v_F is the follower speed, and ψ_V and θ_V are the angles of follower velocity vector with respect to the inertial reference frame (I).

By denoting $\begin{bmatrix} a_{xV} & a_{yV} & a_{zV} \end{bmatrix}^\top$ as the acceleration components in the frame V, $\mathbf{D}_I V_F$ as the derivative of V_F expressed in term of the frame I, ${}^{V}\Omega_{IV} = \begin{bmatrix} \omega_{xv} & \omega_{yv} & \omega_{zv} \end{bmatrix}^\top$ as the angular velocity

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