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Communication free leader–follower formation control of unmanned aircraft systems

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HIGHLIGHTS

- A contributed communication free formation flight in the leader–follower structure is proposed.
- Considering an airborne seeker as the relative measurement sensor, a state space model for the leader–follower system is formulated.
- In the presence of the leader maneuvering, an integrated controller–estimator is designed, and the stability is analyzed.
- The effectiveness of the proposed control strategy is illustrated via simulation examples.

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ABSTRACT

This paper proposes a formation control strategy for unmanned aircraft under which there is no need to information exchange among aircraft. Based on the measurement of relative information such as distances and orientations obtained from practical sensors, the formation is realized by employing the feedback linearization approach. By considering the leader maneuver to be unknown, a nonlinear estimator is designed and the stability of the combined controller–estimator is guaranteed. Simulation results confirm the effectiveness of the proposed formation flight control strategy.

1. Introduction

Recent technological advancements in various areas such as communication engineering and control theory have increased the demand for unmanned vehicles in civil applications especially in dangerous missions. Among these vehicles, unmanned aircraft systems offer a lot of advantages in surveillance, rescue missions, reconnaissance, etc. Especially, development of multiaircraft systems to accomplish cooperative tasks, leads to more effective, flexible, robust, and reliable results compared with single vehicles [1].

Among various problems studied in the area of multiaircraft systems, formation control defined as aircraft swarming considering constraints in relative positions, has been a challenging problem for many years. Various architectures have been studied in formation control in the literature such as behavioral-based [2–4], virtual structure [5–8], and leader–follower [9–12]. The leader–follower is the most popular one in formation control due to its ease of implementation and analysis [13]. In this architecture, a robot (the leader) moves along a trajectory while another one (a follower) keeps desired relative positions or distance and orientation from it by employing a local control strategy [9]. In general, there are three ways to establish desired relative kinematics between the leader and the follower. The first method is "communication based approach" in which state information exchanges between them via radio communication. Under another method, a "vision aided strategy" is utilized in which the follower uses a visual sensor to measure relative information while knowing self position via global positioning measurements. The last method that is considered in this paper is "vision based strategy" in which the follower only is equipped with a relative measurement sensor and does not know its global position and orientation.

Indeed, due to practical issues vision aided and vision based strategies are of particular interest for many researchers. In [9,14,15], leader–follower formation control of nonholonomic mobile robots with first-order models, using omnidirectional cameras was studied. However in [15], a radio communication between the leader and followers was considered for transmitting control

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commands. In [16], three leader–follower formation control strategies were studied. In that paper, a decentralized architecture for control of unicycle-type velocity controlled vehicles was employed and relative distances and angles were computed by using a single camera. There are also some papers that proposed control strategies in which the followers need the leader relative distance and angle to keep a formation. For instance, in [10], the trajectory tracking control of a single mobile robot has been extended to the formation control of multiple mobile robots based on the backstepping technique. In that approach, it was assumed that followers are equipped with instruments to measure their linear velocities and angular velocities as well as their orientations. Moreover, [17] studied an adaptive formation control approach for multiple mobile robots by employing relative measurements in the absence of the velocity information of the leader robot.

Vision based formation flight control from flight guidance point of view was also studied in the literature. For instance, [18] has presented an adaptive integrated guidance-control strategy for formation flight based on the backstepping approach. [19] introduced a guidance law based on the theory of pursuit curves. It was assumed that relative kinematics parameters are available to each UAV from visual measurement. Two-dimensional formation guidance laws for formation flight using only line-of-sight angle information were proposed in [20]. The main idea of that approach was to use the line-of-sight angles information with respect to two nearby vehicles to keep a formation.

The main objective of this paper is to employ seekers as sensors that provide relative measurements for formation keeping in the leader–follower architecture. A fundamental distinction of this work with respect to the existing studies is inaccessibility to the leader direction and having no communication with it. To achieve this goal, we have represented the leader–follower kinematic equations as a multiinput–multioutput system beside the application of seeker which provides a simple structure for formation control of unmanned aircraft systems. Another specification of this work is considering acceleration control command which is more practical than existing studies based on velocity control commands and first-order models. Furthermore, since the leader acceleration is not measurable, estimation of the leader maneuver as a disturbance in a combined estimator–controller is another contribution of the present work.

It is worth mentioning that formation flight control based on visual sensory systems was also studied in the literature. However, they have considered vision aided strategies which mainly are distinct from our work. For example, [21] presented the preliminary design of a vision based sensory system for application to autonomous aerial refueling. In [22], a quaternion based unscented Kalman filter is used to fuse information of relative vision observations with the measurements of navigation sensors and global positioning system. Moreover, in [23], a similar approach while using global positioning system and radio communications was introduced to precise measure of relative positions.

It is notable that due to light weight of small unmanned aircraft (normally less than 25 kg), seeker sensors are more proper for larger unmanned aircraft.

The rest of the paper is organized as follows. In Section 2, the problem formulation is proposed. Section 3 is devoted to both design and analysis of the formation control strategy. Section 4 provides numerical simulations for two examples. Finally, the paper ends with concluding remarks in Section 5.

2. Problem statement

The leader–follower architecture is formulated in this section. As depicted in Fig. 1, the objective is to control the relative distance

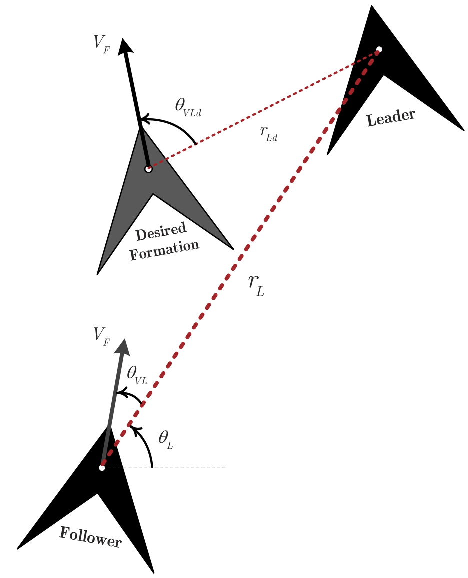

Fig. 1. Leader–follower relative kinematics in formation flight problem.

r_L and the relative angle θ_{VL} such that

$$\lim_{t\to\infty} \theta_{VL}(t) = \theta_{V\,Ld},$$
$$\lim_{t\to\infty} r_L(t) = r_{Ld}$$

where r_{Ld} and $\theta_{V\,Ld}$ are the desired relative distance and the desired relative angle, respectively. Accordingly, at first, a kinematic formulation is provided; then, the state space representation of the problem is expressed.

2.1. Kinematics formulation

In Fig. 2, three coordinate frames are introduced: the frame I is a reference frame, the frame L is line of sight (LOS) frame, and the frame V denotes the follower velocity frame whose first axis indicates the direction of the follower velocity vector.

At first, let us describe the velocity vector of the follower as

$$^{I}V_F = {}^{I}_{V}C\,{}^{V}V_F = \begin{bmatrix} \cos\theta_V & -\sin\theta_V & 0 \\ \sin\theta_V & \cos\theta_V & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_F \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} v_F\cos\theta_V \\ v_F\sin\theta_V \\ 0 \end{bmatrix} \quad (1)$$

where V_F is the follower velocity vector, $^{I}V_F$ is vector V_F with respect to the frame I, ${}^{I}_{V}C$ is the rotation matrix of I with respect to V, θ_V is the angle of the velocity vector with respect to the horizon and v_F is the follower speed. Hence, the following equation describes the acceleration components in the frame V:

$$\begin{aligned} {}^{V}D_I V_F &= \begin{bmatrix} a_{1V} \\ a_{2V} \\ a_{3V} \end{bmatrix} = D_V\,{}^{V}V_F + {}^{V}\omega_{IV} \times {}^{V}V_F \\ &= \begin{bmatrix} \dot v_F \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dot\theta_V \end{bmatrix} \times \begin{bmatrix} v_F \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \dot v_F \\ v_F\dot\theta_V \\ 0 \end{bmatrix} \end{aligned} \quad (2)$$

where $D_I V_F$ is the derivative of V_F expressed in terms of the frame I. Therefore, according to (1) and (2), we have

$$\begin{aligned} \dot x_F &= v_F\cos\theta_V, \\ \dot y_F &= v_F\sin\theta_V, \\ \dot v_F &= a_{1V}, \\ \dot\theta_V &= \frac{a_{2V}}{v_F} \end{aligned} \quad (3)$$