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Technical note

A hardware in the loop simulation testbed for vision-based leader-follower formation flight☆

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ABSTRACT

This paper proposes a hardware in the loop simulation testbed by using airborne seekers (an onboard visual tracking system) as a relative measurement sensor in the leader-follower formation flight. To the best of the authors' knowledge, this is the first study on experimental applications of airborne seekers in unmanned aircraft formation flight. The proposed structure gives an effective method to study the effects of uncertainties such as the camera process delay and the seeker measurement noises on formation keeping. Compensation of errors in visual measurements is considered as well.

1. Introduction

A significant amount of research efforts have been focused on the formation control of unmanned vehicles. Excellent surveys of formation control are found in [1,2] and [3] which review the existing results and the related control approaches. Among various architectures for formation control, the leader-follower structure is more popular in which the leader moves along a predefined trajectory while another vehicles (followers) keep desired relative distances and orientations from the leader. According to sensing capabilities, formation control can be categorized in three classes: communication-based, vision-aided and vision-based control [4]. In the vision-based formation strategy, the follower only is equipped with a relative measurement sensor and does not know its global position and orientation.

Hardware-in-the-loop (HIL) simulation is an effective technique that is used for the development and testing of control systems while some of the control loop components are simulated in a proper environment and the other components are real hardware. Today, HIL techniques are frequently used to reduce time and cost of development and prototyping of engineering systems. Advantages of HIL simulation include the possibility to observe and study system behavior in case of system faults and mechanical parts degradation in time, as well as sensor sensitivity errors [5]. Currently, extensive research is being carried out in academia and industry in the development of simulation platforms suitable for real time HIL experiments. The first approaches to HIL simulation were probably realized for (real-time) flight simulation in 1936 [6]. Nowadays, using HIL simulation is common in many industries such as aerospace systems [7–9], automotive systems [6,10,11], power systems [12–14] and robotics [15–17]. For example, in the field of unmanned aerial vehicles, [18] introduced a HIL framework for flight test on an unmanned helicopter system which includes onboard hardware, flight control, ground station and software. Moreover, in [19], a HIL platform for vision based control of unmanned aerial vehicles is proposed. In this area of research, [20] developed a HIL testbed for visual servoing of fixed wing unmanned aircraft. In that work, a visual servoing algorithm is implemented to drive servo motors that control the control surfaces. Image processing module and visual based autopilot control module are used for the unmanned aerial vehicle on-board systems.

In this paper, we introduce a HIL experimental setup to study application of an electro-optic seeker in the leader-follower formation flight of unmanned fixed wings aircraft. The airborne seeker is a target tracker which usually is used in homing guidance and provides the LOS (line-of-sight) angular rate and the measurements of target motion including relative distance and closing velocity (see [21] and [22] for more details). Recently, using airborne seekers in

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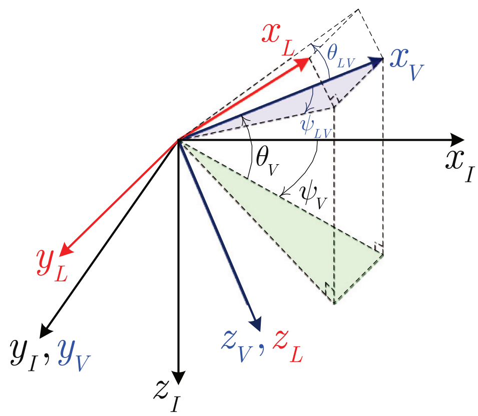

Fig. 1. Defined coordinations.

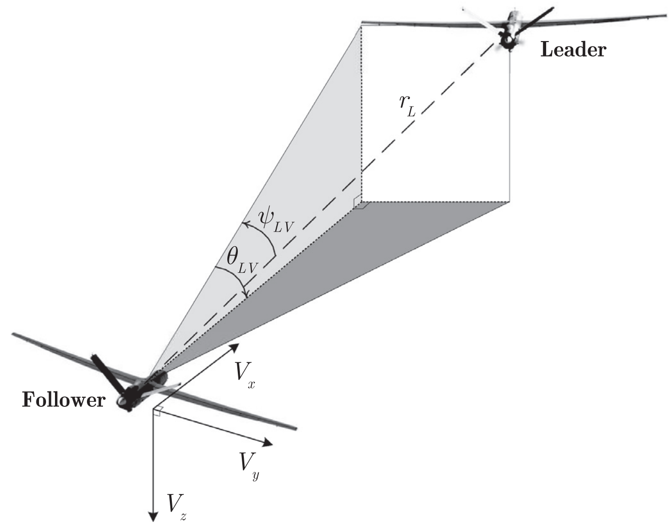

Fig. 2. Leader-follower geometry in the formation flight problem.

the leader-follower formation flight of unmanned aircraft is proposed in [23] and [4]. However, this work, is the first attempt for experimental study of the mentioned topic. Indeed, HIL is a proper facility to investigate the effect of optic sensor delay and seeker mechanism dynamics on the formation keeping. For this purpose, a three dimensional simulation for the leader-follower formation control is presented and then a seeker hardware is used in respect to the simulation using a HIL facility. In the proposed HIL setup, we fixed the seeker on a stand and used a monitor in front of it. The monitor shows a bright spot as the leader image with respect to the follower. The seeker camera locks on this spot and tracks it to regulate the desired relative angles in the formation. The real time HIL simulation results are compared with those of the fully simulated system which just contain a kinematic model of the seeker. Therefore, effects of the electro-optic seeker dynamics on the formation can be studied carefully.

The structure of the paper is as follows. Section 2 describes the leader-follower system equations in which a point mass model for the follower is assumed and the relative kinematics is expressed. Section 3 introduces the controller structure which is used for formation flight. This is followed by Section 4 which explains the experimental setup of the hardware in the loop implementation for the airborne seeker in relation with the simulation of the leader-follower system. Section 5 presents the results of the real-time hardware-in-the-loop testbed for formation control of two unmanned aircraft. Finally Section 6 summarizes the results and provides concluding remarks.

2. The leader-follower system equations

In this section, a kinematic model for the leader-follower system is introduced. For this purpose, consider Fig. 1 in which three coordinate frames *V*, *L* and *I* as the follower velocity frame, the line of sight frame, and the inertial reference frame are defined, respectively. Moreover, in Fig. 2 the leader-follower geometry for the formation flight in three dimensional is depicted. In this figure, r_L is the leader-follower relative distance. Moreover, θ_{LV} and ψ_{LV} are the leader-follower relative angles in pitch and yaw channels, respectively. A desired formation can be achieved via regulation of these three parameters to the predefined constant values.

We used an electro-optical seeker with a schematic as depicted in Fig. 3, to measure these kinematic parameters. A proper tracking loop guarantee that the measured angles θ_{VS} and ψ_{VS} converge to θ_{LV} and ψ_{LV} . On the other hand, if the optic camera is locked on the leader and the seeker, mounted on the follower, do its tracking mission carefully, the measured angles are equivalent to the relative angles in the formation geometry.

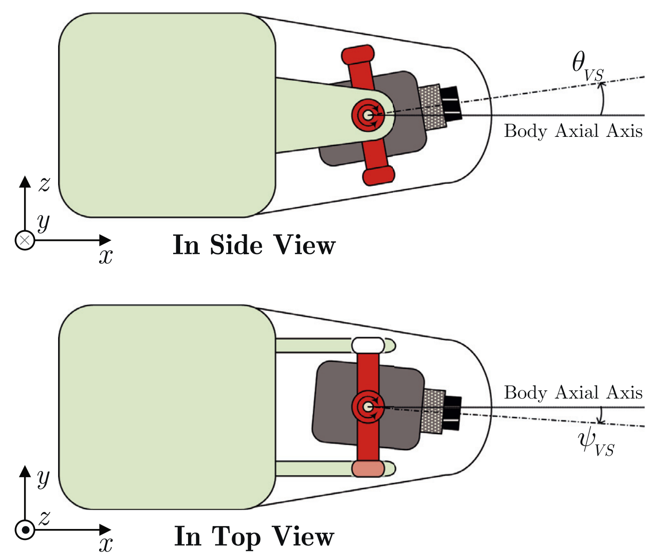

Fig. 3. Schematic of an airborne seeker.

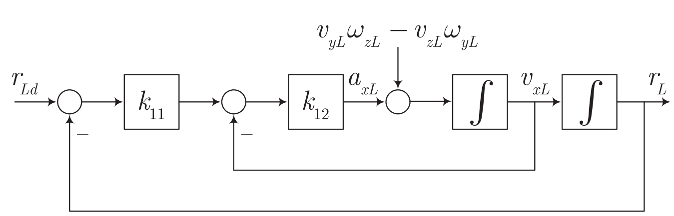

Fig. 4. The control structure for regulation of the relative distance.

Now let us to describe the leader-follower system model. By considering defined coordinate frames, motion equation of the follower can be obtained as follows [23]:

$$\begin{aligned}
\dot{x}_F &= v_F \cos\psi_V \cos\theta_V, \\
\dot{y}_F &= v_F \sin\psi_V \cos\theta_V, \\
\dot{z}_F &= -v_F \sin\theta_V, \\
\dot{v}_F &= a_{xV}, \\
\omega_{zV} &= \frac{a_{yV}}{v_F}, \\
\omega_{yV} &= -\frac{a_{zV}}{v_F},
\end{aligned} \tag{1}$$

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