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Two stage switching control for autonomous formation flight of unmanned aerial vehicles

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ABSTRACT

This paper presents an idea for controlling the formation flight of unmanned aerial vehicles. Formation flight control with a leader–follower configuration based on position and velocity errors has proven to be problematic, especially during the activation of formation flight mode with large distances between leader and follower, and with large differences in leader and follower heading angles. Proposed formation flight control scheme is composed of two stages – guidance on a leader and precise leader following. Synthesis of the two stage switching controller is described, implemented and presented. Proposed control system was checked and verified during simulation tests. Leader and follower flight parameters were presented and analyzed. Proposed control algorithm improves formation flight organization.

1. Introduction

Applicability of Unmanned Aerial Vehicles (UAVs) is very broad and it contains missions like surveillance and reconnaissance purposes, aerial surveys for agriculture, traffic monitoring, pollution control, meteorological data collection, pipeline survey, early fire detection, wildlife population tracking, data collecting for precision farming, etc. [1–4]. Field of UAV applications may be expanded by formation flight. All tasks mentioned previously can be performed more efficiently by flying in formation of UAVs. Formation flight plays a significant role in drag reduction and energy savings concepts which can lengthen the flight duration and traversed distances [5]. Moreover it can facilitate tasks such as data retransmission from long distances.

Nowadays multi-UAV operations, whose special case is a formation flight, are being intensively studied in various research centers around the world [6–10]. These studies mainly focus on formation flight aerodynamics [11–13], analysis of modern control laws [14–16] or synthesis of control laws like optimal [17], adaptive [18], sliding [19], robust [20,21], vision based [22,23] as well as nonlinear [24], where model predictive controller (MPC) with dynamic inversion was used. Classical compensation-type controllers were studied also. In [25] linear plant model was employed to design linear proportional plus integral controller formation hold autopilot. The better part of the developed and experimentally verified formation flight control systems are based on leader–follower configuration, composed of position errors between leader and follower UAVs [26]. During the activation of formation flight mode in the case of large values of position errors and large differences in leader and follower heading, leader following can be problematic and it has been proven during simulation and in flight tests.

This paper addresses the problem of formation flight control of UAVs. In the paper the new approach to the autonomous UAV formation flight control is proposed. Synthesis of the two stage switching controller is described, implemented, tested and presented. The main aims of this work are the simulation tests of proposed formation flight control system. Therefore, constructed for future field tests UAV airframe as well as the definition of its kinematics and dynamics nonlinear equation of motion creating mathematical model were described. Leader and follower onboard control system was characterized. During the tests the longitudinal and lateral positions of the UAVs (leader and follower) were stored and logged. Furthermore, waveforms of position errors were introduced to show control system quality. Two stage switching control method was compared to compensation type controller. Proposed in the paper initial guidance algorithm provides easy method of control follower UAV and prevent instabilities during large distances between leader and follower and string instabilities with more than one follower (which is indicated in literature as a problem). Moreover, switching function was modeled with hysteresis to protect against excessive switching between algorithms and to improve switching control algorithm (Fig. 8). Presented results checked and verified the developed and proposed method of formation flight control. The obtained results allowed us to evaluate

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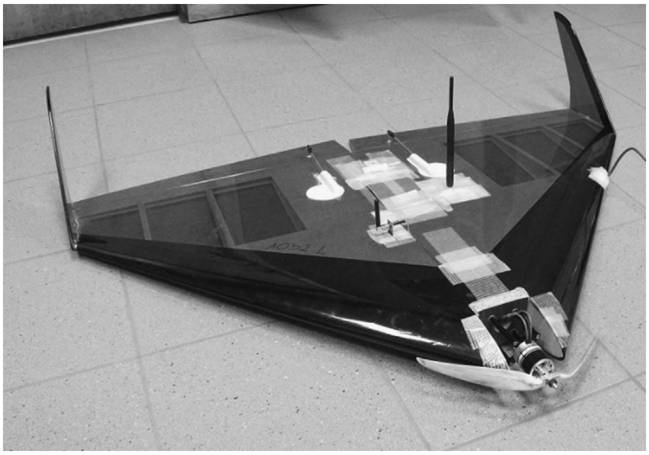

Fig. 1. Bullit 60 MAV used in the studies.

Table 1
Bullit 60 main parameters.

Parameter	Value
Wing span (b)	1.095 [m]
Total length (l)	0.770 [m]
Total mass ready to flight (m)	1.8 [kg]
Wing area (S)	49.7 [dm^2]
Mean chord (c)	0.660 [m]
Tip chord (c_t)	0.170 [m]
Propeller	14″ × 8″
Propeller area (S_p)	0.0031 [m^2]
I_x	0.091108 [kg m^2]
I_y	0.076144 [kg m^2]
I_z	0.165955 [kg m^2]
I_{xz}	0.0011547 [kg m^2]
Angle of attack (α)	3°
Trimmed airspeed (V_{trim})	14 [m/s]
Max. airspeed (V_{max})	34 [m/s]
Min. airspeed (V_{min})	11 [m/s]

the proposed two stage switching formation flight control algorithm and its efficiency and usefulness in UAV missions. Presented first stage of control algorithm highly facilitates UAV formation flight mission organization.

2. Research object

2.1. The Bullit 60

Micro air vehicle (MAV) called Bullit 60 [27] (Fig. 1) was chosen as the research object. Examined MAV is in flying wing configuration and is made of balsa wood covered with foil. MAV is powered by an electric motor located on the front. UAV wing has a symmetrical, bi-convex profile BELL 540 (modified NACA0012). Dimensions and important parameters of the test UAV are collected in Table 1.

Bullit 60 has two elevons as control surfaces. Deflecting the elevons differentially gives the same effect as ailerons and deflecting them together – the same as an elevator. Thus Bullit 60 steering surfaces allow to control its lateral and longitudinal dynamics with three control inputs – aileron and elevator as elevons as well as throttle signal.

2.2. Mathematical model

To describe the spatial motion of the UAV it is necessary to balance the forces and moments acting on it. As the result we get a system of six ordinary differential equations which have to be completed with kinematic relations.

Bullit 60 is symmetric in the x–z plane therefore the moment of inertia tensor can be defined as:

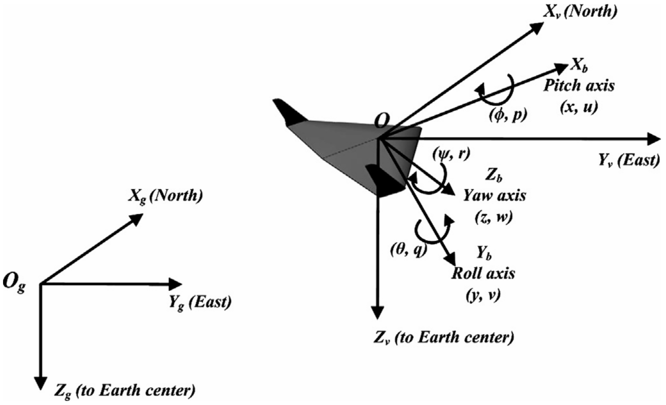

Fig. 2. Definitions of coordinate frames.

$$\hat{\mathbf{I}} = \begin{pmatrix} I_x & 0 & I_{xz} \\ 0 & I_y & 0 \\ -I_{xz} & 0 & I_z \end{pmatrix}. \tag{1}$$

Translational motion dynamics of a small UAV can be defined as follows [28,29]:

$$\begin{aligned} \dot{x} = {} & (\cos\psi\cos\theta)u + (\sin\theta\sin\phi\cos\psi - \sin\psi\cos\phi)v \\ & + (\sin\theta\cos\phi\cos\psi + \sin\psi\sin\phi)w \end{aligned} \tag{2}$$

$$\begin{aligned} \dot{y} = {} & (\sin\psi\cos\theta)u + (\sin\theta\sin\phi\sin\psi + \cos\psi\cos\phi)v \\ & + (\sin\theta\sin\psi\cos\phi - \cos\psi\sin\phi)w \end{aligned} \tag{3}$$

$$\dot{z} = u\sin\theta - v\cos\theta\sin\phi - w\cos\theta\cos\phi \tag{4}$$

$$\begin{aligned} \dot{u} = {} & rv - qw - \mathbf{g}\sin\theta \\ & + \frac{\rho V_*^2}{2m} S\left[C_X(\alpha) + C_{X_q}(\alpha)\frac{cq}{2V_*} + C_{X_{\delta_e}}(\alpha)\right] \\ & + \left[\frac{\rho S_p C_p}{2m}(k_M \delta_t)^2 - V_*^2\right] \end{aligned} \tag{5}$$

$$\begin{aligned} \dot{v} = {} & pw - ru + g\sin\phi\cos\theta \\ & + \frac{\rho V_*^2}{2m} S\left[C_{Y_0} + C_{Y_\beta} + C_{Y_p}\frac{bp}{2V_*} + C_{Y_r}\frac{br}{2V_*} + C_{Y_{\delta_a}}\delta_a\right] \end{aligned} \tag{6}$$

$$\begin{aligned} \dot{w} = {} & qu - pv + g\cos\phi\cos\theta \\ & + \frac{\rho V_*^2}{2m} S\left[C_Z(\alpha) + C_{Z_q}(\alpha) + C_{Y_p}\frac{cq}{2V_*} + C_{Z_{\delta_e}}(\alpha)\delta_e\right] \end{aligned} \tag{7}$$

where x is inertial North UAV position in $\boldsymbol{O_g X_g Y_g Z_g}$ (Fig. 2); y – inertial East UAV position in $\boldsymbol{O_g X_g Y_g Z_g}$ (Fig. 2); z – inertial Down position in $\boldsymbol{O_g X_g Y_g Z_g}$ (Fig. 2); ϕ, θ, ψ – roll angle, pitch angle, yaw angle respectively; u, v, w – body frame velocities measured in $\boldsymbol{O X_b Y_b Z_b}$ (Fig. 2); p, q, r – angular rates measured in $\boldsymbol{O X_b Y_b Z_b}$ (roll rate, pitch rate, yaw rate respectively); C_* – aerodynamic coefficients (values in Table 2); δ_a, δ_e, δ_t – aileron, elevator, throttle commands; V_* – airspeed.

The rotational motion kinematics and dynamics can be written as [28,29]:

$$\dot{\phi} = p + q\sin\phi\,\mathrm{tg}\,\theta + r\cos\phi\,\mathrm{tg}\,\theta \tag{8}$$

$$\dot{\theta} = q\cos\phi - r\sin\phi \tag{9}$$

$$\dot{\psi} = q\frac{1}{\cos\theta}\sin\phi + r\cos\phi\frac{1}{\cos\theta} \tag{10}$$