Proceedings of the 37th Chinese Control Conference
July 25-27, 2018, Wuhan, China

A Double-layer Fuzzy Controller for the Altitude of Fixed-wing Unmanned Aerial Vehicles

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Abstract:
The altitude control of miniature fixed-wing unmanned aerial vehicles(UAVs) faces with many difficulties because of the strongly coupling dynamics and high external disturbances. To deal with these issues, this paper proposes a fuzzy logic based altitude control scheme. Specifically, a double-layer fuzzy controller is developed, taking the altitude error, the measurements of the roll angle, the pitch angle and the speed of the UAV as inputs, to compensate the control performance with an additional pitch angle and speed when the UAV has large roll angles and/or sudden speed losses in winds. The member functions of the fuzzy controller are designed carefully according to numerous simulation experiment data. The effectiveness and anti-disturbance of the proposed controller are validated by a series of high-fidelity semi-physical simulations.

Key Words: Fixed-wing UAVs, Altitude Control, Wind Disturbances, Coupling Dynamics, Fuzzy Control

1 Introduction

Fixed-wing unmanned aerial vehicles (UAVs) have gained increasing interest in recent years both in military and civil applications, such as rescue, surveillance, and agricultural services [1–3].The flight control system then becomes very significant since UAVs are required to deal with complicated circumstances properly in all different applications [3,4]. The altitude control is a key issue of the flight control of miniature UAVs, for both task performance and safety reasons. The fact is small UAVs are generally designed to fly at low altitudes (normally less than 1000 meters, even no more than 100 meters) to provide a close observation of the ground objects. This low-altitude flight makes the UAVs easy to crash [3]. Therefore, the altitude holding is very important for a safe flight of small UAVs. In addition, there are many cases of small UAVs conducting cooperative tasks, such as formation flight and collision avoidance maneuvers, that highly need the UAV to take accurate altitude adjustment. However, very little attention has been specially paid to the challenges of the altitude control of fixed-wing UAVs in most existing work.

In conventional methods, the flight control of fixed-wing UAVs is decoupled into the attitude control and the guidance control problems. And the altitude control problem is always treated as an independent control loop of the guidance control. Therefore, most of the existing altitude control schemes of fixed-wing UAVs only take the pitch angle adjustment as the control scheme in a decoupled way, such as the Proportional-Integral (PI) scheme and the filtered dynamic scheme [5], the Proportional-Derivative (PD) scheme [6], the H∞ Loop-Shaping Method [7]. However, there are strong cross-couplings between the altitude and the lateral dynamics of fixed-wing UAVs in fact [8]. A large roll angle can cause a sudden altitude loss generally. Also, the wind disturbance, which is inevitable in real flights, makes great effects on the altitude control performance of miniature fixed-wing UAVs [9,10]. UAVs flying in winds can easily get speed losses and thus lead to altitude oscillations. Therefore, the altitude control of miniature fixed-wing UAVs flying at low altitudes is faced with great challenges of subjecting to strongly coupling dynamics and high external disturbances. Some work has considered the influence of wind disturbance on the altitude, however, little work has tackled these two issues together [5–10].

This paper develops a double-layer fuzzy controller mainly to tackle the challenges of altitude control of small fixed-wing UAVs. The fuzzy controller is designed as two two-input-one-output controllers, and works to compensate the control performance of a classical PD altitude controller by an additional pitch angle and velocity when the UAV has a large roll angle or flies in winds. The member functions of the fuzzy controller are well tested and designed according to the collected numerous experiment data. A large amount of comparative experiments are carried out on a high-fidelity hardware-in-loop simulation system to test the effectiveness of the proposed controller. And the results prove that the proposed fuzzy control scheme can well eliminate the altitude oscillations caused by large roll angles and wind disturbances.

2 Problem formulations

In this paper, since we only focus on the issue of altitude control of fixed-wing UAVs, assuming that the UAV flies smoothly and has no sideslip, the used kinematic equation takes the form

$$\dot{h} = V \sin\gamma, \tag{1}$$

This work is supported by the National Natural Science Foundation of China under Grant No. 61403406.

where h denotes the altitude of the aircraft, V is the ground speed, γ represents the flight path angle, which can be obtained by equation $\gamma = \theta - \alpha$. Here θ describes the pitch angle, and α is the angle of attack. Note that the attack angle only has very slight changes during the flight which can be ignored in general flights, we then have $\dot{\alpha} = 0$. Thus we can further get [11]

$$\ddot{h} = \dot{V}\sin\gamma + V\cos\gamma\dot{\gamma}, \tag{2}$$

$$\dot{\gamma} = \dot{\theta} = q\cos\phi - r\sin\phi, \tag{3}$$

$$\dot{V} = \frac{1}{m}(-D + T\cos\alpha - mg\sin\gamma), \tag{4}$$

where q and r are projections of the rotational angular velocity of the body-axis with respect to the inertial coordinates on y and z axis of the body coordinates respectively, ϕ represents the roll angle, T represents the force of engine thrust, D describes the drag force. Fig. shows the parameters involved in the longitudinal dynamic model.

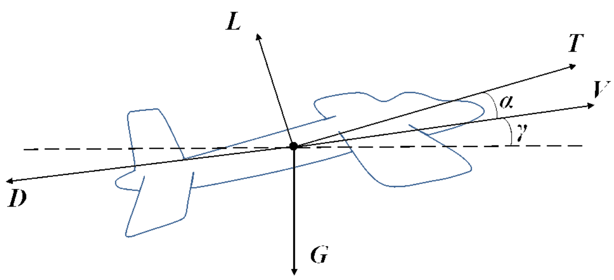

Fig. 1: Parameters involved in the longitudinal dynamic model

As equation (2) illustrates, the altitude of the vehicle is determined by the speed V, the flight path angle γ, and their derivatives. Equation (3)-(4) further show the strong cross-coupling between the flight path angle, the speed and the roll angle of the aircraft.

Since the flight path angle γ is treated as the control object in almost all conventional altitude control schemes, we then have two issues. First, this pitch-angle-adjustment altitude control scheme of fixed-wing UAVs is based on the assumption that the plane has a constant speed. However, it is general in real flights that wind disturbance causes speed losses. Also, the fixed-wing UAVs have to satisfy the minimum airspeed constraint. Thus the ground speed cannot be constant but need to change all the time. Next, it is quiet common for existing work to simplify equation (3) to a linearized equation $\dot{\theta} = q$ in a decoupled way by assuming that the roll angle $/phi$ is a very tiny value [6,7]. However, in fact, the roll angle can be more than 35 degrees for the course angle adjustments during the flight, which can produce a significant moment to the reverse direction of the lift (see Fig.). According to equation (2)-(3), both cases can bring about drastic altitude oscillations. Thus it is of great significance to design a scheme to tackle both the challenges brought by both the coupling dynamics and wind disturbances.

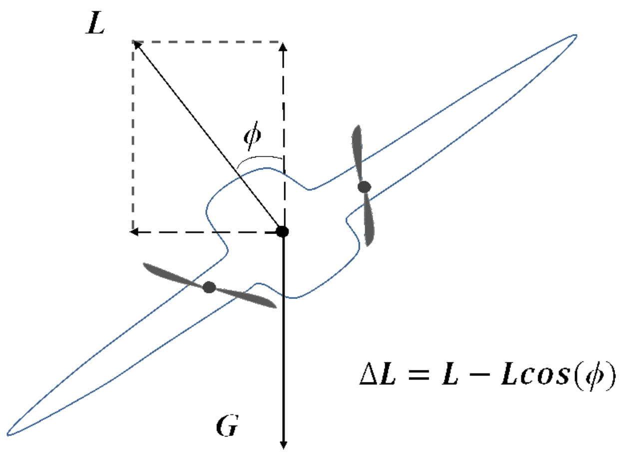

Fig. 2: the roll angle brings about a lift force loss of ΔL

3 Controllers Design

This paper proposes a double-layer fuzzy controller for the altitude control of miniature fixed-wing UAVs, to tackle the issues caused by the coupling dynamics and external disturbances, based on a classical PD controller. The PD controller, like the altitude control scheme used in most conventional methods, generating an desired pitch angle as the input of the altitude control loop, is capable to deal with small altitude errors. Thus the proposed fuzzy controller is designed only to work when the PD controller performs ineffectively. In cases when the aircraft has large roll angles or sudden speed losses, the fuzzy controller generates an additional pitch angle and speed to compensate the altitude control performance.

Equations (2)-(4) imply the complicated coupling dynamics between the altitude control and the speed as well as the roll angle of fixed-wing UAVs. Fuzzy logic based control has found extensive applications for plants that are complex and coupling, especially those nonlinear systems for which linearization method does not work effectivelly [12], and it has been proved to do better than other methods in altitude control [4]. Thus the fuzzy logic method is chosen in this paper to tackle the issues existing in the altitude control of fixed-wing UAVs.

According to the dynamical equations (2)-(4), we have the controlled variables in the altitude control loop as the total pitch angle θ and the compensation speed ΔV (The flight control system generally has an independent part to control the speed.). Except for the the initial output of the pitch angle generated by the PD controller, the outputs of the fuzzy controller are designed as $\Delta u_{f\theta}$ (the compensation pitch angle) and Δu_{fV} (the compensation speed), respectively. We have

$$\theta = \Delta u_\theta + \epsilon\Delta u_{f\theta},$$

$$\Delta V = \epsilon\Delta u_{fV},$$

where Δu_θ represents the initial desired pitch angle, $\epsilon = 1$ when the fuzzy controller works, otherwise $\epsilon = 0$.

The structure of the controller is constructed into two two-input-one-output fuzzy controllers, see equation (5)-(6).

$$\Delta u_{f\theta} = f(\phi, \theta) \tag{5}$$
$$\Delta u_{fV} = f(h_{err}, V) \tag{6}$$

Here $\Delta u_{f\theta}$ and Δu_{fV} are the final outputs of the fuzzy controller after defuzzification. ϕ, θ, V and h_{err} describe the roll angle measurement, the pitch angle measurement, the speed measurement and the altitude error, respectively, which are all the inputs of the fuzzy controller. Denote the pitch angle and the speed compensations before defuzzification as $\Delta u^*_{f\theta}$ and Δu^*_{fV} respectively. Then they are both linear functions of the fuzzed input variables:

$$\Delta u^*_{f\theta} = k_\phi \phi^* + k_\theta \theta^*,$$
$$\Delta u^*_{fV} = k_{h_{err}} h^*_{err} + k_V V^*.$$

Here ϕ^*, θ^*, h^*_{err} and V^* are the fuzzed input variables, $k_\phi, k_\theta, k_{h_{err}}$ and k_V are parameters of the fuzzy controller. After fuzzing the input variables, these parameters are generated according to the designed fuzzy rules.

The member functions are designed carefully according to the collected numerous experiment data, as well as trails and errors. In general, determining the piecewise density of member functions according to the distribution probability of the flight data can be much more effctive than those uniformly partitioned. As shown in Fig. ()-(), the member functions of input variables are designed into triangle but unsymmetrical forms. Fig. () presents that the altitude errors and the pitch angle measurement take the same form of member functions. Fig. () and Fig. () show the member functions of the speed and the roll angle measurements, respectively. Note that the designed unsymmetrical triangle form member functions perform much better than that in which member functions of all input and output variables have average segmentations. For output variables, the compensation pitch angle and speed are both designed to have five member functions. The compensation pitch angle has symmetrical triangular member functions, and member functions of the compensation speed have the same form with the input altitude error.

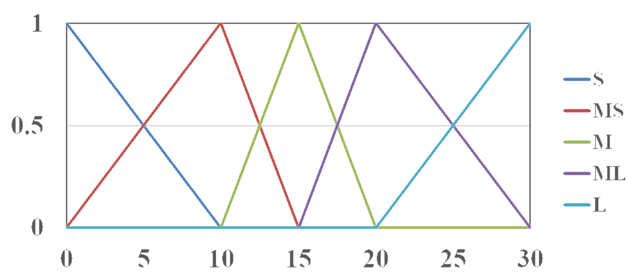

Fig. 3: Form of member functions of the altitude error and pitch angle measurement, with functions named as S (Smal), MS (Medium Small), M (Medium), ML (Medium Large), L (Large).

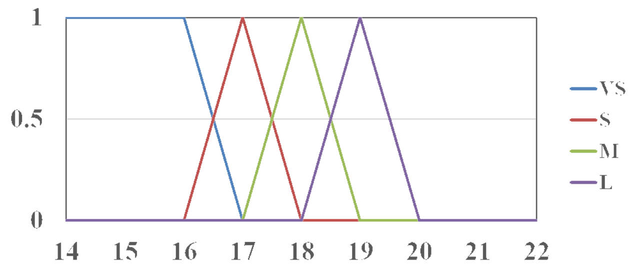

Fig. 4: Member functions of the speed measurement, namely VS (Very Small), S (Small), M (Medium), L (Large).

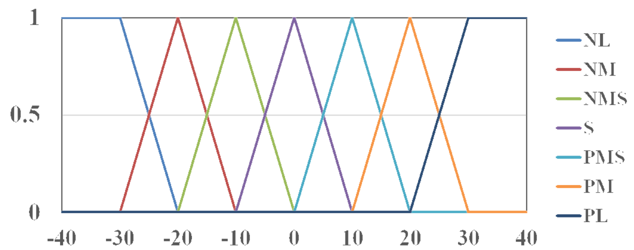

Fig. 5: Member functions of the roll angle measurement, namely NL (Negative Large), NM (Negative Medium), NMS (Negative Medium Small), S (Small), PMS (Positive Medium Small), PM (Positive Medium), PL (Positive Large).

The two decomposed controllers are both realized based on a set of IF-THEN fuzzy rules, which are shown in Tables and . In summary, the bigger the altitude error, the compensations of the speed and the roll angle are, and the larger the compensation factor of the pitch angle should be.

Table 1: Fuzzy rules of the compensation pitch angle $\Delta u_{f\theta}$.

θ \ ϕ	NL	NM	NMS	S	PMS	PM	PL
S	L	ML	MS	S	MS	ML	L
MS	ML	M	MS	S	MS	M	ML
M	ML	M	MS	S	MS	M	ML
ML	M	MS	MS	S	MS	MS	M
L	M	MS	S	S	S	MS	M

Table 2: Fuzzy rules of the compensation speed Δu_{fV}.

h_err \ V	S	MS	M	ML	L
S	MS	S	S	S	S
MS	MS	MS	S	S	S
M	M	MS	MS	S	S
ML	ML	M	MS	S	S
L	L	ML	M	MS	S

4 Experiments

The effectiveness of the proposed fuzzy logic based control scheme is validated by a series of comparative experiments in a high-fidelity hardware-in-loop (HIL) semi-physical simulation system, which is composed of an auto-pilot, a ground control station, an upper monitor Odroid, and an X-Plane simulator. During simulation experiments, the control command is sent from the ground control station to the upper monitor, and the control algorithms are running on the upper monitor which outputs corresponding control signals to the auto-pilot according to the command from the control station. Fig. () shows the composition of the simulation system.

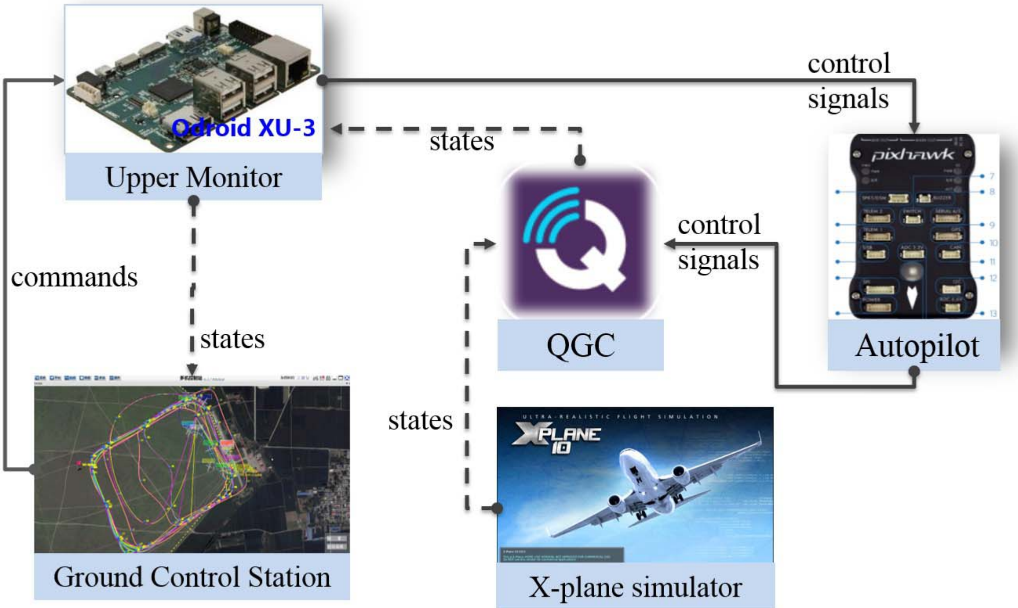

Fig. 6: the high-fidelity hardware-in-loop semi-physical simulation environment, constructed by an auto-pilot, a ground control station, an upper monitor Odroid, and an X-Plane simulator

With the previous description as theoretical foundation, the fuzzy control scheme working with a classical PD controller is embodied as Algorithm 1. In Algorithm 1, the working process of the proposed controller with a classical PD altitude controller is presented. It is worth pointing out that the control system with the proposed fuzzy altitude control scheme can perform effectively in the whole flight process under different wind conditions. Therefore, next, we will show the effectiveness of the proposed control scheme employed in simulations.

Algorithm 1 The fuzzy laltitude control algothrim working with a PD controller

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1: Initialize: h_d;
2: Obtain the state of UAV: $[h, \theta, V, \phi]$;
3: $h_{err} = h_d - h$;
4: Generate the initial pitch angle from the PD controller: Δu_θ, and do step 5-9;
5: Fuzz the state variables: h^*_{err}, θ^*, V^*, ϕ^*;
6: Set values of parameters according to fuzzy rules in Table ()-(): k_θ, k_V, k_h, k_ϕ;
7: Compute the fuzzy outputs:
   $\Delta u^*_{f\theta} = k_\phi \phi^* + k_\theta \theta^*$,
   $\Delta u^*_{fV} = k_{h_{err}} h^*_{err} + k_V V^*$;
8: Defuzzification: $\Delta u_{f\theta}$, Δu_{fV};
9: Set the value of ϵ;
10: Output the total altitude control signal:
   $\theta = \Delta u_\theta + \epsilon \Delta u_{f\theta}$,
   $\Delta V = \epsilon \Delta u_{fV}$.

All simulations are performed with curved paths that need the aircraft to adjust the course angle all the time. The inertial speed of the aircraft is set to be 18m/s, and different wind conditions are provided by the X-Plane simulator. The X-Plane flight simulator is a high-fidelity, comprehensive and powerful flight simulator, and it offers the most realistic flight model available. In the experiments, a widely used airplane flight model, the HilStar17F is used (see Fig.).

Fig. 7: the HilStar17F flight model in X-Plane

For comparisons, the simulation experiments with and without the fuzzy altitude controller are both done in the same setting, including the reference path, the desired altitude and speed, and the wind speed. In both simulation experiments, the reference curved paths are the same, and they are designed to have constantly changed curvatures as well as large turns, in order to lead the plane to change the course angle all the time during the flight, so as to test the altitude performance in cases of large roll angles. Also, during all simulations, the altitude control scheme is realized in the embedded software in the Odroid by C code. Fig. - show results of two groups of contrastive experiments in different wind conditions. In Fig. , the wind speed is set to be 8kt (1kt is about 0.5144 m/s.), which has slight effects on the altitude control performance as the figure shows. In this case, performance of experiments with only the PD controller has the maximum altitude error at 3.943m and -3.699m. And it is presented that with the proposed fuzzy controller, the maximum altitude errors decrease to 0.702m and -0.74m, respectively. Also, in Fig. , when the wind speed is set to be 15kt, the maximum altitude errors without the fuzzy controller have gone to 6.981m and -6.254m. And the simulation results with the fuzzy controller are still much better, with the maximum altitude errors at 0.702m and -0.777m. The simulation results strongly verify the effectiveness of the proposed fuzzy control scheme on dealing with large roll angles and wind disturbances..

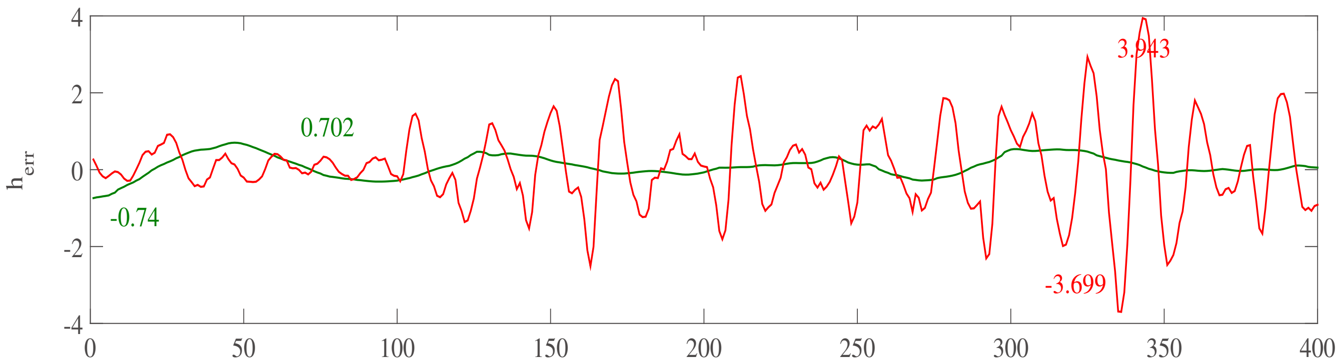

Fig. 8: the results of a group of comparative experiments in winds of 8kt, in which the red curve is the data without the proposed fuzzy controller, and the green curve is the data with the proposed fuzzy controller.

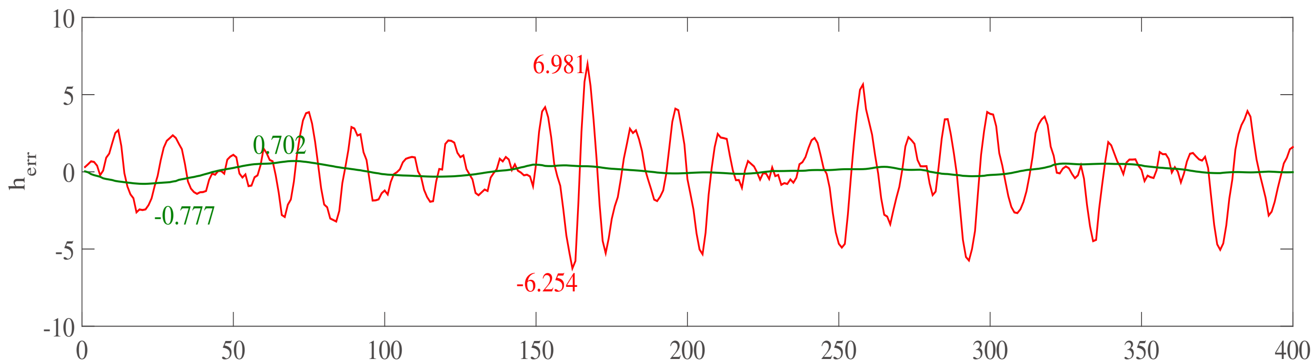

Fig. 9: the results of a group of comparative experiments in winds of 15kt, in which the red curve is the data without the proposed fuzzy controller, and the green curve is the data with the proposed fuzzy controller.

5 Conclusion and future work

In this paper, we developed a double-layer fuzzy controller for fixed-wing UAVs, to deal with the difficulties caused by the coupling dynamics and wind disturbances in the altitude control. The proposed controller compensates the altitude control with an additional speed and pitch angle. Several comparative simulation experiments in different wind conditions were designed and carried out on a high-fidelity semi-phisical simulation system. The results of simulations have validated that the proposed fuzzy control scheme can greatly improve the altitude control performance when the UAV is in winds or has large roll angles.

Future work will firstly implement the proposed altitude control scheme into field flight experiments, and then focus on the integral control of the UAVs in formation flight.

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