Path Following Control for Miniature Fixed Wing Unmanned Aerial Vehicle Under Uncertainties and Disturbances—A Two-Layered Framework

Weinan Wu

Northwestern Polytechnical University

Yao Wang

Northwestern Polytechnical University

Chunlin Gong (✉ gclnpu801@gmail.com)

Northwestern Polytechnical University

Dan Ma

Northwestern Polytechnical University

Research Article

Keywords: Miniature fixed wing unmanned aerial vehicle (MAV), Path following, Vector fields, Fuzzy logic.

Posted Date: December 6th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1126774/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Path Following Control for Miniature Fixed Wing Unmanned Aerial Vehicle Under Uncertainties and Disturbances: A Two-Layered Framework

Weinan Wu¹, Yao Wang², Chunlin Gong^{*3}, Dan Ma⁴

¹ Assistant Professor, School of Astronautics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, ShaanXi, China, 710072, wuweinan@nwpu.edu.cn;

² Ph.D candidate, School of Astronautics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, ShaanXi, China, 710072, wangyao0816@mail.nwpu.edu.cn;

³ Professor, School of Astronautics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, ShaanXi, China, 710072, gclnpu801@gmail.com;

⁴ Ph.D candidate, School of Astronautics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, ShaanXi, China, 710072, madan_p@163.com.

**Correspondence: Chunlin Gong, School of Astronautics, Northwestern Polytechnical University, 127 Youyi West Road, Xi'an, ShaanXi, China, Post code: 710072, E-mail address: gclnpu801@gmail.com.*

Abstract

In this paper a solution to the path following control problem for miniature fixed wing unmanned aerial vehicle (MAV) in the presence of inaccuracy modelling parameters and environmental disturbances is presented. We introduce a two-layered framework to collaborate guidance level with control level. A modified vector fields based path following methodology is proposed in the kinematics phase to track a Dubins path with straight line segments and circle ones. Then a Proportional-Integral-Derivative (PID) controller based on feedback linearization and gain scheduling techniques is designed such that the MAV can reject nonlinear dynamics, system uncertainties and disturbances by using a robust fuzzy control scheme. Eventually, by giving comparison test with control effort and track error as assessment metrics, both the practicality of the framework and the outperformance of the proposed algorithm are well demonstrated.

Keywords: *Miniature fixed wing unmanned aerial vehicle (MAV), Path following, Vector fields, Fuzzy logic.*

¹ Assistant Professor, Northwestern Polytechnical University, ShaanXi, China, 710072, wuweinan@nwpu.edu.cn.

² Ph.D candidate, Northwestern Polytechnical University, ShaanXi, China, 710072, wangyao0816@mail.nwpu.edu.cn

³ Professor, Corresponding author, Northwestern Polytechnical University, ShaanXi, China, 710072, gclnpu801@gmail.com.

⁴ Ph.D candidate, Northwestern Polytechnical University, ShaanXi, China, 710072, madan_p@163.com.

1. Introduction

In recent decades, promising applications of unmanned aerial system (UAS) with a fleet of miniature fixed-wing UAVs (MAV), spring up for substituting human beings in the unclear and unsettled situation, to execute various tasks, such as, environmental disaster relief [1], precision agriculture [2], fighting forest fires [3], and weather forecasting [4]. It is naturally noteworthy that the path following control of MAV is a precondition to accomplish those operational objectives [5-7]. However, owing to the size and low-cost attribute, MAVs are affected much more dramatically than traditional UAV in the presence of what may be considered small environmental disturbances [8], even the modelling parameters of MAV is tough to be accurately acquired. Furthermore, status of existing literatures for path following control of MAV, which might not be as well-known or effective, is the key driving force to carry out our research.

The path following control problem, defined as a matter of guaranteeing a flight vehicle to follow a predefined path in two or three dimensions, by now, has been widely discussed in the literature, where provide various types of solution strategies. One noteworthy way is to categorize the strategy by what underlying framework it operates on, and the included approaches are either trajectory tracking based methodology [9-12] in the control aspect or a path following based methodology [13-15] in the guidance aspect. In principle, already applied in the field of several types of unmanned vehicles, methodologies in the existing literature are sources of inspiration for many researchers who seek to develop this strategy. However, while seeking to document the influence of both the original system-parameter inaccuracy and the wind disturbances which may be relatively insignificant to a common sized UAV, miniature fixed-wing UAV (MAV) is affected so enormously owing to its size and low ability that traditional trajectory tracking methodologies may lead to poor performance. Hence, one further research on the trajectory control problem of MAV is elucidating the underlying mechanism and revealing the inherent cause-effect relationship.

Within the correlated academic community, we can start by borrow lessons from the outstanding work by Sujit [16], where its survey and analysis illustrate disadvantages of both geometric based and control theoretic based algorithms in several aspects, then highlights the importance of asking these questions, even if they cannot answer them just yet. Knowing that either control effort or tracking error in cases with disturbances emerges so apparently presents us an important chance to take a close look at how we are managing disturbances.

Consequently, researchers have since studied the problem, with dissimilar methodologies, in several papers which can be broadly divided into two parts: one using a nonlinear observer-based controller to incorporate the effects of disturbance, Han [17] proposed an active disturbance rejection controller based on the extended state observer; Mokhtari [18], Shao [19], Ma [20] improved their observer-based controller by replacing the original extended state observer with a modified linear one, which was verified quite effectively in UAV or other kinds of flight vehicles; moreover, owing to the advantage of removing steady-state errors, a proportional-integral observer was adopted in the works by Son [21] and Kim [22]. In the papers by Zhu [23] and Edison [24], metaheuristics (such as neural network or genetic algorithm) are adopted to collaborate with path following control process to account for the inherent and environmental disturbances on unmanned

vehicles; Boussaïd [25], Ka [26], Fong [27], Sáez [28] highlighted in their researches that fuzzy logic control is one of the main methodologies to reach artificial intelligent capabilities, and has the potential to accommodate the requirements for effectiveness in the unmanned vehicle's path following control problem. These findings raise several exciting questions that deserve our attention; therefore, a self-adaptive fuzzy logic controller is proposed to deal with the disturbances while tracking the heading and attitude command generated by unmanned vehicle's guidance pattern [29]. Recently, a Line-of-sight guidance collaborated with a fuzzy logic controller is developed by Xiang [30] to account for inaccuracy modelling parameters and time-varying environmental disturbances in an underwater scenario. Nevertheless, the path following control algorithms based on neural network, proportional-integral observer, nonlinear adaptive methods, even incorporates with fuzzy logic to account for disturbances, are yet proved to be effective and practical for MAV, so the urge to reveal this leads to the core content of this paper.

In this paper, a two-layered framework which handles both guidance and control pattern is established. At the guidance layer, a modified vector fields path following algorithm is illustrated to force the MAV to follow a Dubins style instructive path, which is regarded as a classical trajectory generated by the path planner. Then at the control layer, we develop a PID controller based on feedback linearization and gain scheduling technique, to transform the guidance command into rudder and throttle control quantity, and an adaptive fuzzy logic is implemented to adjust the PID gains and supply the robustness accounting for inaccuracy model parameters and environmental disturbances. Furthermore, by giving the verification examination, different simulation cases and comparison test with some mainstream methodologies, both the practicality of the framework and the outperformance of the proposed algorithm are well demonstrated.

The outline of the paper is as follows. In Section 2 the MAV model is given. The path following control problem is presented in Section 3. Section 4 presents the modified vector fields based path following algorithm and a robust fuzzy logic based PID controller. The simulation cases are presented in Section 5 and conclusions are given in Section 6.

2. Vehicle model

In this section, we present the kinematic model, the dynamic model of a MAV, and put out definition of the MAV state variables. The kinematics of the MAV is:

$$\begin{pmatrix} \dot{p}_n \\ \dot{p}_e \\ \dot{p}_d \end{pmatrix} = \begin{pmatrix} \cos \theta \cos \psi & \cos \theta \sin \psi & -\sin \theta \\ \sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi & \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi & \sin \phi \cos \theta \\ \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi & \cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi & \cos \phi \cos \theta \end{pmatrix}^T \begin{pmatrix} u \\ v \\ w \end{pmatrix} \quad (1)$$

Where $(p_n, p_e, p_d)^T$ signifies the location vector of MAV in ground inertial coordinate system; $(u, v, w)^T$ is the velocity vector of MAV in its body coordinate system; θ, ψ, ϕ are the corresponding pitch angle, yaw angle, and roll angle, respectively.

As stated by the apparent connection between θ, ψ, ϕ with p, q, r , equation (1) can be converted to:

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi \sec \theta & \cos \phi \sec \theta \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix} \quad (2)$$

Subsequently, the dynamic model is presented:

$$\begin{pmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{pmatrix} = \begin{pmatrix} rv - qw \\ pw - ru \\ qu - pv \end{pmatrix} + \frac{1}{m} \begin{pmatrix} f_x \\ f_y \\ f_z \end{pmatrix}$$

$$\begin{pmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} \frac{J_z}{\Gamma} & 0 & \frac{J_{xz}}{\Gamma} \\ 0 & \frac{1}{J_y} & 0 \\ \frac{J_{xz}}{\Gamma} & 0 & \frac{J_x}{\Gamma} \end{pmatrix} \left[\begin{pmatrix} 0 & r & -q \\ -r & 0 & p \\ q & -p & 0 \end{pmatrix} \begin{pmatrix} J_x & 0 & -J_{xz} \\ 0 & J_y & 0 \\ -J_{xz} & 0 & J_z \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix} + \begin{pmatrix} l \\ m \\ n \end{pmatrix} \right]$$

$$= \begin{pmatrix} \Gamma_1 pq - \Gamma_2 qr + \Gamma_3 l + \Gamma_4 n \\ \Gamma_5 pr - \Gamma_6 (p^2 - r^2) + \frac{1}{J_y} m \\ \Gamma_7 pq - \Gamma_1 qr + \Gamma_4 l + \Gamma_8 n \end{pmatrix} \quad (3)$$

The variables $\Gamma_1, \Gamma_2, \Gamma_3, \Gamma_4, \Gamma_5, \Gamma_6, \Gamma_7$ and Γ_8 are given by

$$\Gamma_1 = \frac{J_{xz} (J_x - J_y + J_z)}{\Gamma}, \quad \Gamma_2 = \frac{J_z (J_z - J_y) + J_{xz}^2}{\Gamma}$$

$$\Gamma_3 = \frac{J_z}{\Gamma}, \quad \Gamma_4 = \frac{J_{xz}}{\Gamma}$$

$$\Gamma_5 = \frac{J_z - J_x}{J_y}, \quad \Gamma_6 = \frac{J_{xz}}{J_y}$$

$$\Gamma_7 = \frac{(J_x - J_y) J_x + J_{xz}^2}{\Gamma}, \quad \Gamma_8 = \frac{J_x}{\Gamma}$$

Note that the proposed kinematic and dynamic model are mainly described by 12 state variables, which are listed in Table (1).

Table 1. Twelve state variables of the MAV

state variables	definitions
p_n	position component in x-axis direction in $\mathcal{F}^i$
p_e	position component in y-axis direction in $\mathcal{F}^i$
p_d	position component in z-axis direction in $\mathcal{F}^i$
u	velocity component in x-axis direction in $\mathcal{F}^b$

state variables	definitions
v	velocity component in y-axis direction in $\mathcal{F}^b$
w	velocity component in z-axis direction in $\mathcal{F}^b$
ϕ	roll angle of the MAV
θ	pitch angle of the MAV
ψ	yaw angle of the MAV
p	rolling angular velocity in x-axis direction in $\mathcal{F}^b$
q	pitch angular velocity in x-axis direction in $\mathcal{F}^b$
r	yaw angular velocity in x-axis direction in $\mathcal{F}^b$

As for consideration of inaccurate parameters which lie on the vehicle model, the dynamics equation can be presented as follows.

$$\begin{cases} \dot{u} = \frac{n_{22}}{n_{11}}rv - \frac{n_{33}}{n_{11}}qw - g \sin \theta - \frac{d_{11}}{n_{11}}u + \frac{l(u_F, u_T)}{n_{11}} \\ \dot{v} = \frac{n_{33}}{n_{22}}pw - \frac{n_{11}}{n_{22}}ru + g \cos \theta \sin \phi + \frac{d_{22}}{n_{22}}v + \frac{l(v_F, v_T)}{n_{22}} \\ \dot{w} = \frac{n_{11}}{n_{33}}qu - \frac{n_{22}}{n_{33}}pv + \frac{d_{33}}{n_{33}}w + g \cos \theta \cos \phi + \frac{l(w_F, w_T)}{n_{33}} \\ \dot{p} = \frac{n_{55} - n_{44}}{n_{44}}pq - \frac{d_{44}}{n_{44}}qr + \frac{l(p_F, p_T)}{n_{44}} \\ \dot{q} = \frac{n_{44}}{n_{55}}pr - \frac{n_{44}}{n_{55}}(p^2 - r^2) - \frac{d_{55}}{n_{55}}q + \frac{l(q_F, q_T)}{n_{55}} \\ \dot{r} = \frac{n_{44} - n_{55}}{n_{66}}pq - \frac{n_{55}}{n_{66}}qr + \frac{l(r_F, r_T)}{n_{66}} \end{cases} \quad (4)$$

Where $l(u_F, u_T)$, $l(v_F, v_T)$, $l(w_F, w_T)$, $l(p_F, p_T)$, $l(q_F, q_T)$, $l(r_F, r_T)$ represent the control forces and torques acting upon the MAV on its corresponding pattern, respectively; $n(\cdot)$ express hydrodynamic derivatives of the system, $d(\cdot)$ capture hydrodynamic damping effects.

3. Problem statement

The ultimate objective in universal path-following problems is to restrict each trajectory of the controlled vehicle converge to an instructive trajectory P considering the presence of uncertainties, disturbances.

For the problem studied in this paper, the path following task can be achieved by utilizing a robust guidance mechanism to steer the MAV to track an instructive three-dimensional trajectory P (see in Fig.1), which is generally regarded as being parameterized by a virtual reference point p in 3D space. The path

following error is defined by $\varepsilon = \{x_g, y_g, z_g\}^T$ in coordinate system $\mathcal{F}^g$, where x_g , y_g , z_g represent the directional-track error, lateral-track error and altitudinal-track error, respectively.

Fig.1 Description of the problem studied in this paper

Consequently, the problem of robust path following guidance for the MAV can be expressed as: Given an instructive trajectory P , a robust guidance mechanism is required to steer actuators on the MAV to follow P under uncertainties and disturbances, so that its centroid asymptotically approaches to p , its velocity vector's direction coincides with the tangent vector of P simultaneously, and eventually verges on $P(t)$ over time.

4. Robust guidance for path following

In a study of guidance and control problem for the given path following problem under some cases of uncertainties and disturbances, the control process is much more prone to interfere with the tracking quality than the guidance process. Hence, it is not unusual to cultivate a two-layered framework (see in Fig. 2) for the proposed problem.

We do know that the given framework comprises a kinematic and a dynamic layer, and there is an apparent cause-effect relationship between them, as the former depends on the flight situation and it can vary greatly according to the capability of the latter, so a control mechanism should be cultivated to be responsible for both the disturbances and the tracking quality in the dynamics stage, then a guidance mechanism contributes to the tracking accuracy pattern in the kinematics stage.

Therefore, the further avenue for this paper is elucidating the underlying mechanism of the both layers. At the kinematics stage, the ultimate objective is to transform the instructive path described as $[x_p, y_p, z_p]$ to executable guidance commands as $[\chi, h_d, v_a]$ (heading, altitude, and velocity command), which is carried out by vector fields guidance algorithm that appears in a subsequent post. The basic requirement for the dynamics layer is to supply a control mechanism to guarantee steady approaching process of the MAV under

uncertainties and disturbances, and then with an effect of tracking accuracy, thus we combine a fuzzy logic algorithm with a three channel PID controller to derive the appropriate forces and torques on the MAV.

Fig.2 A two-layer framework for the path following problem

4.1 VF-based path following method

4.1.1 Coordinated turn

According to equation (1), it can be seen that the change rate of heading angle is related to the magnitude of pitch angular velocity, yaw angular velocity, pitch angle and roll angle.

$$\dot{\chi} = q \sin \phi \sec \theta + r \cos \phi \sec \theta \quad (5)$$

Each of the above state variables can be calculated by ordinary differential equations. Meanwhile, it is obviously that the change rate of heading angle of the UAV is directly related to its roll angle, and this relationship is deduced as follows.

According to Fig. 3, centripetal force of the MAV in flight can be expressed by heading angular velocity of the UAV and the horizontal components of ground velocity of the MAV as follows:

$$\begin{aligned} F_l \sin \phi \cos(\chi - \psi) &= m v^2 / R \\ &= m v \omega = m (V_g \cos \gamma) \dot{\chi} \end{aligned} \quad (6)$$

Where F_l represents magnitude of lift force on the MAV; v represents magnitude of velocity of the MAV; R represents instantaneous turning radius of the MAV; ω represents magnitude of heading angular velocity of the MAV.

Fig.3 Description of the direction of the force on the MAV during coordinated turns

Similarly, vertical component of lift force on the MAV equals to the component of gravity on the longitudinal plane under the body coordinate system, according to Fig. 4, the expression is:

$$F_l \cos \phi = mg \cos \gamma \quad (7)$$

From the tail of the body

Fig.4 Description of the direction of the force on the MAV during coordinated turns
(from the tail of the body)

Thus, the expression of coordinated turning can be obtained by dividing equation (6) by equation (7), which is given as follows:

$$\chi = \frac{g}{V_g} \tan \phi \cos(\chi - \psi) \quad (8)$$

Turning radius of the MAV is given as $R = V_g \cos \gamma / \chi$, then:

$$R = \frac{V_g^2 \cos \gamma}{g \tan \phi \cos(\chi - \psi)} \quad (9)$$

4.1.2 Design of path following method for the MAV

For MAVs, a significant difference from conventional UAV is that the air velocity during its flight usually reaches 20%~30% of its flight airspeed. Therefore, it is necessary to design an effective path following strategy to overcome the airflow disturbance. Generally, the traditional path following method is to follow a reference point, which is usually set as a virtual MAV whose location changes over time, and in this way the MAV involved and the virtual MAV constitute the pursuit relationship, and the MAV can be restricted on the planned path. However, for MAVs, using the above method will produce some problems. For example, if the MAV flies against the wind into an airspace with strong airflow, its ground speed will slow down, eventually the position of the generated virtual MAV will slow down. Consequently, if the MAV flies downwind, its ground speed must increase, and ground speed of the virtual MAV will increase synchronously. However, the role of gusts is unpredictable, and it is impossible to give where and when to increase or decrease the speed of the virtual MAV. Therefore, the vector guidance algorithm will be given in this section to solve the given problem.

(1) Path following for straight-line paths

A straight-line path can be represented by two vectors as follows:

$$\mathcal{P}_{sl}(\mathbf{r}, \mathbf{q}) = \{\mathbf{x} \in \mathbb{R}^3 : \mathbf{x} = \mathbf{r} + \lambda \mathbf{q}, \lambda \in \mathbb{R}\} \quad (10)$$

Where $\mathbf{r} \longrightarrow \mathbf{r} \in \mathbb{R}^3$ represents starting point of the path;

$\mathbf{q} \longrightarrow \mathbf{q} \in \mathbb{R}^3$ is a unit vector, which represents direction of the path;

Fig.5 Description of $\mathcal{P}_{sl}(\mathbf{r}, \mathbf{q})$ from top view

According to Fig. 5, the heading angle of path $\mathcal{P}_{sl}(\mathbf{r}, \mathbf{q})$ is:

$$\chi_q = \arctan \frac{q_e}{q_n}$$

In order to analysis the straight-line path $\mathcal{P}_{sl}(\mathbf{r}, \mathbf{q})$ in a proper manner or situation, a coordinate system $\mathcal{F}^p$ is given in Fig. 6: the coordinate origin is the terminal of vector $\mathbf{r}$, and the x-axis is consistent with the projection direction of $\mathbf{q}$ in the $\mathbf{i}^i - \mathbf{j}^i$ plane under the coordinate system $\mathcal{F}^i$, the z-axis is parallel to $\mathbf{k}^i$, then y-axis is determined by the right-hand rule. Hence, the conversion relationship between $\mathcal{F}^i$ and $\mathcal{F}^p$ is:

The path error under $\mathcal{F}^p$ is derived as follows:

then two components of the error rate of change are:

For the lateral path following problem, the purpose of vector fields guidance method is to make the lateral error of path close to zero by giving the heading angle command.

As shown in Fig. 7, the characteristic of vector fields guidance method is that, during the flight of MAV, heading angle command vectors generated at different locations have the same amplitude relative to the straight-line path.

Fig.7 Schematic diagram of vector fields guidance for straight-line path

The vector fields path following method for straight-line path covers two cases: 1) $|e_{py}|$ is relatively large; the MAV will fly to the specified path with $\chi^\infty \in (0, \pi/2]$; 2) $|e_{py}|$ is close to zero; the required heading angle should be close to zero. Thus, the required heading angle is given as

$$\chi_d(e_{py}) = -2\chi^\infty \tan^{-1}(k_{path}e_{py})/\pi \quad (14)$$

Where k_{path} is a positive constant. Value of k_{path} has a direct impact on curvature of the corresponding path: as the value of k_{path} increases, the curvature of Value of $\mathcal{P}_{sl}(r, q)$ increases accordingly, and vice versa. So k_{path} should be moderate.

Therefore, heading angle command for tracking lateral path can be deduced as

$$\chi^c(t) = \chi^q - 2\chi^\infty \tan^{-1}(k_{path}e_{py})/\pi \quad (15)$$

Fig.8 Description of $\mathcal{P}_{sl}(r, q)$ in $q-k$ plane

For ease of obtaining the altitude command, the projection of $\mathcal{P}_{sl}(r, q)$ in $q-k$ plane defined as s , is shown in Fig. 8; the proportional relation is derived on the basis of Similar Triangle Theory as

$$\frac{h_d + r_d}{\sqrt{s_n^2 + s_e^2}} = \frac{-q_d}{\sqrt{q_n^2 + q_e^2}} \quad (16)$$

Then

$$\mathbf{s}^i = \begin{pmatrix} s_n \\ s_e \\ s_d \end{pmatrix} = \mathbf{e}_p^i - (\mathbf{e}_p^i \cdot \mathbf{n}) \mathbf{n} \quad (17)$$

Where $\mathbf{e}_p^i = \begin{pmatrix} e_{pn} \\ e_{pe} \\ e_{pd} \end{pmatrix} = \mathbf{p}^i - \mathbf{r}^i = \begin{pmatrix} p_n - r_n \\ p_e - r_e \\ p_d - r_d \end{pmatrix}$, $\mathbf{n} = \frac{\mathbf{q} \times \mathbf{k}^i}{\|\mathbf{q} \times \mathbf{k}^i\|}$ is the unit normal vector of $\mathbf{q} - \mathbf{k}$ plane.

Thus, the altitude command for the MAV to track $\mathcal{P}_{sl}(\mathbf{r}, \mathbf{q})$ is obtained as

$$h_d(\mathbf{r}, \mathbf{p}, \mathbf{q}) = -r_d - \sqrt{s_n^2 + s_e^2} \left(\frac{q_d}{\sqrt{q_n^2 + q_e^2}} \right) \quad (18)$$

(2) Path following for arc paths

In principle, the characteristics of an arc path can be defined as

$$\mathcal{P}_{arc} = (\mathbf{c}, \rho, \lambda) = \left\{ \mathbf{r} \in \mathbb{R}^3 : \mathbf{r} = \mathbf{c} + \lambda \rho (\cos \varphi, \sin \varphi, 0)^T, \varphi \in \left[0, \frac{\pi}{2} \right) \right\} \quad (19)$$

Where $\mathbf{c} = (c_n, c_e, c_d)^T \in \mathbb{R}^3$, $\rho \in \mathbb{R}$, and $\lambda \in \{-1, 1\}$ represent centre location, radius, and rotation direction (1 for clockwise, -1 for counter clockwise) of the corresponding arc path, respectively.

It is assumed that the MAV flies at a constant altitude when tracking arc paths, so the altitude command is $h^c = -c_d$. The tracking command generation principle for arc path can be described in the light of Fig. 9.

Fig.9 Description of $\mathcal{P}_{arc} = (\mathbf{c}, \rho, \lambda)$ from the top view

As shown in Fig. 9, we represent the arc path in polar coordinate system. d is defined as the distance between the centre of the corresponding arc path and the MAV; φ is the defining phase angle. The relative distance and phase angle change rate is derived as

$$\begin{aligned}
\begin{pmatrix} \dot{d} \\ d\dot{\varphi} \end{pmatrix} &= \begin{pmatrix} \cos \varphi & \sin \varphi \\ -\sin \varphi & \cos \varphi \end{pmatrix} \begin{pmatrix} \dot{\rho} \\ \dot{\chi} \end{pmatrix} \\
&= \begin{pmatrix} \cos \varphi & \sin \varphi \\ -\sin \varphi & \cos \varphi \end{pmatrix} \begin{pmatrix} V_g \cos \chi \\ V_g \sin \chi \end{pmatrix} \\
&= \begin{pmatrix} V_g \cos(\chi - \varphi) \\ V_g \sin(\chi - \varphi) \end{pmatrix}
\end{aligned} \tag{20}$$

However, the principle of tracking the arc path is to make $d(t)$, $\chi(t)$ close to ρ and χ^0 at time t , respectively. Thus, similar to tracking criterion of straight-line path, the proposed expression for the arc path is:

$$\chi_d(d - \rho, \lambda) = \chi^o + \lambda \tan^{-1} \left(k_{orbit} \left(\frac{d - \rho}{\rho} \right) \right) \tag{21}$$

Where k_{orbit} is a positive constant.

The tracking command for $\mathcal{P}_{arc} = (c, \rho, \lambda)$ is deduced ultimately as

$$\chi^c(t) = \varphi + \lambda \left[\frac{\pi}{2} + \tan^{-1} \left(k_{orbit} \left(\frac{d - \rho}{\rho} \right) \right) \right] \tag{22}$$

However, in order to handle the precision path following process with or without disturbances, Eq. (22) can be alternated as a modified version:

$$\chi^c(t) = \varphi + \lambda \left[\frac{\pi}{2} + \tan^{-1} \left(k_{orbit} \left(\frac{d - \rho}{k_\rho} \right) \right) \right] \tag{23}$$

Where k_ρ represents is a constant adjustment parameter.

4.2 Robust fuzzy based control mechanism

The typical PID controller has been commonly employed in many aviation-related control applications, but the limitation of the classic PID controller lies on the fixed control parameters, which restricts it to adapt to the nonlinear system with uncertainties and disturbances. However, fuzzy logic control has been proved to be a solution for controlling a system with uncertainties. Therefore, in this part, we design tracking control mechanisms for three command channels firstly, then a fuzzy logic based framework is proposed, then we combine the fuzzy logic with standard PID controller, in order to accomplish robust control for the MAV system.

4.1.1 Tracking control mechanism

(1) Control mechanism for heading command channel

As stated by the principle of coordinated turn in Eq. 5, the transfer function between ϕ with χ can be deduced in the following sequential two steps.

$$\begin{aligned}\chi &= \frac{g}{V_g} \phi + \frac{g}{V_g} (\tan \phi - \phi) \\ &= \frac{g}{V_g} \phi + \frac{g}{V_g} d_\chi\end{aligned}\quad (24)$$

where $d_\chi = \tan \phi - \phi$ signifies a type of system disturbance.

Then the transfer function can be proposed by Laplace transform as:

$$\chi(s) = \frac{g/V_g}{s} (\phi(s) + d_\chi(s)) \quad (25)$$

Subsequently, we use the gain scheduling control structure, which can restrict MAV to adapt to the altered magnitude of wind automatically, as the core of designed control mechanism (see in Fig. (10)).

Fig.10 Control block diagram at feature points

Eventually, the matching control parameters are listed in Tab. 2.

Table 2 Matching control parameters

$V_a \text{ (m/s)}$	k_{p_ϕ}	k_{i_ϕ}	k_{d_ϕ}
10	0.4	0	0
20	1.5	0	0
30	2.5	0	0
40	3.5	0	0

(2) Control mechanism for velocity command channel

The velocity command is obtained by means of combining δ_t with θ , hence, the transfer function from (δ_t, θ) to V_a can be derived as (see the detailed derivation process in the appendix):

$$\bar{V}_a(s) = \frac{1}{s + a_{V_1}} (a_{V_2} \bar{\delta}_t(s) - a_{V_3} \bar{\theta}(s) + d_v(s)) \quad (26)$$

where $a_{V_1} \text{ --- } a_{V_1} = \frac{\rho V_a^* S}{m} [C_{D_0} + C_{D_\alpha} \alpha^* + C_{D_{\delta_e}} \delta_e^*] + \frac{\rho S_{prop}}{m} C_{prop} V_a^*$;

$$a_{V_2} \text{ --- } a_{V_2} = \frac{\rho S_{prop}}{m} C_{prop} k^2 \delta_t^* ;$$

$$a_{V_3} \text{ --- } a_{V_3} = g \cos(\theta^* - \alpha^*).$$

So, the corresponding control mechanism of the combined inputs is presented in Fig. 11.

Fig.11 Control mechanism of the combined inputs

Then we illustrate the respective control mechanism in both aspects, one is the pitch angle pattern, the other is the throttle opening pattern, and it should be pointed out that the mutual influence is ignored in this process.

Similarly, in the aspect of pitch angle, the gain scheduling control structure is adopted to construct the control mechanism, so the control diagram is presented in Fig. 12.

Fig.12 Control mechanism of the velocity command channel (pitch angle)

And the matching control parameters are listed in Tab. 3.

Table 3 Matching control parameters

$V_a (m/s)$	k_{p_v}	k_{i_v}	k_{d_v}
10	-0.0546	0.0197	0
20	-0.0563	-0.024	0
30	-0.0545	0.0304	0
40	-0.0617	0.0422	0

The control diagram with the aspect of throttle opening is showed in Fig. 13.

Fig.13 Control mechanism of the velocity command channel (throttle opening)

(3) Control mechanism for altitude command channel

Typically, we should make more effort to design a moderate control mechanism for altitude channel as a consequence of the wind disturbances. Henceforth, an altitude controller tactic, which is conducted by corporately use both the throttle opening and the elevator, is illustrated in Fig. 14.

Fig.14 Altitude controller tactic

With the purpose of utilizing this tactic properly, we incorporate a control process of altitude by altering pitch angle (see in Fig. 15), which is more prone to affect the whole control process, to handle this control mechanism, in this way can the tactic works and eventually the control mechanism for altitude command channel formulates.

Fig.15 Control mechanism of the altitude command channel

4.1.2 Fuzzy logic control

Derived from the guidance commands $[\chi, h_d, v_a]$ (heading, altitude, and velocity) illustrated in the guidance level, we naturally set the definition of the tracking error vector as $\mathbf{e}_{con} = (e_\chi, e_h, e_v)^T$.

$$\begin{cases} e_\chi(m) = \chi_c(m) - \chi(m) \\ e_h(m) = h_c(m) - h(m) \\ e_v(m) = v_c(m) - v(m) \end{cases} \quad (27)$$

where m is the sample index.

Hence, the error ratio vector $\mathbf{\hat{e}}_{con}$, which is correlated to $\mathbf{e}_{con}$, could be illuminated as:

$$\begin{cases} \hat{e}_\chi(m) = (\chi_c(m) - \chi(m-1))/T \\ \hat{e}_h(m) = (h_c(m) - h(m-1))/T \\ \hat{e}_v(m) = (v_c(m) - v(m-1))/T \end{cases}, \text{ and } T \text{ represents the sample time period in the control loop. However,}$$

according to the basic PID control mechanism presented in 4.1.1, the path following control law in the dynamics level for the MAV can be attained by means of feedback linearization techniques as follows:

$$\begin{cases} l(u_F, u_T) = -\tilde{f}_{22}rv + \tilde{f}_{33}qw + \tilde{f}_{11}g \sin \theta + \tilde{d}_{11}^o u + \tilde{f}_{11}(k_{pu}e_v + k_{iu} \int e_v + k_{du}\hat{e}_v) \\ l(q_F, q_T) = -\tilde{f}_{55}pr + \tilde{f}_{55}(p^2 - r^2) + \tilde{d}_{55}^o q + \tilde{f}_{55}(k_{pq}e_h + k_{iq} \int e_h + k_{dq}\hat{e}_h) \\ l(r_F, r_T) = (\tilde{f}_{55} - \tilde{f}_{44})pq + \tilde{f}_{55}qr + \tilde{f}_{66}(k_{pr}e_\chi + k_{ir} \int e_\chi + k_{dr}\hat{e}_\chi) \end{cases} \quad (28)$$

where $\sim(\cdot)$ represents the modelling parameters which are inaccurate.

In order to handle the stable control process of the path following pattern with inaccurate modelling parameters and wind disturbances, we propose a fuzzy logic to bound the control gains $(k_{p^*}, k_{i^*}, k_{d^*})$ around $(k_{p^*0}, k_{i^*0}, k_{d^*0})$ automatically, and the relationship between the former gains and the latter ones can be explained as follows:

$$\begin{cases} k_{p^*} = k_{p^*0} + \Delta k_{p^*}(e_\chi, \hat{e}_\chi) \\ k_{i^*} = k_{i^*0} + \Delta k_{i^*}(e_\chi, \hat{e}_\chi) \\ k_{d^*} = k_{d^*0} + \Delta k_{d^*}(e_\chi, \hat{e}_\chi) \end{cases} \quad (29)$$

Where $\Delta k_{p^*}(e_\chi, \hat{e}_\chi)$, $\Delta k_{i^*}(e_\chi, \hat{e}_\chi)$, $\Delta k_{d^*}(e_\chi, \hat{e}_\chi)$, named as adaptive incremental gains, are the designed objectives to the fuzzy logic mechanism.

The principle of the fuzzy logic is given in Fig. 16.

Fig.16 Principle of the fuzzy logic

The fuzzy logic will be illuminated typically through three orderly steps: fuzzification, fuzzy inference and defuzzification.

(1) fuzzification

According to the principle illustrated in Fig. 16, we set five types of fuzzy sets, which are named as NB (negative large), NS (negative small), ZO (zero), PS (positive small), and PB (positive large), to represent different magnitude of the inputs, and the corresponding outputs can be transformed into the type of fuzzifications in the same way.

(2) fuzzy inference

On the basis of the training expert system for the rules of classic PID control, the rules of setting the control gains $\Delta k_{p*}(e_* \&)$, $\Delta k_{i*}(e_* \&)$, $\Delta k_{d*}(e_* \&)$ are illuminated in Tab.4-Tab.6.

Table 4 Control rules for $\Delta k_{p*}(e_* \&)$

$\Delta k_{p*}(e_* \&)$	NB	NS	ZO	PS	PB
NB	PB	PS	PS	PS	ZO
NS	PB	PS	PS	ZO	NS
ZO	PB	PS	ZO	NS	NS
PS	PS	ZO	NS	NS	NS
PB	ZO	NB	NB	NB	NB

Table 5 Control rules for $\Delta k_{i*}(e_* \&)$

$\Delta k_{i*}(e_* \&)$	NB	NS	ZO	PS	PB
NB	NB	NB	NS	NS	ZO
NS	NB	NS	NS	ZO	PS

ZO	NB	NS	ZO	PS	PS
PS	NS	ZO	PS	PS	PB
PB	ZO	PS	PB	PB	PB

Table 6 Control rules for $\Delta k_{d*}(e_* \& \dot{e}_*)$

$\Delta k_{d*}(e_* \& \dot{e}_*)$	NB	NS	ZO	PS	PB
NB	PS	NB	NB	NB	PS
NS	ZO	NS	NS	NS	ZO
ZO	ZO	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO
PB	PS	PS	PS	PS	PB

We use table 5 as an example to illustrate the items in each column or row; the first column and the first row signifies the fuzzy sets of e_{con} and $\dot{e}_{con}$, respectively, and the others are outputs of standard IF-THEN rules, which are directly inherited from the design principle of classic PID controllers in different occasions.

(3) defuzzify

When we try to solve the given problem, we need to transform the output into a single numerical value, rather than a fuzzy set proposed in the Tab. 4-Tab. 6. Therefore, the centroid technique [31], which is one of the most popular defuzzification methods, is adopted in this section.

In this way, $\Delta k_{p*}(e_* \& \dot{e}_*)$, $\Delta k_{i*}(e_* \& \dot{e}_*)$, $\Delta k_{d*}(e_* \& \dot{e}_*)$ is achieved, and the process of the fuzzy logic is finished.

4.1.3 Verification simulations

Before the case study, a verification simulation is provided to confirm the effectiveness of the proposed control mechanism in this section. The guidance commands are set as $V_a = 35 \pm 5(m/s)$, $H = 100 \pm 20(m)$, $\chi = \pm 30^\circ$, which represent the command of velocity, altitude, and heading angle, respectively. So, results of the command tracking, some characteristic parameters and tests of influences on path following by different values setting of χ_∞ 、 k_{path} are shown as follows.

Fig.17 Results of tracking command

Fig.18 Results of some angles of the MAV

Fig.19 Results of influences on path following by different values setting of χ_{∞}

Fig.20 Results of influences on path following by different values setting of k_{path}

As a result, the proposed path following control mechanism can not only guarantee stable tracking of the ordered guidance command, but also handle a smooth state change for the MAV.

5. Case study

Two types of case studies, which are utilized respectively to demonstrate the proposed theoretical models and algorithms in the simulation aspect and in the HILS (hardware in the loop simulation) test aspect, are orderly given in this section. In the first case, a designed Dubins path which consists of both straight-line segments and arc segments, is given as the predefined path to follow, and in order to verify the adaptability of the proposed path following control algorithm, we set diverse wind speed as the input disturbances (see in Tab. 2) in this case. In the latter case, a comparative test is conducted to analyse the performance of different mainstream path following algorithms.

5.1 Simulation case

5.1.1 Case 1: circle path following without wind disturbance

In this case, the MAV is restricted to follow an ellipse path which is set with the centre (0m, 0m, 0m) and the radius $R_{el} = 400m$, and k_p in Eq. (23) is set to 100, the disturbance of wind is ignored. So, results of the designed path, the real path with the command of Eq. (22) and the modified path with the command of Eq. (23) are presented in Fig. 1.

Fig.21 Results of circle path following case without wind disturbance

From Fig. 21 it can be clearly seen that, after a transient period, the path following error of the modified one converge to 5m, which is quite smaller than of the real one with the command of Eq. 22. So, in this circumstance, the modified command is more practical and effective.

5.1.2 Case 2: circle path following with wind disturbance

In this case study, a simulation test, which aims to following a circle path under the circumstance where wind disturbance is consist of constant wind and its correlated airflow disturbance, is illustrated as follows.

The airflow disturbance is given as the form of the model designed by Dryden [32], and the corresponding parameters of the constant wind and the airflow disturbance (AD) are listed in Tab. 7, and the designed path is set the same with that in Case study 1.

Table 7 Parameters of the constant wind and the AD

Case 2	Constant wind(m/s)	k_{orbit}	k_p	Wavelength of AD	Turbulence intensity
Test 1	7m/s	2	100	$L_u = L_v = 200, L_w = 50$	$\sigma_u = \sigma_v = 1.06$
Test 2	10m/s	2	100	$L_u = L_v = 200, L_w = 50$	$\sigma_u = \sigma_v = 1.06$

So, results of the actual followed paths, the altitude command and velocity command of test 1 and test 2 are presented in Fig. 22~ Fig. 23, respectively.

Fig.22 Results of circle path following case with wind disturbance

Fig.23 Altitude command and velocity command of test 1 and test 2

From Fig. 22 it can be clearly seen that the path following error of test 1 converges to 22m, which is smaller than the corresponding error in test 2 that converges to 35m eventually, so it is an explicit result affected by different magnitude wind speed. And the altitude control error and velocity control error are within the allowable range, as shown in Fig. 23, so the proposed tracking algorithm is validated to be practical and effective in this case study.

However, in our extension simulation test, we figure out that the setting of parameter k_{orbit} in Eq. 22 is quite interrelated with the path following error, so results about the influences of k_{orbit} on the path following error is illustrated in Tab. 8.

Table 8 Results about the influences of k_{orbit} on the path following error

Case 2-extension	$k_{orbit} = 2$	$k_{orbit} = 3$	$k_{orbit} = 4$	$k_{orbit} = 5$	$k_{orbit} = 6$	$k_{orbit} = 7$
Test 1 (7m/s)	22m	17.5 m	12 m	9 m	-	-
Test 2 (10m/s)	36 m	23 m	17 m	13.7 m	11.5 m	10 m

As shown in Tab. 8, as the value of k_{orbit} increases, the path following error of test 1 and test 2 decrease gradually, but it is noteworthy that k_{orbit} should be bounded to a threshold value, because it may disable the path following process.

5.1.3 Case 3: Dubins path following with wind disturbance

In this case, we set the designed path as a form of Dubins path (see in Fig. 24, 25), which is more common in the path planning level or even in a real scenario conducted by MAV, and the coordinate of track points on Dubins path are: (0,0,-100), (0,5000,-100), (5000,0,-100), (5000,5000,-100), and the orientation angles on each point are: 0° , 45° , 45° , 225° , and the requirement of path following error is bounded below 20m; parameters related to the straight-line and circle segments are: $\chi_\infty = 20^\circ$, $k_{path} = 0.03$; $k_{orbit} = 4$, $k_p = 100$; the parameters of wind disturbance are the same with those of case 2, but the modifications in this study is that the orientation of the wind can be altered; results of the actual followed paths, the error of straight-line and circle segments are presented in Fig. 26~ Fig. 29 and Tab. 9, respectively.

Fig.24 Designed Dubins path

Fig.25 Vertical view of Dubins path

Fig.26 Results of the actual followed paths

Fig.27 Vertical view of Fig. 1

Fig.28 Path following error of the straight-line with 7m/s north wind

Fig.29 Path following error of the circle path with 7m/s north wind

Table 9 Results of the path following error with diverse wind direction

Case 3	North	Northeast	East	Southeast	South
7m/s	13.4	11.2	4.55	10.4	13.2
10m/s	19.2	17	5.5	15	18.6

From Fig. 26~ Fig.29 and Tab. 9 it can be clearly seen that the path following errors during the process are within the allowable range, so it is validated that the proposed model and algorithm are practical in this case study.

5.2 Hardware in the loop case

In this case, a comparative test is conducted to analyse the performance of different mainstream path following algorithms, which include Carrot Chasing Algorithm (Carrot), Non-linear Guidance Law (NLGL), Pure Pursuit and Line-of-Sight based Path Following (PLOS), Linear Quadratic Regulator based Path Following (LQR) and VF with Fuzzy control algorithm proposed in this paper, and the ultimate objective is to verify the practicality and effectiveness of the proposed algorithm in a reasonable manner. Thus, we define two types of factors which evaluate performances of the participating algorithms/laws from different perspectives; the former is called total error (Te) (illustrated in Eq. 30), which represents the cumulative path following error; the latter (total control consumption: Tc) (illustrated in Eq. 30) represents the cumulative control consumption which consists of both total rudder deflection angle and throttle consumption to trace the designed path. Finally, the index of performance given by the participating algorithms/laws is presented in Eq. 31.

$$Tc = \sum_{t=0}^{t=T} u^2(t) \quad (30)$$

$$Te = \sum_{t=0}^{t=T} |d(t)|$$

$$\xi = \Gamma \bar{Tc} + (1 - \Gamma) \bar{Te} \quad (31)$$

Where Γ is the weight value; ξ is the comprehensive score; $\bar{Tc}$ is the mean control consumption, and $\bar{Te}$ is the mean tracking error.

In order to test the participating algorithms/laws in a quite similar condition, we employ two PC/104 (see in Fig. 30) to be the distributed platforms for the model of MAV and the participating algorithms, and the system on each PC/104 is the Real Time Linux, which is responsible for the certainty of calculation, then the link between the two platform is RS232.

Fig.30 PC/104 computer

The designed path and the related parameters are set the same with those in case 3, and the results are shown in Fig. 31.

Fig.31 Comparative results of algorithms/laws

The performance of participating path following algorithms/laws with change in weight value Γ is displayed in Figure 31. The VF with fuzzy logic algorithm is quite advantageous for any weight value distribution from 0 to 1. When Γ varies within 0.7~1, the NLGL performs close to VF with fuzzy, and the Carrot, PLOS, LQR are quite the same with each other, but it is obviously that the performance of all the 5 algorithms is similar, which indicates that the control effort of each algorithm is quite the same; as Γ changes within the range of 0~0.7, the ranking of performance is: VF with fuzzy, NLGL, LQR, PLOS, and Carrot, and the gap according to the score is relatively apparent, so the VF with fuzzy control algorithm is validated to be more efficient when considering both the control effort and tracking error, and this is more practical for a fixed wing MAV with limited ability to execute a real mission.

6. Conclusions

A detailed study of vector fields with fuzzy control based path-following algorithm for a fixed-wing MAV is achieved with system uncertainties and wind disturbances.

We establish a two-layered framework to manage both the guidance level and the control level. The vehicle is steered by using a vector-field based guidance law, where the instructive path is divided into the straight-line and circle segment, to eliminate the path-following errors. To compensate for the system uncertainties and time-varying wind disturbances, a fuzzy logic based PID controller is proposed to handle the control level.

The simulation test of the fuzzy PID controller is illustrated to verify its practical and effectiveness. Simulation study proves the effectiveness of the proposed path following and control algorithm by three different cases with diverse scenario settings, and a HILS test is given to demonstrate the outperformance of the proposed algorithm through a comparative method where both tracking errors and control effort are reasonably considered.

7. Data availability statements

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

8. Statements & Declarations

8.1 Funding

This work was supported by the National Natural Science Foundation of China [grant numbers 72001173].

8.2 Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

9. References

- [1] Maza I, Caballero F, Capitán J, et al. Experimental results in multi-UAV coordination for disaster management and civil security applications[J]. Journal of intelligent & robotic systems, 61(1): 563-585 (2011)
- [2] Schmale Iii D G, Dingus B R, Reinholtz C. Development and application of an autonomous unmanned aerial vehicle for precise aerobiological sampling above agricultural fields[J]. Journal of Field Robotics, 25(3): 133-147(2008)
- [3] Sujit P B, Kingston D, Beard R. Cooperative forest fire monitoring using multiple UAVs[C]//2007 46th IEEE Conference on Decision and Control. IEEE: 4875-4880 (2007)
- [4] Frew E W, Argrow B. Embedded reasoning for atmospheric science using unmanned aircraft systems[C]//2010 AAAI Spring Symposium Series (2010)
- [5] Askari A, Mortazavi M, Talebi H A. UAV formation control via the virtual structure approach[J]. Journal of Aerospace Engineering, 28(1): 04014047 (2015)

- [6] Su Z, Wang H, Yao P, et al. Back-stepping based anti-disturbance flight controller with preview methodology for autonomous aerial refueling[J]. Aerospace Science and Technology, 61: 95-108 (2017)
- [7] Wu J, Wang H, Li N, et al. Path planning for solar-powered UAV in urban environment[J]. Neurocomputing, 275: 2055-2065 (2018)
- [8] Muniraj D, Palframan M C, Guthrie K T, et al. Path-following control of small fixed-wing unmanned aircraft systems with H^∞ type performance[J]. Control Engineering Practice, 67: 76-91 (2017)
- [9] Wang B, Dong X, Chen B M. Cascaded control of 3D path following for an unmanned helicopter[C]//2010 IEEE Conference on Cybernetics and Intelligent Systems. IEEE, 70-75 (2010)
- [10] Ratnoo A, Sujit P B, Kothari M. Adaptive optimal path following for high wind flights[J]. IFAC Proceedings Volumes, 44(1): 12985-12990 (2011)
- [11] Healey A J, Lienard D. Multivariable sliding mode control for autonomous diving and steering of unmanned underwater vehicles[J]. IEEE journal of Oceanic Engineering, 18(3): 327-339 (1993)
- [12] Li Z, Sun J, Oh S. Design, analysis and experimental validation of a robust nonlinear path following controller for marine surface vessels[J]. Automatica, 45(7): 1649-1658 (2009)
- [13] Rysdyk R. Unmanned aerial vehicle path following for target observation in wind[J]. Journal of guidance, control, and dynamics, 29(5): 1092-1100 (2006)
- [14] Hota S, Ghose D. A modified Dubins method for optimal path planning of a miniature air vehicle converging to a straight line path[C]. American Control Conference. IEEE, 2397-2402 (2009)
- [15] Nelson D R, Barber D B, McLain T W, et al. Vector field path following for miniature air vehicles[J]. IEEE Transactions on Robotics, 23(3): 519-529 (2007)
- [16] Sujit P B, Saripalli S, Sousa J B. Unmanned aerial vehicle path following: A survey and analysis of algorithms for fixed-wing unmanned aerial vehicles[J]. IEEE Control Systems Magazine, 34(1): 42-59 (2014)
- [17] Han J. From PID to active disturbance rejection control[J]. IEEE transactions on Industrial Electronics, 56(3): 900-906 (2009)
- [18] Mokhtari M R, Braham A C, Cherki B. Extended state observer based control for coaxial-rotor UAV[J]. ISA transactions, 61: 1-14 (2016)
- [19] Shao X, Wang H, Zhang H P. Enhanced trajectory linearization control based advanced guidance and control for hypersonic re-entry vehicle with multiple disturbances[J]. Aerospace Science and Technology, 46: 523-536 (2015)
- [20] Ma D, Xia Y, Li T, et al. Active disturbance rejection and predictive control strategy for a quadrotor helicopter[J]. IET Control Theory & Applications, 10(17): 2213-2222 (2016)
- [21] Son Y I, Kim I H, Choi D S, et al. Robust cascade control of electric motor drives using dual reduced-order PI observer[J]. IEEE Transactions on Industrial Electronics, 62(6): 3672-3682 (2014)
- [22] Kim S K. Offset-Free One-Step Ahead State Predictor for Power Electronic Applications Using Robust Proportional-Integral Observer[J]. IEEE Transactions on Industrial Electronics, 63(3): 1763-1770 (2015)
- [23] Zhu D, Hua X, Sun B. A neurodynamics control strategy for real-time tracking control of autonomous underwater vehicles[J]. The Journal of Navigation, 67(1): 113-127 (2014)

- [24] Edison E, Shima T. Integrated task assignment and path optimization for cooperating uninhabited aerial vehicles using genetic algorithms[J]. Computers & Operations Research, 38(1): 340-356 (2011)
- [25] Boussaïd I, Lepagnot J, Siarry P. A survey on optimization metaheuristics[J]. Information sciences, 237: 82-117 (2013)
- [26] Kar S, Das S, Ghosh P K. Applications of neuro fuzzy systems: A brief review and future outline[J]. Applied Soft Computing, 15: 243-259 (2014)
- [27] Fong S, Deb S, Chaudhary A. A review of metaheuristics in robotics[J]. Computers & Electrical Engineering, 43: 278-291 (2015)
- [28] Sáez D, Cortés C E, Núñez A. Hybrid adaptive predictive control for the multi-vehicle dynamic pick-up and delivery problem based on genetic algorithms and fuzzy clustering[J]. Computers & Operations Research, 35(11): 3412-3438 (2008)
- [29] Khodayari M H, Balochian S. Modeling and control of autonomous underwater vehicle (AUV) in heading and depth attitude via self-adaptive fuzzy PID controller[J]. Journal of Marine Science and Technology, 20(3): 559-578 (2015)
- [30] Xiang X, Yu C, Zhang Q. Robust fuzzy 3D path following for autonomous underwater vehicle subject to uncertainties[J]. Computers & Operations Research, 84: 165-177 (2017)
- [31] Ramli N, Mohamad D. A comparative analysis of centroid methods in ranking fuzzy numbers[J]. European Journal of Scientific Research, 28(3): 492-501 (2009)
- [32] Dryden H L. A review of the statistical theory of turbulence[J]. Quarterly of Applied Mathematics, 1(1): 7-42 (1943)

Definitions, Acronyms and Abbreviations

3D: Three-dimensional	VF: Vector fields
UAS: Unmanned aerial system	NB: negative large
UAV: Unmanned aerial vehicle	NS: negative small
MAV: miniature fixed wing unmanned aerial vehicle	
PID: Proportional-Integral-Derivation	

10. Vitae

Weinan Wu, Assistant Professor, Northwestern Polytechnical University.

Yao Wang , Ph.D candidate, Northwestern Polytechnical University.

Chunlin Gong Professor, Northwestern Polytechnical University.

Dan Ma, Ph.D candidate, Northwestern Polytechnical University.