Deviation Correction and Stability Augmentation Control for UAV Taxiing

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ABSTRACT

For the taxiing deviation correction control of medium and small sized UAV and the taxiing rollover problem which is likely to happen during deviation correction, this paper analyzed the force acting on UAV during taxiing, established the six degrees of freedom mathematical model of UAV taxiing, including the landing gear absorber model and the tire model. The Fuzzy-PID (proportion integration differentiation) control system based on ACO (ant colony algorithm) was designed to optimize PID parameters offline and to adjust PID parameters online. The cause of UAV rollover was analyzed, the fuzzy stability augmentation control system was presented to enhance the taxiing stability of UAV by synergetic controlling nose wheel, elevator and aileron. The simulation results show that the Fuzzy-PID control system based on ACO has obvious effect on deviation correction, and the control system can enhance the taxiing stability of UAV and keep UAV from rolling over effectively. the feasibility and validity of the control system was verified.

1 INTRODUCTION

In recent years, the flight performance of UAV is taken seriously in the development of UAV[1]. Although taking off and landing only take 2%-3% of the whole mission time, there are a lot of accidents happened during this time[2]. As for medium and small sized UAV, whose mass is light and tires are small, usually, the runways they used are simple, interference factors such as gust and unfairness of runway will make strong disturbance to UAV during taxiing, the disturbance will change the yaw angle of UAV and make lateral deviation[3]. If the deviation couldn't be corrected effectively, the UAV may taxi out of runway. If the deviation is corrected sharply, the UAV is easy to roll over[4]. So it can be concluded that the deviation correction and stability augmentation control is an important mission during taking off and landing.

In terms of UAV taxiing modeling, GU Hong-bin[5] and ZHANG Ming[6] established the taxiing model of UAV which used the rigid tricycle landing gear. F. Holzapfel[7] presented the accurate landing gear model. Kapseong Ro[8]、W.A.Ragsdale[9]and Xiaohui Wei[10] established taxiing model of UAV with stretch landing gear. Phil Evans[11] investigated the UAV taxiing performance while the landing gear break down. But some of them used simplified tire theory to solve the lateral force of tire, when the sideslip angle of tire was large, that will make the large error. And few of them considered the stretch of landing gear will change the attitude of UAV, which will influence the taxiing stability of UAV.

In terms of UAV taxiing control, Song Lei[3] investigated the instability problem which was observed during high-speed taxi tests of an experimental flying-wing aircraft. Am Cho[12] designed the deviation correction control system with linear quadratic regulator. WANG Yong[13] presented the deviation correction laws based on genetic algorithm. WU Cheng-fu[14]and YUAN Zhao-hui[15] used fuzzy logic to correct the taxiing deviation. JI Li-li[16] designed the deviation correction control laws with traditional PID control. But for the taxiing control of medium and small sized UAV, the control system above considered the deviation correction performance only, few of them considers the stability of UAV during taxiing, in fact, the UAV may roll over when the deviation is corrected sharply.

To solve the taxiing rollover problem which is likely to happen during deviation correction, this paper presents a deviation correction and stability augmentation control system. The UAV taxiing mathematical model is established, which considered the landing gear absorber model and the accurate tire model. The cause of rollover was analyzed. The fuzzy controller was designed to enhance the stability of UAV by synergetic controlling nose tire, elevator and aileron. The Fuzzy-PID control system based on ant colony algorithm (ACO) was designed to optimize parameters offline and adjust parameters online, it enhanced the performance of deviation correction. Finally, through simulation and taxiing experiments, the feasibility and validity of the control system is verified.

2 UAV TAXIING MODEL

A small UAV[17] is investigated in this paper, the UAV is adopted with tandem wing configuration, tricycle landing gear and steerable nose wheel, the control surface are elevator and aileron. When the UAV taxis with three wheels on the ground, there are gravity, thrust, aerodynamic force and ground reaction force acting on UAV. In this paper, the ground reaction force on landing gear is selective analyzed, the air oil absorber model and tire model are built.

2.1 *Landing gear absorber model*

The air oil absorber is researched in this paper, in the axial direction of landing gear, the air spring force $F_{elastic}$ and the oil damping force F_{damp} are considered only. The axial force of landing gear which acts on UAV can be expressed by

$$P = F_{\text{elastic}} + F_{\text{damp}} \tag{1}$$

where

$$F_{\text{elastic}} = \frac{P_0 V_0 S_g}{V_0 - S_g \delta} \tag{2}$$

$$F_{\text{damp}} = \frac{K_o \rho_o S_o{}^3 \delta'^2}{2 S_d{}^2} \tag{3}$$

In the equation, P_0 and V_0 are initial pressure and initial volume of the air cavity respectively. δ is the compression stroke of the absorber. S_g , S_o and S_d are piston area of air cavity, piston area of oil cavity and damping hole area respectively. K_o and ρ_o are oil damping coefficient and oil density. Compression stroke δ and compression velocity δ' can be got from UAV attitude and attitude rate:

$$\begin{cases} \delta_a = L_a - a\sin\vartheta - h \\ \delta_{bl} = L_{bl} + b\sin\vartheta - b_w \sin\gamma - h \\ \delta_{br} = L_{br} + b\sin\vartheta + b_w \sin\gamma - h \end{cases} \tag{4}$$

$$\begin{cases} \delta'_a = V_z - a\omega_z \\ \delta'_{bl} = V_z + b\omega_z - b_w\omega_x \\ \delta'_{br} = V_z + b\omega_z + b_w\omega_x \end{cases} \tag{5}$$

In the equation, δ_a, δ_{bl} and δ_{br} are compression stroke of front landing gear, left rear (LR) landing gear and right rear (RR) landing gear respectively. δ'_a, δ'_{bl} and δ'_{br} are compression velocity of front landing gear, LR landing gear and RR landing gear respectively. L_a, L_{bl} and L_{br} are uncompressed length of front landing gear, LR landing gear and RR landing gear respectively. a is lengthways projection distance between center of gravity and front landing gear. b is lengthways projection distance between center of gravity and rear landing gear. b_w is lateral projection distance between center of gravity and rear landing gear. ϑ , γ and ψ are pitch angle, roll angle and yaw angle of UAV. ω_x and ω_z are pitch rate and roll rate of UAV. h is height between ground and central of gravity. V_z is the velocity component on z axes in ground coordinate system.

2.2 Tire model

As is shown in figure 1, there are three force acting on the tire, they are support force P , rolling friction force of tire N and lateral force of tire S . The support force P can be solved through analyzing axial force of landing gear. The rolling friction coefficient between ground and tire is μ_r , so the rolling friction force of three tires can be expressed by:

$$\begin{cases} N_a = \mu_r P_a \\ N_{bl} = \mu_r P_{bl} \\ N_{br} = \mu_r P_{br} \end{cases} \tag{6}$$

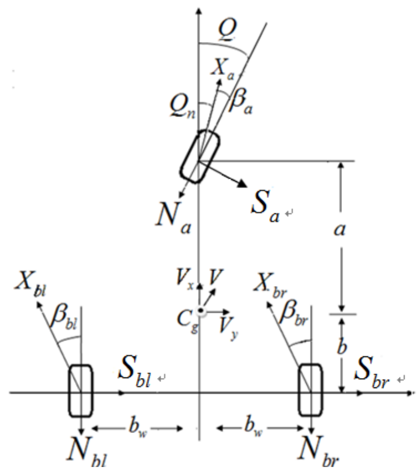

Figure 1 : Ground force acting on tires

Then the lateral force of tire is analyzed emphatically: UAV needs to turn the front wheel to control the yaw angle, and there is friction force between ground and tire, which is perpendicular to the rotation surface of tire, this force is lateral force of tire. The angle between rotation force and velocity direction of tire is slip angle of tire. There are two stages while calculating the lateral force of tire: the elastic deformation stage and the slip stage. The critical slip angle is defined to distinguish the two stages.

The critical slip angle β_c is determined by support force P , tire cornering stiffness k_β and the rolling friction coefficient μ_r . The critical slip angle can be expressed by:

$$\beta_c = \frac{3\mu_s |P|}{k_\beta} \tag{7}$$

If the slip angle of tire is equal or less than the critical slip angle ($|\beta| \le \beta_c$), the lateral force of tire can be expressed by:

$$S = -\mu_s |P| (1 - B^3) sign(B) \tag{8}$$

$$B = 1 - \frac{\beta_c |\tan(\beta)|}{3\mu_s |P|} \tag{9}$$

If the slip angle of tire is equal or less than the critical slip angle ($|\beta| > \beta_c$), the lateral force of tire can be expressed by:

$$S = -\mu_s |P| \operatorname{sign}(\beta) \tag{10}$$

Where, β can be solved from figure 1:

$$\begin{cases} \beta_a = Q - \arctan\left(\dfrac{V_y + ra}{V_x \cos\theta}\right) \\ \beta_{bl} = \arctan\left(\dfrac{rb - V_y}{rb_w + V_x \cos\theta}\right) \\ \beta_{br} = \arctan\left(\dfrac{rb - V_y}{V_x \cos\theta - rb_w}\right) \end{cases} \tag{11}$$

In the equation, β_a, β_{bl} and β_{br} are slip angle of front tire, LR tire and RR tire. V_x and V_y are velocity component on X axes and Y axes in body coordinate system.

The force and moment acting on UAV from ground can be solved from equation (12)and (13). In the equation, $\boldsymbol{T}$ is transfer matrix from stable coordinate system to body coordinate system, Q is deflection angle of front wheel. Combine ground force and aerodynamic force together, the taxiing model of UAV can be got.

$$\boldsymbol{F_{be}} = \begin{bmatrix} F_{bex} \\ F_{bey} \\ F_{bez} \end{bmatrix} = \boldsymbol{T} \begin{bmatrix} -(S_a \sin Q + N_a \cos Q + N_{bl} + N_{br}) \\ S_a \cos Q - N_a \sin Q + S_{bl} + S_{br} \\ -(P_a + P_{bl} + P_{br}) \end{bmatrix} \tag{12}$$

$$\boldsymbol{M_{be}} = \begin{bmatrix} M_{bex} \\ M_{bey} \\ M_{bez} \end{bmatrix} = \boldsymbol{T} \begin{bmatrix} (P_{bl} + P_{br})b_w - (S_a \cos Q - N_a \sin Q + S_{bl} + S_{br})h \\ P_a a - (P_{bl} + P_{br})b - (S_a \sin Q + N_a \cos Q + N_{bl} + N_{br})h \\ (S_a \cos Q - N_a \sin Q)a - (S_{bl} + S_{br})b \end{bmatrix} \tag{13}$$

3 DEVIATION CORRECTION AND STABILITY AUGMENTATION CONTROL

3.1 Instability analysis of UAV taxiing

From figure 1, the force acting on UAV can be got, when the UAV turns right, these force will generate the negative pitching moment and the left rolling moment (figure 2), there will be a roll-over tendency for UAV. Because the absorber could be compressed, the UAV will present the negative pitching and left rolling attitude. In this attitude, the aerodynamic lift and engine thrust will increase the roll-over tendency of UAV. So if turning angle of front wheel is too much, the UAV is easy to roll over.

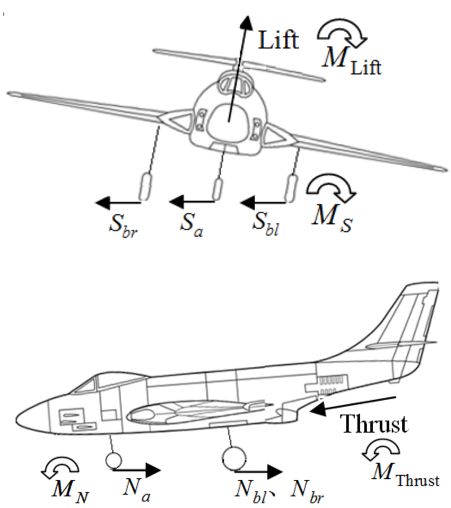

Figure 2: Analysis of rollover force

The rollover accident is simulated in this paper, when the compression stroke of absorber decreases to zero, it can be considered that there is no support force between ground and tire, the rollover accident happened. In simulation, the turning angle of front wheel increases 1° starting from 0°, until the UAV roll over, the critical turning angle $Q_{critical}$ can be gotten. The simulation above is done in different taxiing velocity, and then the critical rollover condition can be got, it's shown in figure 3. It can be found the lower the gravity center is, the higher the stability is. It also can be found if the taxiing velocity $V > 10m/s$, the critical turning angle of front wheel is small, the UAV is easy to roll over due to the large turning angle of front wheel, so it can be considered the stability of this UAV is poor.

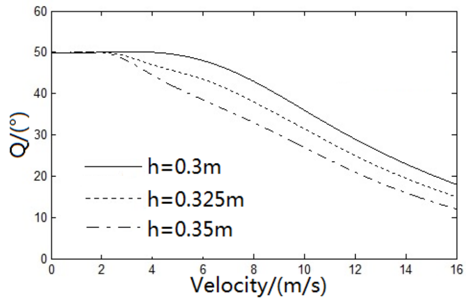

Figure 3: Critical condition of taxiing rollover

3.2 Stability Augmentation Control

In order to enhance the UAV taxiing stability and avoid roll-over accident, the fuzzy stability augmentation control system is designed. Through deflecting the elevator and aileron, the aerodynamic moment is generated to balance the rollover moment, the UAV attitude could keep steady. The fuzzy logic rules are used to control the turning of front wheel and the deflection of elevator and aileron, the rules are shown below:

1）When the taxiing velocity of UAV is low, and the turning angle of front wheel is small, there is no rollover risk, the elevator positive deflects through large angle, the negative pitching moment is generated to increase the pressure between the ground and the front tire, that can improve the turning efficiency of UAV. The aileron deflects through small angle, that can decrease the air drag, the UAV could reach the taking-off velocity as soon as possible.

2）When the taxiing velocity of UAV is low, and the turning angle of front wheel is large, there is small rollover risk, the elevator negative deflects through small angle, the aileron deflects through small angle.

3）When the taxiing velocity of UAV is high, and the turning angle of front wheel is small, there is small rollover risk, the elevator positive deflects through small angle, the aileron deflects through large angle, the large drag is generated to decrease the lateral velocity of UAV, the large rolling moment is generated to balance the rollover moment.

4）When the taxiing velocity of UAV is high, and the turning angle of front wheel is large, there is large rollover risk, the elevator negative deflects through large angle, the aileron deflects through large angle, the resultant moment is generated to prevent the UAV from rolling over.

The fuzzy logic rules of elevator deflection and aileron deflection are shown in table 1. The fuzzy language is NB (Negative big), NM (negative medial), NS (negative small), ZO (zero), PS (positive small), PM (positive medial), PB (positive big). Membership function is triangle and normal type, the position and coverage area of fuzzy subset are adjusted to get the membership function with good convergence property and rapid respond. the membership function of elevator deflection is shown as figure 4.

V	Q						
	NB	NM	NS	ZO	PS	PM	PB
ZO	PS/NS	PM/NS	PM/ZO	PB/ZO	PM/ZO	PM/PS	PS/PS
PS	NS/NM	NS/NS	PS/NS	PB/ZO	PS/PS	NS/PS	NS/PM
PM	NB/NB	NM/NM	ZO/NS	PS/ZO	ZO/PS	NM/PM	NB/PB
PB	NB/NB	NB/NB	ZO/NM	PS/ZO	ZO/PM	NB/PB	NB/PB

Table 1: Fuzzy control rules of elevator/aileron

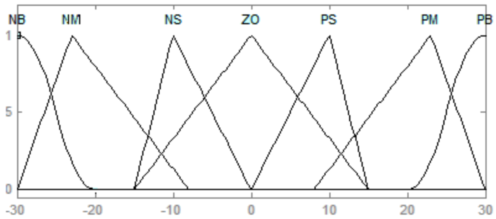

Figure 4: Membership function of elevator deflection

According the fuzzy rules in table 1, the centroid method is used to solve ambiguity, the fuzzy logic surface of elevator and aileron are shown as figure 5 and figure 6.

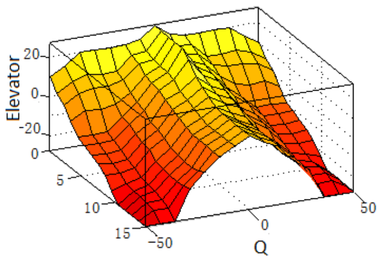

Figure 5: Fuzzy control rules of elevator

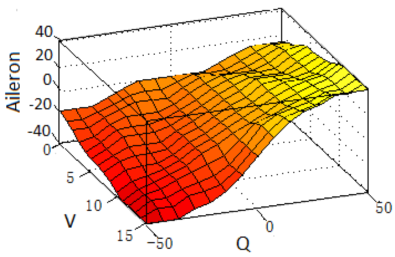

Figure. 6: Fuzzy control rules of aileron

3.3 Deviation correction control

The UAV correct deviation through controlling the turning of front wheel. The Fuzzy-PID control system based on ant colony algorithm (ACO) is designed to control the deviation correction during taxing, the control structure is shown as figure 7, the ACO is used to optimize the PID parameters offline, and the fuzzy logic control is used to adjust PID parameters online.

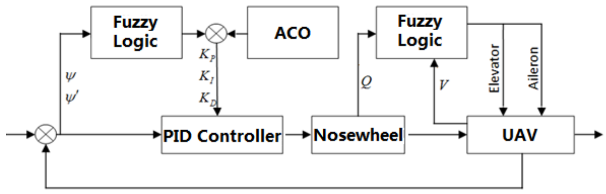

Figure. 7: Deviation correction and stability augmentation control system

In the control system, ACO is used to optimize the K_P, K_I, K_D three gain parameters, the objective function is:

$$J_{\text{PID}} = \int_0^{\infty} \left(k_1 \left|e(t)\right| + k_2 u(t)\right) dt + k_3 t_d + k_4 \sigma_p \tag{14}$$

In the equation, $e(t), u(t), t_d, \sigma_p$ are system error, control quantity, rise time and overshoot respectively, k_1, k_2, k_3, k_4 are weight.

It assumes there are m ants, K_P , K_I , K_D are three sets, the ants need to pass three nodes in K_P , K_I and K_D in order, and according to the transition probability, the ants random select the next point. The transition probability can be solved by:

$$P_{ij}^{k}(t) = \begin{cases} \dfrac{\left[\tau_{ij}(t)\right]^{\varsigma}\left[\eta_{ij}(t)\right]^{\tau}}{\sum\limits_{s \in allowed(t)^k} \left[\tau_{is}(t)\right]^{\varsigma}\left[\eta_{is}(t)\right]^{\tau}} & , \ j \in allowed(t)^k \\ 0 & , \ j \notin allowed(t)^k \end{cases}$$

(15)

In the equation, $P_{ij}^{k}(t)$ is the transition probability of nth ant at t time; $\tau_{ij}(t)$ and $\eta_{ij}(t)$ are the pheromone content and visibility between two neighbor nodes; ς and τ are the relative importance of the route and the visibility; $allowed(t)^k$ is the node set that can be selected by nth ant at the t time. At the t time, the visibility of nodes can be expressed by:

$$\eta_{ij}(t) = 1/d_j(t) \tag{16}$$

$d_j(t)$ is the distance between the current node and the optimal node in last round. When all of m ants finish once circulation, the pheromone between two neighbor nodes will be updated, the update rules are shown as below:

$$\Delta\tau_{ij}(t) = \sum_{k=1}^{m} \Delta\tau_{ij}^{k}(t) \tag{17}$$

$$\Delta\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{18}$$

$$\Delta\tau_{ij}^{k}(t)=\begin{cases}\dfrac{Q_{\text{ant}}}{J_{\text{PID}}}, & \text{if the ants pass the node}\\ 0, & \text{else}\end{cases} \tag{19}$$

In the equation, Q_{ant} is the pheromone intensity of the ant. After N_c times iteration, the optimal solution of objective function and the optimal parameters of PID can be gotten. In this control system, when the initial velocity is $5m/s$ and $10m/s$, the initial yaw angle error is 5.7° and 11.5°, the parameters optimization results is shown as table2.

Parameters	$\psi=5.7^\circ$ $V=5m/s$	$\psi=5.7^\circ$ $V=10m/s$	$\psi=11.5^\circ$ $V=5m/s$	$\psi=11.5^\circ$ $V=10m/s$
K_P	3.00	3.00	3.00	3.00
K_I	0.12	0.13	0.02	0.10
K_D	0.61	0.75	0.72	0.84

Table 2: Parameter optimization results with ACO

The Fuzzy-PID control system is consist of fuzzy logic controller and PID controller. In the fuzzy logic controller, the yaw angle error $|\psi|$ and error rate $|\psi'|$ are input into controller, the output are the increment ΔK_P, ΔK_I and ΔK_D, as is shown in formula (20), through adjusting the parameters $K_{P\text{fuzzy}}$, $K_{\text{I fuzzy}}$ and $K_{\text{D fuzzy}}$ online, the PID parameters fuzzy self-tuning system is generated.

$$\begin{cases}K_{P\text{fuzzy}}=K_P+\Delta K_P\\ K_{\text{I fuzzy}}=K_I+\Delta K_I\\ K_{\text{D fuzzy}}=K_D+\Delta K_D\end{cases} \tag{20}$$

PID parameters fuzzy logic rules are shown below:

1) When $|\psi|$ is large, in order to speed up the response of system, the large K_P and small K_D, K_I should be used.

2) When the $|\psi|$ is medium, in order to decrease the overshoot of system and keep the rapid response speed, K_P should be decreased and the medium K_D and K_I should be used.

3) When the $|\psi|$ is small, in order to decrease the state error of system, the large K_P and K_I should be used. Considering the anti-disturbance performance of system, if the $|\psi'|$ is large, the small K_D should be used, else the K_D should be medium.

The fuzzy logic rules of PID parameters are shown in table 3, according the fuzzy logic rules, the PID parameters fuzzy self-tuning controller is designed.

4 SIMULATION

In order to verify the deviation correction property and the stability augmentation performance of the control system, the UAV taxiing is simulated under the initial condition $V=10m/s$ and $\psi=11.5^\circ$. The simulation results are shown in figure8-figure11.

The roll angle of UAV is recorded during the process of correction deviation, the result is shown in figure.8, it could be found that after using the fuzzy stability augmentation control, the roll angle change of UAV is smaller, and the attitude of UAV is steadier; The critical rollover condition of UAV which use the fuzzy stability augmentation control is analyzed. From figure 9 it could be found that after using the fuzzy stability augmentation control, the critical turning angle of front wheel becomes larger, that means the UAV could correct deviation with a larger range; The taxiing track and yaw angle of UAV are recorded during the process of correction deviation, from figure.10 and figure.11, it could be found that compared with the UAV which uses fixed parameters PID controller, the UAV which uses the ACO-Fuzzy control system has better effect on the deviation correction response, the overshoot, and the steady time, the deviation distance is smaller.

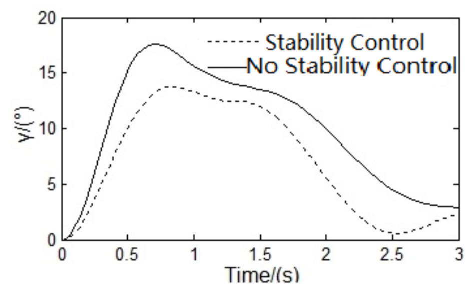

Figure. 8: Change of roll angle during deviation correction

Table 3 Fuzzy logic rules of $\Delta K_P/\Delta K_I/\Delta K_D$

ψ	ψ'						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB/PS	PB/NB/NS	PM/NM/NB	PM/NM/NB	PS/NS/NB	ZO/ZO/NM	ZO/ZO/PS
NM	PB/NB/PS	PB/NB/NS	PM/NM/NB	PS/NM/NM	PS/NS/NM	ZO/ZO/NS	NS/ZO/ZO
NS	PM/NB/ZO	PM/NM/NS	PM/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/PS/NS	NS/PS/ZO
ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NM/PM/NS	NM/PM/ZO
PS	PS/NM/PB	PS/NS/ZO	ZO/ZO/ZO	NS/PS/ZO	NS/PS/ZO	NM/PM/ZO	NM/PB/ZO
PM	PS/ZO/PB	ZO/ZO/NS	NS/PS/PS	NM/PS/PS	NM/PM/PS	NM/PB/PS	NB/PB/PB
PB	ZO/ZO/PB	ZO/ZO/PM	NM/PS/PM	NM/PM/PM	NM/PM/PS	NB/PB/PS	NB/PB/PB

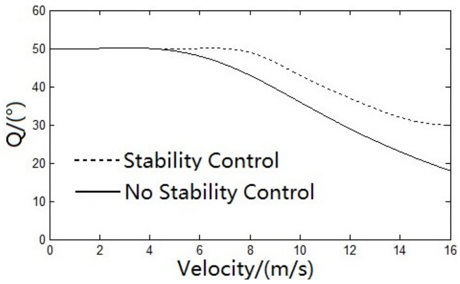

Figure 9: Critical condition of taxiing rollover

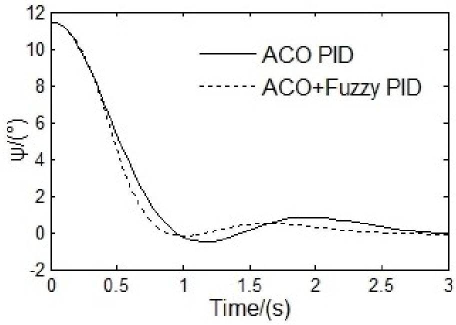

Figure 10: Change of yaw angle during deviation correction

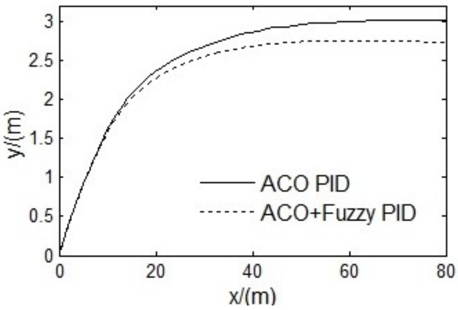

Figure 11: Taxiing track during deviation correction

5 CONCLUSION

Through establishing the mathematical model of UAV taxiing, the process of UAV rollover is simulated, the critical rollover condition is gotten, the results shows the stability of UAV is poor during deviation correction. The fuzzy stability augmentation controller and the fuzzy-PID controller based on ACO is designed, the simulation results show that the Fuzzy-PID control system based on ACO has obvious effect on deviation correction, and the control system can enhance the taxing stability of UAV and keep UAV from rolling over effectively. The simulation results validate the feasibility and validity of control system.

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