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A Joint Attitude Control Method for Small Unmanned Aerial Vehicles Based on Prediction Incremental Backstepping

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Abstract. *A new second-order joint attitude control method for Small Unmanned Aerial Vehicles (SUAVs) is presented in this paper. Based on lyapunov theory, a second-order backstepping control law is developed. An incremental control approach called Incremental Backstepping (IB) is used to increase the robust performance of the second-order control system. A new joint incremental backstepping attitude controller is proposed for SUAVs based on the movement equations. A prediction filter is added to enhance the accuracy of the sensors data and eliminate the time delay. The simulation results show the approach presented is valid.*
Keywords: Unmanned aerial vehicle, Backstepping control, Nonlinear control, Incremental backstepping.

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1. **Introduction.** At present, there are several linear control methods, such as Proportion-Integration-DifferentiationPID,widely applied in SUAVs [1]. These conventional methods have shortcomings as follows: much time is required in designing and verifying gain parameters to meet the control needs while the derived gain parameter has no generality [2]; besides, the respectively independent design of attitude control and navigation control leads to too many design parameters in the flight control and the complication of the control system design; whats more, compared to manned aerial vehicles and large and medium size unmanned aerial vehicles, SUAVs fly in low-Reynolds situations in most cases, because of complicated aerodynamic and non-linear properties, the robustness property of the flight control is relatively poor [3].

To solve problems mentioned above, a number of nonlinear control methods are presented, among which Nonlinear Dynamic Inversion (NDI) flight control method is a popularly accepted one. With this method, the control law is developed based on motion model of the aircraft; the nonlinearity can be cancelled by means of nonlinear feedback and exact state transformation so that the precise linearity of the system can be realized [4]; moreover, NDI control method has advantages: the designed control law is of generality and there is no need to adjust the control gain. Thus, this control method has been widely applied in varieties of flight controllers [5, 6, 7, 8, 9].

However, Nonlinear Dynamic Inversion (NDI) depends on the premise that the parameters of UAVs models are highly precise. If there is error in the parameter of UAVs models, the inverse error will arise in the system in the process of solving dynamic inversion, which leads to instability of the system. Whats more, as the NDI lacks inherent stability in the procedure of the flight control law design [4], this causes the problem of the certification.

Backstepping control method is an alternative one to realize the dynamic inversion. Based on Lyapunov stability analysis, this method theoretically supports the overall stability of the closed-loop system. Backstepping control method has been widely used in the flight controller [10, 11]. In References [12, 13, 14], backstepping control is used in the steamship flight controller, paper [15] illustrates the application of backstepping control in reentry vehicles and paper [16] discusses its application in the missile flight control.

The design of backstepping control is to resolve all the design problems of the whole system into a series of low-level subsystems and recursively select Lyapunov control functions and feedback control [17]. By making use of the extra freedom degree existing in the subsystem, Backstepping method, compared to other methods, has looser conditions when it comes to solving stability control, track control and robustness control. It can retain more nonlinearity properties and at the same time theoretically guarantees the control stability.

However, it is hard to obtain precise dynamic models in the real flight. Therefore, to achieve the effect of robust control, IB [18] and Sensor Based Backstepping (SBB) [19, 20] are used to reduce the dependence of the model parameters by feeding back angular accelerations. Nevertheless, IB and SSB rely too much on sensors data. Besides, in the control loop, collecting sensor data, transmitting signals, computing control commands, then servo implementation, there is delay in the whole procedure and computing errors will arise [21].Aiming to solve this problem, Prediction-Incremental Backstepping(PIB) attitude control algorithm based on IB is proposed below.

2. **Second-Order Backstepping Control Law.**

The key process of the backstepping control law is the construction of control system Control Lyapunov Function(CLF).

Definition 2.1. *Suppose the control system is shown as,*

$$\dot{\mathbf{x}} = f(\mathbf{x}) + g(\mathbf{x})\mathbf{u} \tag{1}$$

If there is a continual differentiable positive definite function $V(\mathbf{x})$, as for $x \in \mathbf{D}$, and $x \neq 0$, there is,

$$\frac{\partial V}{\partial \mathbf{x}} g(\mathbf{x}) = 0 \Rightarrow \frac{\partial V}{\partial \mathbf{x}} f(\mathbf{x}) < 0 \tag{2}$$

then the function $V(\mathbf{x})$ is CLF.

If there is CLF in the control system, the backstepping control law constructed is the global stability according to reference [17]. The backstepping method can be used in many strict feedback control system. With second-order system backstepping law described in Equation (3) and (4), the attitude control law of SUAVs is hence deduced.

$$\dot{\mathbf{x}}_{\mathbf{1}} = f(\mathbf{x}_1) + g(\mathbf{x}_1)\mathbf{x}_2 \tag{3}$$

$$\dot{\mathbf{x}}_{\mathbf{2}} = h(\mathbf{x}_2) + \eta(\mathbf{x}_2)\mathbf{u} \tag{4}$$

The control goal is that the state variable $\mathbf{x}_1$ tracks $\mathbf{y_r}$ the given input . Design steps of the backstepping controller is as follows: Step 1: Definition track error:

$$\mathbf{z}_1 = \mathbf{x}_1 - \mathbf{y}_r \tag{5}$$

$$\mathbf{z_2} = \mathbf{x}_2 - \alpha \tag{6}$$

Where α is implicit control input, that is, the new stability control law in the first step of backstepping.With regard to Eq.(5), CLF is designed:

$$\mathbf{V}_1 = \frac{1}{2}\mathbf{z}_1^2 \tag{7}$$

the derivative is:

$$\dot{\mathbf{V}}_1 = \mathbf{z}_1\dot{\mathbf{z}}_1 = \mathbf{z}_1[f(\mathbf{x}_1) + g(\mathbf{x}_1)\mathbf{x}_2 - \dot{\mathbf{y}}_r] \tag{8}$$

Based on Definition 1,we choose:

$$\alpha = -g^{-1}(\mathbf{x}_1)[\mathbf{c}_1\mathbf{z}_1) + f(\mathbf{x}_1) - \dot{\mathbf{y}}_r] \tag{9}$$

with $\mathbf{c}_1 > 0$.

Step2: Using variables to replace and rewrite Eq.(5) and Eq.(6) to obtain the derivative:

$$\dot{\mathbf{z}}_\mathbf{1} = f(\mathbf{x}_1) + g(\mathbf{x}_1)(\alpha + \mathbf{z}_2) - \dot{\mathbf{y}}_r \tag{10}$$

$$\dot{\mathbf{z}}_\mathbf{2} = \dot{\mathbf{x}}_\mathbf{2} - \dot{\alpha} = h(\mathbf{x}_2) + \eta(\mathbf{x}_2)\mathbf{u} - \dot{\alpha} \tag{11}$$

CLF is constructed:

$$\mathbf{V}_2 = \frac{1}{2}\mathbf{z}_1^2 + \frac{1}{2}\mathbf{z}_2^2 \tag{12}$$

Derive (12), and substitute (9) to obtain:

$$\begin{aligned}\dot{\mathbf{V}}_2 &= \mathbf{z}_1\dot{\mathbf{z}}_\mathbf{1} + \mathbf{z}_2\dot{\mathbf{z}}_\mathbf{2} \\ &= \mathbf{z}_1[f(\mathbf{x}_1) + g(\mathbf{x}_1)(\alpha + \mathbf{x}_2) - \dot{\mathbf{y}}_r] + \\ &\mathbf{z}_2[g(\mathbf{x}_1)\mathbf{z}_1 + h(\mathbf{x}_2) + \eta(\mathbf{x}_2)\mathbf{u} - \dot{\alpha}] \\ &= -\mathbf{c}_1\mathbf{z}_1^2 + \mathbf{z}_2[g(\mathbf{x}_1)\mathbf{z}_1 + h(\mathbf{x}_2) + \eta(\mathbf{x}_2)\mathbf{u} - \dot{\alpha}]\end{aligned} \tag{13}$$

The conventional backstepping control law is derived:

$$\mathbf{u} = \eta^{-1}(\mathbf{x}_2)[-\mathbf{c}_2\mathbf{z}_2 - g(\mathbf{x}_1)\mathbf{z}_1 - h(\mathbf{x}_2) + \dot{\alpha}], \mathbf{c}_2 > 0 \tag{14}$$

The controller constructed is shown in the following diagram.

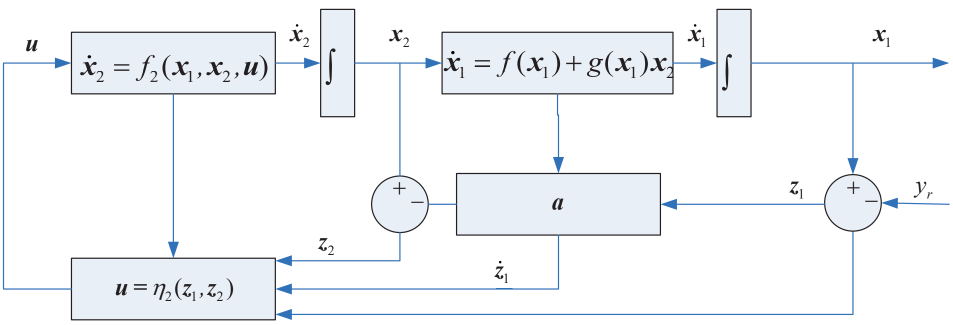

FIGURE 1. Second-order backstepping control system diagram

3. **Incremental Backstepping Control Law Deduction.** Similar to the incremental dynamic inversion method[3], the incremental backstepping method transforms the control structure into the incremental form, that is, the control increment as the control input. The controller relies more on data of the sensor. The deduction process is as follows:

Step 1: Eq. (4) is Taylor expanded in the $[\mathbf{x}_{2,0}, \mathbf{u}_0]$, neighborhood and retains one order term:

$$\dot{\mathbf{x}}_{\mathbf{2}} \approx (h(\mathbf{x}_2, 0)) + \eta(\mathbf{x}_2, 0)\mathbf{u}_0 + \frac{\partial}{\partial \mathbf{x}_2}[h(\mathbf{x}_2) + \eta(\mathbf{x}_2)]|_{\substack{x_2 = x_{2,0} \\ u = u_0}} \tag{15}$$

$$(\mathbf{x}_2 - \mathbf{x}_{2,0}) + \frac{\partial}{\partial \mathbf{x}_2}[\eta(\mathbf{x}_2)\mathbf{u}]|_{\substack{x_2 = x_{2,0} \\ u = u_0}} (\mathbf{u} - \mathbf{u}_0)$$

which can be analyzed and straightened into:

(1) The first and second item of the right side is equal to $\dot{x}_{2,0}$,

$$\dot{\mathbf{x}}_{\mathbf{2,0}} = h(\mathbf{x}_{2,0}) + \eta(\mathbf{x}_{2,0})\mathbf{u}_0 \tag{16}$$

(2) The increment of control input and state derivative is far less than variables of the state volume. When there is sufficient time-scale separation design or in the incremental control period,

$$\frac{\partial}{\partial \mathbf{x}_2}[h(\mathbf{x}_2) + \eta(\mathbf{x}_2)\mathbf{u}]|_{\substack{x_2 = x_{2,0} \\ u = u_0}} (\mathbf{x}_2 - \mathbf{x}_{2,0}) \approx 0 \tag{17}$$

(3) In addition:

$$\frac{\partial}{\partial \mathbf{x}_2}[\eta(\mathbf{x}_2)\mathbf{u}]|_{\substack{x_2 = x_{2,0} \\ u = u_0}} (\mathbf{u} - \mathbf{u}_0) = \eta(\mathbf{x}_2, 0)\triangle\mathbf{u}_0 \tag{18}$$

(4) Finally, it is straightened as:

$$\dot{\mathbf{x}}_2 = \dot{\mathbf{x}}_{2,0} + \eta(\mathbf{x}_{2,0})\triangle\mathbf{u} \tag{19}$$

Step 2: Substitute the Eq.(19) to Eq.(13) to derive:

$$\begin{aligned} \dot{\mathbf{V}}_2 &= \mathbf{z}_1\dot{\mathbf{z}}_{\mathbf{1}} + \mathbf{z}_2\dot{\mathbf{z}}_{\mathbf{2}} \\ &= \mathbf{z}_1[f(\mathbf{x}_1) + g(\mathbf{x}_1)\mathbf{x}_2 - \dot{\mathbf{y}}_r] + \\ &\mathbf{z}_2[h(\mathbf{x}_2) + \eta(\mathbf{x}_2)\mathbf{u} - \dot{\alpha}] \\ &= -\mathbf{c}_1\mathbf{z}_1^2 + \mathbf{z}_2[\dot{\mathbf{x}_{2,0}} + \eta(\mathbf{x}_{2,0})\triangle\mathbf{u} - \dot{\alpha}] \end{aligned} \tag{20}$$

Based on Definition 1, the derivative is:

$$\triangle\mathbf{u} = -\eta^{-1}(\mathbf{x}_{2,0})(\mathbf{c}_2\mathbf{z}_2 + \dot{\mathbf{x}}_{2,0} - \dot{\alpha}), \mathbf{c}_2 > 0 \tag{21}$$

The IB control diagram is shown as Figure 2.

4. **SUAVs Joint Incremental Backstepping Attitude Control.** The backstepping control above is applied to the flight control of SUAVs. The force equation and moment equation of the nonlinear rigid body motion equation of Fixed-wing UAVs in the aircraft-body coordinates are expressed in reference [5] .

The definitions of components of angular velocity, Euler angle and velocity in the aircraft-body coordinates in this section are shown in Fig. 3:

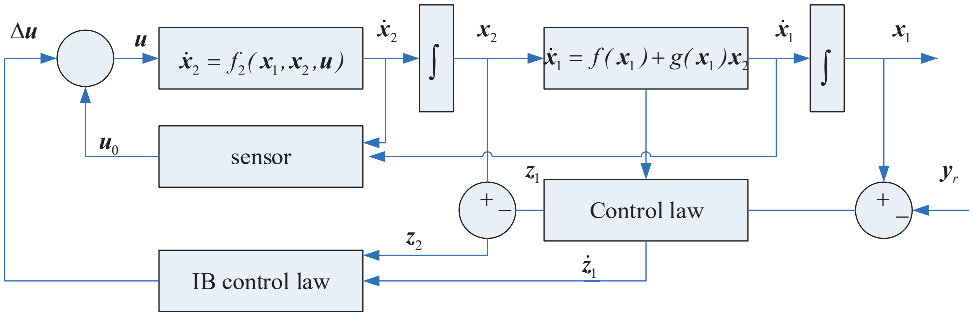

FIGURE 2. IB control diagram

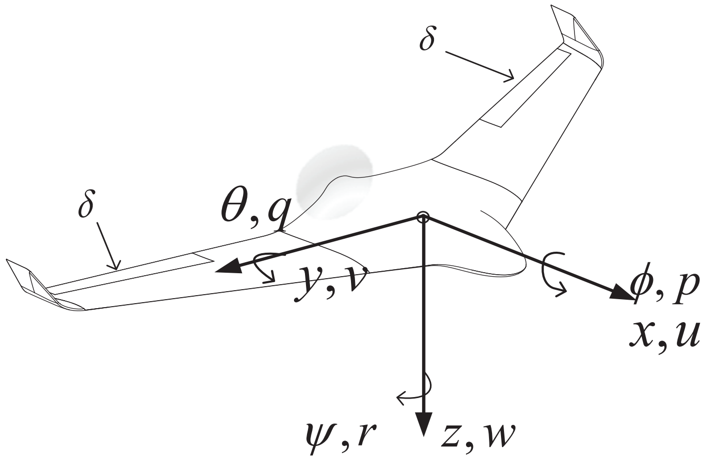

FIGURE 3. Definition of each component in the aircraft-body coordinates

Based on backstepping control deduction process above, the attitude and angular rate cascade incremental backstepping control law is obtained. The definition of each variable in Eq.(3) and Eq.(4) is as follows[22]:

$$\begin{cases} \mathbf{x}_1 = [\ \phi \quad \theta \quad \beta\ ]^T \\ \mathbf{x}_2 = \omega = [\ p \quad q \quad r\ ]^T \\ \mathbf{u} = [\ \delta_a \quad \delta_e \quad \delta_r\ ]^T \\ f(\mathbf{x}_1) = [\ 0 \quad 0 \quad A_\beta\ ]^T \\ g(\mathbf{x}_1) = \begin{bmatrix} 1 & \sin\phi\cos\theta & \cos\phi\tan\theta \\ 0 & \cos\kappa\phi & -\sin\phi \\ \frac{w}{\sqrt{u^2+w^2}} & 0 & \frac{-u}{\sqrt{u^2+w^2}} \end{bmatrix} \end{cases} \tag{22}$$

The difination of $\mathbf{A}_\beta$ is according reference [22].From Eq. (24), there is

$$\mathbf{M} = \mathbf{J}\dot{\omega} + \omega \times \mathbf{J}\omega \tag{23}$$

in which M is moment vector$\begin{bmatrix} L & M & N \end{bmatrix}^T$,and $\mathbf{J}$ is :

$$\begin{bmatrix} I_x & 0 & -I_{xz} \\ 0 & I_y & 0 \\ -I_{xz} & 0 & I_z \end{bmatrix} \tag{24}$$

$\mathbf{M}$ can be decomposed into the following parts: the moment $\mathbf{M}_c$ generated from the control surface deflection and the aircraft body moment $\mathbf{M}_a$ derived from the aircraft state and aerodynamic coefficient, that is:

$$\mathbf{M} = \mathbf{M}_a + \mathbf{M}_c \tag{25}$$

The control of rudder deflection δ is the actual input of the system. Taking SUAVs as example, the control of rudder includes aileron δ_a , elevation δ_e , direction δ_r . Eq.(23) can be expressed as:

$$\mathbf{M}_a + (\mathbf{M}_c)_\delta \delta = \mathbf{J}\dot{\omega} + \omega \times \mathbf{J}\omega \tag{26}$$

in which, the equation of $\mathbf{M}_a$,$(\mathbf{M}_c)_\delta$ can refer to [3, 22]. Substitute them into Eq.(4) and the equation is rewritten into the state equation form:

$$\dot{\omega} = \mathbf{J}^{-1}[\mathbf{M}_a + (\mathbf{M}_c)_\delta \delta - \omega \times \mathbf{J}\omega] \tag{27}$$

that is:

$$\dot{\omega} = \mathbf{J}^{-1}[\mathbf{M}_a - \omega \times \mathbf{J}\omega] + \mathbf{J}^{-1}(\mathbf{M}_c)_\delta \mathbf{u} \tag{28}$$

so there is:

$$\eta(\mathbf{x}_{2,0}) = \mathbf{J}^{-1}(\mathbf{M}_c)_\delta \tag{29}$$

$$h(\dot{\mathbf{x}}_2) = \mathbf{J}^{-1}[\mathbf{M}_a - \omega \times \mathbf{J}\omega] \tag{30}$$

Based on deduction processes from Eqs.(15) to (21), the UAVs' incremental backstepping attitude control law can be obtained, shown in Eq.(31):

$$\begin{aligned} \triangle\mathbf{u} &= -\eta^{-1}(\mathbf{x}_{2,0})(\mathbf{c}_2\mathbf{z}_2 + \dot{\mathbf{x}}_{2,0} - \dot{\alpha}) \\ &= \mathbf{J}(\mathbf{M}_c)_\delta^{-1}[(\mathbf{c}_2(\dot{\mathbf{x}}_2 - \dot{\alpha}) + \dot{\mathbf{x}}_{2,0} - \dot{\alpha})] \\ &= \mathbf{J}(\mathbf{M}_c)_\delta^{-1}[(\mathbf{c}_2(\dot{\omega} - \dot{\alpha}) + \dot{\omega}_0 - \dot{\alpha})] \end{aligned} \tag{31}$$

5. **Prediction Incremental Backstepping Attitude Control.** The incremental backstepping control, with angular acceleration as feedback, reduces the control systems sensitivity to aerodynamic parameters and enhances the robustness of the flight control. However, the collection of angular acceleration is greatly affected by sensor performance and environment. At present, acceleration measurement on SUAVs mainly depends on MEMS sensors, whose calculation is shown in Eq. (32)[22]:

$$\dot{\omega} = \frac{\omega_K - \omega_{K-1}}{\Delta T} \tag{32}$$

In real systems, delay exists during measurement, communication and calculation of angular acceleration value sensors. From Eq. (32), it can be seen that the measurement and calculation of angular acceleration value is rather sensitive to time and the delayed acceleration value as feedback causes new errors in the system. To solve this problem, the linear prediction filter method based on gradient descent solution is presented to predict angular acceleration value. The realization process of this method is as follows:

(1) To choose prediction filter parameters. Since incremental backstepping control is adopted in the control system and from Eq. (32) it can be known that the input of this

closed-loop is ω_c , the output ω_0 and that during a control period the rudder deflection δ_0 generates angular acceleration, thus rudder deflection δ_0 , input ω_c and output ω_0 are used as prediction parameters in this paper.

(2) To construct prediction filter. Choose the linear prediction filter convenient for computation [23, 24]. The equation can be expressed as follows:

$$\dot{\omega}_K = \sum_{i=1}^{M} [\lambda_1 + \omega_{c_{(k-i\Delta t)}} + \lambda_2 \omega_{0_{k-i\Delta t}} + \lambda_3 \delta_{k-i\Delta t}] + e \tag{33}$$

in which λ_1,λ_2 and λ_3 are coefficients of observed values ω_c , $\triangle t$ is control period, e is calculation error and M s value decides the dependence order of the prediction filter. The higher the order is, the higher precision of the prediction is, but the more the computation load is. Thus M s value in this paper is 4.

(3) Gradient descent solution. The objective function is set as:

$$f(\lambda, \omega_c, \omega_0, \delta, \dot{\omega}) = \lambda[\omega_c, \omega_0, \delta]^T - \dot{\omega} \tag{34}$$

In which $\dot{\omega}$ is angular acceleration prediction value calculated by the filter,λ to make the objective function the minimum value:

$$\min f(\lambda, \omega_c, \omega_0, \delta, \dot{\omega}) \tag{35}$$

The gradient iterative calculation is shown from Eq. (36) to Eq. (38):

$$\mathbf{J} = \frac{\partial f(\lambda, \omega_c, \omega_0, \delta, \dot{\omega})}{\partial \lambda} = [\omega_c, \omega_0, \delta] \tag{36}$$

$$\nabla f(\lambda, \omega_c, \omega_0, \delta, \dot{\omega}) = \mathbf{J}^T f(\omega_c, \omega_0, \delta, \dot{\omega}) \;\; = \begin{bmatrix} \lambda_1 \omega_c^2 + \lambda_2 \omega_0 + \lambda_3 \delta - \dot{\omega} \\ \lambda_1 \omega_c + \lambda_2 \omega_0^2 + \lambda_3 \delta - \dot{\omega} \\ \lambda_1 \omega_c + \lambda_2 \omega_0 + \lambda_3 \delta^2 - \dot{\omega} \end{bmatrix} \tag{37}$$

$$\lambda_{k+1} = \lambda_k - \mathbf{u}_k \nabla f(\lambda, mathbf \omega_c, \omega_0, \delta, \dot{\omega}) \tag{38}$$

Where $\mathbf{J}$ is the Jaccobi matrix of the objective function and the parameter $\mathbf{u}$ is the speed damping coefficient of the convergence calculation. Overshoot calculation appears due to avoiding being affected by measurement noises. The calculation can be expressed in the following equation:

$$\mathbf{u}_k = \alpha \| \omega_{0_k} \| \Delta t, \alpha > 0 \tag{39}$$

In which is Δt the control period,α value is decided by the noise measured by the output angular velocity. Substitute the coefficient λ_{k+1} derived from the iteration above into Eq. (35) to calculate the prediction angular acceleration, so the angular acceleration prediction incremental backstepping SUAVs' attitude control is derived.

6. **Simulation Verification.** To verify the effectiveness of the PIB method, the flight test is conducted in the Cangxia UAVs Hard-in-the-Loop simulation platform. The input command is the roll angle of 20-second- period pulse from minus 25 to plus 25.The PIB method is compared with IB and Backstepping method, the result of which is shown in Fig. 4. Fig. 4 The Roll Angle Control Response of Three Control Methods It can be seen from the three tests above that three control methods track maneuvering commands comparatively well in ideal parameters. As for Backstepping control method, because the given aircraft model parameter is an ideal truth-value parameter without error, its command tracking performance is the best; As for IB and PIB control methods, in calculating control quantity, the aerodynamic moment generated by the aircraft body is not calculated, which causes some control errors. However, PIB, with the prediction value of

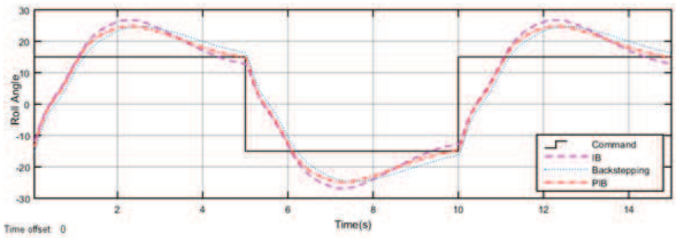

FIGURE 4. The Roll Angle Control Response of Three Control Methods

angular acceleration as feedback, has higher control precision than IB. As shown in Fig. 5 with an increase of UAVs'pitch moment coefficient, roll angle moment coefficient, lifting coefficient by thirty pencent, the flight simulation is conducted in circumstances of model mismatch. Then the same attitude command is instructed to Fig. 4, the simulation result of which is shown in Fig. 5. Fig. 5 The Response of Roll Angle under Model Mismatch It

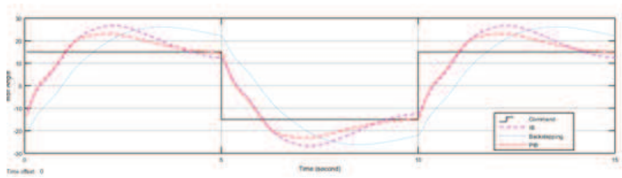

FIGURE 5. The Response of Roll Angle under Model Mismatch

can be known from the simulation result in Fig.5 that when there are parameter errors, the maximum error of the roll angle control of Backstepping method is ten degree more than that of PIB control method, while the maximum error of incremental backstepping control method is 4more than PIB.

7. **Conclusion.** Aiming to solve low precision model parameters and poor control robustness in SUAVs, the prediction incremental backstepping attitude control method is presented in this paper, which includes:

(1) The second-order backstepping control law is deduced, based on which the incremental backstepping controller is constructed.

(2) The incremental backstepping control method is applied to UAVs attitude control and the cascade attitude angle and angle velocity incremental backstepping attitude control are constructed.

(3) The angular acceleration linear prediction filter is designed and the angular acceleration prediction value is solved with gradient so that the accuracy and real-time of the angular acceleration is enhanced. With less computation load, this method can be conveniently used in projects.

The semi-physical simulation flight verifies that this method, in the circumstance of low precision of UAVs parameters, is more effective than Backstepping method and IB method.

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