On New UAV Flight Control System Based On Kalman & PID

ZHANG Peng, LIU Jikai

***Abstract*—Combining Kalman filter with PID controller is applied to design UAV (Unmanned Air Vehicles) formation flight control system which contains Kalman & PID controllers of speed and pitch angle for UAV. According to characteristic of UAV flight, the PID parameters were adjusted to realize control stability of UAV flight. The simulation results verify the validity and feasibility of the proposed method. Because of controlling quality deterioration caused by the detection signal polluted by the noise, it ensures the minimum overshoot in the control processing. In addtion, Kalman&PID control is superior in short transition, good stability, anti-disturbance, good control and etc. it also fulfills the requirement of real-time and accurate control.**

***Key words*—UAV, Kalman&PID Controller, Formation Flight**

I. INTRODUCTION

UAV (unmanned air vehicles) will be used in the main battlefield of the future war because of fewer casualties, better hidden, more flexible and less military expenditure. Many countries have taken the development of UAV as priority. Nowadays, UAV is mainly in form of single plane, so achieving synergy formation is the inevitable trend. Cooperative formation means that a number of UAVs ranked according to a certain shape to maintain unchanging formation or the relative position of the same formation in a certain range of mobility throughout the flight [1]. Synergistic formation can expand the horizons, improve the hit rate and reduce wind resistance of the formation flight, etc. [2], in order to improve operational efficiency and reduce energy consumption. And it can change the flying formation according to the nature and requirements of task at any time. It is so important to control the flying posture of UAV as to make formation flying better, including the relative position control and attitude control of the UAV etc. Despite the UAV cooperative formation of structure design, formation control, close co-operation algorithm [3] and the anti-collision schemes are discussed and studied, but practical applications are seldom involved.

Currently, the strategies of UAV formation flying control mainly adopt n UAVs formation flight at high altitude as the basic environment. Each aircraft has a set of inertial navigation systems. One aircraft, who contains a set of GPS navigation systems, is regarded as the lead plane while the others are considered as wing planes. Each UAV shares navigation information through the JTIDS and estimates its position and velocity information in real time, so that the control law can be imposed to maintain the original formation when UAV deviates from the formation. To maintain the stability of flying formation, it is the key point that the control system can input control signal into wing planes in the event of disturbances or sudden maneuvers completed. The control system design of UAV is mainly based on PI control, PID control, adaptive control and optimal control [4].

"Feature Model" Theory [5],[6], proposed by academician Wu Hongxin proposed, firstly demonstrated the theoretical basis of the application of PID controller. It states that PID controller has unique advantages which will be the smallest unit of the intelligent complex control system [7]. This theory become the focus of attention and combined with other control methods become a hot topic. The world's leading academic journals Control Engineering Practice and IEEE Control Systems Magazine in 2001 and 2006 respectively, published a special edition about PID control. In 2000, IFAC Digital Control Working Group held PID conference in Terrassa of Spain, in which the theme is "Past, Present and Future of PID Control". The world's leading control theory scholar, Professor ASTROM, pointed that PID controller would continue to play an important role in the control project in the future and become the basic unit of various complex controllers. The paper aims to studying regulation quality variation under the interference of strong noise. To solve this problem, the paper combines Kalman filter with the traditional PID controller to design formation flight control system based on Kalman & PID controllers and track the status of formation flying. The simulation results show that Kalman & PID controller has better dynamic performance than the traditional controller in respect of simpler design, higher precision, easier implement, etc. At the same time, the control effect has been significantly improved.

II. RESEARCH BACKGROUND

The basic idea of PID control is to combine the proportional, integral, differential coefficient of bias by linear combination to control the controlled object. By using PID control, the system performance depends on the three appropriate parameters [8], PID control law is

$$u(t) = k_p[e(t) + \frac{1}{T_I}\int_0^t e(t) + T_D\frac{de(t)}{dt}] \qquad (1)$$

Where k_p scale factor, T_I integral time constant, T_D derivative time constant.

In most cases, PID controller has good effect in controlling, but in the special circumstance of high-speed and high-altitude flight, the influences of air flow, pressure, temperature may cause a dramatic disturbance. The practice

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proves that PID controller can not properly complete the control tasks under such circumstance, particularly in the flight which needs strict requirements of control quality. If overshoot, slow response, long adjusting happen in control process, the flight formation will be in the confusion, or even collision accident. So, UAV formation flight has high risk by using PID control itself. The reference [9] proposed a navigation positioning of formation members method, based on lead planes combination navigation and lead / wing planes relative measurement. In the method, lead planes use INS / GPS combination navigation and wing planes use INS / JTIDS combination navigation with Kalman filter to estimate the INS errors. The simulation results show the feasibility of the method, and the formation members led to higher navigation accuracy. But because the wing planes use the errors of lead planes as the true value to result in static errors. The reference [1] applied fuzzy control theory together with the traditional PID control in the UAV formation flight control. This PID fuzzy controller makes integral to the fuzzy value of the error. Although the system can eliminate the large static error, to reduce the near zero limit cycle oscillation needs to increase more control rules and lift the complexity of system design. In this paper, the combination of the Kalman filter and the traditional PID controller not only eliminates the static error but also ensures the system design simple, robustness strong, reliable, on-site engineering staff familiar with as well.

III. KALMAN&PID CONTROL

Considering that the signal and noise are the random process of multi-dimensional non-stationary random, their time variability and the power spectrum is not fixed to result in difficult to automatically adjust the PID controller parameters, and the desired control effect can not be achieved. the Kalman filter is used to filter the detection signal noise, that is to remove noise, extract the true signal as feedback. Then the usage of PID controller will solve the existing problems. Because the Kalman filter is applicable not only to estimate the smooth scalar system, but also give the minimum variance unbiased estimating to the multi-input and non-stationary multi-output time-varying system. In addition, the Kalman filter algorithm is a recursive algorithm, especially suitable for running on computer, so the application of the Kalman filter to PID controller technology will have very broad prospects in unmanned aircraft, space technology, radar, navigation, industrial production and other fields.

3.1 Principle of Kalman Filter

Let the state vector sequence and non-stationary dynamic equation with the following:

$$\begin{aligned} x(t+1) &= \Phi x(t) + \Gamma w(t) \\ y(t) &= \mathrm{H} x(t) + v(t) \end{aligned} \tag{2}$$

Where t discrete time, $x(t)$ denotes a set of state variables consisting of multi-dimensional state vector, $x(t) \in R^n$ the system state at time t, $y(t) \in R^m$ observation signal at time t for the state. $w(t) \in R^r$ the input white noise, $v(t) \in R^m$ the measurement noise. Φ, Γ, H are known matrix. Φ is known as the state Transfer matrix, H the observation matrix [10].

Recursive Kalman filter steps are as follows:

(1)State step in forecasting:

$$\hat{x}(t+1 \mid t) = \Phi \hat{x}(t \mid t) \tag{3}$$

(2)State Estimation:

$$P(t+1 \mid t) = \Phi P(t \mid t) \Phi^T + \Gamma Q \Gamma^T \tag{4}$$

(3)Filter gain:

$$K(t+1) = P(t+1 \mid t)\mathrm{H}^T \left[\mathrm{H} P(t+1 \mid t) \mathrm{H}^T + R \right]^{-1} \tag{5}$$

(4) One step prediction mean square error:

$$\hat{x}(t+1 \mid t+1) = \hat{x}(t+1 \mid t) + K(t+1)\varepsilon(t+1) \tag{6}$$

(5) Mean square error:

$$P(t+1 \mid t+1) = \left[I_n - K(t+1)\mathrm{H} \right] P(t+1 \mid t) \tag{7}$$

One step prediction of the new expression of interest by the state:

$$\varepsilon(t+1) = y(t+1) - \mathrm{H}\hat{x}(t+1 \mid t) \tag{8}$$

The above is the basic equation of the Kalman filter. As long as the initial value $\hat{x}(0 \mid 0), P(0 \mid 0)$ is given, according to the measurement time $t+1$ can be calculated $y(t+1)$ through the recursive state estimation $\hat{x}(t+1)$ of the moment. If amplitude of the interference controlling signal $w(t)$ and the measurement noise signal $v(t)$ are both 0.1 white noise signal and amplitude of input signal is 1.0, a frequency of 1.5Hz sinusoidal signal. Kalman filter realizes signal filtering. Figure 1 and Figure 2 demonstrate Kalman filter filtering.

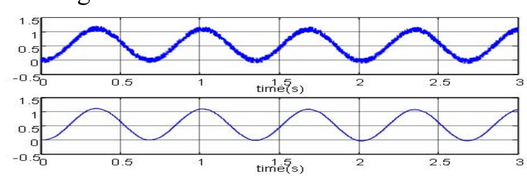

Fig.1. Signal with Noise and Real Signal after Filtering Noise

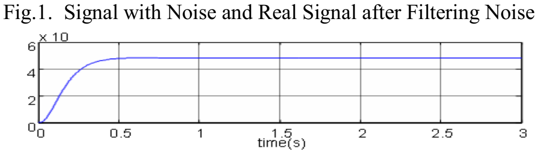

Fig.2. Error Correlation Curves

3.2 Kalman&PID Control System Design

Kalman & PID control system is shown in Figure 3, in which y_v is the output signal contaminated by noise and y_e is output signal modified by the Kalman filter. Amplitudes of the interference controlling signal $w(t)$ and noise measurement signal $v(t)$ are both 0.002 white noise signal. The input signal is a step signal. Kalman filter is used to achieve the signal filtering, taking $Q=1, R=1$, Q and R are respectively the noise variance and then the simulation will be in this environment.

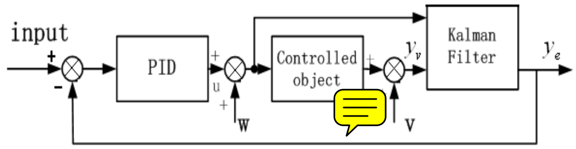

Fig. 3. Kalman&PID Control System Diagram

Ⅳ. UAV Model Formation

To maintain neat formation, it is necessary to precisely control the formation of each of UAVs in flight. The most important thing of UAV formation is to maintain the relative distance between the wing planes and the lead planes (forward, lateral and vertical). UAV itself is a multi-input and multi-output nonlinear system. In order to facilitate system analysis and controller implementation, horizontal fight is regarded as the general movement and the speed is controlled by the throttle. Meanwhile lateral roll pitch angle and vertical angle are controlled by the steering. Therefore, the control of the UAV is mainly divided into the distance control, the roll angle and lateral control and vertical pitch angle control. The plane equation linearized to get the equation of small perturbation linearized state. For such simplified formation, PID control and optimal control is more representative [11]. In the small disturbance conditions, making wing planes fix forward movement, vertical movement and lateral movement between the cross-linking, which is not severely affected, can divide plane movement equation into independent equations of forward, vertical and lateral movement to discuss. As pitch angle and roll angle are controlled by the steering and rudder machine to the angular velocity of the transfer function are the second-order system, they have similar solution. Due to space limitations, only the forward moving control and vertical moving control are considered in this paper.

4.1. Forward Moving Control

The aim of forward motion control is intended to minimize the forward distance errors. On receiving the control signal, UAV can perform quickly and accurately. In the control of the UAV, it should try to avoid the presence of overshoot in order to prevent collision.

The logical relationship of forward motion control: throttle input → the thrust→ forward velocity → forward distance. When the UAV are flying in straight uniform state, the two first-order linear model in series can be expressed as to the UAV Forward Model [12], as shown in Figure 4 that represents the first model of the transfer function of the engine, the experimental data obtained according to the engine, said the thrust of the throttle response; Model 2 indicates that the forward speed of the thrust response. Therefore, the open-loop transfer function of controlled object as follows:

$$G_1(s)=G_T(s)G_V(s)=\frac{K_T}{1+\tau_T s}\times\frac{K_V}{1+\tau_V s}=\frac{0.5}{1+s}\times\frac{1}{0.37+10s}$$
$$=\frac{0.5}{10s^2+10.37s+0.37} \tag{9}$$

Sampling time is 0.05s, Tustin transforms with discrete objects, and describes the form of a discrete state equation.

$$x(t+1)=Ax(t)+B(u(t)+w(t))$$
$$y(t)=Cx(t) \tag{10}$$

With measurement noise output of the controlled object

$$y_v(t)=Cx(t)+v(t) \tag{11}$$

Where $A=\begin{bmatrix}-1.037 & -0.037\\ 1 & 0\end{bmatrix}, B=\begin{bmatrix}1\\0\end{bmatrix}, C=\begin{bmatrix}0 & 0.05\end{bmatrix}$

Root locus are shown in Figure 5, all characteristic roots are in the left half plane, so the system is stable.

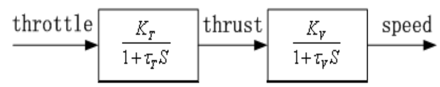

Fig.4. Forward Moving Control Diagram

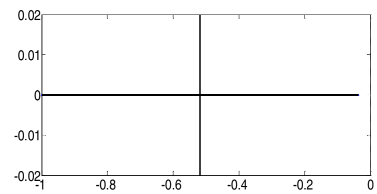

Fig.5. Root Locus Chart of Forward Moving Control System

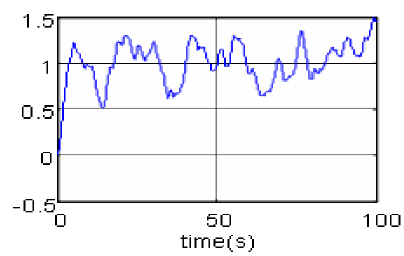

Fig.6 The Forward Step Response of PID Control after no-Filtering

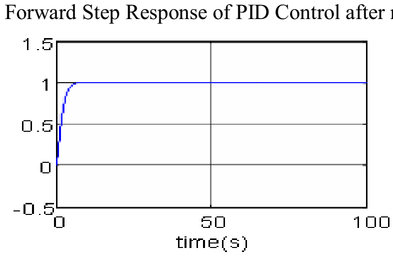

Fig.7 The Forward Step Response of PID Control after Filtering

The object can be taken directly to the open-loop transfer function (9) into the Kalman & PID control block diagram. Through the MATLAB simulation, the step responses respectively with and without filtering are shown in Figure 6 and Figure 7. So PID control performance after Kalman filtering is significantly improved, 0% overshoot, no steady state deviation.

4.2. Vertical Moving Control

The Vertical small disturbance linearized equation of flight control system l is calculated as follows according to the aerodynamic parameters (vertical movement does not consider throttle input):

$$\begin{bmatrix}\Delta V\\ \Delta a\\ \Delta w_z\\ \Delta\vartheta\end{bmatrix}=\begin{bmatrix}-0.045 & 0.183 & 0 & -0.241\\ -0.312 & -1.945 & 1 & 0\\ 0.152 & -22.511 & -2.036 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\Delta V\\ \Delta a\\ \Delta w_z\\ \Delta\vartheta\end{bmatrix}+\begin{bmatrix}-0.007\\ 0.124\\ -17.105\\ 0\end{bmatrix}\Delta\delta_z \tag{12}$$

Where ΔV is the percentage velocity of increment (m / s); a for the angle of attack (rad); w_x for the pitch rate (rad / s); ϑ for the pitch angle (rad); δ_Z for the elevator deflection angle (rad).

Vertical movement is divided into two modes, short-period mode and long-period mode. The initial period of the step response takes the angle of attack and angular velocity as the representative of the short-periodic motion. Flight speed is essentially the same. If $V=0$, the Vertical movement is simplified and the freedom short-period model is as follows:

$$\begin{bmatrix}a\\ w_z\end{bmatrix}=\begin{bmatrix}-1.945 & 1\\ -22.511 & -2.036\end{bmatrix}\begin{bmatrix}a\\ w_z\end{bmatrix}+\begin{bmatrix}0.124\\ -17.105\end{bmatrix}\delta_z \tag{13}$$

This simplified equation can be used to calculate the transfer function from steering gear to the pitch rate is:

$$\frac{\vartheta(s)}{\delta_z(s)}=\frac{-17.11s-36.06}{s^2+3.981s+26.47} \tag{14}$$

The system uses a steering inertia model, transfer function is:

$$G(s)=\frac{-1}{0.1s+1} \tag{15}$$

Rate this pitch angle can be drawn to open-loop system transfer function

$$G_2(s)=\frac{171.1s+360.6}{s^3+13.981s^2 66.28s+264.7} \tag{16}$$

Sampling time is 1 ms, Tustin transforms with discrete objects, and describes the form of a discrete state equation

$$x(t+1)=Ax(t)+B(u(t)+w(t))$$
$$y(t)=Cx(t) \tag{17}$$

With measurement noise output of the controlled object

$$y_v(t)=Cx(t)+v(t) \tag{18}$$

where $A=\begin{bmatrix}-13.981 & -66.28 & -264.7\\ 1 & 0 & 0\\ 0 & 1 & 0\end{bmatrix}$, $B=[1\ 0\ 0]^T$,

$C=[0\ \ 171.1\ \ 360.6]$

Root locus are shown in Figure 9, the root locus we can see that all characteristic roots are in the left-half plane, the system is stability.

It can directly make the controlled open-loop transfer into Kalman & PID control block diagram, and then through the MATLAB simulation, the response results before and after adding filtering are shown in Figure 10 and Figure 11.Without adding filters, the controlled object are controlled unstably. After adding filters, using the same PID control results in no overshoot and less than 10s transition time. It shows that after adding Kalman filter, the PID control performance has been improved significantly.

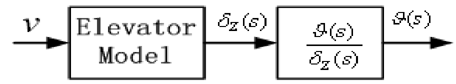

Fig.8 Vertical Moving Control Diagram

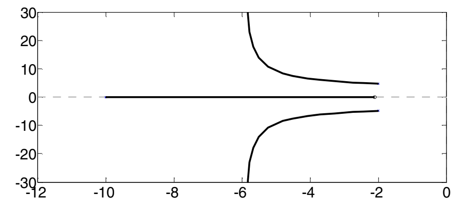

Fig.9 Root Locus Chart of Vertical Moving Control System

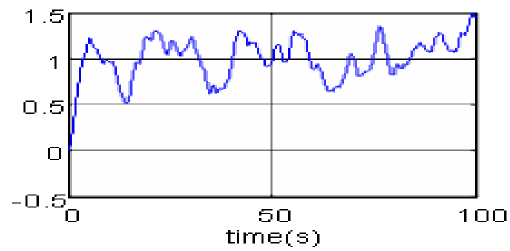

Fig.10 The Vertical Moving Step Response of PID Control after no-Filtering

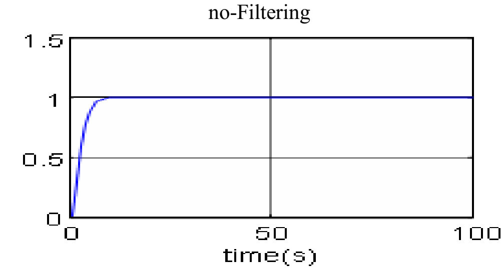

Fig.11 The Vertical Moving Step Response of PID Control after Filtering

IV. CONCLUSION

Applying Kalman filter into the traditional PID control system, in fact, is an intelligent PID. In the case of ensuring control performance, there are more advantages than former intelligent PID, such as greater reliability and more values in engineering. This method can be utilized in the multi-plane formation flight. Because of controlling quality deterioration caused by the detection signal polluted by the noise, it ensures the minimum overshoot in the control system. The Kalman & PID control combines the advantages of both, which are little overshoot, short transition, good stability, Anti-disturbing and etc. it also fulfills the requirement of real-time and accurate control.

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