K7-24

Robust Reconfigurable Flight Control System Using Feedback Linearization

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The design method is introduced for a flight control system so as to have robustness against fault or disturbances. The nonlinear motion of an aircraft can be expressed as a combination of slow and fast dynamics by using the time scale separation technique. The extended Kalman filter is applied to the faster dynamics in order to estimate system parameters that will vary with time. The command signal for the fast time scale controller is generated by applying the disturbance accommodating control (DAC) theory to the slow time scale controller. The numerical simulation is performed to verify the robustness of the proposed control system for the developed UAV.

1. Introduction

The dynamic inversion (DI) method is widly used in controlling nolinear systems. The method, however, does not guarantee internal stability for nonminimum phase systems[1]. Then we use the time scale separation technique with DI method. The flight dynamics can be separated into slow and fast dynamics by using teimscale properties. The method allows the design process to be performed without state transformation. In approach of this paper, the extended Kalman filter (EKF) and the disturbance accommodating control (DAC) observer[2] are applied to fast dynamics and slow dynamics, respectively. Therefore, the proposed flight control system has robustness against fault or disturbances because system parameters are estimated in real time. The validity of the proposed flight control system is verified through the numerical simulation.

2. Aircraft Dynamics

For designing a nonlinear control low, nonlinear equations with respect to rotational motion of an aircraft are given as follows:

$$\dot{\boldsymbol{y}} = \boldsymbol{f}_S + \boldsymbol{g}_S \boldsymbol{\omega} \tag{1}$$

$$\dot{\boldsymbol{\omega}} = \boldsymbol{f}_F + \boldsymbol{g}_F \boldsymbol{u} \tag{2}$$

where

$$\boldsymbol{f}_S = \begin{bmatrix} \left\{ -L - T\sin\alpha + mg\begin{pmatrix} \sin\alpha\sin\theta \\ +\cos\alpha\cos\phi\cos\theta \end{pmatrix} \right\} \Big/ mV\cos\beta \\ \left\{ Y - T\cos\alpha\sin\beta + mg\begin{pmatrix} \cos\alpha\sin\beta\sin\theta + \cos\beta\sin\theta\sin\phi \\ -\sin\alpha\sin\beta\cos\phi\cos\theta \end{pmatrix} \right\} \Big/ mV \\ 0 \end{bmatrix}$$

$$\boldsymbol{g}_S = \begin{bmatrix} -\cos\alpha\tan\beta & 1 & -\sin\alpha\tan\beta \\ \sin\alpha & 0 & -\cos\alpha \\ 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \end{bmatrix}$$

$$\boldsymbol{f}_F = \begin{bmatrix} I_x & 0 & -I_{zx} \\ 0 & I_y & 0 \\ -I_{zx} & 0 & I_z \end{bmatrix}^{-1} \begin{bmatrix} (I_y - I_z)QR + I_{zx}PQ + L_0 \\ (I_z - I_x)PR + I_{zx}(R^2 - P^2) + M_0 \\ (I_x - I_y)PQ - I_{zx}QR + N_0 \end{bmatrix}$$

$$\boldsymbol{g}_F = \bar{q}S \begin{bmatrix} I_x & 0 & -I_{zx} \\ 0 & I_y & 0 \\ -I_{zx} & 0 & I_z \end{bmatrix}^{-1} \begin{bmatrix} bC_{l\delta_a} & 0 & bC_{l\delta_r} \\ 0 & \bar{c}C_{m\delta_e} & 0 \\ bC_{n\delta_a} & 0 & bC_{n\delta_r} \end{bmatrix}$$

$$\boldsymbol{y} = [\alpha \quad \beta \quad \phi]^T,\ \omega = [P \quad Q \quad R]^T,\ \boldsymbol{u} = [\delta_a \quad \delta_e \quad \delta_r]^T$$

3. Flight Control System

Equations (1) and (2) can be considerd slow motion and fast motion of the aircraft dynamics. Both equations include uncertain variation of aerodynamic coefficients such as the nonlinear function $\boldsymbol{f}_S$, $\boldsymbol{f}_F$, and $\boldsymbol{g}_F$. Aerodynamic coefficients would be influenced by failure or damage of the aircraft. We design the following controllers for each dynamics to have robustness agains the influences. The proposed flight control system are shown in Fig.1.

3.1. Slow Time Scale Controller

When designing a flight control system with the two timescale assumption, the outer-loop controller is designed to control the slow dynamics. In the outer-loop, the nolinear term $\boldsymbol{g}_S$ does not include aerodynamic coefficients. To apply DAC observer to the slow dynamics expressed by Eq.(1), all unknown parameters $\boldsymbol{f}_S$, which includes aerodynamic coefficients, is estimated by using DAC observer.

The time derivative of the error between $\boldsymbol{y}$ and its command $\boldsymbol{y}_c$ can be obtained as

$$\begin{aligned} \dot{\boldsymbol{e}} = \dot{\boldsymbol{y}} - \dot{\boldsymbol{y}}_c &= \boldsymbol{f}_S + \boldsymbol{g}_S\boldsymbol{\omega} - \dot{\boldsymbol{y}}_c \\ &= \boldsymbol{z} + \boldsymbol{g}_S\boldsymbol{\omega} \end{aligned} \tag{3}$$

where $\boldsymbol{z}$ is unknown parameter including aerodynamic cofficients. The parameter is defined as first order spline function of time t.

$$\boldsymbol{z} = \boldsymbol{c}_0 + \boldsymbol{c}_1 t \tag{4}$$

$$\boldsymbol{\eta} = \dot{\boldsymbol{z}} = \boldsymbol{c}_1,\quad \dot{\boldsymbol{\eta}} = \ddot{\boldsymbol{z}} = 0$$

Then the DAC observer can be designed as follows:

$$\frac{d}{dt}\begin{bmatrix} \underline{\boldsymbol{e}} \\ \underline{\boldsymbol{z}} \\ \underline{\boldsymbol{\eta}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{I} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{e} \\ \boldsymbol{z} \\ \boldsymbol{\eta} \end{bmatrix} + \begin{bmatrix} \boldsymbol{I} \\ \boldsymbol{0} \\ \boldsymbol{0} \end{bmatrix} \boldsymbol{g}_S\boldsymbol{\omega} + \begin{bmatrix} \boldsymbol{L}_1 \\ \boldsymbol{L}_2 \\ \boldsymbol{L}_3 \end{bmatrix} (\boldsymbol{e} - \underline{\boldsymbol{e}}) \tag{5}$$

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The command for the fast scale controller is defined as Eq.(6) so that the estimate values converges to actual values in this method.

$$\boldsymbol{\omega}_c = -\boldsymbol{g}_S^{-1}\underline{\boldsymbol{z}} \tag{6}$$

3.2. Fast Time Scale Controller

In the inner-loop, the control input for the aircraft is designed to follow the desired angular rate that is defined by Eq.(6).

$$\boldsymbol{u} = \boldsymbol{g}_F^{-1}(\boldsymbol{v}_F - \boldsymbol{f}_F) \tag{7}$$

Controller for the fast time scale dynamics $\boldsymbol{v}_F$ is designed as the following equation.

$$\boldsymbol{v}_F = \boldsymbol{k}_1(\boldsymbol{\omega}_c - \boldsymbol{\omega}) + \boldsymbol{k}_2\int(\boldsymbol{\omega}_c - \boldsymbol{\omega}) \tag{8}$$

where $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are control gains. Control derivatives that are shown in nolinear terms $\boldsymbol{f}_F$ and $\boldsymbol{g}_F$ vary with time when moving surfaces of the aircraft break down. Then EKF is applied to the fast dynamics expressed by Eq.(2) to estimate control derivatives in real time.

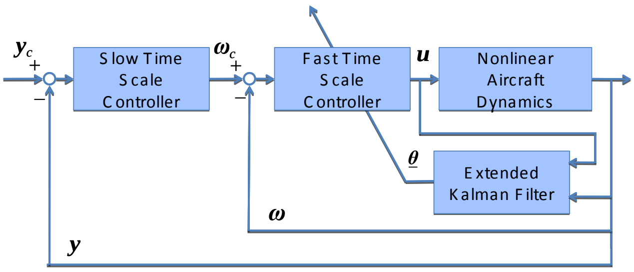


Figure 1. Flight Control System

4. Numerical Simulation

The flight control system is desinged for nonlinear longitudinal aircraft motion. Numerical rresults are shown in Figs.2 and 3.

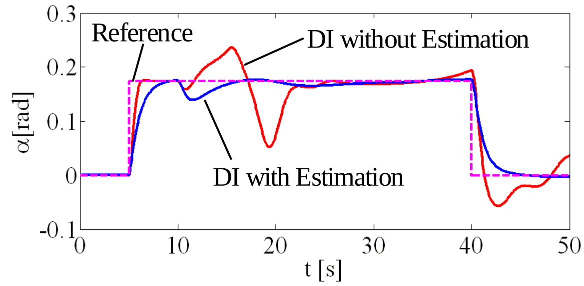
Figure 2 shows time histories of the angle of attack α and the control derivative $C_{m\delta e}$. In this case, the control surface is damaged at ten seconds form the beginning of the simulation. It is clear from Fig.2(a) that the angle of attack converges rapidly to its reference when the control derivative is estimated in real time.

It is supposed that the control surface moves in opposite direction from ten seconds. It should be noted from Fig.3(a) that the angle of attack can follow the reference when using EKF. The estimated value agree with its actual value in spite of the damage.

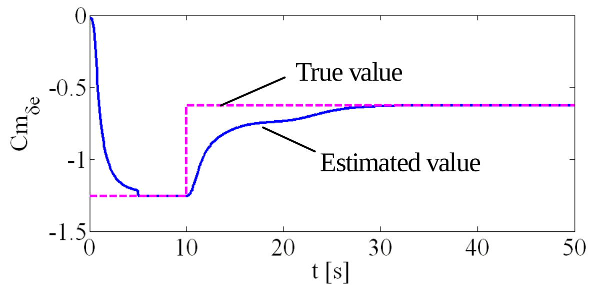
5. Conclusions

In this paper, EKF and DAC observer is applied to aircraft dynamics which is separated into fast and slow motion by using timescale properties. The control of the aircraft with unexpected parameter variation was achieved when using the proposed flight control system.

Experiments will be demonstrated to verify the proposed control system by using the developed UAV.

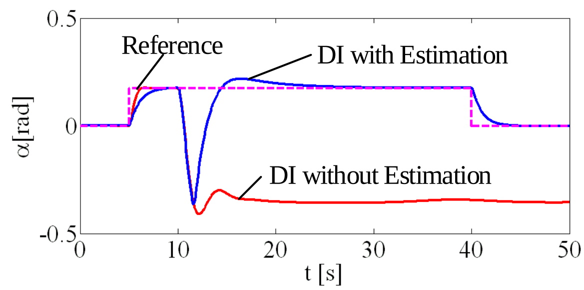


(a) Time history of α

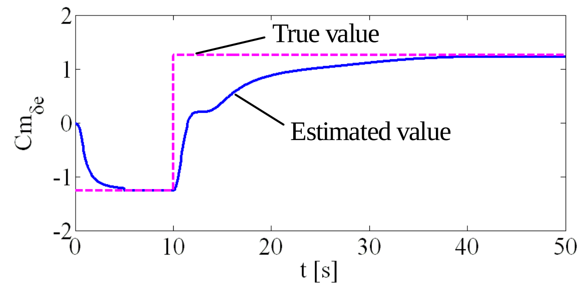


(b) Time history of $C_{m\delta e}$

Figure 2. Half driving rate of elevator scenario



(a) Time history of α



(b) Time history of $C_{m\delta e}$

Figure 3. Elevator reverse scenario

Reference

[1] Taeyoung Lee and Youdan Kim "Nonlinear Adaptive Flight Control Using Backstepping and Neural Networks Controller", JOURNAL OF GUIDANCE ,CONTROL, AND DYNAMICS, Vol.24, No.4, pp.675-682, July-August 2001.

[2] C. Toumes and C.D. Johnson "Application of Linear Subspace Stabilization and Linear Adaptive Techniques to Aircraft Flight Control Problem Part I the Inner loop", Proceedings of the Thirtieth Southeastern Symposium on System Theory , pp. 146-150, 1998.