Sensors & Transducers, Vol. 178, Issue 9, September 2014, pp. 276-281

Sensors & Transducers

Non-affine Nonlinear Flight Control System Based on Robust Adaptive Fault-tolerant Control

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Received: 25 June 2014 /Accepted: 29 August 2014 /Published: 30 September 2014

Abstract: For non-affine nonlinear flight control systems, a non-affine nonlinear robust fault tolerance control method is proposed. Here, the fault tolerance control framework is used, and on this basis, observer-based auxiliary system is designed to implicit fault parameters and disturbances information. Then reconfigurable controller is designed using the dynamic of observer-based auxiliary system, which can realize non-affine nonlinear systems robust adaptive fault-tolerant. Simulation results show the effectiveness of the proposed method. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Non-affine, Nonlinear, Observer, Adaptive, Fault tolerant.

1. Introduction

At present, the nonlinear control has achieved rapid development in the theory and application, such as feedback linearization, sliding mode control, backstepping control and so on. Reference [1] summarizes and induces some major nonlinear control methods. Adaptive technology can estimate unknown parameters on-line, so combining with many nonlinear control methods design fault-tolerant control. Adaptive control need to estimate the parameters and the control input for affine forms, namely, uncertain parameters and control input, they shall be an explicit form. The common method of flight control system is linearization near the balancing point, if the current state of the aircraft and the control input affine form. So the controller is designed based on the linear model of balancing point near can cause the closed-loop system is unstable, or even divergence.

To design a non-affine nonlinear system fault-tolerant controller is not a simple thing, there are two difficulties to fully solve. One is how to design an adaptive parameter estimation algorithm, the second is how to design a reconfigurable control algorithm. A common adaptive parameter estimation algorithm is the system model in parameter values near the Taylor series expansion, using Taylor's series of low-order observer design parameters. Such for parameter perturbation of a small scale system can obtain a better estimate, wide range changes of system parameters, this method is hard to get ideal parameters estimate. If the system external interference exists at the same time, the estimated parameters exist error, even do not achieve the parameter estimates. So, how to design ideal for non-affine nonlinear uncertain system parameters estimator is worth exploring. Some non-affine nonlinear system there exist certain disadvantages to the reconfigurable controller, commonly used inverse system method to look for the inverse system model. Although references [2] proved its inverse there must be a controlled system, but finding inverse system is not easy thing, such as control input implicit in the sine and cosine function.

Reference [3] put forward a kind of affine controller design method, but the biggest drawback of the method increases the system order. Based on reference [4] time-scale separation method to design a kind of non-affine controller, but the shortcoming is that it is hard to combination effectively the method and adaptive technology, the sliding mode techniques. In order to get an effective non-affine controller design method, in the reference [5] a controller design method is put forward, to introduce a filter is used to approximate estimate linear working point.

At present, the non-affine nonlinear system of fault-tolerant control related research results are rare. Using the proposed fault tolerant control framework, a technology based on state observer design parameter information and interference information implied auxiliary system design controller, realize the non-affine nonlinear robust adaptive fault-tolerant control system. The method application of flight control system, the simulation results show the effectiveness of the proposed method.

2. Problem Description

Here we consider the following non affine nonlinear systems

$$\dot{x} = f(x,u) + d(t), \tag{1}$$

where $x \in R^r$ is the state vector, $u \in R^n$ is the input vector, $d \in R^r$ is the unknown bounded external disturbance vector, $f(.)$ is the nonlinear function. As the research object, based on the actuator failure without considering actuator dynamic situation, we get failure model of actuator failure after each input channel can be expressed

$$\begin{aligned} &u_i = \sigma_i u_{ci}, \quad \sigma_i \in [\underline{\sigma}_i, \bar{\sigma}_i] \\ &0 < \underline{\sigma}_i \le 1, \quad \bar{\sigma}_i \ge 1, \quad i = 1,2,\cdots,n \end{aligned}, \tag{2}$$

where σ_i is the failure factor. $\underline{\sigma}_i, \bar{\sigma}_i$ are the maximum and minimum values of failure factor. When $\sigma_i = 1$, no failure happens. So, the control input actuator failure can be expressed as [6]

$$u(t) = [u_1(t), u_2(t), \cdots\cdots, u_n(t)]^T = \Sigma u_c(t), \tag{3}$$

where $\Sigma = \text{diag}(\sigma_1, \cdots, \sigma_n)$. Then, under the failure of the non-affine nonlinear system can be expressed as

$$\dot{x} = f(x, \Sigma u_c) + d(t), \tag{4}$$

Equation (4) can be written as a general form

$$\dot{x} = f(x, u_c, \sigma) + d(t), \tag{5}$$

where $\sigma = [\sigma_1, \cdots, \sigma_n]^T$. A hypothesis is given below.

Hypothesis: $f(x, u_c, \sigma)$ is smooth and continuous differentiable function of x, u_c, σ. Control input u_c is bounded. The system output reference model is

$$\dot{x}_m = A_m x_m + B_m r, \tag{6}$$

where $x_m \in R^r$ is the state vector of reference model, A_m is the stable reference model system matrix, $r \in R^l$ is the input of the reference model.

3. Fault-tolerant Control System Design

3.1. Auxiliary System Design

σ estimated value is $\hat{\sigma}$. First order Taylor series of function $f(x, u_c, \sigma)$ expand, then we can get

$$f(x,u_c,\sigma) = f(x,u_c,\hat{\sigma}) + g_1(x,u_c,\hat{\sigma})(\sigma - \hat{\sigma}) + \xi(t), \tag{7}$$

where

$$\begin{aligned} &g_1(x,u_c,\hat{\sigma}) = \left.\frac{\partial f(x,u_c,\sigma)}{\partial \sigma}\right|_{\sigma=\hat{\sigma}}, \\ &\xi(t) = \sum_{i=2}^{\infty} \left.\frac{\partial^i f(x,u_c,\sigma)}{\partial \sigma^i}\right|_{\sigma=\hat{\sigma}} \left(\sigma - \hat{\sigma}\right)^i, \end{aligned} \tag{8}$$

Based on (7) and (8), (5) can be written as the following equation

$$\dot{x} = f_1(x,u_c,\hat{\sigma}) + g_1(x,u_c,\hat{\sigma})\sigma + \upsilon(t), \tag{9}$$

where

$$f_1(x,u_c,\hat{\sigma}) = f(x,u_c,\hat{\sigma}) - g_1(x,u_c,\hat{\sigma})\hat{\sigma}, \tag{10}$$

$$\upsilon(t) = \xi(t) + d(t), \tag{11}$$

It can see that $\upsilon(t)$ is unknown and bounded, namely $\|\upsilon(t)\| \le \bar{\upsilon}$. $\varepsilon = z - x$, where: z is observed value of state x. The design observer is shown as

$$\hat{z} = A(z - x) + f_1(x,u_c,\hat{\sigma}) + g_1(x,u_c,\hat{\sigma})\hat{\sigma} + \nu(t), \tag{12}$$

By the adaptive law, we can get $\hat{\sigma}$ [7]

$$\dot{\hat{\sigma}} = \text{Proj}_{[\underline{\sigma}_i,\bar{\sigma}_i]}\left\{-2\gamma_1 g_1^T(x,u_c,\hat{\sigma})P\varepsilon\right\}, \quad (13)$$

where $\gamma_1 > 0$, $P = P^T > 0$. P is the solution of $A^T P + PA = -Q$. $Q = Q^T > 0$; A is the Hurwitz matrix. It can ensure that the estimate is set between the minimum $\underline{\sigma}_i$ and maximum $\bar{\sigma}_i$; $\gamma_1 > 0$, $P = P^T > 0$. The sliding mode design is shown as [8]:

$$\nu(t) = \begin{cases} -\dfrac{P\varepsilon}{\|P\varepsilon\|}m(t) & \text{if } \|P\varepsilon\| \neq 0 \\ 0 & \text{otherwise} \end{cases}, \quad (14)$$

Time-varying parameter $m(t)$ is updated by adaptive law

$$\dot{m}(t) = \Gamma\varepsilon^T\varepsilon, \quad m(0) > 0, \quad (15)$$

Failure factor estimation error is $\tilde{\sigma} = \hat{\sigma} - \sigma$. By the observer equation (12) and equation (9), we can get observation error dynamic equation.

$$\dot{\varepsilon} = A\varepsilon + g_1(x,u_c,\hat{\sigma})\tilde{\sigma} + \nu(t) - \upsilon(t), \quad (16)$$

Continuous sliding mode item is shown as

$$\nu(t) = -\frac{P\varepsilon}{\|P\varepsilon\| + \rho}m(t), \quad (17)$$

where $\rho = \rho_0 + \rho_1\|\varepsilon\|$, ρ_0 and ρ_1 are constant.

3.2. Controller Design and Stability Analysis

Based on observer (12), we use the proposed non affine nonlinear system controller design method, namely $F(x,u_c,\hat{\sigma}) = f_1(x,u_c,\hat{\sigma}) + g_1(x,u_c,\hat{\sigma})\hat{\sigma}$. The observer (12) can be written as the following

$$\dot{z} = A\varepsilon + F(x,u_c,\hat{\sigma}) + \nu(t), \quad (18)$$

where u_n is in the vicinity u_c. $F(x,u_c,\hat{\sigma})$ will expand for Taylor series in place u_n

$$F(x,u_c,\hat{\sigma}) = F(x,u_n,\hat{\sigma}) + F_d(x,u_n,\hat{\sigma})(u_c - u_n) + O(t), \quad (19)$$

where

$$F_d(x,u_n,\hat{\sigma}) = \left.\frac{\partial F(x,u_c,\hat{\sigma})}{\partial u}\right|_{u_c=u_n}, \quad (20)$$

$$O(t) = \sum_{i=2}^{\infty}\left.\frac{\partial^i F(x,u_c,\hat{\sigma})}{\partial u^i}\right|_{u_c=u_n}(u_c - u_n)^i,$$

where $F_n(x,u_n,\hat{\sigma}) = F(x,u_n,\hat{\sigma}) - F_d(x,u_n,\hat{\sigma})u_n$, then (18) can be expressed as

$$\dot{z} = A\varepsilon + F_n(x,u_n,\hat{\sigma}) + F_d(x,u_n,\hat{\sigma})u_c + \nu(t) + O(t) \quad (21)$$

By (19), we can see that if u_n is closer u_c, the higher-order dimensionless $O(t)$ of Taylor series is tending to zero, namely

$$\lim_{u_n \to u_c} O(t) = 0, \quad (22)$$

where u_c is calculated by the controller design, the current time is unknown. So we can't get it near u_n directly. Then, we introduce filter that it is used to estimate and determine u_n. The filter is

$$\dot{u}_n = -\zeta u_n + \zeta u_c, \quad (23)$$

So, by the filter (23), you can get $\lim_{\zeta\to\infty} u_n = u_c$, namely $\lim_{\zeta\to\infty} O(t) = 0$. Then, through the above analysis, the observer dynamic equation (18) can be expressed as

$$\begin{aligned}&\dot{u}_n = -\zeta u_n + \zeta u_c \\ &\dot{\hat{x}} = A\tilde{x} + F_n(x,u_n,\hat{\sigma}) + F_d(x,u_n,\hat{\sigma})u_c + \nu(t) + O(t)\end{aligned}, \quad (24)$$

Control gain K can obtain by the following Riccati equations

$$K^T P_1 + P_1 K = -Q_1, \quad (25)$$

where $P_1 = P_1^T > 0$, $Q_1 = Q_1^T > 0$.

In this paper, the design block diagram is shown in Fig. 1.

4. Simulation Verification

Next, using the UAV track angle and speed control system prove the effectiveness of the proposed method. The dynamic model is [9]

$$\begin{aligned}\dot{V} &= g\left(\frac{T-D}{W} - \sin\gamma\right) \\ \dot{\gamma} &= \frac{g}{V}(n\cos\mu - \cos\gamma), \\ \dot{\chi} &= \frac{gn\sin\mu}{V\cos\gamma}\end{aligned} \quad (26)$$

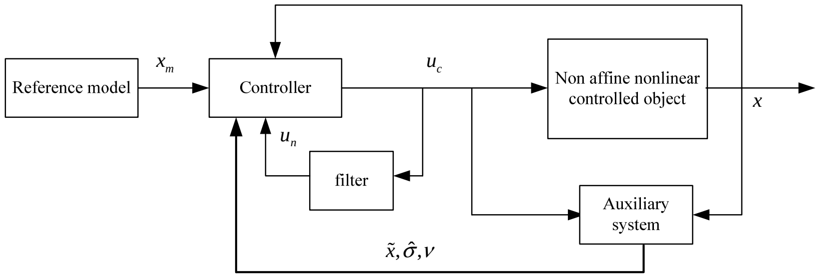


Fig. 1. The proposed fault tolerant control system block diagram.

State variables have the flight speed V, path angle γ ,azimuth angle χ. Control inputs have thrust T, load coefficient n, slope angle μ.

State variables are $x=[V,\gamma,\chi]^T$, control input are $u=[T,n,\mu]^T$, actuator failure factors are $\sigma=[\sigma_1,\sigma_2,\sigma_3]^T$, external disturbance are $d=[d_1,d_2,d_3]^T=[0.2\cos(2t),0.0002\sin(t),0.0002\cos(t)]^T$. Then equation (26) can be expressed as [10]

$$\begin{aligned} \dot{x}_1 &= c_{11}x_1^2+\frac{c_{12}\sigma_2^2u_2^2}{x_1^2}+c_{13}\sin(x_2)+c_{14}\sigma_1u_1+d_1 \\ \dot{x}_2 &= \frac{1}{x_1}(c_{21}\cos(x_2)+c_{22}\sigma_2u_2\cos(\sigma_3u_3))+d_2 \\ \dot{x}_3 &= \frac{c_{31}\sigma_2u_2\sin(\sigma_3u_3)}{x_1\cos(x_2)}+d_3 \end{aligned} \quad , \quad (27)$$

where $c_{11}=-0.5\rho gSC_{D_0}/W,\ c_{12}=-2kgW/(\rho S)$, $c_{13}=-g$, $c_{14}=g/W$, $c_{21}=-g$, $c_{22}=g$, $c_{31}=g$.

The reference trajectory of the speed V is 300 m/s. The reference trajectory of path angle γ and azimuth angle χ is the following two reference model outputs

$$\begin{aligned} \dot{x}_{m1} &= x_{m2} \\ \dot{x}_{m2} &= -9x_{m1}-6x_{m2}+9r_\gamma(t) \end{aligned}, \quad (28)$$

$$\dot{x}_m = -x_m + r_\chi(t), \quad (29)$$

Assumes that the actuator failure occurred as follows

$$\begin{aligned} \sigma_1 &= \begin{cases} 1.5(2.6/3-0.02t) & 10<t\le 30 \\ 1.5(0.02t-1/3) & 30<t\le 50 \\ 1 & \text{others} \end{cases} \\ \sigma_2 &= \begin{cases} 1 & t\le 20 \\ 0.6 & 20<t \end{cases} \\ \sigma_3 &= \begin{cases} 1 & t\le 20 \\ 0.8 & 20<t \end{cases} \end{aligned} \quad , \quad (30)$$

Initial state value is $V(0)=300$ m/s, $\gamma(0)=0$ deg, $\chi(0)=0$ deg, $m(0)=0.15$, $\sigma(0)=[1,1,1]^T$. Design parameters of auxiliary system are $A=\mathrm{diag}(-2,-2,-2)$, $\gamma_1=2$, $\Gamma=1000$, $\rho_0=5$. The filter parameter is $\zeta=50$. The controller gain is $K=\mathrm{diag}(1,1,1)$, $P=\mathrm{diag}(0.3,1800,2000)$ [11].

Case 1: considering normal circumstances, the designed controller is:

$$\begin{aligned} \dot{u}_n &= -\zeta u_n + \zeta u_c \\ u_c &= -F_d^{-1}[F_n|_{\hat{\sigma}=1} + Ke - A_m x_m - B_m r] \end{aligned}, \quad (31)$$

The response curve of the system tracking error is shown in Fig. 2. The Fig. 2 shows that the proposed non affine control method is effective. It can better achieve estimated tracking.

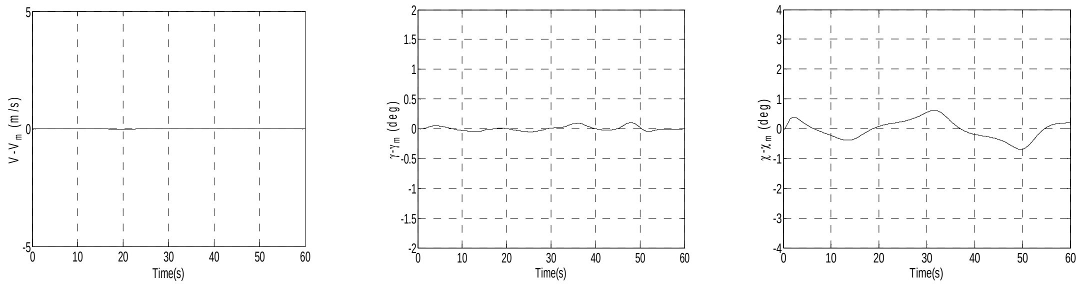
Case 2: When the fault happens, the controller still uses (30). System tracking error response curves are shown in Fig. 3.

It cannot achieve input tracking reference trajectory under the condition of non fault-tolerant control.

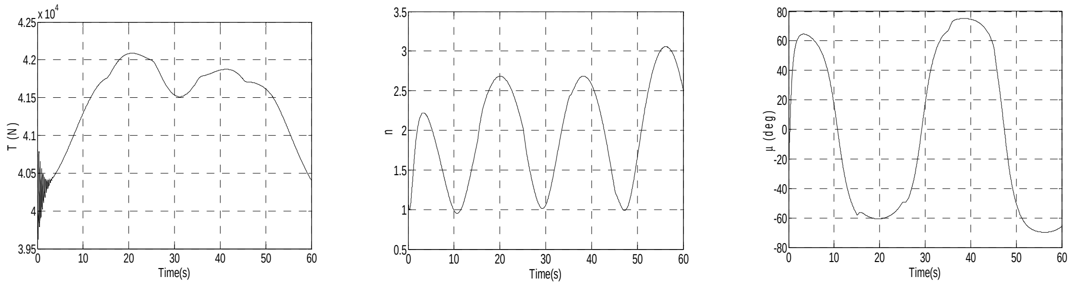
5. Conclusions

In view of the existing parameter uncertainty and disturbance of non-affine nonlinear systems, we give a kind of non-affine nonlinear fault-tolerant controller design method. The observer is designed to apply to parameter that it is in the form of non-affine nonlinear systems, and in the presence of wide range change parameters, observer is still good robustness.

Observer will imply fault information and disturbance information. For the non-affine nonlinear system, the controller design is not easy. We present a dynamic approximate method of affine nonlinear systems. Non-affine nonlinear system is simplified to an affine nonlinear system with time-varying parameters, then parameters are estimated by the filter. Using a non affine flight control system verify the effectiveness of the proposed method, it can realize robust fault-tolerant control of non-affine nonlinear systems.

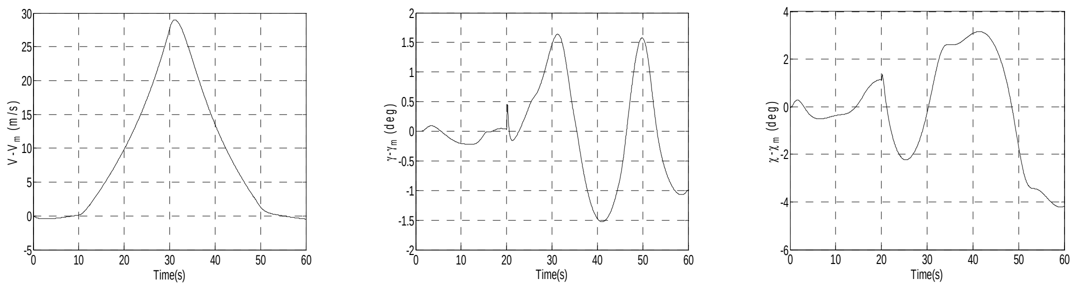


(a) Speed tracking error curve (b) Path angle error curve (c) Path azimuth error curve

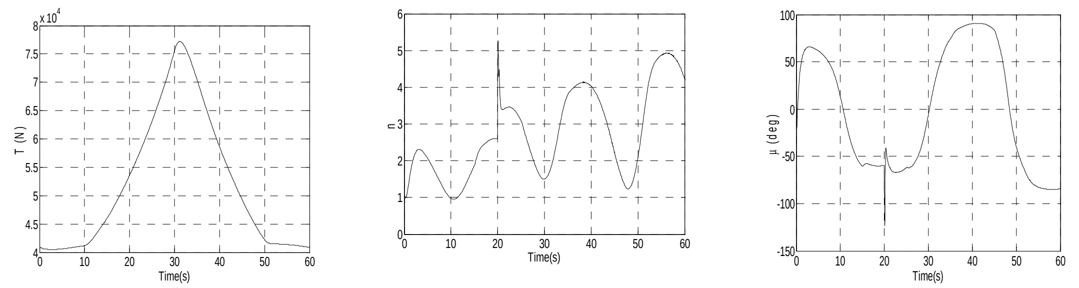


(d) Thrust response curve (e) Load factor response curve (f) Tilt angle response curve

Fig. 2. The system response curve under case 1.



(a) Speed tracking error curve (b) Path angle error curve (c) Path azimuth error curve



(d) Thrust response curve (e) Load factor response curve (f) Tilt angle response curve

Fig. 3. The system response curve under case 2.

Acknowledgements

This work was supported by Qing Lan Project of Jiangsu province, 333 Project of Jiangsu province, Aeronautical Science Foundation of China (No. 20111052010), the National 863 Program (No. 2007AA01Z404), Universities Natural Science Research Project of Jiangsu Province (No. 13KJD520005), Modern Educational Technology in Jiangsu province (2013-R-26144).

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