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Actuator Fault Detection and Isolation for Helicopter Unmanned Arial Vehicle in the Present of Disturbance

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ABSTRACT

Helicopter unmanned aerial vehicle (HUAV) are an ideal platform for academic researchs. Abilities of this vehicle to take off and landing vertically while performing hover flight and various flight maneuvers have made them proper vehicles for a wide range of applications. This paper suggests a model-based fault detection and isolation for HUAV in hover mode. Moreover in HUAV, roll, pitch and yaw actuator faults are coupled and affect each other, hence, we need a method that decouples them and also separates fault from disturbance. For this purpose, a robust unknown input observer (UIO) is designed to detect bias fault and also catastrophic fault such as stuck in actuators of HUAV. The robust UIO isolates roll and pitch actuator faults from yaw actuator fault. The novelty of this manuscript is the design of two UIO observers to detect and decouple the faults of helicopter actuators, one for lateral and longitudinal actuators and the other for pedal actuator. Also the proposed method is compared with extended Kalman filter (EKF). Simulation results show effectiveness of the proposed method for detection and isolation of actuator faults with less number of observers and it is able to decouple fault and disturbance effects.

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NOMENCLATURE

d_{col}	collective input	a_{1f}, b_{1f}	Longitudinal and lateral stabilizer flapping angles
d_{lon}	longitudinal input	g	gravity acceleration
d_{lat}	lateral input	k_{β}	Main rotor blade restoring spring constant
d_{ped}	pedal input	h_{mr}	Height of main rotor hub above center of mass
$W^B = [p \quad q \quad r]^T$	Roll, pitch, and yaw rates in body frame	h_{tr}	Height of tail rotor axis above center of mass
T_{mr}^h, T_{tr}^h,	main and tail rotor thrust	Q_{mr}^h, Q_{tr}^h	main and tail rotor counter-torque

1. INTRODUCTION

To provide a safe flight with a helicopter unmanned aerial vehicle (HUAV), it is necessary to detect its faults and make emergency landings on time. The fault may occur in sensors, controllers, or actuators. Loss of control is the most important factor in air events [1]. This paper addresses the additive faults such as bias and stuck in case of an external disturbance.

In case of a bias fault, the control level always has a constant difference between the actual and expected deviation. In the stuck fault, the actuator is locked in a place. In the last decade, some FDI methods have been proposed to deal with actuator faults and enhance the safety of various unmanned aerial vehicles UAVs.

A sliding mode observer (SMO) is designed for detection, isolation and estimation of the actuator faults for the quadrature nonlinear Lipschitz model for an incipient fault that is more difficult to detect [1, 2]. Multiple model adaptive estimation (MMAE) method is used to detect and isolate actuator or sensor faults [3, 4]. Two systematic algorithms, intelligent Output-Estimator and Model-Free technique were presented that detect and isolate actuator fault of quadrotor UAV [5]. Lee and Choi

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[6] used the Interactive Multiple Neural Adaptive Observer for Sensor and Actuator Fault Detection and Isolation of quadcopter. Zhong et al. [7] have presented a robust actuator fault detection and diagnosis (FDD) scheme for a quadrotor UAV (QUAV) in the case of external disturbances. In literature [8, 9] an applicable method was proposed for detecting an incipient fault in the QUAV.

Avram et al. [10] designed a nonlinear adaptive estimation technique for a quadrotor that consists of a nonlinear fault detection estimator and a bank of nonlinear adaptive fault isolation estimators .

In general, the major problem in HUAV actuator FDI methods is the detection of various faults when HUAV is in a windy environment. HUAVs almost have small size and lightweight and external disturbance affects their correct operation. So, detecting actuator fault and the external disturbances separating faults and disturbances is more difficult. Also, in this model, roll, pitch and yaw actuators faults are coupled and affect each other. Unknown input observers (UIOs) are used to separate FDI from external disturbances. The major contribution of this paper is the design of just two UIOs for decoupling actuator faults.

The rest of this paper is organized as follows. Section 2 describes plant model. The UIO is designed in Section 3 for detecting actuator faults. Section 4 presents simulation of the designed observers. Finally, the results are given in Section 5.

2. HUAV MODEL DESCRIPTION

HUAVs are categorized in terms of weight and size, and have four input references to perform various flight maneuvers that are collective input and change the reference value of the main rotor thrust. In fact, this input changes the thrust vector and HUAV flight height, The longitudinal input and lateral input that causes the device to move forward and backward right and left respectively and the pedal input that changes the tail rotor thrust value as a result of which, the HUAV rotates around it [11]. This inputs are applied to HUAV with four servo actuators, including the collective pitch servo, elevator servo, aileron servo and rudder servo.

2. 1. Mathematical Model

Equations of the helicopter are explained in literature [12, 13]. The cross-coupling terms are neglected as they small in hover mode and are summarized in a single $\dot{x} = f(x.u)$ expression as Equation (1).

$$
\begin{aligned}
\dot{p} &= \frac{1}{J_{xx}}((T_{mr}^{h} h_{mr} + k_{\beta})(K_B d_{lat} + K_F b_{1f}) - T_{tr}^{h} h_{tr}) \\
\dot{q} &= \frac{1}{J_{yy}}((T_{mr}^{h} h_{mr} + k_{\beta})(K_B d_{lon} + K_F a_{1f}) - Q_{tr}^{h}) \qquad (1) \\
\dot{r} &= \frac{1}{J_{zz}}(T_{tr}^{h} d_{tr} - Q_{mr}^{h}) \\
\dot{a}_{1f} &= -\frac{a_{1f}}{\tau_f} - q + \frac{K_H}{\tau_f} d_{lon} \\
\dot{b}_{1f} &= -\frac{b_{1f}}{\tau_f} - p + \frac{K_H}{\tau_f} d_{lat}
\end{aligned}
$$

The main rotor thrust (T_{mr}^{h}) and counter-torque (Q_{mr}^{h}) are in the following form:

$$
\begin{aligned}
T_{mr}^{h} &= C_{mr}^{h}(C_c d_{col} + D_c) + \frac{(D_{mr}^{T})^2}{2} - \ldots \\
& D_{mr}^{T}\sqrt{C_{mr}^{T}(C_c d_{col} + D_c) + \frac{(D_{mr}^{T})^2}{4}}
\end{aligned}
\qquad (2)
$$

$$
Q_{mr}^{h} = C_{mr}^{Q}(T_{mr}^{h})^{3/2} + D_{mr}^{Q} \, , \qquad (3)
$$

where C_{mr}^{T} , D_{mr}^{T} , C_{mr}^{Q} and D_{mr}^{Q} are constant, and depend on the density of air and some characteristic of the HUAV main rotor including the radius of disc, angular rotation rate, lift curve slope and blade chord length. The tail rotor thrust and counter-torque is in following form.

$$
\begin{aligned}
T_{tr}^{h} &= C_{tr}^{h}(C_t d_{ped} + D_t) + \frac{(D_{tr}^{T})^2}{2} - \ldots \\
& D_{tr}^{T}\sqrt{C_{tr}^{T}(C_t d_{ped} + D_t) + \frac{(D_{tr}^{T})^2}{4}}
\end{aligned}
\qquad (4)
$$

$$
Q_{tr}^{h} = C_{tr}^{Q}(T_{tr}^{h})^{3/2} + D_{tr}^{Q} \, , \qquad (5)
$$

where C_{tr}^{T} , D_{tr}^{T} , C_{tr}^{Q} and D_{tr}^{Q} are constant, and depend on density of air and some characteristic of HUAV tail rotor such as the radius of disc, angular rotation rate, the lift curve slope and blade chord length.

3. UNKNOWN INPUT OBSERVER

According to the study on fault detection, one of the best methods for fault detection in systems is the use of observers. The UIO observer is a robust observer that can detect or estimate faults and is robust to external disturbances and uncertainties. Assuming the use of output sensors, two UIO observers can be used to detect the faults of helicopter operators, one for lateral operators and the other for pedal operators. The observer's function is such that the third input in the first observer and the first and second inputs do not play a role in the second observer.

3. 1. Unknown Input Observer Design

Unknown input Observer (UIO) is design as state estimation error vector e(t) approaches zero asymptotically, regardless of the presence of the unknown input or disturbance in the system. Suppose equation of system is described as:

$$\begin{cases} \dot{x} = Ax(t) + Bu(t) + Ed(t) \\ y(t) = Cx(t) \end{cases} \tag{6}$$

The structure for a full-order observer is described as:

$$\begin{cases} \dot{z} = Fz(t) + TBu(t) + Ky(t) \\ \hat{x} = z(t) + Hy(t) \end{cases} \tag{7}$$

where $\hat{x}$ and z are estimated state vector and state of observer respectively. For error we have

$$\begin{aligned} \dot{e}(t) &= \dot{x}(t) - \dot{\hat{x}}(t) \\ &= Ax(t) + Bu(t) + Ed(t) - \dot{z}(t) - H\dot{y}(t) \end{aligned} \tag{8}$$

With substituting Equations (6) and (7) into Equation (8), we obtain:

$$\begin{aligned} \dot{e}(t) = {} & Ax(t) + Bu(t) + Ed(t) - Fz(t) - TBu(t) \\ & - KCx(t) - HC(Ax(t) + Bu(t) + Ed(t)) \end{aligned} \tag{9}$$

With adding and subtracting $(A - HCA - KC)\hat{x}(t)$ from Equation (9), we have

$$\begin{aligned} & \dot{e}(t) = (A - HCA - KC)e(t) \\ & +(A - HCA - KC - F)z(t) + (A - HCA - KC)Hy \\ & +(B - TB - HCB)u(t) + (I - HC)Ed(t) \end{aligned} \tag{10}$$

F, T, K and H are matrices to be designed as the state estimation error vector e(t) which approaches zero asymptotically and the following relation must be true.

$$\begin{aligned} & (HC - I)E = 0 \\ & T = I - HC \\ & F = A - HCA - K_1C \\ & K_2 = FH \\ & K = K_1 + K_2 \end{aligned} \tag{11}$$

Necessary and sufficient conditions to design and prove of observer stability have been demonstrated by Ducard [4] and are not mentioned here.

3. 2. Robust Actuator Fault Isolation Schemes

System equation with actuator fault can be described using the following equation for $i = 1, 2, \ldots r$.

$$\begin{cases} \dot{x} = Ax(t) + B^i u^i(t) + B^i f_a^i(t) + b_i(u_i(t) + f_{ai}(t)) + Ed(t) \\ y(t) = Cx(t) \end{cases} \tag{12}$$

where b_i is i_{th} column of the matrix B, B^i is obtained from the matrix B by deleting the i_{th} column b_i, u_i is i_{th} component of u, u^i is obtained from the vector u by deleting the i_{th} component u_i. If we define

$$E^i = [E \quad b_i], d^i(t) = \begin{bmatrix} d(t) \\ u_i(t) + f_{ai}(t) \end{bmatrix}:$$

$$\begin{cases} \dot{x} = Ax(t) + B^i u^i(t) + B^i f_a^i(t) + E^i d^i(t) \\ y(t) = Cx(t) \end{cases} \tag{13}$$

Based on the above system description, r UIO-based residual generators can be constructed as:

$$\begin{cases} \dot{z}^i(t) = F^i z^i(t) + T^i B^i u^i(t) + K^i y(t) \\ r^i(t) = (I - CH^i)y(t) - Cz^i(t) \end{cases} \tag{14}$$

where F^i, T^i, K^i and H^i (i= 1, 2…r) are obtained in each observer as before.

4. SIMULATION RESULTS

In order to validate the RThSEKF approach, seven scenarios are simulated on an unmanned helicopter. In this paper, model parameters are adopted from the literature [14] which describes the ANCL helicopter.

The wind gust model block implements a wind gust of standard "1-cosine" shape [14].

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 2.78(0.2112T_{mr} + 80.52) \\ 0 & 0 & 0 & 0.67(0.2112T_{mr} + 80.52) & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & -7.14 & 0 \\ -1 & 0 & 0 & 0 & -7.14 \end{bmatrix}$$

$$B = \begin{bmatrix} 2.78(0.0288T_{mr} + 10.98) & 0 & -0.3336 \\ 0 & 0.67(0.0288T_{mr} + 10.98) & 0.075 \\ 0 & 0 & 0.8798 \\ 0 & 2 & 0 \\ 2 & 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}, E = \begin{bmatrix} 0 \\ 0 \\ -.83Q(T_{mr}) \\ 0 \\ 0 \end{bmatrix}$$

The goal is to hold the helicopter in hover and check the actuator's fault. The state vector and the input vector that we use in this goal are in the form of Equation (7): $x = [p, q, r, a_{1f}, b_{1f}]$ and $u = [d_{lon}, d_{lat}, T_{tr}]$. For designing UIO, according to [14] and considering the fact that the collective actuator is healthy and considering that the fault in the longitudinal and lateral actuator results in the change of the pitch angle of the main rotor blades and the fault in the pedal actuator results in the change of the pitch angle of tail Rotor blades, two UIO are used to detect faults. The design method is described below. The UIO 1 is used to detect faults in longitudinal and lateral actuator, and the UIO 2 is used to detect a fault in the pedal actuator.

UIO 1: The dynamic equation for the first UIO is:

$$\dot{z}^1(t) = F^1 z(t) + K^1 y(t) + T^1 \begin{bmatrix} b_1 & b_2 \end{bmatrix} \begin{bmatrix} u_1(t) \\ u_2(t) \end{bmatrix}$$

where b_1 and b_2 are the first two columns of B, and the parameter matrix for this UIO are:

$$H^1=\begin{bmatrix}0.9995 & -0.0225 & 0\\ -0.0225 & 0.0005 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix},T^1=\begin{bmatrix}0.0005 & 0.0225 & 0 & 0 & 0\\ 0.0225 & 0.9995 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0 & 1\end{bmatrix}$$

$$F^1=\begin{bmatrix}-10 & 0 & 0 & 1.6618 & .1551\\ 0 & -20 & 0 & 73.8759 & 6.8951\\ 0 & 0 & -30 & 0 & 0\\ 0 & -1 & 0 & -7.14 & 0\\ -1 & 0 & 0 & 0 & -7.14\end{bmatrix},K^1=\begin{bmatrix}0.0051 & 0.2248 & 0\\ 0.4497 & 19.9899 & 0\\ 0 & 0 & 0\\ 0.0225 & -0.0005 & 0\\ -0.9995 & 0.0225 & 0\end{bmatrix}$$

The third element of vector z^1 (z_3^1) has no inputs of y, u_1 and u_2 , hence it will stay at zero if the initial values of z_3^1 is zero and the observer matrix F^1 is designed to be stable. The full-order UIO can be reduced to:

- The state estimation is:

$$\begin{bmatrix}\dot{z}_1^1\\ \dot{z}_2^1\\ \dot{z}_4^1\\ \dot{z}_5^1\end{bmatrix}=\begin{bmatrix}-10 & 0 & 1.6618 & 0.1551\\ 0 & -20 & 73.8759 & 6.8951\\ 0 & -1 & -7.14 & 0\\ -1 & 0 & 0 & -7.14\end{bmatrix}\begin{bmatrix}z_1^1\\ z_2^1\\ z_4^1\\ z_5^1\end{bmatrix}$$
$$+\begin{bmatrix}0.0211 & 0.2266\\ 0.9402 & 10.074\\ 0 & 2\\ 2 & 0\end{bmatrix}\begin{bmatrix}u_{lat}\\ u_{lon}\end{bmatrix}+\begin{bmatrix}0.0051 & 0.2248\\ 0.4497 & 19.9899\\ 0.0225 & -0.0005\\ -0.9995 & 0.0225\end{bmatrix}y$$

$$\hat{x}^1=\begin{bmatrix}z_1^1+.9995y_1-.0225y2\\ z_2^1-.0225y1+.0005y2\\ y_3\\ z_4^1\\ z_5^1\end{bmatrix}$$

- The residual is generated by:

$$r^1=y_1-\hat{y}_1=y_1-\hat{x}_1=z_1^1+.9995y_1-.0225y_2$$
$$=0.0005y_1-z_1^1+0.0225y_2$$

As is clear, this relationship only depends on the first and second inputs and outputs. The third input and output do not play a role in this observer, so in the event of a fault, the third input does not represent a diagnostic observer. Also, disturbance does not appear in the residual, and disturbance, and fault in the UIO observer are completely separate.

UIO 2: The dynamic equation for the second UIO is:

$$\dot{z}^2(t)=F^2z(t)+K^2y(t)+T^2b_3u_3(t)$$

where b_3 is the third column of B, and the parameter matrices for this UIO are:

$$H^2=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 0\\ 0 & 0.1984 & 0\\ 0.0478 & 0 & 0\end{bmatrix},T^2=\begin{bmatrix}0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & -0.1984 & 0 & 1 & 0\\ -0.0478 & 0 & 0 & 0 & 1\end{bmatrix}$$

$$F^2=\begin{bmatrix}0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\\ 0 & 0 & -30 & 0 & 0\\ 0 & -2 & 0 & -21.8067 & 0\\ -2 & 0 & 0 & 0 & -21.8067\end{bmatrix},K^2=\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\\ 0 & -5.3271 & 0\\ -2.0429 & 0 & 0\end{bmatrix}$$

Similar to UIO 1 the first and the second states can be eliminated, and the UIO2 can also be reduced as:

$$\begin{bmatrix}\dot{z}_3^2\\ \dot{z}_4^2\\ \dot{z}_5^2\end{bmatrix}=\begin{bmatrix}-30 & 0 & 0\\ 0 & -21.8067 & 0\\ 0 & 0 & -21.8067\end{bmatrix}\begin{bmatrix}z_3^2\\ z_4^2\\ z_5^2\end{bmatrix}+$$
$$\begin{bmatrix}0.8798\\ -0.0015\\ 0.016\end{bmatrix}\begin{bmatrix}u_{ped}\end{bmatrix}+\begin{bmatrix}0 & 0 & 0\\ 0 & -5.3271 & 0\\ -2.0429 & 0 & 0\end{bmatrix}y$$

The residual is generated by:

$$r^3=y_3-\hat{y}_3=y_3-\hat{x}_3=y_3-z_3^2$$

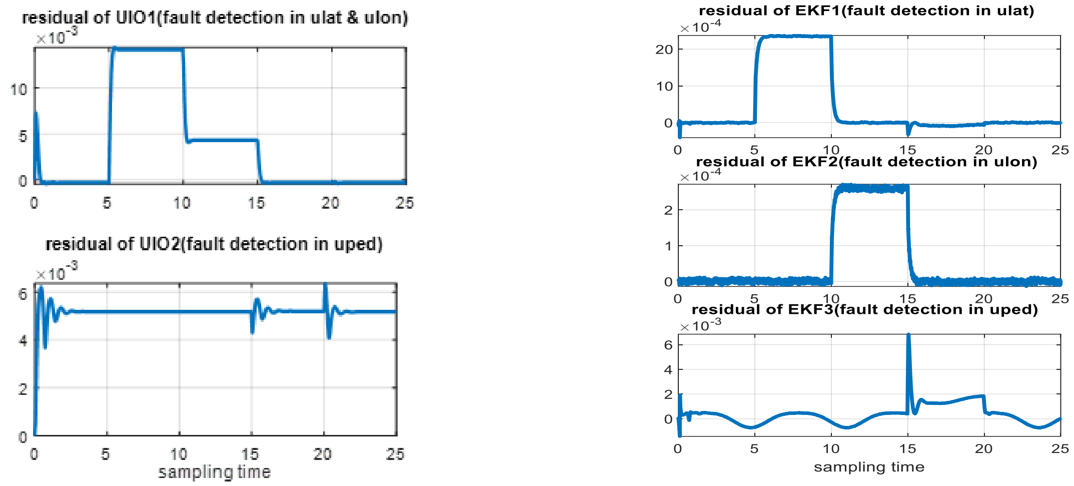
This relationship indicates that the residual only depends on the third input, and the change indicates the occurrence of a fault in the system. Various types of fault are introduced to the system in two scenarios in following. In these scenarios we suppose $d=0.001\sin(t)+0.005\cos(2t)$ and also we compare the designed method with the EKF [3].

4. 1. Scenario 1: Bias Faults

In this scenario, small bias faults are simulated for three actuator inputs in the case of disturbances. From t=5-10s, lateral servo has a bias fault at 0.02. For t=10-15s, longitudinal servo has a bias fault near to the equilibrium position in the no fault mode in 0.01. For t=15-20s, ruder servo has a bias fault whose value equals 0.05. Figure 1 shows residuals for the UIO 1 and UIO 2 for this scenario. As can be seen, the method is capable of accurately diagnosing the faults by the two observers, and the disturbance dose not affect it, in other words it is robust but in EKF we need more observers and it is not decoupled from disturbance.

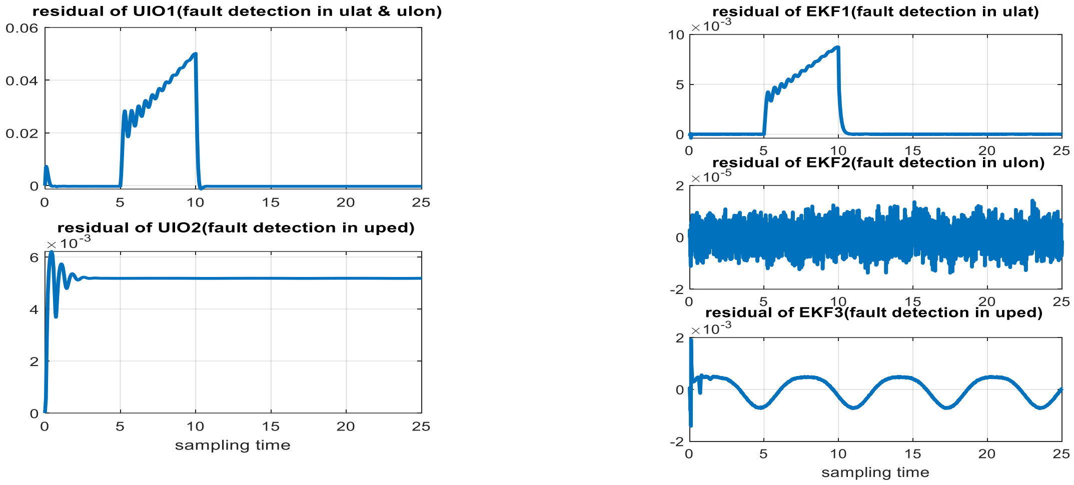
4. 2. Scenario 2: Actuator Stuck Faults

In order to apply stuck fault to the HUAV actuator, the control between the actuator and the controller is disconnected, and the actuator stuck at a point. In this scenario, starting from t=5-10s, the lateral servo (d_{lat}) has a stuck fault in position 0.01. Figure 2 shows that the method is able to detected faults in the presence of disturbance. As it is shown that disturbance is decoupled from the fault in UIO, but in EKF disturbance affect on the residuals.



(a) (b)

Figure 1. Residuals for Scenario 1: (a) UIO,(b): EKF



(a) (b)

Figure 2. Residuals for scenario 2: (a) UIO,(b): EKF

5. CONCLUSION

This paper describes FDI for HUAV actuators for detecting and isolating additive faults such as bias and stuck in the presence of external disturbances in hover mode. It is important that, actuator fault detection can be decoupled and separated from disturbance. For this purpose, the unknown input observer is proposed. Two unknown input observers are designed for decoupling actuator faults. Results show effectiveness of the proposed method for various faults in HUAV actuators in comparison to the EKF. In EKF, we need three observers and it is not decoupled from disturbance. The proposed method can be used for other plants with additive faults.

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Persian Abstract

چکیده

بالگردهای بدون سرنشین سیستمی کاربردی برای تحقیقات دانشگاهی می‌باشد. توانایی این وسیله در فرود و فراز عمودی و همچنین قابلیت پرواز در حالت هاور و مانورهای پروازی مختلف، آن را به وسیله محبوبی در بسیاری از کاربردهای تبدیل کرده است. این مقاله یک روش تشخیص و جداسازی عیب برای بالگردهای بدون سرنشین در حالت پروازی هاور ارائه می‌دهد. در این وسیله عملگرهای رول، پیتچ و یاو کوپل بوده و عیب‌های آن‌ها روی یکدیگر تاثیر می‌گذارد بنابراین ما نیاز به روشی داریم که آن‌ها را از هم کوپل کند و همچنین قادر به جداسازی عیب از اغتشاش باشد. برای این منظور مشاهده‌گر ورودی ناشناخته مقاوم ارائه شده است که قادر به تشخیص عیب‌های بایاس و عیب‌های مهمتر مانند قفل عملگر می‌باشد. این مشاهده‌گر ورودی ناشناخته عیب‌های جانبی را از عیب یاو جدا می‌کند. نوآوری مقاله در طراحی تنها دو مشاهده‌گر برای این جداسازی می‌باشد یکی برای عیب‌های جانبی و دیگری برای یاو. همچنین این مشاهده‌گر با کالمن فیلتر توسعه یافته مقایسه شده است. نتایج عملکرد خوب مشاهده‌گر را با تعداد کمتر مشاهده‌گر و دکوپله کردن اثر عیب و اغتشاش را نشان می‌دهد.