Fault Tolerant Control for a Rotary Wing Aircraft

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SNE 28(3), 2018, 93 - 96, DOI: 10.11128/sne.28.sn.10424
Received: Sept. 15, 2016 (Selected EUROSIM Congress 2016 Postconf. Publ.), Revised July 30, Accepted: August 25, 2018
SNE - Simulation Notes Europe, ARGESIM Publisher Vienna,
ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. In this study, a fault tolerant control strategy for a rotary wing aircraft is proposed in the presence of actuator faults. A linear mathematical model which is derived from the nonlinear model by using MATLAB/Simulink. An observer based state estimation approach is widely used in fault tolerant area. Generalized Observer Scheme (GOS) based on Unknown Input Observer (UIO) is utilized to detect and isolate the actuator faults. In fault-free conditions, Linear Quadratic Tracking (LQT) is preferred to stabilize the quadrotor to obtain a faster system response. When it comes to a faulty case, LQT cannot handle the compensation of steady-state error owing to power loss in the actuator. Therefore Linear Quadratic Regulator (LQR) with integral action is selected by the fault diagnosis unit to compensate steady-state error due to the actuator fault. Simulation results are presented to demonstrate the performance of the proposed fault tolerant control strategy.

Introduction

Mini-flying vehicles with four rotors which are called quadcopters have attracted many researchers in recent years.

He and Zhao adopt the attitude controller is a nonlinear controller for a quadrotor helicopter. It consists of a linear control part and a nonlinear control part, where the linear control part is a PD controller which parameters were tuned by Ziegler-Nichols rules, and the nonlinear control part is a feedback linearization item which converts a nonlinear system into a linear system. The linear parts are, respectively, PID controller with the PID controller parameters tuned by Ziegler-Nichols rules and PD controller with the PD controller parameters tuned by Genetic Algorithm.

They claim the attitude controller adopted is highly robust and the controller design method is a simple and practical one in engineering (He and Zhao, 2014).

Zhang et al. give a tutorial of the platform configuration, methodology of modeling, comprehensive nonlinear model, the aerodynamic effects, and model identification for a quadrotor (Zhang *et al*, 2014).

Jeong et al. propose a multilayered quadrotor control method that can move the quadrotor to the desired goal while resisting disturbance. Their proposed control system is modular, convenient to design and verify, and easy to extend. It comprises three layers: a physical layer, a displacement control layer, and an attitude control layer (Jeong *et al*, 2014).

Yang et al. built the affine nonlinear model for the quadrotor helicopter attitude system. With the consideration of unknown actuator faults such as the loss of effectiveness and lock-in-place, an adaptive fuzzy controller based on the sliding mode has been proposed to realize the direct self-repairing control for this attitude system. Through a series of simulations, it has verified the availability of the proposed method which can make the system recover from the actuator faults and has good tracking performance (Yang *et al*, 2014).

Zhang et al. present the newest research on quadrotor. First, they analyzed the actuator dynamic and aerodynamic effect of the quadrotor. Then, they established a reliable nonlinear dynamic model of the quadrotor. They designed a series of PID controllers with feedforward control and feedback linearization using the backstepping method. They claim real experiments were executed and the effectiveness of the proposed dynamic model and control method is demonstrated by the experimental result (Zhang *et al*, 2014).

Sadr et al. consider a quadrotor with a cable-suspended load with eight degrees of freedom. The purpose of the study is to control the position and attitude of the quadrotor on a desired trajectory in order to move the considered load with a constant length of cable (Sadr *et al*, 2014).

An et al. propose a sliding mode observer design framework based on the Lie group method of numerical integration on manifolds, and they design a Second-Order Geometric Sliding Mode Attitude Observer for the angular velocity estimation of quadrotor attitude (An *et al*, 2013).

Pipatpaibul and Ouyang propose a trajectory tracking control of UAVs utilizing online iterative learning control (ILC) methods. They claim simulation results prove the ability and effectiveness of the online ILCs to perform successfully certain missions in the presence of disturbances and uncertainties (Pipatpaibul and Ouyang, 2013).

1 Control System of the Quadrotor

In this study, firstly, a quadrotor model is obtained in the simulation as seen Figure 1. Secondly, a linear model is transformed from this nonlinear model. Two controllers, LQT and LQR with integral action, are designed to stabilize the quadrotor system. After the fine tuning of the controllers, X, Y and Z response of the system are shown as in Figure 4-9.

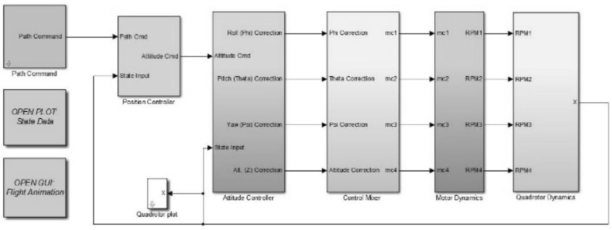

Figure 1. Nonlinear model of the quadrotor

The conventional PID structure consists of proportional, integral and derivative contributes as shown in Figure 2.

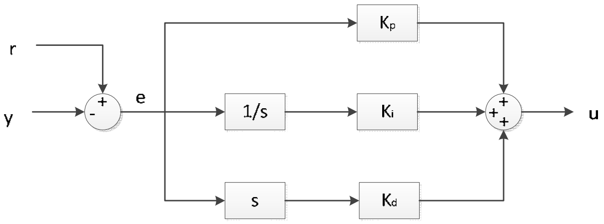

Figure 2. Conventional PID structure.

Equation

$$u(t) = K_p e(t) + K_i \int_0^t e(\upsilon)d\upsilon + K_d \frac{de(t)}{dt} \qquad (1)$$

demonstrates traditional PID.

Here, u is the controller output, e is the error between reference value (r) and sensor value (y), K_p is the proportional coefficient, K_i is the integral coefficient and K_d is the derivative coefficient.

Conventional PID structure has two main disadvantages. When the reference is a step input, the output of the derivation will be an impulse which can saturate the actuators since the derivative action is computed from the error. When the integral value is high and the error switches its sign, it takes a lot of time to restore its linear behavior. This problem is called integral wind-up. To overcome the problems described above, improved PID structure is proposed in Figure 3.

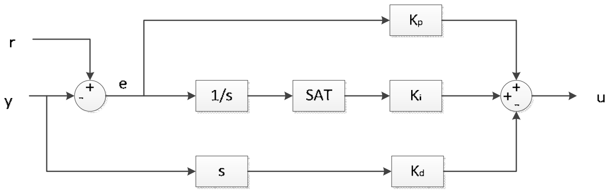

Figure 3. Improved PID structure

2 Simulation Results

As seen in Figure 4 and 5, simulating the model with a PD controller was an effective control solution. Here, X = 2 m for 4 sec. and Y = 2 m for 6 sec. are used for reference input. The system is stable for other input values. Here, linear and nonlinear models show similar performances for inputs. There are no steady state errors. Table 1 shows PD gains for X and Y axis.

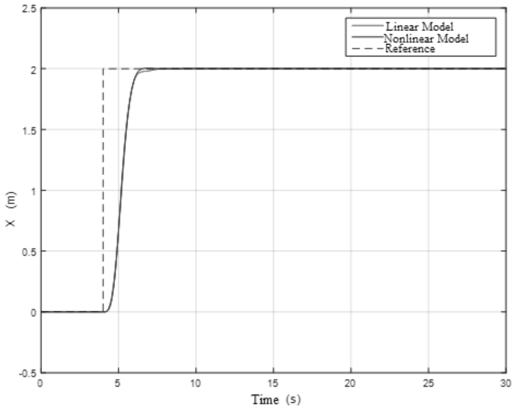

Figure 4. PD control for X axis.

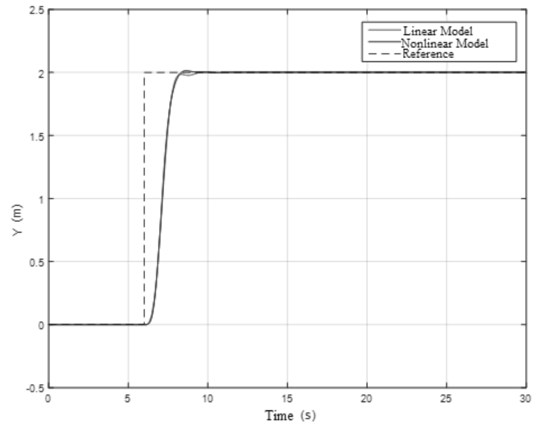

Figure 5. PD control for Y axis.

	P	D
X Controller	0.48	0.1
Y Controller	0.36	0.05

Table 1. PD Gains for X and Y Axis

As seen in Figure 6, simulating the model with a PID controller was an effective control solution. Here, $Z = 4$ m for 0 sec. is used for reference input. Here, the linear model is faster than the nonlinear model. Both of them have maximum overshoot but both of them are stable and there are no steady state errors. Table 2 shows PID gains for Z axis.

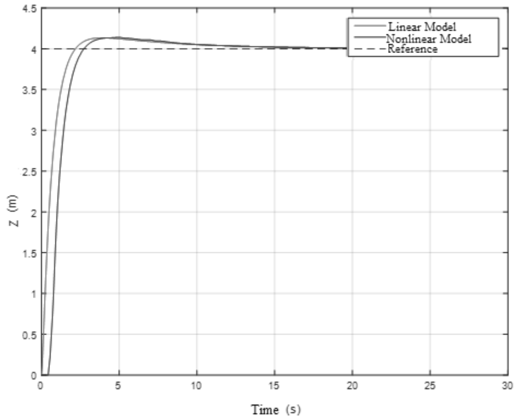

Figure 6. PID control for Z axis.

	P	I	D
Z Controller	50	8	35

Table 2. PID Gains for Z Axis

As seen in Figure 7, yaw angle is used 30 degree for 8 sec. for reference input. Here, linear model was faster than nonlinear model. Table 3 shows PID gains for yaw controller.

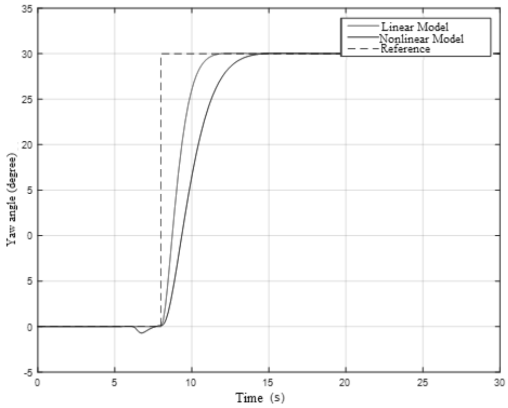

Figure 7. PID control for Z axis.

	P	I	D
Yaw Controller	2	0	4.14

Table 3. Yaw Controller Gains

As seen in Figure 8 and 9, both the linear and nonlinear model were nearly similar performances. The PID gains of the pitch and roll controller are shown in Table 4.

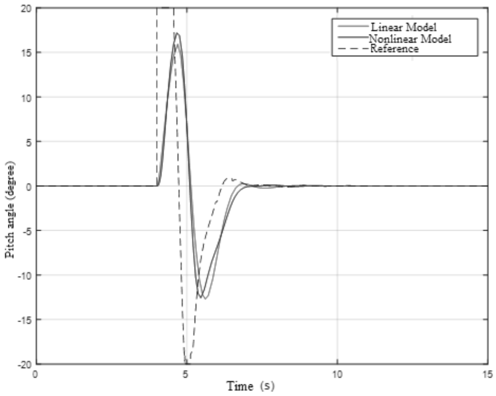

Figure 8. PID control for Z axis.

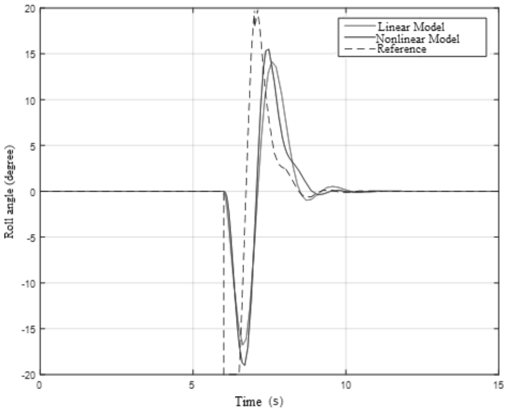

Figure 9. PID control for Z axis.

	P	I	D
Pitch Controller	3.3	0.5	1.5
Roll Controller	3.3	0	1.2

Table 4. Pitch and Roll Controller Gains.

3 Conclusion

In this study, an active fault tolerant control method is introduced for the actuator faults in the quadrotor vehicle. The linear model of the quadrotor is derived from nonlinear equations. This model is utilized in simulating actuator faults. The unknown input observer is used as a method of detecting the fault and GOS to isolate it. Since LQT has no steady-state error in normal operation condition, there is no need to include integral effect when there is no fault. When it comes to a faulty case, it is seen that LQT could not compensate steady-state error. To eliminate the steady-state error, switching from LQT to LQR with integral action is performed. Results show that the proposed method represents fast response combining with the elimination of the error.

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