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Hybrid modeling based double-granularity fault detection and diagnosis for quadrotor helicopter

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ABSTRACT

Fault detection and diagnosis (FDD) is an effective technology to assure the safety and reliability of quadrotor helicopters. However, there are still some unsolved problems in the existing FDD methods, such as the trade-offs between the accuracy and complexity of system models used for FDD, and the rarely explored structure faults in quadrotor helicopters. In this paper, a double-granularity FDD method is proposed based on the hybrid modeling of a quadrotor helicopter which has been developed in authors' previous work. The hybrid model consists of a prior model and a set of non-parametric models. The coarse-granularity-level FDD is built on the prior model which can isolate the faulty channel(s); while the fine-granularity-level FDD is built on the nonparametric models which can isolate the faulty components in the faulty channel. In both coarse and fine granularity FDD procedures, principal component analysis (PCA) is adopted for online fault detection. Using such a double-granularity scheme, the proposed FDD method has inherent ability in detecting and diagnosing structure faults or failures in quadrotor helicopters. Experimental results conducted on a 3-DOF hover platform can demonstrate the feasibility and effectiveness of the proposed hybrid modeling technique and the hybrid model based FDD method.

1. Introduction

Quadrotor helicopters are typical modern complex systems, and have in general more complicated aerodynamic characteristics and quite special flight attitudes compared with fixed-wing aircrafts [1,2]. On one hand, they have placed greater demands on accurate system model and robust controller design to assure flight quality and safety, which has raised the great interest of research in the field of control theory and application. On the other hand, quadrotor helicopters are prone to various faults or failures along with the growth of running time; therefore, Fault Detection and Diagnosis (FDD) is becoming a new hotspot of quadrotor helicopters to assure their safety and reliability.

FDD has been the subject of intensive research in various research fields for more than 40 years, and fruitful results have been reported in the literatures and books [3–9]. Faults in a control system are usually classified into actuator fault, sensor fault and structure fault [10]. For the flight control systems of quadrotor helicopters, Table 1 summarizes the reported faults and the corresponding FDD methods [11–24]. Despite these encouraging achievements, there are still many problems unsolved in the existing FDD methods when applied to quadrotor helicopters, such as:

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Table 1
Common faults in quadrotor helicopters and the employed FDD methods.

Methods	Faults	Advantages	Drawbacks
Luenberger observers	Bias, dead zone, scale factor on accelerometer [11]	Small false alarm rate	
	Bias on velocity and mach measurements [12]	Short detection delay	Computational burden
	Bias elevator or pitch rate sensor [13]	Robustness to model uncertainty	Difficult to distinguish faults from unmodeled disturbances
	Control surfaces (loss of effectiveness, locking) [14]	Isolation of simultaneous faults	
Kalman filters	Loss of control effectiveness [15,16]	Same advantages as Luenberger observers	Well-established for linearized models only;
	Failures of sensors in an engine [17]	Gaussian measurement noise and state perturbations are taken into account	Gaussian assumptions are not always valid
	Bias on sensor in flight control surface [18]		
Sliding mode observers		Fault estimation	
	Bias in IMU [19]	Quick convergence	Computational burden
	Drift in rudder throttle [20]	Estimation of some disturbances	Difficult in parameter tuning
Neural networks	Collective control stuck [21]		Choice of network structure may be difficult
	Bias/drift of IMU sensors or actuators [22]	Require no dynamical models	Huge on-line learning time
	Tail or wing damage [23]		Learning convergence not guaranteed
	Elevator bias [24]		

(1) Most FDD methods use linearized system models, which may pose strong constraints on their application potentials;
(2) Most FDD methods are purely model-based, while the measurement data that contain rich information on system behaviors and incipient faults are not fully utilized;
(3) Sensor and actuator faults have been extensively studied so far; however, structure faults are rarely mentioned.

Focusing on the above unsolved problems, this paper dedicates to improve the modeling accuracy to obtain a reliable and efficient FDD method. Hybrid modeling strategy [25–27] is an effective way to get more accurate models and to make full use of measurement data, which has been used in various industrial processes and aerospace fields [28–30]. A hybrid modeling strategy for a quadrotor helicopter based on physical effect analysis and nonlinearity measure has been proposed by the authors [31,32]. It clarified the scopes of the prior model and the nonparametric model according to the physical effects, and used fuzzy inference to select proper linearization methods in accordance with the nonlinearity degrees. The prior model was used to assure the global generalization performance; while the nonparametric model can explain the un-modeled characteristics so as to increase the accuracy and obtain a good local approximation performance.

Based on the hybrid modeling technique, this paper focuses on hybrid model based fault detection and diagnosis. The key contributions can be summarized as follows:

(1) A double-granularity fault diagnosis method is presented based on the hybrid model of a quadrotor helicopter. The coarse-granularity-level diagnosis is built on the prior model which can be used to isolate the faulty channel(s). The fine-granularity-level diagnosis is built on the nonparametric model to isolate the faulty component(s) in the faulty channel(s).
(2) The proposed FDD method has superior ability in detecting and diagnosing structure faults. As verified in Section 4, two structure faults are simulated on a quadrotor helicopter experimental platform. One is a broken-rotor-blade fault and the other is a motor fault. Experimental results can show the effectiveness and superiority of the proposed FDD method for structure faults.

2. Quadrotor helicopter

Quadrotor helicopter is a kind of multi-rotor helicopter that is lifted and propelled by four rotors. Such a four-rotor design allows quadrotor helicopters to be highly reliable and maneuverable. The main mechanical components in a quadrotor helicopter include a frame, four propellers, four electric motors, and electrical components such as electronic speed control module, on-board computer or controller board, and battery.

Attitude control of a quadrotor helicopter can be achieved by adjusting the rotor angular speeds. Fig. 1 shows the schematic system of a quadrotor helicopter, where φ, θ and ϕ denote the yaw angle, pitch angle and roll angle, respectively; $\Omega 1$–$\Omega 4$ are angular speeds of the four propellers; F1–F4 are lift forces; and M1–M4 denote the corresponding motors. Adjusting the speeds of M1 and M3 can change the pitch angle; while adjusting the speeds of M2 and M4 can change