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A Review on Fault Diagnosis and Fault Tolerant Control Methods for Single-rotor Aerial Vehicles

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Abstract Faults or failures are inevitable to occur and their prompt detection and isolation are essential for the dependability of various systems and for avoiding damages to the system itself, persons and the environment. Therefore, the safety of helicopter platforms have attracted the attention of many researchers in the past two decades. In order to deal with these problems, this paper presents an overview of the recent development and current researches in the field of fault diagnosis, including analytical/model-based, signal processing-based and knowledge-based techniques, and also passive/active fault- tolerant control approaches. Among various helicopters, single-rotor aerial vehicles, i.e. manned helicopters, unmanned helicopters, two and three degree-of-freedom unmanned helicopter experimental platforms, are considered for providing an overall picture of the fault diagnosis and fault-tolerant control approaches based on the review of journal articles in last two decades, conference articles in last several years and some books.

Keywords Helicopters · Unmanned aerial vehicles · Faults/failures · Fault diagnosis · Fault-tolerant control · Review

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1 Introduction

Helicopters are widely used due to their features of long hovering in the air, Vertical Take-Off and Landing (VTOL) capability, low-altitude, low-speed and flexible flight. The structural characteristics and application conditions make helicopter accident rate far higher than fixed-wing aircraft. The development of sophisticated and reliable Unmanned Helicopters (UH) has become an attractive research topic in academic communities worldwide [12] and numerous research groups/companies designed their unmanned helicopter platforms, such as Yamaha-R50-based Unmanned Aerial Vehicle (UAV) helicopters of Carnegie Mellon University [1], GTMax of Georgia Institute of Technology [45], Lion UAV family of National University of Singapore [2] and ServoHeli family of Shenyang Institute of Automation in Chinese Academy of Sciences [73, 75]. In case of faults or failures occurrence, helicopters do not have the same properties as of fixed-wing aircrafts or airships. More than 160 civil helicopter accidents occurred in the United State of America in 2012 [4]. Faults or failures are inevitable to occur, especially for unmanned helicopter systems, they normally have small size, light weight, compact structure and have no sensor or actuator redundancy.

Thus, a fault/failure in any part of the unmanned helicopter can be catastrophic. If the fault/failure is not detected and accommodated, the helicopter may crash [40]. The faults or failures detection and isolation are essential and Fault Diagnosis (FD) techniques have been widely used in process industry to detect faults in actuators, sensors or components. Recent books/surveys [16, 31, 42, 49] and [29] are recommended to readers for an overview of FD techniques. With FD techniques, control strategies or mission planning schemes are able to be adjusted after detection of a fault. Generally speaking, FD contains three steps: fault detection, fault isolation and fault estimation. Fault detection is to decide whether or not a fault has occurred, fault isolation is to determine the location of the fault, and fault estimation is to determine the kind of the fault and its severity. In order to maintain the acceptable performance of the system after a fault occurs, Fault-Tolerant Control (FTC) or Fault Detection, Isolation and Recovery (FDIR) technique is necessary. FTC and FDIR techniques are means to increase reliability and safety to the system. In this article, we will focus on FTC techniques applied and to be applied to rotary-wing, in particular, single-rotor manned and unmanned helicopters. In general, FTC approaches can be classified into two types: passive and active [99]. In passive FTC systems, controllers are fixed and designed to be robust against a class of presumed faults. Active FTC systems react to the system faults actively by reconfiguring control actions so that the stability and acceptable performance of the entire system can be maintained. To achieve a successful active FTC system, diagnosing system faults is necessary. For an overall picture of the FTC approaches, the readers can refer to recent books [10, 59, 80, 94, 96] and survey papers ([99] and others).

Because of helicopters' highly nonlinear feature, difficulty in control and less hardware redundancy, increasing demands for helicopter safety has attracted more and more attention in the research and development of FD and FTC techniques. Several review/survey papers related to the safety topic on aerial vehicles have appeared in recent years both in FD and FTC frameworks [18, 19, 22, 81] and [23]. In this paper, we presents an overview on the existing works on fault diagnosis and fault-tolerant control approaches for helicopters. The proposed review includes journal articles in last two decades, conference articles in last several years and some books, in open literature, relating to FD and FTC approaches on helicopters, containing mainly on-line and real-time approaches.

Compared to [78] and [77] written by the same authors, this paper contains some discussions on FD and FTC approaches with more details on specific techniques devoted to helicopters. Some of these approaches are proposed specifically for helicopters while some of them are common FD/FTC approaches and illustrated by helicopters. However, both of them are successfully applied for all kinds of helicopters or helicopter models.

In comparison with a recent contribution [98], this paper mainly focus in details on single rotorcraft helicopters, including both manned/

unmanned helicopters with a particular attention on two Degree-Of-Freedom (DOF) and three-DOF UH experimental platforms. All of the three platforms are as shown in Fig. 1.

Generally, manned helicopters have large scale and are non-cost-sensitive so that they can be installed with more sensors and actuators. Some manned helicopters have multi-redundant systems which include actuators, sensors and flight control computers. So researchers do not need to consider failures in these parts (this work can be done by redundancy management). At the same time, it is improbable to achieve redundancy of helicopter transmission system so that the ability to predict the Remaining Useful Life (RUL) of helicopter transmission system is necessary. Normally, human pilots are in the control loop of helicopters so that besides predicting RUL, the major role of FD systems is to provide various of faults/failures information to the pilot in order to accommodate faults by humans.

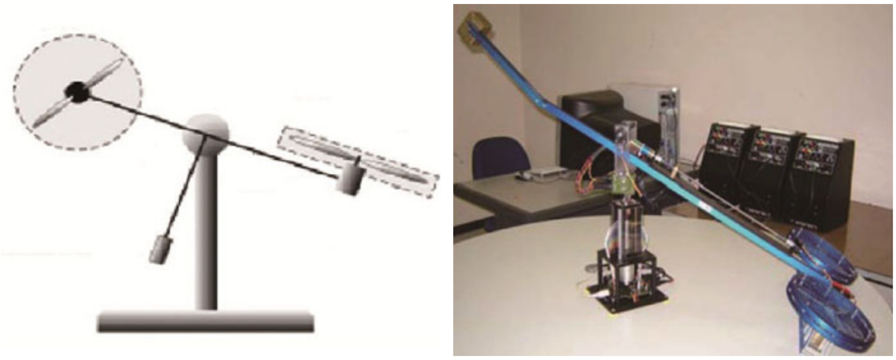
Compared with manned helicopters, in most cases, UHs have small scale and they are cost-sensitive so that they almost have no redundant sensors or actuators. It means that once any one of these sensors or actuators with malfunction, the UH will lost part of function or, even worse, crash. Therefore, the major of FD/FTC systems for UHs is to ensure maximum functionality and security of aircrafts. Hence, FD systems should provide faults/failures information to FTC systems as much as possible.

Due to complex dynamic model and great danger, a lot of FTC methods for UHs are limited in simulations. Though two- and three-DOF UH experimental platforms cannot be called real helicopters, they are easily and safely used for FD/FTC theory research and illustration. Some methods have been illustrated by these experimental platforms.

Since their different characteristics, FD/FTC methods for these three systems focus on different

Fig. 1 Some kinds of platforms

(a) Manned helicopter [3] (b) Unmanned helicopter [73]



(c) 2DOF experimental platform [64] (d) 3DOF experimental platform [88] problems. This paper will provide a review for the three different experimental platforms with associated information on the developed FD and FTC techniques. Section 2 presents a summary of FD approaches investigated or developed according to three different kinds of platforms. Next, a review of FTC schemes is provided in Section 3. Section 4 ends the paper by conclusions.

2 Fault Diagnosis Approaches

Faults or failures are inevitable in helicopters due to abnormal operation or material aging. Thus, actuator faults represent partial or total loss of actuator's control action. The actuator faults of helicopters mainly include constant output faults, constant gain change faults and drift faults. A constant output fault means no matter what the input value is the actuator will stay at a fixed position, like servo stuck and main rotor flameout (stuck at zero position). Constant gain faults represent that the actual output values of actuators are γ ($\gamma \in [0 \cdots 1]$) percent of the normal case, like servo power and main rotor power lost their efficiency. Drift faults mean the actuator output value changes with the attitude of the helicopter, like a weather-vane changes with the wind. Heredia et al. [40] proposed a different way to classify actuator faults according to the location of actuators and whether they are yet stuck or not. (1) One servo involved in rolling (or pitching) motion has a failure, but does not get stuck. (2) The servo involved in rolling (or pitching) motion actually gets stuck, so both the collective and the rolling (or pitching) actuators will not work. (3) The collective actuator can no longer work, or it may work with a limited range, due to a failure in the mechanical links.

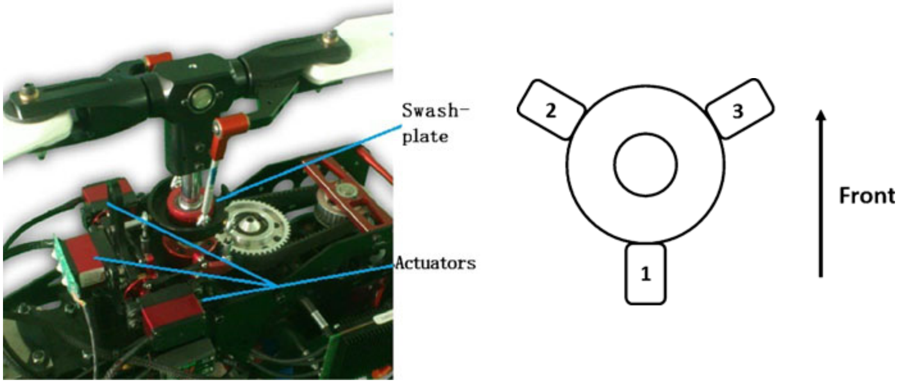
Sensor faults, which mainly include total faults, constant bias faults, constant gain faults and outlier faults [37], represent incorrect readings from the helicopter instruments. Total faults are very serious condition, in which the sensor outputs are not related to the values of measured physical parameters. Constant bias faults are often-occurred faults in analog sensors [68]. The expression of these faults is constant values added behind correct values of the sensors output. Constant gain faults are the same as the actuator faults. Outlier faults generally appear in the Global Positioning System (GPS) sensor. The sensor may output a large error value at a moment and then the sensor output correct values. For example, typical results obtained in 24-hour static tests show that estimated position error was less than 2 cm most of the time, but also include several groups of 2 to 5 contiguous points with a 20–60 cm error, which appear from time to time with no predictable frequency [35].

Component faults represent changes in the physical parameters of the helicopter, like helicopter tail loss and part of tail rotorcraft loss [30]. The model of component faults cannot be described systematically. They will influence the plant model. For single-rotor aerial vehicles, the main rotor mainly provides thrust, pitch and roll torque. The tail rotor mainly provides yaw moment which is used to offset the inverse moment provided by the main rotor. Typically, there are totally five variables which can be controlled by pilots or control systems. Three of them are used to control the main rotor through swashplate, another one for tail rotor and the last one for engine power. A photo of real swashplate and relevant three actuators are shown in Fig. 2 and an abstract picture of them can be found in Fig. 2. In simple terms, the attitude of the swashplate can be approximated as the attitude of main rotor plate. By setting the appropriate coordinate system and direction of actuator movement, the relationship between actuator control increments and attitude control increments can be achieved as follows:

$$\begin{cases} S_1 = C - P \\ S_2 = C + R + P/2 \\ S_3 = C - R + P/2 \end{cases} \qquad \begin{cases} C = (S_1 + S_2 + S_3)/3 \\ P = (-2S_1 + S_2 + S_3)/3 \\ R = (S_2 - S_3)/2 \end{cases} \tag{1}$$

where S_1, S_2, S_3 are control increments of the three actuators and C, P, R are collective moment, pitch and roll control increments respectively.

The existing FD techniques can be split into three categories: analytical/model-based



(a) Real swashplate (b) Abstract swashplate

Fig. 2 Swashplate and relevant three actuators

approaches, signal processing-based approaches, and knowledge-based approaches.

Analytical/model-based FD approaches focus on mathematical models. Because of flight dynamics and aerodynamics, helicopter modeling is rather complex and difficult, especially rotor modeling [46]. Generally, there are three types of models: Linear Time-Invariant (LTI) model, Linear Parameter Varying (LPV) model and nonlinear model. So far, many research teams have constructed their own unmanned helicopter platforms for their research purpose and a number of system identification methods have been proposed to derive linear or nonlinear model for specific flight conditions or envelope [11].

Signal processing-based approaches do not require accurate analytical models. These methods can be used for both linear systems and nonlinear systems in principle based on signal data directly. Signal processing-based methods are built on the basis of thorough analysis on the failure mechanism to determine signal characteristics which can mostly represent failures.

Knowledge-based FD approaches introduce a wide range of information in relationship with diagnosis objectives. In particular, knowledge-based FD approaches can make full use of knowledge of experts in the field and avoid dependence of accurate mathematical models.

Taking into account different plants have different requirements for FD, following discussions will be carried out according to experimental platforms.

2.1 Manned Helicopters

Many researches are related to manned helicopter transmission systems. Faults in transmission systems can be described easily by vibration data with fault-free frequency signatures rather than to get a reliable analytical transmission system model.

Schwartz et al. [82] designed quadratic detectors based on the estimated signal statistics but without any predetermined features so that it may find features in the data which might normally be overlooked. With the quadratic detector the significant detection features can be selected automatically and the final detection results are nearly perfect. Li et al. [52] defined an effective gear fault location detection methodology using Acoustic Emission (AE) sensors for splitting torque gearbox by analyzing the arrival time of the AE bursts to determine the gear fault location. Siegel et al. [83, 84] proposed a methodology for predicting helicopter rolling element bearing failure in which a series of processing steps in prior, including feature extraction, feature selection, and health assessment are included. The authors outlined the advantages and disadvantages of different methods in each step. Loughlin et al. [56] used conditional time-frequency moments which have a simple physical interpretation. They are the mean, median and mode frequencies and the spread about the mean frequency at a given time. This method characterized the faults well and can differentiate between different fault classes. In the time-frequency analysis, some methods have been proposed for particular faults such as Randall [79], Williams et al. [89], Girondin et al. [32], Hood et al. [41] and also Ehinger et al. [24].

Besides signal processing-based approaches, some knowledge-based approaches are also considered to diagnose faults on helicopter transmission systems, like rule extracting based on Maximum Characteristic Granule (MCG) [86], rule extraction based on granular computing [87], genetic algorithms [26] and multi-sensor mixtures Hidden Markov Models (HMM) [17]. Various of knowledge used by these methods are also composed of vibration signal.

Vibration monitoring is widely used to observe the condition of a process or an equipment. Normally, it is hardly to collect vibration signal of the source directly due to the design and construction of the machinery. Therefore, vibration sensors have to collect vibration signal indirectly which means the transmission of the vibration signal from the source to the sensor is complex and easy to be disturbed. Therefore, the task of these approaches is not only to recognize the difference between normal or fault condition, but also to separate the useful information from the original measurement signal. Some methods of extract signal features have been widely used like frequency spectral analysis and statistic analysis. According to these features, specific faults or failures can be detected and various types of faults or failures can be isolated with adding classifier.

In addition to transmission system, Ganguli et al. [27, 28], and also Morel et al. [58] proposed rotor system fault detection methods using physics-based model and Neural Network (NN). Damages analyzed include moisture absorption, damaged lag damper and damaged pitch-control system. Relative changes in rotor blade response and vibration due to the presence of faults are used to train neural networks for damage detection and identification. Kuo et al. [50] and Liu et al. [55] proposed expert system methods for FD of the whole helicopter.

Analytical/model-based FD approaches are also used for manned helicopters. Alkahe et al. [6] proposed a model-based damage detection algorithm for rotating blades based on Multiple-Model Adaptive Estimation (MMAE). To use the multiple-model approach presented, the structural model of a rotating blade must be determined. Based on blade element analysis, there are two local degrees of freedom at each end, vertical translation and rotation, resulting in a total four degrees of freedoms per element. After constructing the continuous state transition matrix and calculation of the reduced stiffness, the blade model is achieved. Due to various damage locations and levels are considered, a Kalman filter is tuned according to each model. Based on the residuals of each one of these filters, prediction error covariance matrix can be computed for describing the true damaged behavior in the best manner.

Additionally, some common analytical/model-based FD approaches are proposed and successfully used for manned helicopters. These methods can also be used for UHs by replacing helicopter models with UH models. Zhang et al. [97] assume that $\dot{f}(x) = 0$ after the fault occurrence at time t_f to simplify the observer design and use it for fault estimation of a helicopter in the vertical plane. Consider a polytopic LPV system and the on-line fault estimation using the Fast Adaptive Fault Estimation (FAFE) algorithm can be expressed as:

$$\hat{f}(t) = -\Gamma \int_{t_f}^{t} \big(F(\rho(\tau))(\dot{e}_y(\tau) + e_y(\tau))\big)\, d\tau \tag{2}$$

where t_f denotes the instant when fault occurs, Γ is a constant learning rate, e_y is the output error, $F(\rho(\tau))$ is a symmetric positive matrix and $\rho(\tau)$ is the gain scheduling parameter of the LPV system.

Jiang et al. [43] developed a new real-time fault estimation module for the actuator effectiveness. Consider a linear stochastic system with an actuator fault, the actuator fault can be estimated as following:

$$\begin{aligned}\hat{f}(k-1) = (E_3)^{-1}[y_2(k) - A_3\hat{x}(k-1) \\ - B_3u(k-1)]\end{aligned} \tag{3}$$

where A_3, B_3, E_3 are parts of system matrices A, B, E with appropriate dimensions and y_2 is part of output y. Then the method is extended to the model with unknown input estimation $\hat{\xi}$:

$$\begin{aligned}\hat{f}(k-1) = (E_3)^{-1}[y_2(k) - A_3\hat{x}(k-1) \\ - B_3u(k-1) - D_3\hat{\xi}(k-1)]\end{aligned} \tag{4}$$

Table 1 FD methods for manned helicopters

Locations	Approaches	FD types	References
Gears	Time domain analysis	Signal	[51]
Gears	Frequency domain analysis	Signal	[24, 79, 82]
Gears	Time-frequency domain analysis	Signal	[41, 56, 90]
Gears	Wavelet transform	Signal	[52]
Gearbox	HMM	Knowledge	[17]
Gearbox	Genetic algorithms	Knowledge	[26]
Bearing	Time domain analysis	Signal	[83, 84]
Bearing	Frequency domain analysis	Signal	[32]
Transmission system	Time-frequency domain analysis	Signal	[89]
Transmission system	Bicoherence analysis	Signal	[34]
Transmission system	Granular computing	Knowledge	[87]
Transmission system	MCG	Knowledge	[86]
Whole	Expert system	Knowledge	[50, 55]
Rotor	NN	Knowledge	[27, 28, 58]
Rotor	MMAE	Model	[6]
Actuators	Observer	Model	[54, 97]
Actuators	KF	Model	[43]
Sensors	LS/RLS	Model	[53]

where D_3 denotes a part of system matrix D. At last, a dynamic model of a helicopter in the vertical plane is used for illustrating the proposed method.

Liu et al. [54] designed an Unknown Input Observer (UIO) to track actuator fault parameters and decouple the effects of faults and unknown inputs.

Simulation results are obtained through a LTI model which has four states, horizontal velocity, vertical velocity, pitch rate, pitch angle and two control inputs, collective pitch, longitudinal cyclic pitch. The proposed method can successfully eliminate the influence of disturbance on faults identification and the fault parameters can be tracked by the adaptive fault identification scheme.

Litt et al. [53] used Recursive Least Squares (RLS) method to compute the value of the fault parameters and the maximum time.

As summarized in Table 1, for manned helicopter FD approaches, most of researches are relation to transmission systems.

2.2 Unmanned Helicopters

Considering limited redundancy of UHs, almost all approaches are focus on faults/failures of sensors or actuators. The major role of FD systems is to provide faults/failures information for FTC systems as more as possible so that analytical/model-based approaches, including more system information, are widely used for UH fault diagnosis.

2.2.1 Sensor Faults

Firstly, analytical/model-based approaches are given. Heredia et al. [38, 39] used an input-output model and observer for sensor faults estimation. UHs are non-linear coupled multiple-input, multiple-output (MIMO) systems. However, when dealing with non-aggressive flight scenarios, they can be treated as linear system with some motion constraints, like maximum speed and maximum attitude angle. Because only output estimation is required, an input-output model of the helicopter system can be identified for output prediction. The model is an Auto Regressive eXogenous (ARX) model, specific discrete-time, time-invariant and linear dynamics. Based on the output prediction, the residual generator is constructed for each independent sensor. The residuals can be described by the following equation:

$$R(k) = \sum_{i=1}^{n} m_i (c_i(k) - \hat{c}_i(k))^2 \tag{5}$$

where m_i is a weighting coefficient, c_i and $\hat{c}_i$ are real and estimated sensor outputs, respectively. The fault is supposed to be occurred at the first time when the residual goes above the threshold level.

In order to illustrate the proposed method, series of experiments have been done with MARVIN helicopter. Five types of sensor faults/failures are considered totally, including total sensor failure, stuck with constant bias sensor failure, drift or additive-type sensor fault, multiplicative-type sensor fault and outlier data sensor fault. It can be achieved from experimental results, sensor failures and outlier data sensor faults are easily detected by the FD method while the other faults are detected depending on the error size.

Heredia et al. [36, 37] also obtained the UH model from input-output experimental data with the Observer/Kalman Filter Identification (OKID) method and presented a system for helicopter sensors fault detection based on the OKID method. Considering the standard state-space difference equation for an LTI system and adding a discrete-time observer with unknown initial condition, one can achieve:

$$\begin{aligned} x(k+1) &= \bar{A}x(k) + \bar{B}v(k) \\ y(k) &= Cx(k) + \bar{D}v(k) \end{aligned} \tag{6}$$

where $\bar{A} = A + GC$; $\bar{B} = [B + GD \quad -G]$; $\bar{D} = [D \quad 0]$, G is the observer gain and $v(k) = [u(k) \;\; y(k)]^T$.

The main advantage of the proposed method is that there is no need to estimate neither the system matrices nor the measurement and process noise covariance matrices, because all information are extracted from experimental input-output data. Based on the detection and diagnosis of the above five types of faults/failures, Heredia et al. [36, 37] present the OKID method which is slightly better and more robust than a classical Kalman filter.

In a different way, Wu et al. [91] proposed an Adaptive Extended Set-Member Filter (AESMF) method for sensor faults diagnosis. Set-Member Filter (SMF) is an approach to process unknown but bounded noise data, and the final result is a set which includes the true value. Under normal circumstances, the center of the set can be recognized as an estimation of the noise data. In SMF algorithm, the feasible set of the state should be defined first. Normally, ellipsoid set is selected to present the feasible set of the system state. The state of the AESMF is defined as an ellipsoid set in the following equation:

$$E(\hat{x}, P) = \{x \in R^n | (x - \hat{x})^T P^{-1} (x - \hat{x}) \leq 1\} \tag{7}$$

where $\hat{x}$ is the center of the ellipsoid, P is an envelope matrix which defines the ellipsoid characteristics. The author introduced the ellipsoid bound P_{k+1} as the indication of the sensor fault. P_{k+1} is update by a group of equations, the core of the method in this paper, which are divided into prediction step and measurement update step. Through experimental illustration, both sensor faults and failures of 3-axis angular velocities, accelerations and velocities can be detected and isolated.

Besides analytical/model-based approaches, Qi et al. [76] presented an adaptive threshold Neural Network (NN) method, a Knowledge-based approach, for UH sensor failure diagnosis. The adaptive threshold approach eliminates the influence of thresholds changing caused by varying flight condition. In this method, a three-layer Back Propagation (BP) network structure are used.

The neural network sensor fault detection and identification structure is mainly composed by the Main NN (MNN) and the Decentralized NN (DNN). The account of the former one is equal to the number of sensor types and the latter one is equal to the number of specified sensors of each type. Then the author defined four different failure detection parameters based on the two kinds of NN, including MNN Estimation Error Norm (MEEN), MNN and DNN Estimation Error Norm (MDEEN), DNN Estimation Error Norm (DEEN) and Fault Detection Error Summation (FDES). The sensor faults can be declared by:

$$FDES(k) \geq \min(MEEN - i_t, MDEEN - i_t) \tag{8}$$

where i_t is the adaptive threshold. The thresholds can be adaptively adjusted according to the average value, the standard deviation, the rate of change and the bias of thresh. Fault type identification and fault identification are also achieved. Two cases of faults have been simulated, one is a heading fault of compass while the other one is a pitch rate fault of Inertial Measurement Unit (IMU). From simulation results, the adaptive threshold NN method shows better performance than fixed threshold algorithm.

Signal processing-based approaches are also used for UH sensor fault detection. Qi and Han [68] proposed a novel wavelet-based approach, for detecting an abrupt sensor fault. With the wavelet-based method, the UH sensor fault FD system can detect the faults/failures locations of abrupt signal effectively.

2.2.2 Actuator Faults

Some FD approaches used for sensors are also applicable for actuators. Heredia et al. [38, 40] use an input-output model and observer for actuator faults estimation. They used the same observer for output prediction as [38, 39]. Then the residuals can be described by the following equation:

$$R(k) = \sum_{i=1}^{3} m_i(v_i(k) - \hat{v}_i(k))^2 + \sum_{i=1}^{3} n_i(\omega_i(k) - \hat{\omega}_i(k))^2 \tag{9}$$

where v_i and ω_i are real linear and angular velocities, m_i and n_i are weighting coefficients. For residuals evaluation, they choose reasoning methods which can optimize the use of priori knowledge:

$$IF < S_{\mathrm{coll}}\ AND\ S_{\mathrm{roll}} > THEN < F_{\mathrm{rollservo}} > \tag{10}$$

where S_{coll} is true if the collective residual goes above the threshold level, and S_{roll} is true if the roll residual goes above the threshold level. The expression means that if S_{coll} and S_{roll} are both true, the roll servo arise faults, because the servo in rolling motion affects both collective and rolling motion.

Experiments with real flight data obtained from a UH and simulation data came from a full nonlinear mathematical model illustrate that the method can detect and isolate UH faults/failures successfully.

Arne et al. [8] have designed a fault isolation observer for both square and non-square linear systems and provide a design which guarantees stability of the observer and minimize the influence of disturbances on the residuals at the same time. The fault isolation observer is as following:

$$\begin{aligned} \dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t) + L(y(t) - C\hat{x}(t)) \\ r(t) &= V(y(t) - C\hat{x}(t)) \end{aligned} \tag{11}$$

By proper selection of the observer gains $(L,\ V)$ with parametric approach, the observer can achieve stable fault isolation in square systems and non-square systems. To illustrate the presented methods, a linearized model of CE-150 model helicopter with $n = 6$ and $n_u = 2$ which describes the coupled pitch- and yaw-dynamics are used.

Kalman filters are also used for fault diagnosis, including standard Kalman Filter (KF), Extended Kalman Filter (EKF) and Unscented Kalman Filter (UFK). UKF approximates the distribution of the state with a finite set of points. Since the nonlinear models are used without linearization, it is much simpler to implement and less time consuming for a real time application compared to EKF. Qi et al. [70, 71, 74] and [69] proposed several UKF-based FD methods for UH actuator faults/failures. In order to represent actuator faults/failures, Actuator Healthy Coefficients (AHCs) are proposed.

$$U_{\mathrm{out}}(k) = \Gamma_f(k)U_{\mathrm{in}}(k) + \Delta_f(k) \tag{12}$$

where $U_{\mathrm{in}}(k)$ is defined as actuator inputs, $U_{\mathrm{out}}(k)$ as actuator outputs and

$$\Gamma_f(k) = \begin{pmatrix} \gamma_1(k) & 0 & \cdots & 0 \\ 0 & \gamma_2(k) & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & \gamma_r(k) \end{pmatrix}$$

$$\Delta_f(k) = \begin{pmatrix} \delta_1(k) & 0 & \cdots & 0 \\ 0 & \delta_2(k) & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & \delta_r(k) \end{pmatrix} \tag{13}$$

where γ_i and δ_i are the proportional effectiveness and faults/failures bias of ith actuator's AHCs. Then the AHCs parameter and state vectors are concatenated into a single augmented state vector for joint estimation, $x_k^a = [P, \aleph, V^B, \Omega^B, \Gamma_F, \Delta_F]^T$. The joint state equations are:

$$\begin{cases} x^a(k) = \tilde{f}(x^a(k-1), u(k)) + \omega^a(k) \\ y(k) = \tilde{h}(x^a(k)) + v(k) \end{cases} \tag{14}$$

Several UKF methods are proposed for joint estimation. The first one is Square Root UKF (SR-UKF) [69]. In the SR-UKF implementation, the square-root of the state covariance propagates and updates directly. The second one is Adaptive UKF (AUKF) [71], where the adaptive estimation of the process noise covariance Q^ω is considered. The third one is KF-based Adaptive UKF [70, 74]. It is composed of two parallel master-slave filters. The slave filter employs KF to estimate the noise covariance while the master UKF estimates the state, using the current noise covariance. Simulation results show that compared to the standard UKF and MIT rule-based UKF, the KF-based adaptive UKF is much simpler and highly effective.

All of these methods are illustrated by a mathematical model identified with the real flight data of SIA-Heli-90. The dynamic equation of a typical rigid RUAV in/near hovering flight based on Newton-Euler equation can be described as:

$$\begin{pmatrix} mE & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} \dot{V}^B(t) \\ \dot{\Omega}^B(t) \end{pmatrix} + \begin{pmatrix} \Omega^B(t) \times mV^B(t) \\ \dot{\Omega}^B(t) \times I\Omega^B(t) \end{pmatrix} = \begin{pmatrix} F_{ext}^B(t) \\ M_{ext}^B(t) \end{pmatrix} \tag{15}$$

where external forces and moments during hovering can be written as:

$$\begin{aligned} F_{ext}^B(t) &= \begin{pmatrix} x_M(t) \\ y_M(t) + y_T(t) \\ z_M(t) \end{pmatrix} + R_{TP\to B} \begin{pmatrix} 0 \\ 0 \\ mg \end{pmatrix} \\ M_{ext}^B(t) &= \begin{pmatrix} R_M(t) + y_M(t)h_M + z_M(t)y_M(t) + y_M(t)h_M \\ M_M(t) + M_T(t) - x_M(t)h_M + z_M(t)l_M \\ N_M(t) - y_M(t)l_M - y_T(t)l_T \end{pmatrix} \end{aligned} \tag{16}$$

where $R_{TP\to B}$ is a rotational matrix, h_M, l_M, l_T are distance between forces and center of gravity. The forces and moments can be expressed as:

$$\begin{cases} x_M(t) = -T_M(t)\sin a_1(t) \\ y_M(t) = -T_M(t)\sin b_1(t) \\ z_M(t) = -T_M(t)\cos a_1(t)\sin b_1(t) \\ R_M(t) = -b_1(t)(dR(t)/db_1(t)) - Q_M(t)\sin a_1(t) \\ M_M(t) = -a_1(t)(dR(t)/da_1(t)) - Q_M(t)\sin b_1(t) \\ N_M(t) = -Q_M(t)\cos a_1(t)\cos b_1(t) \\ y_T(t) = -T_T(t) \\ M_T(t) = -Q_T(t) \end{cases} \tag{17}$$

where $T_M(t)$, $T_T(t)$, $Q_M(t)$, $Q_T(t)$, $a_1(t)$, $b_1(t)$ are the main rotor torque, the tail rotor torque, main rotor anti-torque, tail rotor anti-torque, the longitudinal and lateral flapping angle respectively.

Wu et al. [92] proposed a FD method based on adaptive extended set-membership filter. Comparing with KF-based methods which are according to features of stochastic noise, set-member filter requires noise data being bounded but do not require statistical properties of noise data, like mean and standard-deviation. So set-member methods have the advantage of wide adaptation and strong robustness. The proposed AESMF method can improve estimation stability and boundaries accuracy compared with extended set-membership filter because the process noise Q_k can update online adaptively based on MIT rule. In simulation, the normal ESMF track the changed coefficients slowly, but the AESMF can convergent to the current coefficients in much shorter time.

Table 2 FD methods for unmanned helicopters

Locations	Approaches	FD types	References
Sensors	Observer	Model	[38, 39]
Sensors	OKID	Model	[36, 37]
Sensors	AESMF	Model	[91]
Sensors	Wavelet transform	Signal	[68]
Sensors	NN	Knowledge	[76]
Actuators	Observer	Model	[8, 38, 40]
Actuators	UKF	Model	[69–71, 74]
Actuators	AESMF	Model	[92]
Rotor	Time domain analysis	Signal	[47]

Kaliappan et al. [47] detected the faults by measuring the change rate of data with respect to time. The method uses the sliding window data from the flight dynamics.

Totally, FD approaches for both sensors and actuators are summarized in Table 2, where it clearly appears that analytical/model-based FD techniques are devoted to UHs widely.

2.3 Two- and Three-DOF UH Experimental Platforms

Two- and three-DOF UH experimental platforms have a lot of advantages for FD researches which attract many researchers' interest. These platforms have many advantages, like simple dynamic model, easy modeling, safe experimental environment and low cost. Some FD methods proposed for these platforms are also suitable for UHs.

Montes de Oca et al. [64] developed an Unknown Input Observer (UIO) with LPV system for fault identification of a two-DOF UH. The actuator fault can be identified as an unknown input.

Two fault scenarios are considered for illustrating the proposed method, input voltage fault of the tail motor and input voltage fault of the main motor. The simulation results show that the input voltage fault of the main motor can be estimated with very high accuracy while there are some errors when it estimates the fault of tail-rotor input voltage.

Waschburger et al. [88] presented an experimental validation of wavelet-based analytical redundancy technique on a three-DOF UH platform. The results indicate that the technique under consideration can successfully detect a fault with small magnitude.

2.4 Discussion

A review of fault diagnosis methods is given according to different platforms such as manned helicopters, unmanned helicopters, two- and three-DOF UH experimental platforms. In Tables 1 and 2, a fact can be noted that for manned helicopters most of researches are in connection with transmission systems with signal processing-based approaches while for unmanned helicopters researchers are more interested in sensors and actuators with analytical/model-based approaches. The reason behind the fact is different characteristics and needs of different systems as mentioned earlier. Deeply, according to this fact, FD approaches for helicopters can be divided into two classes according to their purpose but not platforms. One class of these approaches is for RUL and the other class is for FTC. The major goal of the first class systems is to monitor and achieve whether some parts of aircrafts go wrong. Based on the result, the systems need to give information or alarm about faults/failures to human pilots or engineers for fault tolerance or repairing. Considering human beings have a lot of knowledge about helicopters, the systems do not need to provide many details of faults/failures. Compared with the first class, the second class systems are designed for unmanned systems or driver assistance systems which have poor or partial knowledge of the whole system. In order to achieve FTC, they need as much data as possible. So the second class systems need to provide not only whether there are faults/failures or not but also what, where and when faults/failures occur.

As summarized in Table 3, FD approaches are organized according to three FD types for describing these methods from a different perspective. Most of observer methods for single rotorcraft have been synthesized for LTI model and focused on actuator/sensor faults. However nonlinear models have been assumed for stochastic approach. Compared to analytical/ model-based approaches, many signal processing-based methods are devoted to helicopters where human is

Table 3 FD approaches classification by FD types

FD types	Approaches (model)	Locations	Platform	References
Analytical Model based	Observer (LTI)	Actuators	UH	[8, 38, 40]
	Observer (LTI)	Sensors	UH	[38, 39]
	OKID (LTI)	Sensors	UH	[36, 37]
	LS/RLS (LTI)	Sensors	Helicopter	[53]
	Observer (LTI)	Actuators	Helicopter	[54, 97]
	Observer (LPV)	Actuators	2DOF UH	[64]
	MMAE (LPV)	Rotor	Helicopter	[6]
	KF (LTI)	Actuators	Helicopter	[43]
	UKF (nonlinear)	Actuators	UH	[69–71, 74]
	AESMF (nonlinear)	Sensors	UH	[91]
		Actuators	UH	[92]
Signal Processing Based	Wavelet transform	Attitude	3DOF UH	[88]
	Wavelet transform	Sensors	UH	[68]
	Wavelet transform	Gears	Helicopter	[52]
	Time domain analysis	Rotor	UH	[47]
	Time domain analysis	Bearing	Helicopter	[83, 84]
	Time domain analysis	Gears	Helicopter	[51]
	Frequency domain analysis	Gears	Helicopter	[24, 79, 82]
	Frequency domain analysis	Bearing	Helicopter	[32]
	Time-frequency domain analysis	Gears	Helicopter	[41, 56, 90]
	Time-frequency domain analysis	Trans. system	Helicopter	[89]
	Bicoherence analysis	Trans. system	Helicopter	[34]
Knowledge Based	NN	Rotor	Helicopter	[27, 28, 58]
	NN	Sensors	UH	[76]
	Expert system	Whole	Helicopter	[50, 55]
	Granular computing	Trans. system	Helicopter	[87]
	HMM	Gearbox	Helicopter	[17]
	MCG	Trans. system	Helicopter	[86]
	Genetic algorithms	Gearbox	Helicopter	[26]

included in the closed-loop and receive information from FD systems in order to accommodate faults. Finally, UHs are rarely considered with knowledge-based FD approaches.

3 Fault-tolerant Control Approaches

FTC theory has attracted considerable attention globally. The task of FTC systems is to ensure system stability and maintain acceptable performance of controlled system when fault/failure occurs, which generally leads to critical changes in the system parameters, or even in the dynamics of the system [85]. Because any systems may occur faults/failures inevitably, FTC systems are treated as the final line of defense to protect system safety. Helicopters have poor stability and not easy to control with the multivariable, nonlinear coupling and flexible structure dynamics. Taking the wind disturbance, engine vibration and other disturbance into account during the flight, its mechanical parts and control systems are prone to be fault/failure.

Comparing with fixed-wing UAV, helicopters have stronger coupling and less hardware redundancy. Helicopters have an upper control system that mechanically relates the helicopters blade angles to the three main rotor actuators, via an intermediary swashplate [25]. When any one of the three actuators goes out of order, because of the coupling of control axes, the flight control system can achieve UHs' attitude stability through swashplate reconfiguration and adjust UHs' altitude through rotor speed reconfigurable flight control. The details can be found in [25] and the authors in [21] also gave details with a practical flight experiment.

3.1 Manned Helicopters

Considering the reason mentioned earlier, there are not a lot of articles paying attention to FTC methods for manned helicopters. Besides swashplate reconfiguration, helicopter optimal control after power failure also attract researchers' attention [9, 66, 100]. In order to deal with power failure, an eight-DOF model is proposed [9]: six states for a rigid fuselage, one state for the angular velocity of the main rotor and one for the available engine power. While the helicopter control vector has four components: collective pitch angle, lateral and longitudinal cyclic pitch angles of the main rotor, and the tail rotor collective pitch angle. The main rotor angular velocity and the engine dynamic model are respectively as following:

$$I_R\dot{\Omega}(t) = k_s\frac{P_s(t)}{\Omega(t)} - M_{zW}(t) \tag{18}$$

$$\dot{P}_s(t) = \frac{P_{\max} - P_s(t)}{T_s} \tag{19}$$

where I_R is the main rotor moment of inertia, $\Omega(t)$ is the main rotor speed, k_s is the coefficient in expression of helicopter power consumption, $P_s(t)$ is the actual available power, $P_{\max}$ is the maximum available power, $M_{zW}(t)$ is the main rotor torque and T_s is the coefficient in power calculation.

The performance index for landing, which should be minimized by control input, is assumed as a quadratic function of selected state variables:

$$\begin{aligned} J = {} & W_\Omega\left(\frac{\Omega(t)-\Omega_0}{\Omega_{\text{norm}}}\right)^2 + W_U\left(\frac{U(t)}{U_{\text{norm}}}\right)^2 \\ & + W_V\left(\frac{V(t)}{V_{\text{norm}}}\right)^2 + W_W\left(\frac{W(t)}{W_{\text{norm}}}\right)^2 \\ & + W_P\left(\frac{P(t)}{P_{\text{norm}}}\right)^2 + W_Q\left(\frac{Q(t)}{Q_{\text{norm}}}\right)^2 \\ & + W_R\left(\frac{R(t)}{R_{\text{norm}}}\right)^2 \end{aligned} \tag{20}$$

where $U(t)$, $V(t)$, $W(t)$ and $P(t)$, $Q(t)$, $R(t)$ are fuselage angular velocities and linear velocity components respectively.

In addition to these, some other common FTC schemes used for helicopters are presented. Firstly, a passive adaptive controller is proposed by Kapoor et al. [48] for coaxial rotor helicopter under propeller failure. The mathematical model of coacial rotor helicopter can be described as:

$$\begin{cases} m\ddot{x}(t) = -u(t)\sin\theta(t) \\ m\ddot{y}(t) = u(t)\cos\theta(t)\sin\phi(t) \\ m\ddot{z}(t) = u(t)\cos\theta(t)\cos\phi(t) - mg \\ \ddot{\psi}(t) = \tau_\psi(t) \\ \ddot{\theta}(t) = \tau_\theta(t) \\ \ddot{\phi}(t) = \tau_\phi(t) \end{cases} \tag{21}$$

where $u(t)$, $\tau_\psi(t)$, $\tau_\theta(t)$, $\tau_\phi(t)$ are the control inputs. The adaptive failure compensation is implemented as $u(t) = \bar{u}(t) + v_z(t)$, $\tau_\psi(t) = \bar{\tau_\psi}(t) + v_\psi(t)$, where $\bar{u}(t)$ and $\bar{\tau_\psi}(t)$ are original control laws, $v_z(t)$ and $v_\psi(t)$ are adaptive control laws,

$$\begin{aligned} v_z(t) &= \left(\frac{1-\sigma(t)}{1+\sigma(t)}\right)\bar{u} \\ v_\psi(t) &= -\pi(t)\frac{1-\sigma t}{2}u \end{aligned} \tag{22}$$

where $\sigma(t)$ and $\psi(t)$ are the update law,

$$\begin{aligned} \dot{\sigma}(t) &= -\frac{\Gamma_1 m\ddot{e}_z(t)}{\bar{u}(t)\cos\theta(t)\cos\phi(t) - m\ddot{e}_z(t)} \\ \dot{\psi}(t) &= -\Gamma_3\dot{e}_\psi(t) - \Gamma_4 e_\psi(t) \end{aligned} \tag{23}$$

where Γ_1, Γ_3, Γ_4 are constants, m is the mass of the aircraft, $\theta(t)$ and $\psi(t)$ are pitch and yaw angles respectively, $e_z(t)$ and $e_\psi(t)$ are difference between the expected and the actual value.

Luan et al. [57] proposed model reference adaptive control approach, also a passive FTC method, which has an outer-loop adaptive compensator for improving its self-repairing capability.

In addition to passive FTC methods, active FTC approaches are also developed. Liu [54] proposed an adaptive fault-tolerant H_∞ output feedback controller and gave a complete controller design steps.

Table 4 FTC methods for manned helicopters

Locations	Approaches	FTC types	References
Actuators	Adaptive control	Passive	[48, 57]
Actuators	Adaptive H_∞ control	Active	[54]
Actuators sensors	KF	Active	[43]
Components	Adaptive sliding mode backstepping control	Active	[15]

Chen et al. [15] proposed an adaptive sliding mode backstepping technology for vertical flight, which includes the altitude and the collective angle of the blades of the helicopter. The control law can be given as $u(t) = u_c(t) + \Delta u(t)$, where $u_c(t) = [u_{th}(t) \;\; u_{\theta_c}(t)]^T$ and $\Delta u(t) = [0 \;\; u_f(t)]^T$. The $u_{th}(t)$ and $u_{\theta_c}(t)$ are inputs of the throttle and collective pitch respectively. The added control input signals $u_f(t)$ is

$$u_f(t) = \frac{1}{g_5}\hat{f}(t) \tag{24}$$

where g_5 is one of the system parameters and $\hat{f}(t)$ is the fault estimate given by fault observer.

Jiang et al. [43] designed a controller for loss of actuator effectiveness. The actuator faults are modeled as $f(k) = R(k)u(k)$ and the estimation of $R(k)$ is $\hat{R}(k)$. The compensation law is defined as following:

$$u_R(k) = (I - \hat{R}(k))^{-1}u(k) \tag{25}$$

The resulting closed-loop system with the above law is

$$\begin{aligned} x(k+1) = {} & Ax(k) + B(I - R(k))(I - \hat{R}(k))^{-1}u(k) \\ & + \omega(k) \end{aligned} \tag{26}$$

As summarized in Table 4, all of these FTC methods, both passive and active, are based on adaptive control theory.

3.2 Unmanned Helicopters

Firstly, a fault-tolerant control framework for UHs was presented by Drozeski [20]. He proposed a method to improve reliability by integrating reconfigurable flight control, reconfigurable path planning, and mission adaptation. It consists of three layers: the lowest layer generates actuator control inputs and uses adaptive neural networks for FTC; the middle one receives waypoints and generates a vehicle flight path with a reconfigurable path planner; the third one is responsible for mission assignment and has mission adaptation function for occurrence of faults.

Compared with FD methods, less FTC methods are proposed. Garcia et al. [30] presented a controller, with fuzzy logic scheme, capable of waypoint navigation under tail rotor failure. The main effects caused by a tail rotor fault is the rotational rate of the vehicle around the main shaft. In other words, the heading of UHs will be out of control with tail rotor failure. The controllers utilize errors from the desired location and the vehicles velocities along the X, Y, and Z axis in the vehicles frame of reference. A membership functions table can be found in this article.

Qi et al. proposed adaptive control methods [69, 71, 72] for UH actuators FTC with AHCs and state estimation-based feedback linearization. The authors proposed that if all the states are measured accurately, the UH model can be described as:

$$\begin{pmatrix} \dot{P}(t) \\ \dot{V}^P(t) \\ \dot{\aleph}(t) \\ \dot{\Omega}(t) \end{pmatrix} = \begin{pmatrix} R\begin{pmatrix} -T_M(t)\sin a_1(t)/m \\ -(T_M(t)\sin a_1(t) + T_T(t))/m \\ -T_M(t)\cos a_1(t)\sin b_1(t)/m \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \\ R_{TP\to B}F^B_{ext}(t)/m \\ \Im\Omega^B(t) \\ I^{-1}(M^B_{ext}(t) - \Omega^B(t) \times I\Omega^B(t)) \end{pmatrix} \tag{27}$$

Then, the system can be approximately linearized by assuming that $a_1,\ b_1$ are near zero and T_M/T_T is infinite.

$$\begin{pmatrix} \dot{P}(t) \\ \dot{V}^P(t) \\ \dot{\aleph}(t) \\ \dot{\Omega}(t) \end{pmatrix} = \begin{pmatrix} R_{TP\rightarrow B}\begin{pmatrix} 0 \\ 0 \\ -T_M(t)/m \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \\ R_{TP\rightarrow B}F^B_{ext}(t)/m \\ \Im\Omega^B(t) \\ I^{-1}(M^B_{ext}(t) - \Omega^B(t) \times I\Omega^B(t)) \end{pmatrix} \tag{28}$$

where P is the position vector, V is the velocity vector, $\aleph$ is the attitude angle vector, Ω is the angular velocity vector.

Chen et al. [14] proposed a self-repairing control law using quantum control method. In quantum computation, $|0\rangle$ and $|1\rangle$ denote the two basic states of micro-particles. The quantum state $|\varphi\rangle$ can also be a linear combination of the states. At the same time, a one-dimensional fuzzy feedforward compensation is investigated for improving the anti-disturbance performance. The model of the vertical flying platform is as following:

$$M(q)\ddot{q} + C(q,\ \dot{q}) + G(q) = F(u) \tag{29}$$

where $M(q)$ represents the inertia matrix, $C(q, \dot{q})$ is the Coriolis matrix, $G(q)$ denotes the vector of the conservative forces and $F(u)$ is the vector of generalized forces. Simulation results show that the proposed method based on quantum control and fuzzy feedforward compensation can achieve satisfactory self-repairing capabilities.

Chandhrasekaran et al. [13] introduced an integral hardware-in-the-loop simulation system for UH fault tolerance. The system can achieve simple fault injection, fault tree analysis, fault detection and recovery.

Finally, all of these FTC methods are summarized in Table 5 where one can find that more attention are paid to actuators than sensors.

3.3 Two- and Three-DOF UH Experimental Platforms

Some significant FTC methods are presented for UH experimental platforms. Most of these methods can also be illustrated by UHs.

In [64], Oca et al. designed a controller which is able to stabilize the faulty plant using LPV techniques with gain synthesis based on solutions of Linear Matrix Inequalities (LMIs). The control strategy is as following:

$$u_{f,k} = -S\hat{f}_k + K_1(x_k - x_{f,k}) + u_k \tag{30}$$

where $\hat{f}_k$ is the fault estimate which can be achieved by UIO theory. The purpose of first factor $(S\hat{f}_k)$ is to estimate the fault. The second factor is to eliminate the estimation error, with the control law K_1. $x_{f,k}$ converges asymptotically to x_k independently of the presence of the fault f_k. u_k represents the control input without fault.

In addition to the above method, LPV virtual actuator FTC approach is proposed in [60, 65] by the authors. The main idea of this FTC method is to adapt the faulty plant to the nominal controller instead of adapting the controller to the faulty plant. In this way, the faulty plant together with the virtual actuator block allows the controller to tackle the plant as in a fault-free case. In [65], the virtual actuator K_1, as shown in Eq. 30, is obtained by solving the LMI. In [60], a LPV virtual actuator system is defined as following:

$$x_{\Delta,k+1} = A(\vartheta_k)x_{\Delta,k} + B(\vartheta_k)u_{c,k} - B_f(\vartheta_k)u_{fk} \tag{31}$$

$$u_{f,k} = M(\vartheta_k)x_{\Delta,k} + S(\vartheta_k)u_{c,k} \tag{32}$$

where B_f is the input matrix including faults, ϑ_k is the system vector of time-varying parameters, $x_{\Delta,k} \in R^n$ represents the state vector of the virtual actuator and $u_{c,k}$ denotes the control input without fault. If the system is controlled by:

$$u_{c,k} = -K(\vartheta_k)\hat{x}_k \tag{33}$$

Table 5 FTC methods for unmanned helicopters

Locations	Approaches	FTC types	References
Actuators	Fuzzy logic control	Passive	[30]
Actuators	Quantum/fuzzy	Passive	[14]
Actuators	Adaptive control	Active	[69, 71, 72]
Sensors network	Fault tree	Passive	[13]

where $\hat{x}_k = x_{f,k+1} + x_{\Delta,k+1}$. The closed-loop system with virtual actuator is:

$$\begin{pmatrix} \hat{x}_{k+1} \\ x_{\Delta,k+1} \end{pmatrix} = \begin{pmatrix} A - BK & 0 \\ (B_f S - B)K & A - B_f M \end{pmatrix} \times \begin{pmatrix} \hat{x}_k \\ x_{\Delta,k+1} \end{pmatrix} \tag{34}$$

The design of LPV virtual actuator is to select matrix M and K for guaranteeing closed-loop stability of the reconfigured system and original system respectively while matrix S is such that $B_f S = B$

Oca et al. [61–63] proposed an approach to design an Admissible Model Matching (AMM) FTC method for LPV systems. The advantage of this approach is that it allows the controller design to be defined by a set of admissible faults. The main idea of the AMM approach is that, instead of looking for an exact or best matching to a given single behavior, a family of closed-loop behaviors that are acceptable is specified. In other words, the system $x(k+1) = Ax(k) + Bu(k)$ with control law $u(k) = Kx(k)$ can be represented by $x(k+1) = (A_n + B_b K_n)x(k)$. For a given fault $(A_f\ , B_f)$, the target is to find a feedback gain K_f that provides an admissible closed-loop behavior:

$$A_f - B_f K_f \in M \tag{35}$$

where M is a set of closed-loop behaviors that are acceptable and can be achieved by solving constrained optimization problem. In [63], considering a LPV system, the goal of designing a FTC system with AMM method is to find the gain $K(\vartheta_k)$:

$$A(\vartheta_k) - B(\vartheta_k)K(\vartheta_k) = M^{'},\ M^{'} \in M \tag{36}$$

where ϑ_k is defined as $\vartheta(p(k),\ \hat{f}s(k))$ with operating point $p(k)$ and fault estimation $\hat{f}(k)$. Finally, $K(\vartheta_k)$ can be solved by LMI methods. In addition to this, in [61, 62], the authors proposed both active and passive AMM-based FTC system with $H_2/H\infty$ performance.

Afonso et al. [5] investigated a predictive control method for actuator faults. The main target is to find a new setpoint $x^{'}_{\text{ref}}(k)$ at each time k in order to make the problem feasible and to progressively steer the system state towards the original setpoint x_{ref}.

A summary of FTC methods devoted to two- and three-DOF UH experimental platforms can be found in Table 6.

3.4 Discussion

A review of fault-tolerant control methods is given according to different platforms. Compared to FD methods, only few FTC methods for helicopters have been proposed. One of all reasons behind the fact is that redundancy of helicopters is limited compared with fixed-wing aircrafts, since redundancy is the key factor in any FTC systems. Among common methods, unfortunately, various control (re)allocation techniques developed for fixed-wing aircrafts [7, 33, 44] cannot be extended to helicopters. Manned helicopters with large scale can equip redundant sensors and actuators to compensate for this problem. But for small scale UHs, it's impossible to increase the number of sensors or actuators. Therefore, researchers should try to ensure the effectiveness of FTC systems for reducing the effects caused by actuator failures. A good way is to use fault monitor to prevent from failures, because FTC systems are rare to be effective in the case of no redundancy. On the other hand, the research of control strategies for actuator failures in systems without or with less redundancy will be very meaningful but a real challenge.

A summary of FTC methods devoted to three platforms can be found in Table 7. As summarized in Table 7, sensor faults are rarely considered as a major FTC problem. Generally speaking, sensor masking, also called software or virtual sensor, does not require the redesign of the controller

Table 6 FTC methods for two- and three-DOF UH experimental platforms

Locations	Approaches	FTC types	References
Actuators	Virtual actuator	Active	[60, 64, 65]
Actuators	Predictive control	Passive	[5]
Actuators	AMM and H_2/H_∞ control	Both	[61, 63]
Components	AMM	Both	[62]

Table 7 Fault tolerant control methods

Types	Locations	Techniques	Platform	References
Active	Actuators	Swashplate reconfiguration	Helicopter	[21, 25]
		Adaptive control	UH	[69, 71, 72]
		Adaptive H_∞ control	Helicopter	[54]
		Virtual actuator	2DOF UH	[60, 64, 65]
	Actuators sensors	KF	Helicopter	[43]
	Components	Adaptive sliding mode backstepping control	Helicopter	[15]
Passive	Actuators	Adaptive control	Helicopter	[48, 57]
		Predictive control	3DOF UH	[5]
		Fuzzy logic control	UH	[30]
		Quantum/fuzzy	UH	[14]
	Sensors network	Fault tree	UH	[13]
Both	Actuators	AMM and H_2/H_∞ control	2DOF UH	[61, 63]
	Components	AMM	2DOF UH	[62]

[67, 93, 95]. A switching principle is commonly used to switch from a corrupted sensor to reliable estimation of the corrupted sensor issued from FD technique.

At the same time, it is easily found from Tables 4 to 7 that FTC methods have little relation to the platforms. This is quite different from FD methods. One reason may be that FTC technologys are not widely used for manned or unmanned helicopters so that they don't form an independent system like RUL for manned helicopters.

4 Conclusions

A review of existing researches in the areas of Fault Diagnosis (FD) and Fault-tolerant Control (FTC) for helicopters is given, including manned helicopters, unmanned helicopters, two- and three-DOF UH experimental platforms.

Although great quantity of papers about FD or FTC approaches for helicopters have been proposed, there are still many problems. For FD approaches, almost all of them just deal with sensor or actuator faults/failures. In other words, it is rather difficult to diagnose sensor and actuator faults/failures at the same time. Especially, sensor faults and actuator faults can interconvert into each other in some cases. Compared with FD methods, less papers pay attention to FTC methods for helicopters. In this way, the research on FTC for helicopters is new and full of challenge. From the perspective of fault types, most of them are partial loss effectiveness while there are few papers dealing with failures, like actuator stuck.

With the development of unmanned systems, including UHs, their functions and performance are becoming more and more powerful, but their reliability has not achieved the same development. In this case, FD and FTC schemes provide a good way to improve system reliability. Especially for UHs, they almost have no hardware redundancy so that FD and FTC systems are more important for them. FD and FTC approaches will play an important role not only in the future UHs but also in other future manned and unmanned systems.

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