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# Fault Diagnosis and Fault Tolerant Control Methods for Manned and Unmanned Helicopters: A Literature Review

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*Abstract*— **With the development of unmanned helicopters, the dependability of helicopters have attracted more and more attention of many researchers. In order to deal with these problems, fault diagnosis and fault tolerant control methods were used for manned or unmanned helicopter platforms. This paper presents an overview of the existing works on fault diagnosis, including analytical/model-based, signal processing-based and knowledge-based techniques, and passive/active fault tolerant control approaches for helicopters mainly with single rotor. Before the main part of the review, a short description of fault classification is presented. Compared with the former work, this review contains some in-depth discussion of various fault diagnosis techniques and a survey for fault tolerant control methods.**

## I. INTRODUCTION

Due to their features of long hovering in the air such as Vertical Take-Off and Landing (VTOL) capability, low-altitude, low-speed and flexible flight, helicopters have a wide range of military applications but also in the civilian domain. Unmanned Helicopters (UH) has become an attractive research topic in academic communities worldwide [1] and numerous research groups/companies designed their unmanned helicopter platform, such as Yamaha-R50-based Unmanned Aerial Vehicle (UAV) helicopters of Carnegie Mellon University [2], GTMax of Georgia Institute of Technology [3], Lion UAV family of National University of Singapore [4] and ServoHeli family of Shenyang Institute of Automation in Chinese Academy of Sciences [5], [6].

In case of faults (degradation) or failures (out of order) occurrence on sensor, actuator or component, helicopters do not have the same properties as of fixed-wing aircrafts or airships. Especially, an unmanned helicopter system normally has small size, light weight, compact structure and has no sensor and actuator redundancy. A fault or failure in any part of the unmanned helicopter can be catastrophic. If the fault/failure is not detected and accommodated, the helicopter may crash [7]. The structural characteristics, conditions of use and environment make helicopter accident rate far higher than fixed-wing aircraft. In 2012, 160 civil helicopter accidents occurred in the United State of America [8].

To achieve acceptable performance of the system closed to the nominal one when a fault occurs, Fault Tolerant Control (FTC) or Fault Detection, Isolation and Recovery (FDIR) method should be used for control system design. FTC and FDIR techniques are means to increase reliability and safety to the system. In this article, FTC techniques applied and to be applied to rotary-wing, in particular, single-rotor manned and unmanned helicopters are considered. In general, FTC approaches can be classified into two types: passive and active [9]. 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 component failures actively by reconfiguring control actions so that the stability and acceptable performance of the entire system can be maintained. For an overall picture of the FTC approaches, the readers can refer to recent books [10], [11], [12], [13] and [14] and survey papers ([9] and others). To achieve a successful active FTC system, faults diagnosing system is required.

Fault Diagnosis (FD) techniques have been widely used in process industry to detect faults in actuators, sensors or components and generate crucial information to achieve a successful active FTC system design. With FD techniques, the control strategy or mission planning after detection of a fault can be changed. Generally speaking, FD contains three steps: fault detection, fault isolation and fault estimation. Recent books/surveys [15], [16], [17] and [18] are recommended to readers for on overview of FD techniques. 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 fault and its severity.

In recent years, several review/survey papers related to the safety topic on aerial vehicles have appeared in recent years both in FD and FTC frameworks [19], [20], [21], [22] and [23]. Despite of helicopters' highly nonlinear feature,

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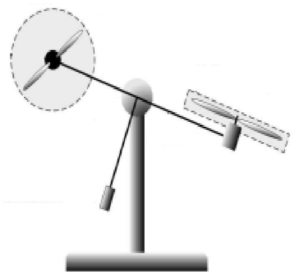
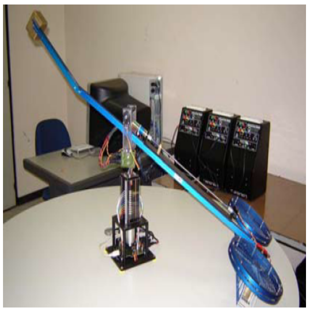
(a) Helicopter [26]

(b) UH [5]



(c) 2DOF UH [27]



(d) 3DOF UH [28]

Fig. 1. Some platforms

difficulty in control and also less hardware redundancy available compared to fixed-wing aircrafts, increasing demands for helicopter safety has attracted more and more attention in the research and development of FD and FTC methods. This paper presents an overview on the existing methods on fault diagnosis and fault tolerant control approaches for helicopters. Compared to a recent contribution [24], this paper mainly focus in details on single rotorcraft helicopters, like helicopters and UHs. At the same time, two Degree-Of-Freedom (DOF) and three DOF UH platforms are also included. All of these platforms are as shown in Fig.1. 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 only on-line and real-time approaches. The experimental plants include manned and unmanned helicopters. Generally, unmanned helicopters have small scale which limits these vehicles to instal redundant actuators or sensors. Compared with unmanned helicopters, manned helicopters have large scale with many redundant actuators and sensors. Due to their different characteristics, FD or FTC methods for these two systems will focus on different parts. Some content presented in this article, fault classification and some basic summaries on FD approaches, have been described in the former work [25]. Compared to [25], this paper contains some deeper discussion of FD approaches and a survey for FTC approaches.

The paper is organized as follows: Section II is dedicated to fault classification. A summary of FD approaches investigated or developed for manned or unmanned helicopters has been presented in Section III. Section IV provides a review of FTC methods. Section V ends the paper by conclusions.

## II. Fault Classification

Faults can be classified according to their locations of occurrence in helicopters as illustrated in Fig. 2.

***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 $\gamma$ ($\gamma \in [0 \cdots 1]$) 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 helicopter, like a weather-vane changes with the wind. On the other hand, Heredia et al. [7] classify actuator faults according to the location of actuators and whether they are yet stuck or not. One servo involved in rolling (or pitching) motion has a failure, but does not get stuck. The servo involved in rolling (or pitching) motion actually gets stuck, so both the collective and the rolling (or pitching) actuators will not work. The collective actuator can no longer work, or it may work with a limited range, due to a failure in the mechanical links.

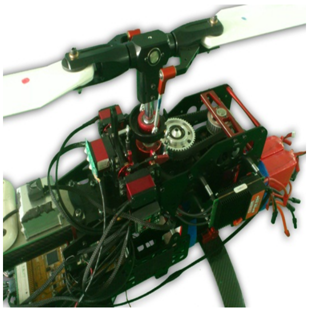
***Sensor faults*** represent incorrect readings from the measurements that the helicopter is equipped with. Sensor faults mainly include total faults, constant bias faults, constant gain faults and outlier faults [29]. Total faults are very serious condition, in which the sensor outputs are not related to the values of measured physical parameters. Constant bias faults are often-occurred faults in analog sensors [30]. The expression of these faults is constant values added after 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 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 [31].

***Component faults*** represent faults in the component of the plant itself. This fault represents changes in the physical parameters of the helicopter, like helicopter tail lost and part of tail rotorcraft lost [32]. The model of component faults cannot be described systematically. They will influence the plant model.

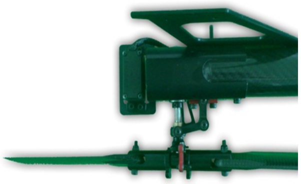
## III. Fault Diagnosis Approaches

Following discussions will be carried out according to the three categories of FD approaches devoted to manned and unmanned helicopters: analytical/model-based approaches, signal processing-based approaches, and knowledge-based approaches.

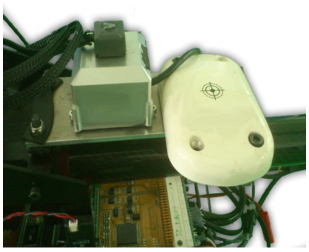
(a) Main and tail rotorcraft



(b) Main rotorcraft and swashplate with 3 servo motors and gear box



(c) Tail



(d) GPS and sensors

Fig. 2. UH from SIA with sensors, actuators and components

### A. Analytical/model-based FD methods

Analytical/model-based FD approaches consider mathematical model to carry out FD in real-time. Because of flight dynamics and aerodynamics, helicopter modeling is very complex and difficult, especially rotor modeling [33]. So far, many research teams are constructing 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 [34]. Generally, there are three types of models: Linear Time-Invariant (LTI) model, Linear Parameter Varying (LPV) model and nonlinear model.

Widely used model-based approaches mainly include various kinds of observers and Kalman Filters (KF) to estimate states or parameters. Zhang et al. [35] assume that $\dot{f}(x) = 0$ after the fault occurrence to simplify the observer design and use it for fault estimation of an unmanned helicopter in the vertical plane. Heredia et al. [36], [37], [7] used an input-output model and Luenberger observer for actuators and sensors fault estimation. It can be seen from the experimental result, a constant sensor output fault or a sensor out-of-order fault are easily detected by the fault detection system with a short time delay. However, a faulty sensor with additive or multiplicative error are detected depending on the fault magnitude. If the ratio between fault magnitude and noise level are too small, they cannot be detected. Arne et al. [38] have designed fault isolation observers for square and non-square linear systems and provide a design that guarantees stability of the observer and minimize the influence of disturbances on the residuals at the same time. Montes de Oca et al. [27] have developed an Unknown Input Observer (UIO) with LPV system for fault identification of a two DOF unmanned helicopter. Liu et al. [39] designed an UIO to track actuator fault parameters and decouple the effect of faults and unknown inputs.

Standard Kalman Filter (KF), Extended Kalman Filter (EKF) and Unscented Kalman Filter (UFK) are intensively considered. The Kalman filter in state-space model is equivalent to an optimal predictor for a linear stochastic system in the input-output model. 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. [40], [41], [42] and [43] proposed states and parameters joint estimation based on square-root UKF and KF-based adaptive UKF with a full nonlinear model of the UH. The KF-based adaptive UKF is composed of two parallel master-slave filters. Compared to UKF, the KF-based adaptive UKF is a much simpler and highly effective estimation method. Alkahe et al. [44] proposed a model-based damage detection algorithm for rotating blades based on a set of KFs. Heredia et al. [45], [29] 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. 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, as all the information is extracted from experimental input-output data.

In a different way, Wu et al. [46] proposed an Adaptive Extended Set-Member Filter (AESMF) method for sensor fault diagnosis. Set-member filter 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. Comparing with KF methods which are based on features of stochastic noise, set-member filter requires noise data being bounded and known 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. Besides observer-based, KF-based and set-member based approach, Litt et al. [47] used Recursive Least Squares (RLS) method to compute the value of the fault parameters and the maximum time it takes to achieve an appropriate identification depends upon how fast the fault parameters converge. A classification of the existing research is given in Table I. This classification includes the types of models, faults and approaches used. As illustrated in Table I, it clearly appears that analytical/model-based FD techniques are devoted to UH. Moreover, as highlighted in Table I, most of observer methods considered for single rotorcraft have been synthesized for LTI model and focused on actuator/sensor faults. However nonlinear models have been assumed for stochastic approach.

TABLE I

ANALYTICAL/MODEL-BASED FD METHODS

| Model | Approaches | Locations | Platform | References |
|---|---|---|---|---|
| LTI | Observer | Actuators | UH | [7], [38], [36], [39] |
| | Observer | Sensors | UH | [36], [37] |
| | OKID | Sensors | UH | [29], [45] |
| | KF | Actuators Sensors | UH | [48], [49] |
| | LS/RLS | Sensors | Helicopter | [47] |
| LPV | Observer | Actuators Components | Helicopter | [35], [44] |
| | | Actuators | 2DOF UH | [27] |
| Nonlinear | UKF | Actuators | UH | [40], [42], [41], [43] |
| | AESMF | Sensors | UH | [46] |

### B. Signal processing-based methods

Signal processing-based approaches can be used for both linear systems and nonlinear systems in principle based directly on signal data and do not require accurate analytical model. 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. Some researchers used wavelet transform technology. Qi and Han [30] proposed a novel wavelet-based approach to detect an abrupt sensor fault in a UH system. Li et al. [50] 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. Waschburger et al. [28] presented an experimental validation of wavelet-based analytical redundancy technique on a 3DOF UH platform. Besides wavelet technique, Kaliappan et al. [51] detected the faults by measuring the rate of change of data with respect to time. Siegel et al. [52], [53] proposed a methodology for predicting helicopter rolling element bearing failure. It includes a series of processing steps in prior, including feature extraction, feature selection, and health assessment. The authors outlined the advantages and disadvantages of different methods in each step. Loughlin et al. [54] used conditional time-frequency moments which have a simple physical interpretation. The mean, median and mode frequencies are obtained at a given time, and the spread about the mean frequency also. This method characterized the faults well and can differentiate between different fault classes. Schwartz et al. [55] designed quadratic detectors based on the estimated signal statistics and not on some predetermined features so that it may find features in the data that might normally be overlooked. With the quadratic detector the significant detection features can be selected automatically and the final detection results were nearly perfect. In the time-frequency analysis, some methods have been proposed for particular faults such as Randall [56], Williams et al. [57], Girondin et al. [58], Hood et al. [59], Ehinger et al. [60] and also Hassan et al. [61].

Most of articles about signal processing-based methods aim to helicopter transmission system, like gears and bearings, based on analyzing vibration signals. Vibration monitoring is widely used to observe the condition of a process or equipment. Normally, it is hardly able to collect vibration signal of the source directly due to the design and construction of the machinery. Therefore, vibration sensors which are typically acceleration sensors have to collect vibration signal indirectly. That means the transmission of the vibration signal from the source to the sensor is complex and easy to be disturbed. Therefore, the task of signal processing-based 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 to extract signal features have been widely used like frequency spectral analysis and statistic analysis. According to these features, specific fault or failure can be detected. Further, with adding classifier, various types of faults/failures can be isolated. As summarized in Table II, compared to analytical/model-based approaches, many signal processing-based methods are devoted to helicopter where human is included in the closed-loop and received information from FD in order to accommodate fault by a human pilot.

TABLE II

SIGNAL PROCESSING-BASED FD METHODS

| Approaches | Locations | Platform | References |
|---|---|---|---|
| Wavelet Transform | Attitude | 3DOF UH | [28] |
| | Sensors | UH | [30] |
| | Transmission system | Helicopter | [50] |
| Time Domain Analysis | Rotor | UH | [51] |
| | Bearing | Helicopter | [52], [53] |
| | Gears | Helicopter | [62] |
| Frequency Domain Analysis | Gears | Helicopter | [55], [56], [60] |
| | Bearing | Helicopter | [58] |
| Time-Frequency Domain Analysis | Gears | Helicopter | [54], [59], [63] |
| | Transmission system | Helicopter | [57] |
| Bicoherence Analysis | Rotor | Helicopter | [61] |

### C. Knowledge-based methods

A wide range of information in relationship with diagnosis objectives is required by knowledge-based FD approaches. In particular, these approaches can make full use of knowledge of experts in the field and can avoid a reliance on accurate mathematical model. Among these approaches, expert system [64], [65], rule extracting based on Maximum Characteristic Granule (MCG) [66], rule extraction based on granular computing [67], genetic algorithms [68] and multi-sensor mixtures Hidden Markov Models (HMM) [69] are considered to diagnose faults on specific subsystems of helicopter.

However, as a kind of knowledge-based FD approaches, Neural Network (NN) is widely used. For instance, Ganguli et al. [70], [71], and also Morel et al. [72] proposed a rotor system fault detection method using physics-based model and 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. Qi et al. [73] presented an adaptive threshold NN scheme for UH sensor failure diagnosis. The adaptive threshold approach eliminates the need for thresholds changing with flight condition varying. As illustrated in Table III, UH are rarely considered with knowledge-based FD approaches.

TABLE III
KNOWLEDGE-BASED FD METHODS

| Approaches | Locations | Platform | References |
|---|---|---|---|
| NN | Rotor | Helicopter | [71], [70], [72] |
| | Sensors | UH | [73] |
| Expert System | Whole | Helicopter | [65], [64], [74] |
| Granular Computing | Transmission system | Helicopter | [67] |
| HMM | Gearbox | Helicopter | [69] |
| MCG | Transmission system | Helicopter | [66] |
| Genetic Algorithms | Gearbox | Helicopter | [68] |

### *D. Discussion*

Generally speaking, FD contains three steps: fault detection, fault isolation and fault estimation. For analytical/model-based and knowledge-based FD approaches, most of them include all of the three steps. Compared with this, most of the signal processing-based approaches just include one or two. The main reason of this phenomena is the different characteristics of these approaches. Model-based and knowledge-based FD approaches include more system information which is the base of fault isolation and estimation. For example, in ideal condition, analytical model includes system information so that it is possible to achieve system state directly and correctly. A difference between real data and ideal data in real time can be evaluated to detect, isolate and estimate faults.

Two classes of helicopters should be considered for literature review: manned and unmanned helicopters. Most analytical/ model-based FD approaches are used for UH platforms and the other two FD approaches mainly focus on manned helicopter platform. Manned helicopters have large scale and are non-cost-sensitive so that they can be installed more sensors and actuators. Some manned helicopters have multi-redundant system 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 very improbable to achieve redundancy of helicopter transmission system so that the ability to predict the remaining useful life (RUL) of helicopter transmission system is a real challenge. Faults of transmission system can be described easily by vibration data with fault-free frequency signatures rather than to get an reliable analytical transmission system model, consequently, signal processing-based approaches are a better choice. More than half articles about knowledge-based FD approaches collected in this paper also use vibration data as their analytical basis. Compared with manned helicopter, in most cases, UHs have small scale and they are cost-sensitive so that they almost have no redundant sensors and actuators. In this case, analytical/model-based FD approaches can provide whole information of faults which is the basis of FTC schemes.

## IV. FAULT TOLERANT CONTROL APPROACHES

FTC theory has drawn a lot of attention in wide ranges. The task of FTC system is to ensure the stability and maintain acceptable performance of controlled system when fault/failure occurs, which generally leads to critical changes in the system parameters, or even to the changes in the dynamics of the system [75]. Because any system may occur fault/failure inevitably, FTC system can be treated as the final line of defense to protect system safety. UHs are not easy to control with the multivariable nonlinear coupling and flexible structure dynamics. Taking into account the wind disturbance, engine vibration and other disturbance during the flight, its mechanical parts and control systems are prone to fault/failure.

Comparing with fixed-wing UAV, UHs have stronger coupling and less hardware redundancy. UHs have an upper control system that mechanically relates the helicopters blade angles to the three main rotor actuators, via an intermediary swashplate [76]. When any of the three actuators failure occurs, because of the coupling of control axes, the flight control system can achieve UH's attitude stability through swashplate reconfiguration and adjust UH's altitude through rotor speed reconfigurable flight control. The details can be found in [76] and the authors in [77] also give details with a practical flight experiment.

Besides swashplate reconfiguration, there are some common FTC schemes used for UH. Drozeski [78] 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. Montes de Oca et al. [79], [80], [81] proposed an approach to design an Admissible Model Matching (AMM) FTC for LPV systems. The advantage of this approach is that it allows the controller design to be defined by a set of admissible faults. In [27], authors designed a controller able to stabilize the faulty plant using LPV techniques with gain synthesis based on solutions of linear matrix inequalities (LMIs). LPV virtual actuator FTC approach is also proposed in [82], [83]. Virtual actuator is based on the main advantage of fault compensation principle under stability condition issue from gain redesign concepts. In this way, the faulty plant associated with the virtual actuator block allows the controller to tackle the plant as in a fault-free case. Qi et al. [84], [43] proposed adaptive control and feedback linearization [41] for UH actuators FTC with Actuator Healthy Coefficients (AHCs) and UKF or adaptive UKF-based FD approaches. Liu [39] proposed an adaptive fault tolerant $H_\infty$ output feedback controller with an observer for actuator faults. Based on a bank of pre-defined sensor and actuator fault signatures, Rago et al. [48] proposed a specific Kalman filter able to simultaneously detect, isolate and accommodate fault according to the selection of pre-defined gains associated to appropriate pre-defined sensor and actuator fault signatures. Other methods include fault tree analysis [85], adaptive control [86], [87], predictive control [88], adaptive sliding mode backstepping technology [89], fuzzy logic [32], fuzzy feedforward and quantum control [90].

A summary of FTC methods devoted to manned and unmanned helicopters can be found in Table IV. As highlighted in Table IV, 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 [91], [92], [93]. A switching principle is commonly used to switch from corrupted sensor to reliable estimation of the corrupted sensor issued from FD technique. Redundancy is the key factor in any FTC system. Compared with fixed-wing aircrafts, helicopters' hardware redundancy is very limited. Among common methods, various control (re)allocation techniques developed for fixed-wing aircrafts [94], [95], [96] cannot be unfortunately extended to helicopters. 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, people should try to ensure the effectiveness of FTC systems to reduce the effects caused by actuator failures. A best way is to use fault monitor to prevent from failure, because FTC systems can almost do nothing in the case of no redundancy. On the other hand, the research of control strategies for actuator failure in systems without redundancy will be very meaningful and a real challenge. Consequently, as presented in Table IV, actuator/component FTC methods have been paid more attention by researchers mainly on unmanned helicopters.

TABLE IV
FAULT TOLERANT CONTROL METHODS

| Types | Locations | Techniques | Platform | References |
|---|---|---|---|---|
| Active | Actuators | Swashplate Reconfiguration | Helicopter | [76], [77] |
| | | Adaptive Control | UH | [43], [84], [41] |
| | | Adaptive $H_\infty$ Control | Helicopter | [39] |
| | | Virtual Actuator | 2DOF UH | [82], [83], [27] |
| | Actuators Sensors | KF | UH | [48] , [49] |
| | Components | Adaptive Sliding Mode Backstepping Control | Helicopter | [89] |
| Passive | Actuators | Adaptive Control | Helicopter | [86], [87] |
| | | Predictive Control | 3DOF UH | [88] |
| | | Fuzzy Logic Control | UH | [32] |
| | | Quantum Control | UH | [90] |
| | Sensors Network | Fault Tree | UH | [85] |
| Both | Actuators | AMM and $H_2/H_\infty$ Control | 2DOF UH | [80], [81] |
| | Components | AMM | 2DOF UH | [79] |

## V. CONCLUSIONS

A review of existing researches in the area of Fault Diagnosis (FD) and FTC (Fault Tolerant Control) for helicopters is given, including both unmanned and manned. With the development of science and technology, researches on FD and FTC methods for helicopters have made a number of encouraging progresses. However there are still many problems, like different faults decoupling, simultaneous diagnosis of multiple faults and comprehensive diagnosis. With the development of unmanned systems, including Unmanned Helicopters (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 an appropriate 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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