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Research on Fault Detection and Diagnosis for Small Unmanned Aerial Vehicle

Abstract: As the core of aircraft, the state of the flight control system can impact the survivability and mission effectiveness of the aircraft obviously. The fault diagnosis of the flight control system when it breaks down can provide some essential information for subsequent reconfigurable control, which can guarantee the system stability. At present the sensor and actuator faults are mostly studied and the damaged body of the small unmanned aerial vehicle (SUAV) considers very few. Some important methods and focus problems for fault diagnosis are firstly analysed and summarized. Then the research status of the air dynamics and fault detection and diagnosis (FDD) is introduced in the paper. Methods of the pneumatic parameters and properties on the SUAV and the key technologies of FDD are also analysed. At last the experiment of the SUAV is created by using the FDD subsystems. A specific plan and research methods are provided through the paper. Meanwhile, it provides the theory and research foundation for reconstruction control system.

Keywords: SUAV; flight control system; FDD; fault and damage; reconfigurable control

1 Introduction

The SUAV (internationally called portable UAV), which is shown as Fig1, has a simple structure, lightweight, high efficiency, flight speed and distance and cost advantages. So it is commonly used in the military and civil fields. The SUAV is the intricate system among multidisciplinary which is related to mathematics, mechanics, materials, energy, machinery, electronics, control, communication, navigation and computer, and so on. It exists in the obvious nonlinear and uncertainty during the working. Thus if any component failure of the SUAV is not found and removed in time, the huge economic loss even catastrophic consequences will be caused. For example, on October 14, 2011, china international general aviation conference was held in pushing, Shanxi Province. While the aerobatic flight was shown, the plane crashed and one pilot was injured and one was killed in the following explosion.
The seven astronauts were killed in the Challenger space shuttle disaster in 1986. So it is the important thing that how to improve the reliability and safety of SUAV system and prevent and stop the occurrence and development [1, 2]. Therefore, the fault detection and diagnosis (FDD), as one of the most

![Structure diagram of fixing-wing SUAV](Image)

Fig. 1: Structure diagram of fixing-wing SUAV

Important content about self-repairing technology is important to determine whether the failure occurs timely and accurately, position the location and type of failure, and determine the size and timing of failure [3–7]. Research on fault diagnosis is important to improve the safety and reliability of aircraft, survivability and combat effectiveness. And it has become one of the most popular research topics in comprehensive design of modern aircrafts. In this paper, based on a large number of literature references, fault diagnosis methods of flight control system are discussed comprehensively. And then the key technologies of the aerodynamic performance and FDD are put forward.

## 2 Problem Statement and Preliminaries

FDD has been widely researched because of its importance. To date, many fault diagnosis techniques have been suggested to deal with this problem by the researcher. And these methods can be divided into two categories according to the relationship with the model: one is based on the model and other has no direct links with the detailed model.
2.1 FDD Method Based on the Model

The method is based on the modern control theory and optimization methods. First of all, the hardware redundancy is replaced by analytical redundancy based on the mathematical model of the system. Then, the residual signal can be got by comparing the actual output values and estimate values, which is calculated by the constructed observer. Next, analysis results are evaluated based on the criterions or thresholds. According to the different generating forms of residual signals, these methods can be divided into state estimation, parameter estimation method and the equivalent spatial method.

2.1.1 State Estimation Diagnosis Method

State estimation method is firstly presented by Beard [8]. Numerous researches have been made under the theoretical foundation of Beard. And these studies are classified into branches: filtering method and observer methods. The kernel of this algorithm is that: (1) design the feedback gain matrix of observer in order to display the influences of one fault or faults in the residual signal in defined direction; (2) estimate the state based on the variations of residual signal, if there are faults in the system, the changes of residual signal will be stronger; vice versa, the changes of residual signal will be small under normal conditions.

It is obvious that the method based on state estimation has fine performances in practical application if we can get the accurate mathematical model of the system. Furthermore, the requirements of the input signal are not very strict and it is not necessary to keep the uninterrupted trigger signal all the time. However, with the development and non-linear characteristics of control systems, it is hard to build an accurate mathematical model. In addition, this method cannot be found the damage position and detect the damage degree clearly. These shortcomings limit the applications of state estimation methods.

2.1.2 Parameter Estimation Diagnosis Method

The basic principle of parameter estimation is to detect and analyse the faults based on the model parameters and its corresponding changes. It is not necessary to calculate the residual series. Generally speaking, aiming at reliable diagnostic results. This method is utilized cooperating with other state estimate method in the non-linear system. Currently, this method contains Kalman filter methods, a robust tracking filter, hybrid methods using parameter estimation and state estimation.

Comparing with the state estimation method, parameter estimation method is relatively worse in real time and the input signal on the system requirements more
The uninterrupted trigger signal is crucial, which limits the practical application of the parameter estimation method. However, it can locate the damage position and detect the damage degree of sensors, actuators and controlled objects.

2.1.3 Equivalent Spatial Method

The essence of equivalent spatial method is the equivalent mathematical relationship between inputs and outputs of an analytical model. The purpose of fault detection and isolation can be completed by evaluating the inputs and outputs of system [9]. The primary means of equivalent spatial method is to set up “an equivalent vector and system” by excluding the input and the realization of the equivalent disturbance decoupling. And the special structures residuals are built through a weighting matrix.

Equivalent spatial method is a non-threshold approach and needs more redundant signal. The computation load will be increased significantly if the numbers of measurements are big. Therefore, this method is particularly suitable for measurements in a more redundant signals or low dimension system.

2.2 The Method Does Not Rely on the Model

The foundation of the techniques based on the model is in a position to build up the mathematical model. However, the system is becoming more and more complex with the automation of the system. It is not possible to get the accurate mathematical model. Therefore, diagnostic methods, which break the limitations of the system model, have got many attentions. Generally speaking, these methods are divided into two aspects: the method based signal processing and the methods based on experience knowledge.

2.2.1 Methods Based On Signal Processing

This method is to analyse the frequency, amplitude, phase, and various features of output of the system based on the signal processing technique. These methods not only contains the conventional method, such as time domain analysis, FFT transform and spectrum analysis (Spectrum analysis) methods, but also includes wavelet transform (Wavelet transform), correlation analysis method, the signal modal estimation, information fusion, etc. [10–14]. Among them, the FDD based on wavelet transform is a new signal processing technique.
From above analysis, the advantages of based on signal processing method are not needed accurate mathematical model and have good performance on real time. Disadvantages of based on signal processing methods are summarized as follows:

- Depends on the results of signal processing
- Affected by signal noise
- Lack of fault information in the beginning
- Confined to specific signals and certain failures
- Difficult to expand or applied to different object

### 2.2.2 Methods Using Experience Knowledge

Currently, this area is a hot topic because of it does not need a quantitative mathematical model but take full advantage of expert diagnostic knowledge and diagnostic objects. All the methods in this area are divided into symptom–based approach and a qualitative model–based approach. The symptom–based approaches contain an expert system, fuzzy reasoning, neural networks, support vector machine, rough sets grounds occupied by the enemy, DS evidence theory, the gray system theory, etc. the methods based on qualitative model mainly include qualitative observer, knowledge observer, qualitative simulation, directed graph, fault trees. A few of typical methods are introduced in following context.

#### 2.2.2.1 Methods Based on Artificial Neural Network

The artificial neural network has significant advantages over other methods of non–linear system because of its abilities in self–learning, high fault tolerance and parallel computing power. There are two kinds of working forms: one is off–line diagnosis. It is a learning process and uses separately. When the system fails, faulty information or phenomenon will be imputed to the neural network and the reasonable solution will be outputted after the self–organization, self–learning processes of neural network it. Fresh is on line diagnosis. The neural network is directly connected with the system, and fault information will be got automatically. That is to say. The processing of study and use is combined.

Neural network has the capability to simulate the continuous nonlinear function and to learn from the samples. Any knowledge of the rules can be stored in the form of a neural network through the example. It has good robustness and represents a new methodology to store the information in the distribution level. As for the specified problems, in order to achieve fault detection and diagnosis, faults reasons and resources can be deduced by the neural network and input signal [15–19].
2.2.2.2 Methods Based on Fuzzy Theory

Aiming at the uncertainty, un-accuracy and process noise of the process itself, and the fuzzy logic is proposed in fault diagnosis. It has noble superiorities in time-delay, time-varying and non-linear. The principles of fuzzy consist with the inherent human thought process. It is facilitated to deal with the qualitative knowledge. The concept of membership function is introduced in the processes of transforming the certain judge to define judge. For the application of fuzzy theory in fault diagnosis, there are three basic diagnostic thoughts [20–27]:

–Based on fuzzy relations and the synthesis algorithm
–Based on fuzzy knowledge processing technology
–Based on fuzzy clustering algorithm

2.2.2.3 Intelligent Diagnosis Based on Expert System

Fault diagnosis expert system is one of the most important studies in compelling diagnosis. One of the most widely used class of intelligent diagnosis system, mainly for those who are not difficult to build accurate mathematical models or mathematical models of complex systems. It uses the practice of experts in long-term experience accumulated knowledge base, and to design a computer program to simulate a human expert reasoning and decision-making process fault diagnosis. The system is constructed by the knowledge base, inference machine, integrated database, man-machine interface and explain the module parts. Knowledge base and the inference engine is the core of expert system [9].

Expert system–based fault diagnosis method to the use of expert knowledge and experience, without a mathematical model of the system and the diagnosis is easy to understand. It has been widely used. However, these methods have their shortcomings. First, knowledge acquisition is more difficult that is the main bottleneck. Secondly, the accuracy of diagnosis depends on the knowledge base of expertise and knowledge rich or low. Finally, when the rule is large, there is a match in the conflict in the reasoning process. Issues such as combinatorial explosion make the inference become slow and inefficient.

3 Aerodynamics for SUAV

3.1 Low Reynolds Numbers and Low Aspect Ratios

Low Reynolds is the important trait for SUAV, which has a great effect on the lift force character, drag force character and lift drag ratio character. For the miniature dimensions, the aspect ratio is expected to be very small. This result in the lift coefficient decrease, drag coefficient increase and easy air separation that make the
pneumatic and motor performance degrades [28–30]. This is explored at home and abroad but mostly by experiments. For instance, aerodynamics of a series of flat, curving and rectangular thin wings and string Reynolds number from 60000 to 200000 are studied through the experiments in [31]. The aerodynamic forces and flow field is researched by experiments on low aspect ratios wings with different shapes and 70000 ~ 200000 series of Reynolds in [32] and in [33] the lift–to–drag ratio character in the different sharps wings is done the experimental research and so on. Their research findings are used in the design of SUAV structure.

3.2 Research Methods for Pneumatic Performance

In SUAV aerodynamics model, the commonly used method is to set up a mathematical model, the CFD, wind tunnel test and aerodynamics identification based on flight test data, etc.[28–30,34,35].

Aerodynamic mathematical model is the analytical relation among the SUAV air power (lift, resistance, lateral force; pitch, yaw, roll pneumatic torque), flight motion state parameters (speed, angular velocity and Angle of attack, lateral spreads Angle, flight height, etc.) and control input (the elevator, aileron, rudder; various control the rudder deflection Angle, etc.). An accurate and reasonable boundary layer model is not obtained to SUAV with CFD method for low Reynolds number effect. So the existing software also can't solve its aerodynamic performance problems. Because of the small size, the wind tunnel tests are done and other institutions are used, which has all kinds of inevitable errors and affect the accuracy of the test data. Therefore it is just an effective and feasible method that kinematic equation is firstly built and then pneumatic parameter identification is done by flying experiments. Such as, aerodynamic characteristics with the low Reynolds number and low aspect ratios wings are studied through the numerical analysis, and the influence on the different aspect ratios and bending wings to aerodynamic characteristics is shown in [36]. In [37], dynamic equation are established for unmanned spacecraft, aerodynamic performance under low Reynolds number is researched by the orthographic hybrid mesh method and then lift coefficient , the resistance coefficient, lift–to–drag ratio in the different Reynolds number corresponding to different angle of attack is obtained. In [38], unsteady N–S equations are solved through the simple method. The flow field characteristics of the wings with a low Reynolds number and low aspect ratios are researched and the aerodynamic characteristics influence of laminar separation bubble of the front wing tips and the vortex is analysed. Aircraft system identification parameter model collection is built, and then multiple input multiple output system identification method was used to identify the unknown parameters, which shows that the algorithm has good stability and precision according to the simulation calculation and test flight results in [39].
Now the research on the dynamic characteristics of the SUAV with broken-wing is less done at home. In this paper, the dynamic equation is established; the dynamical parameters and performance are analysed on the normal condition. While the wing of SUAV is broken or lost. The change of the parameters has an effect on the SUAV system. So the method is used to for the dynamic model and the flight test combination, in order to study the aerodynamic characteristics with the aid of the nonlinear system parameter identification.

4 Key Technologies

Based on the present research situation and development of the discipline, the research contents and key technologies are put forward with damaged-wing SUAV, as shown in Fig.2, FDD for broken-wing SUAV.

![Image of Schematic diagram of FDD for broken-wing SUAV](image_url)

**Fig. 2:** Schematic diagram of FDD for broken-wing SUAV
Mainly include two parts. One part is called as the fault mechanism research. The research content is mainly that the motion equation is built for broke–wing SUAV, and then a new nonlinear system identification algorithm are explored. The aerodynamic characteristics are analysed in combination with SUAV flight test data analysis and pneumatic conditions to ensure the routine flight for broken–wing SUAV. The fault mechanism is studied and the motion state for broken–wing SUAV is simulated by using 3D software and virtual reality technology; the other part is FDD subsystem. The fault sensitive parameters are found through the movement equation or increase specified a device to obtain the diagnosis information and even gain the fault trait signal. By the abnormal state of the fault trait, a novel nonlinear fault pattern recognition and identification method is raised to establish a set of FDD subsystem, which can provide the conditions for the follow–up reconfigurable control system. The subsystem with strong robustness cannot be affected by noise. Interference, modelling error influence and also with the strong adaptive ability can improve itself to produce information such as external input change and structural changes. This is the key point for research.

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