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Study on Fault Prognostics and Health Management for UAV

Jihui PAN, Wenqing QU, Hao XUE, Lei ZHANG and Liang WU
ASN UAV Test Jingbian Co., Ltd., China

Abstract. With the improvement of automation and intelligence degree of unmanned aerial vehicle, its application scenarios and service scope continue to expand. The UAV system is complex and the task environment is changeable, which poses new challenges to its safety and reliability. Fault prediction and Health management (PHM) technology can effectively reduce the risk of mission interruption caused by faults, and improve the quality of UAV mission throughout its life cycle. Firstly, the framework of UAV PHM technology is proposed based on the basic concepts of UAV and PHM technology, and then the research status of UAV fault diagnosis and fault prediction technology is analyzed and summarized. Finally, the challenges of UAV fault diagnosis and prediction technology are discussed. In addition, the development trend of UAV PHM technology is summarized from four aspects: failure mechanism basis, condition monitoring technology, fault model construction and intelligent technology application, aiming to provide certain reference for the research and development of the new generation of UAV PHM technology.

Keywords. UAV, PHM technology, fault diagnosis, failure prediction

1. Introduction

UAVs, short for unmanned aircraft, are unmanned aircraft operated by radio remote control devices and preprogrammed controls. Because of their unique advantages over manned aircraft, drones tend to be better suited for "dull or dangerous" missions. At present, UAVs are mainly used in the military field to carry out corresponding combat missions and training. However, with the continuous development, UAVs are also gradually entering the civil fields such as aerial photography, observation and inspection [1].

UAV is a complex system which integrates aviation technology, computer control technology, sensing technology and electronic technology. With the development of UAV technology, the function of UAV is becoming more and more powerful, and its service mission is further extended. UAV mission diversity and service environment uncertainty pose new challenges to UAV mission success rate. To ensure that UAVs can successfully perform operations, training, transportation, mapping or other missions, and reduce the threat of mission disruption and substantial property damage caused by system component failures during UAVs service, the safety and reliability of UAVs need to be continuously improved. Traditional passive maintenance support methods, such as event-based post-maintenance and time-based periodic maintenance, are easy to cause unnecessary downtime, and there are maintenance damage risks, which can no longer meet the current demand for reliability and economy of UAVs.

The prognostics and health management technology are a state-based and prognostic maintenance method, which not only provides prognostics for system failure, but also provides prognostics for system health. Use of PHM technology for unmanned aerial vehicle key system and the important component to conduct a comprehensive monitoring, fault diagnosis and fault prediction, analysis of health status judgement and management, to enhance unmanned aerial vehicle the reliability of key components and the whole vehicle system, effective guarantee further UAV mission success rate, and reduce the operation of the whole life cycle maintenance cost. Therefore, the research on UAV PHM technology is of great significance for the development of UAV undertakings in China.

From unmanned aerial vehicle and the concepts of PHM technology, this paper elaborates the system framework of PHM technology for unmanned aerial vehicle, unmanned aerial vehicle both home and abroad are the key system of fault diagnosis and fault prediction technology research status, analysis and induction, further summarizes and discusses the unmanned aerial vehicle fault diagnosis and prediction technology research challenges and future development trend of existing, Try to provide reference for domestic UAV PHM technology research.

2. UAV PHM technology

2.1. Overview of PHM technology

In 2019, 392,000 drones were registered and 67,218 valid driver licenses were issued. In 2020, a total of 523,600 UAVs were registered, with 88,994 valid driver licenses. In 2021, 832,000 drones were registered and 120,800 valid driver licenses were issued. The development potential of civil UAVs is full, and the types of civil UAVs are changing from consumer to complex industrial. In the process of performing tasks, unmanned aerial vehicle each functional components in the critical systems or sensors in the event of failure, the light can affect the task quality, directly will cause unmanned aerial vehicle tasks fail, and may result in unmanned aerial vehicle equipment loss, even delay strategy and tactics for military drones layout, and might become serious consequences.

Because UAVs are detached from the ground and have various tasks, their mission environments are often characterized by strong vibration, multiple disturbances and alternating high and low temperatures, which increases the possibility of multiple failures such as progressive, abrupt and uncertain failures of key systems or functional components of UAVs. At the same time, limited by practical factors such as size, airborne capability and equipment power consumption, although the hardware redundancy technology of UAVs is adopted, it is difficult to reach the redundancy level of manned aircraft, and the failure of key systems or functional components of UAVs will have a more serious impact on the service performance and safety of UAVs. In addition, UAV has the characteristics of unmanned driving and data transmission delay. Due to the lack of pilot's state perception, quick judgment, flexible decision-making and real-time regulation of the aircraft, it is difficult to deal with unexpected situations and different faults. Therefore, while UAVs have good service performance, they must also have good health management ability to cooperate with them, so as to reduce accidents caused by faults and ensure the continuity of the mission, so as to give full play to the practical value of UAVs in the whole life cycle.

PHM technology arises at the historic moment under the demand of information warfare for the combat effectiveness and precision support of weapons and equipment. The technology uses advanced sensors and various inference models and intelligent algorithms to realize the monitoring, prediction and management of devices. PHM technology can be divided into three levels: fault diagnosis, fault prediction and health management, which can be further subdivided into: real-time status monitoring, fault detection and isolation, remaining service life and fault prediction, maintenance and task assistance decision-making and resource management and other specific functions. PHM technology can timely monitor, diagnose and predict the occurrence of failure effectively, combining with all kinds of information resources to provide a series of safeguard measures so as to realize the situation and system maintenance, can avoid the accident and reduce the loss on the basis of manpower, financial resources, to get the most out of equipment efficiency, the high cost and maintenance cost of complex equipment has important engineering significance.

2.2. UAV PHM system architecture

The UAV PHM system is mainly composed of airborne sensor system, ground PHM processing system and maintenance support system. Airborne systems are wired or wirelessly transmitted to the ground processing system, which transmits the results to maintenance departments after processing. The maintenance unit determines the specific maintenance plan based on the results of the PHM system and the abnormal conditions observed by operators and maintenance personnel. Prepare required spare parts and materials according to the plan, select qualified maintenance personnel for maintenance, and update the technical data after maintenance. The main subsystems of PHM system are described below [2]. UAV PHM system architecture in Table 1.

Table 1. UAV PHM system architecture

Subsystem	Functions
Sensor installation	The sensors are distributed on each subsystem of UAV
Signal acquisition and processing Signal data acquisition	Digital to analog conversion, denoising, filtering, compression and other effective processing
Status monitoring status	Compare these data with the expected data value in the database, and provide fault alarm according to the predetermined parameter limit value
Fault prediction and diagnosis	Using the data of the previous system, historical statistical data and various parameters of the UAV system, based on algorithms, experience, modeling, trends and other methods and means to predict the failure situation, remaining life and future system health and stability trend of the UAV system
Health assessment	The health status of each subsystem and component is determined by the factory parameters, historical maintenance data and working status of the UAV system, using various comprehensive evaluation methods such as machine learning and deep learning
Decision making and maintenance	Use the information provided by each part of the PHM system to make maintenance decisions quickly and effectively and make maintenance plans

- Sensors are installed on each subsystem of the UAV in a distributed manner to build a whole-system sensor network, monitor real-time data of the operation status of the UAV system, master and evaluate the health of the UAV, and make UAV maintenance decisions based on the situation [3]. At present, sensors mainly transmit the acquired data to other parts of the PHM system through wired and wireless means.

- The collection of signal data is the premise and basis of the operation of PHM system, and the collected data needs to be processed effectively. There are many types and large quantities of UAV operation status data, which need to be sorted out and processed into computer-readable format through digital-to-analog conversion, denoising, filtering, compression and other methods [4]. Through to determine the status of unmanned aerial vehicle to extract fault features, due to malfunction and parameters that is not one to one correspondence, therefore need a variety of algorithms, such as: change fast Fourier (FFT), discrete wavelet transform (DWT), average filtering method, etc., to infer unmanned aerial vehicle fault condition, so as to achieve maximum PHM system fault diagnosis ability and precision.

- The condition monitoring system mainly receives the data from the data processing, and then compares these data with the expected data values in the database, so as to judge the state of the UAV system and provide fault alarm capability according to the predetermined parameter limit.

- Fault prediction and diagnosis of fault prediction and diagnosis is the main function of PHM system, the data of the front part mainly is to use the system and historical statistical data and the UAV system parameters, based on the algorithm, experience, methods such as modeling, trend method can be used to predict the failure condition of the UAV system, the residual life and future trend of the system of the healthy and stable, Provide effective information for subsequent decision making and maintenance.

- Health assessment in the part of receiving data from the other parts in the system, factory by unmanned aerial vehicle system parameters, history data and the maintenance work state, use all kinds of machine learning and deep learning comprehensive evaluation method to determine each subsystem and components such as health, the health data records, and determine whether there is the possibility of failure, It can provide information support for maintenance decision whether the UAV system can continue to perform the mission.

- Decision making and maintenance the part mainly USES PHM system information, the parts in unmanned aerial vehicle in the operation of the system can quickly and efficiently to make maintenance decision, make the maintenance plan, can quickly repair after the plane landed, ensure unmanned aerial vehicle can continue to flight mission, can improve the UAV system of continuous operational capability in wartime. The interface display is mainly to display the data of condition monitoring, fault diagnosis and health evaluation. The information is transmitted to the manufacturer, maintenance base and equipment unit through the network service system, so as to understand the status of the UAV system and facilitate the maintenance.

3. Present and future of UAV PHM technology in China

3.1. Major progress achieved

At present, stage research achievements have been made in UAV fault detection, fault diagnosis and fault prediction, as well as UAV PHM system framework design, and different degrees of engineering applications have been obtained. The main progress is summarized as follows :1) Domestic UAV PHM technology research is relatively comprehensive, involving sensors, actuators, data links, airborne equipment and other aspects, laying a solid foundation for further in-depth research. 2) Based on the foreign research results and domestic early research basis, it has a late-development advantage to carry out the research on UAV PHM technology in China. With the in-depth research of PHM technology in many fields and the continuous investment in China's aviation field, China's UAV PHM technology continues to improve, and the gap between China and foreign countries becomes smaller and smaller. 3) A variety of artificial intelligence methods have been gradually mature in the frontier research fields such as image recognition, speech processing and image enhancement. At present, the application research of UAV PHM technology based on artificial intelligence method has been in the preliminary development stage, which indicates that artificial intelligence method will bring infinite potential for the development of UAV PHM technology in China.

3.2. Challenges

China's UAV PHM technology has achieved fruitful theoretical and application results, but it still faces many problems and challenges. 1) UAV condition monitoring technology is not perfect. Due to multiple limitations such as UAV size, on-board capability and sensor technology, a large number of UAVs currently only integrate multiple feedback sensors for control purposes, without embedding sensors sensitive to fault or performance degradation characteristics. Therefore, the existing UAVs have not realized the comprehensive dynamic monitoring of UAVs, and the acquired dynamic information of UAVs service is incomplete, which cannot realize the full coverage of UAVs fault diagnosis. The absence of monitoring data also limits the advantages of AI methods in UAV fault diagnosis and prediction techniques. 2) The technical foundation of UAV PHM is relatively weak. Although UAV is widely used and the development momentum is strong at present, the UAV industry, especially industrial-grade UAV, is still in the initial stage of rapid development, and the failure form, failure mechanism and degradation process theory of key system and functional components of UAV are not deep enough. At the same time, as UAVs are mostly used in military strategic deployment, there are few literatures describing UAVs PHM technology in detail, and there is a lack of advanced experience for reference, so it is necessary to move forward in exploration. 3) It is difficult to analyze the coupling characteristics of faults in redundant structures. Unmanned aerial vehicle is a typical multiple redundant complex equipment, its structure and function are highly redundant features, unmanned aircraft system level different parts relationship is complex, reflected in the diversity of performance of a system parameter and nonlinear coupling characteristics between multi-source parameters, and the degree of coupling, sequence, different intensity, will have difficulties for system reliability and health assessment, The coupling relationship among various performance parameters, system behavior and fault forms of UAVs needs to be sorted out in depth. 4) It is difficult to characterize the system performance degradation in finite sample space. Due to the high reliability of UAVs, they are characterized by rare fault samples, difficult to obtain samples, unbalanced samples, low sample information density and fragmentation in the operation and service process. Limited sample space brings great challenges to fault diagnosis, degradation behavior characterization, life prediction and health status assessment of critical systems and functional components of UAVs.

3.3. Development direction and trend

At present, China has a good research foundation of PHM technology, and has explored and accumulated some experiences of PHM technology in the fields of civil aircraft, helicopters, armored vehicles, high-speed railways and other equipment. It is believed that with the further application and popularization of UAV PHM technology in China will usher in a high tide of development. By analyzing the existing literature and the current demand of UAV PHM technology, the development direction and trend of the field can be preliminarily determined as follows:

- Fault mode and degradation mechanism analysis: fault modeling mechanism is the foundation of UAV PHM technology. The key systems and functional components of UAVs have some practical problems, such as failure uncertainty, unpredictability, coupling and multiplicity, which restrict the future improvement space of UAVs PHM technology. Based on failure physics research, random and cognitive uncertainty should be considered. Through multidisciplinary simulation technology and accelerated life experiment, the system should be expanded from functional components to subsystems and then to the whole UAV, and then to the super system. To realize the transparency of the transmission relationship between the failure mode, failure mechanism, fault propagation law and fault behavior of UAV system, so as to guide the basic layout of UAV PHM technology.
- Advanced sensor technology and condition monitoring technology: Perfect monitoring technology can provide data guarantee for UAV PHM technology. Monitoring means "see", and only when "see" is wide can "go" far. Intelligent sensor technology to support, relying on advanced lightweight sensors can solve each system component adaptation sensor and optimal distribution problems, and can realize unmanned aerial vehicle from functional components to all-round real-time monitoring and running of the system level situational awareness, eventually reach for unmanned aerial vehicle fault diagnosis, prediction and health management to provide complete and reliable source of data, To realize the full coverage of UAV fault diagnosis under complete monitoring. Then, the multi-dimensional data of the dynamic evolution of UAV from normal, degraded, ill-conditioned, faulty and other multi-state lifetime are collected to realize the accumulation of data and the construction of a complete UAV dynamic information database within the service cycle.
- Data mining and modeling technology under incomplete information: With the help of artificial intelligence methods, hidden information of data can be fully mined, data quality and value can be improved. Aiming at the uav

information incomplete, insufficient fault samples is difficult to obtain, a single scenario labels such as limited sample space problem, the possibility of a structure under the small sample distribution framework, at the same time, through deep learning network model such as access to agree with the original sample distribution twin samples in order to implement the data the expansion and diversity of ascension. Furthermore, artificial intelligence algorithms such as deep transfer learning and incremental learning are used for data mining and data fusion. This can solve the problem of cold start when UAV fault data is insufficient and single scene label is insufficient, and improve the modeling accuracy and generalization ability of UAV fault diagnosis and prediction under limited sample space and incomplete information.

- Intelligent diagnosis and prediction technology under the fusion of artificial intelligence and big data: As a representative of artificial intelligence, deep learning method has strong multi-layer nonlinear feature learning ability, which can automatically learn useful features in high-dimensional input data and achieve higher fault diagnosis accuracy. At present, intelligent diagnosis based on deep learning has achieved remarkable results [5], and the application of deep learning in UAV fault diagnosis has also achieved initial results. In the future, with the enrichment of various UAV monitoring data samples, the UAV PHM technology that integrates multi-source information and builds a deep learning model framework based on deep learning, extracts features and fits mapping relationships from time domain, frequency domain or time-frequency domain, and realizes intelligent fault identification and prediction will attract much attention.
- Life prediction and health assessment decision under complex network and variable working conditions: The UAV is composed of multiple key systems, and each system contains a large number of sensors, so the UAV can be regarded as a special complex network. By sorting out the logical relationship between data information features and fault modes and information fusion based on the topological properties of complex networks, the fault evolution process of key systems and functional components of UAVs can be clarified, and then the system performance degradation trend can be judged [6-8]. The service of UAVs under variable working conditions will make its performance degradation trend diversified. The prediction model constructed by deep learning, correlation analysis or multi-granularity model under variable working conditions will make the remaining life prediction of UAVs more accurate and reliable. Prediction, evaluation and decision-making in complex networks and variable operating conditions are conducive to the realization of UAV hierarchical mission planning, flight self-calibration and self-repair based on the residual accuracy of critical systems in the whole life cycle. In addition, differentiated life prediction for individual service task conditions of UAVs on the basis of global prediction can further improve the accuracy of prediction and bring better use experience [9-13].

4. Conclusion

Under the background of artificial intelligence technology and big data, the UAV PHM technology is reviewed. On the basis of introducing the concept of UAV and PHM technology, the PHM technology framework of UAV system is designed and described. The research status of UAV fault detection, diagnosis and prediction technology at home and abroad is further analyzed. The progress, existing problems and challenges of UAV PHM technology in China are summarized and summarized. Finally, it points out the overall development trend of UAV PHM technology based on accurate fault modeling mechanism, perfect monitoring technology as guarantee, information mining and modeling technology under the deep integration of artificial intelligence and big data as the core, and accurate diagnosis, prediction and task management under complex networks and variable working conditions as the goal.

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