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A Review of Aircraft Engine Fault Prediction and Performance Optimization Based on Deep Learning

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ABSTRACT

This paper is aimed at presenting a systematic review of the recent studies on the use of deep learning techniques in aircraft engine health management for fault detection and performance enhancement. This comes in the light of increased growth in the air transport industry, the efficiency of aircraft engines and the efficiency of their maintenance have emerged as key issues in the safety and efficiency of air transport. This paper also identifies some of the key issues emerging from this area such as the data issues and the need to develop very accurate models for faulting and performance enhancement. Some of the most advanced techniques, namely the Long Short-Term Memory (LSTM) networks and Convolutional Neural Networks (CNNs) are discussed as potential solutions to these challenges. The theoretical descriptions of the working principles, as well as the strengths and weaknesses of the methods in question with regard to the problems of aircraft engine health management, are elaborated. Furthermore, this paper introduces the application of Reinforcement Learning as a new technique in the area of optimal control of engine parameters with the hope of improving the dependability and maintainability of aircraft engines and in the process of achieving sustainable growth in the aviation industry. The issues on model interpretability, model generalization and model deployment are also discussed and research guidelines for the future work in this field are also outlined. In this paper, the state of the art and the importance of deep learning as well as the applications of deep learning in aircraft engine health management are discussed based on the literature and case studies.

KEYWORDS

Deep Learning; aircraft engine; fault prediction; performance optimization; health management

1. INTRODUCTION

1.1. Research Background and Significance

Since the aircraft engine is considered as the “heart” of aircraft the condition of the engine is directly linked to the safety, reliability and the cost of the flight. The basic ways of engine health management are based on the schedule of the vehicle and previous knowledge. While this method has provided a certain level of aviation safety in the early stage, with the development of the aviation industry and its increasing needs, these methods cannot satisfy the current aviation operation’s demand for engine reliability and maintainability.

Today, the situation has been changed due to the appearance of the deep learning approach for solving these problems. Deep learning is capable of processing high dimensional complex data sets and it can learn features and create effective failure prediction models from the data. Hence, the use of deep learning in the area of aircraft engines’ assessment and management is vital.

1.2. Technology Development and Application

The technology of aircraft engine health management has grown from the earlier statistical methods and time based maintenance to the current advanced technology. The early failure prediction was earlier based on expert knowledge and experience and historical data and although some level of health monitoring was achieved, the result was not very effective in a complex and dynamic environment.

In 2007, Nathan Bolander et al. presented a physical model-based approach for the estimation of RUL of aircraft engine bearings with particular reference to outer ring failures. Matthew et al. presented a physical prognostic approach in 2012 that considers the combined effect of several damage mechanisms acting on a component and used it for the prognostic maintenance of systems and components.

As the number and types of sensors have grown, it paved way for the use of deep learning algorithms. Beginning in 2014, the data-driven approach was introduced and researchers applied the time series data of gas path systems and through CNNS, features were extracted and predictions about the performance were made. In 2016, a hybrid model that based on both CNNS and RNNS was applied for RUL prediction. This method enables the extraction of local features and the identification of the degradation process, which in turn enhances the prediction's reliability. By 2024, Civil Aviation University of China proposed a new deep learning model that incorporates attention mechanism with LSTM which is a type of Long Short-Term Memory Network. [1] The way of integrating samples enhances the model's ability in generalization and has reference value for RUL prediction of various types of engines.

LSTM and CNN in deep learning technology have specific features in dealing with time series data and feature dimensions. LSTM is suitable for analyzing time series in order to identify long - and short-term dependencies while the engine is in operation, thus increasing the chances of accurate failure prediction. Hence, CNN because of its feature extraction capacity, is able to identify complex faults in the system and enhance the system's performance. Some of these technologies have been gradually introduced in the engine health management systems to improve the effectiveness of the fault identification and the optimization of the engines.

1.3. Scope of Article Review

Deep learning technology has also been used in aircraft engine health management, and has shown good results, but there are still many problems, including data acquisition and labeling, the poor generalization of the models, and the lack of theoretical support. Therefore, this paper aims to systematically review the application status of deep learning technology in aircraft engine fault prediction and performance optimization, analyze the problems faced, and discuss the future development direction.

2. APPLICATION OF DEEP LEARNING IN FAULT PREDICTION

2.1. Data Preprocessing and Feature Extraction

When the deep learning is used on aircraft engine fault prediction, data preprocessing and feature extraction are the keys. Preprocessing of data is often a part of data cleaning, denoising, normalization and standardization of data. These steps help in cleaning the data and if the outliers are present then they do not affect the model to a great extent. However, in order to increase the training speed and the accuracy of the model, feature extraction technique is used as well. The feature extraction can be done by using statistical methods, frequency domain analysis or the use of deep learning network such as autoencoders to map the raw data into a form that is more informative. All these preprocessing and feature extraction steps help in building the models and enhance the precision and dependability of fault prediction.

2.2. Modeling and Innovation

In the area of aircraft engine failure prediction, the deep learning has somehow revolutionized the modeling process. Most of the previous approaches to prediction have been based on machine learning algorithms like the support vector machine, and decision tree. However, some of the deep learning models such as CNNS and RNNS are capable of learning the patterns and features of data indirectly from large complex data through its layers. This capability is especially useful in the case of time series data and multi-dimensional data which is the forte of deep learning.

Weimin Liu and Zhongzhi Hu proposed a method for estimating residual life of aero engines based on CNN and long short-term memory neural network (LSTM). [2] This approach performs feature learning on sensor data by using convolutional neural network, and processes the time series by LSTM and the remaining life of the engine is predicted through the fully connected layer. Due to this reason deep learning is very efficient when it comes to the processing of time series data and multidimensional data.

In 2018, Nanjing University of Aeronautics and Astronautics combined deep belief network and decision fusion algorithm to propose an aero engine fusion diagnosis model based on deep learning. [3] The model uses deep learning to extract hidden features to obtain confidence, and then performs decision fusion and data simulation to verify validity. This fusion strategy improves the accuracy of fault classification and anti-interference ability.

The research on deep learning optimization algorithms is also progressing, and the "Research on Optimization Algorithms in Deep Learning" published by Chen Shuang et al from Beijing University of Civil Engineering and Architecture in 2022 mentioned the improved version of gradient descent algorithm, adaptive learning rate adjustment strategy and model regularization technology. [4] These optimization algorithms' proposal and application are a reliable solution to enhance the deep neural networks' performance and training time.

2.3. Performance Evaluation and Future Direction

There are some disadvantages in applying deep learning in aircraft engine fault prediction as follows. For instance, CNN and LSTM: they are very good at feature extraction and time series prediction but they need large number of labelled data to train and they are computationally very expensive. However, the deep belief network and the decision fusion algorithm enhance the classification accuracy of the faulted system; the model has a poor explainability and needs enhancement in the generalization of complex systems.

Future research could also aim at working on better algorithms to minimize the need for training data and enhancing the performance of the models. Moreover, it is also an important direction for future study to discuss more about the model optimization approaches like regularization techniques in the model and the methods for adjusting the learning rate of the model in order to get better generalization performance and minimize over-fitting. As the result, the implementation of deep learning for the aircraft engine failure prediction will be more useful and accurate in the future.

3. DEEP LEARNING METHODS FOR PERFORMANCE OPTIMIZATION

3.1. Aircraft Engine Performance Degradation Analysis

Performance degradation analysis is an important part of aircraft engine health management. By analyzing the pattern of engine performance degradation, potential failures can be predicted and appropriate maintenance measures can be taken. For example, in 2023 researchers proposed a new forecasting method that uses principal component analysis to orthogonalize statistical time-domain features and input these features into supervised regressors such as random forests, extreme random forests, XGBoost, and artificial neural networks to predict the health of engine units, the eventual failure of components, and the remaining useful life. In addition, a performance attenuation modeling and residual life (RUL) prediction method based on nonlinear Wiener process has been proposed, which takes into account the nonlinear and three-source uncertainties in the performance attenuation of aero engines.

3.2. Application Cases of Deep Learning in Aero Engine Performance Optimization

For deep learning application cases of performance optimization, in the field of aero engine blade defect detection, a study based on deep learning uses an improved YOLOv5s model (DDSC-YOLOv5s) to improve detection accuracy. Through the deformable convolutional networks, it ensures the identification of the defects of various shapes and through the depth-separable convolutions it increases the efficiency of feature extraction. [5] The size of anchor frame is further fine tuned by using the k-means clustering technique. From the experiment results, the mAP50 is increased to 83.8% and the calculation amount is increased only by 7.9%, which enhances the detection efficiency and accuracy. It also identifies the application of this technology in current inspection systems for better management of the engines and to avoid failures.

In addition, some scholars predicted the remaining life of aero engines by using 1D-CNN and Bi-LSTM hybrid models, which combined one-dimensional convolutional neural network and bidirectional short-duration memory neural network to improve the accuracy and reliability of prediction. The AVIC Research Institute found that the ANN-Flux algorithm performed well in predicting the remaining useful life, reducing the root mean square error (RMSE) of the remaining useful life of the test split of the dataset by 38% compared to previous work [6].

Another practical application case came from Pratt and Whitney, which used MSC Nastran software for high-precision 3D solid/shell unit modeling and rotor dynamics analysis of a real aircraft engine model. Through the use of modal frequency response analysis and hyperelement method, the analysis efficiency is significantly improved, while maintaining the high accuracy of the calculation results.

Last but but not least, a new study from June 2024 proposes a novel fault prediction method based on brain-heuristic pulsed Echo State Network (Spike-ESN) models. [7] By designing a pulse input layer based on Poisson distribution, the method extracted the time characteristics in the aero engine sequence data, and read the internal state of the pulse reservoir by ridge regression method, which significantly improved the prediction accuracy and efficiency, helped to diagnose faults in advance, reduce maintenance costs, and improve flight safety.

3.3. Challenges and Improvement Directions of the Model

While deep learning methods demonstrate a high level of effectiveness in aircraft engine performance optimization, there are some issues and further possibilities. The task of explaining the models in limitation is a challenging one. Deep learning models, are often referred to as black box models because it is quite challenging to understand how the models arrive at their conclusions. This is quite crucial in the aviation industry, which operates under condition of safety and reliability. How to improve the interpretability of the model so that experts can understand and trust the predicted results of the model is an urgent problem to be solved.

Among the future directions of improvement, transfer learning and meta-learning are a trend, through which researchers can use existing knowledge to accelerate the training process of new models, especially in cases where labeled data is insufficient. Meta-Learning can help the model quickly adapt to the new data distribution and improve the generalization ability of the model. Adversarial networks

(Gans) can also be generated: Gans can be used to generate more synthetic data to compensate for the lack of real data. Also, Gans can enhance the stability of the models and handle the data imbalance problem. Last, I find the Transformer architecture to be quite useful. It has been seen that Transformer can work well for sequence data, especially for the modelling of long distance relationships. Possible future work could be to look at the applicability of the Transformer architecture for predicting the performance of the engine and determine the level of engine degradation to increase the model performance and efficiency.

4. CONCLUSION AND SUMMARY

In this systematic review, we have highlighted the possibility of deep learning techniques in aircraft engine health management with an incidence on fault prognosis and performance improvement. The development of air transport industry has called for better and efficient engines and effective procedures on maintenance which cannot be easily obtained through normal methods. Through the application of improved deep learning models like LSTM and CNN to solve these problems researchers have been able to come up with better diagnostic tools as well as better ways of managing the operations of engines.

The results of the current literature review show that deep learning has a good prospect and challenges in this area. However, there is some limitation in the use of these techniques such as the issue of interpretability of the models used, issues to do with the generalization of the results and the implementation of the results in practical scenarios. These issues provide future research agenda to further enhance these models to improve their applicability and applicability to real life situations and contexts. This paper has therefore established that deep learning has the potential to greatly enhance aircraft engine health management but more work needs to be done to enhance the effectiveness of this important field.

REFERENCE

[1] Zhao, H. L., & Liu, Y. W. (2015). Aero engine failure risk prediction based on Monte Carlo simulation. Journal of Beijing University of Aeronautics and Astronautics, 41(3), 545-550.

[2] Liu, W. M., & Hu, Z. Z. (2021). An aeroengine residual life prediction method based on neural network. Aeroengines, 47(3), 8-15.

[3] Che, C. C., Wang, H. W., Ni, X. M., et al. (2018). Fusion Diagnosis of aero Engine Fault Based on Deep Learning. Journal of Beijing University of Aeronautics and Astronautics, 44(3), 621-628.

[4] Chen, S., Zhang, C. L., & Li, M. L. (2022). Research on Optimization Algorithm in Deep Learning. Artificial Intelligence and Robotics Research, 11(4), 448-462.

[5] Li, X., Wang, W., Sun, L., & Zhang, J. (2022). Deep learning-based defects detection of certain aero-engine blades and vanes with DDSC-YOLOv5s. Scientific Reports, 12, 13067.

[6] Cohen, J., Huan, X., & Ni, J. (2023). Fault Prognosis of Turbofan Engines: Eventual Failure Prediction and Remaining Useful Life Estimation. arXiv: cs.SY, 14, 3486.

[7] Liu, M.-R., Sun, T., & Sun, X.-M. (2023). Brain-Inspired Spike Echo State Network Dynamics for Aero-Engine Intelligent Fault Prediction. IEEE Transactions on Instrumentation and Measurement, 72, 1-13.