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Review Article

Predictive Maintenance for Aircraft Engine Using Machine Learning: Trends and Challenges

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Abstract: This article aims to prove that Machine Learning (ML) methods are effective for Predictive Maintenance (PdM) and to obtain other developing methods that suitable applied on PdM, especially for aircraft engine, and potential method that can apply on future research, and also compared between articles in International and Indonesia institution. Maintenance factors are important to prognostic the states of a machine. PdM is one of the factor strategies based on real-time data to diagnosis a failure of the machine through forecasting remaining useful life (RUL), especially on aircraft machine where the safety is priority due to enormous cost and human life. ML is the technique that accurately prediction through the data. Applied ML on PdM is the huge contribution for saving cost and human life guarantee of safety. This work provides the literature survey for recent research which trends and challenges on PdM of aircraft engine using ML that compared the research from international and Indonesia from 2016 to 2021. Result of this work shows that ML method, Long Short-Term Memory (LSTM) and Gated Recurrent Unit (GRU) are the best method to calculate PdM with more than 99% on rate accuracy, and low level of Indonesia institution research which focused on PdM on aircraft engine using ML

Keywords: Aircraft engine, machine learning, remaining useful life, predictive maintenance

1. Introduction

The capacity of machinery working cannot last forever, sometimes it will be broken-down because of out-date operation. Machinery system that included sensors are just monitoring state of the machine, but cannot make a report the machine in good or bad condition. To avoid the worse event (failure) and to get information about status of a machine, maintenance strategy must apply on machinery system that scheduled. There are three best practice of maintenance strategy Corrective, Preventive, and Predictive Maintenance.

Corrective maintenance (CM) is the basic of maintenance strategy, this maintenance performed when the machine stopped working. The corrective maintenance can be applied when machine have spare, if not it will stop all the operation and it will be disadvantages [1], while preventive maintenance (PM) is scheduled maintenance or time-based maintenance which machine or system periodically will be maintenance though the status of the machine in healthy condition, as example a machine maintenance annually. Predictive maintenance (PdM) is based on preventive maintenance, but continuous monitoring the state of machine, the maintenance performed when it is needed or in optimal way. PdM indicated state of machine to performed schedule to maintenance based on historical data, integrity factors, statistical inference methods, and engineering approaches [2]. The prediction process needs some mathematical methods and techniques to apply on maintenance

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strategy, but due to increasing of technology and methods, machine learning has possibility to employing PdM on every cases.

Machine learning (ML) is subsection of Artificial Intelligence, this methods or algorithm capable to learning based on training which is the given information about something, and it can be using in future when the algorithm applied. There are three types of ML: Supervised learning make calculation or prediction based on known or labeled data, unsupervised learning focus on clustering data while process, and reinforce learning focus on interaction to environment. Deep learning (DL) is the development algorithm from ML to fix its limitation [3]. DL implemented artificial neural network (ANN) for its algorithm and give big impact to supervised learning method. DL algorithm widely employed such as image processing, face and speech recognition. Both ML and DL algorithm are suitable for prediction, classification, and make cluster process. Random Forest (RF) and SVM are popular methods in ML, then Convolutional Neural Network (CNN) and Recurrent Neural Network (RNN) are most frequent implemented methods in DL. As prediction tool, both ML and DL divided into two techniques: Regression and Classify technique. Difference between two techniques is output of the method, while regression technique is leaning on prediction value of a variable including time-series data, labeling of variable (discrete) is focus for classify technique. The classify technique has better accuracy than regression [3,4].

To validate the result of using ML and DL method, Evaluation is important to indicate the performance of the model that have been trained. Root Mean Squared Error (RMSE) is frequent evaluation method for regression technique, this evaluation indicating how concentrated the output is around the line of best fit on prediction data. The evaluation method for classify technique are Accuracy defined parameter which indicating output values of prediction compared with the actual value, Precision described level of accuracy between output of prediction compared with all data, and Recall defined as level of correct result compared by the number of results should have been return, which mean the higher recall value, the higher data collected, and there is no data will miss from accuracy and precision process [4].

Prognostic and health management (PHM) on aviation industry will be expand because of its effect on economic and human safety, an advance maintenance shall be applied on this industry to inform the aircraft engines condition. PdM is a maintenance advance technique which can be apply on aviation industry because of its high precision prediction which can reducing cost operation and increasing the safety by calculate remaining useful time (RUL) of aircraft engines [5].

As literature systematic review of employed ML on PdM for aircraft engine, there are previous works about similar topic as the basic information for this article. Comprehensive survey on PdM system architecture has done somewhere [6], that provide review of existing approaches for PdM from traditional base to using ML and DL approaches, this work also emphasis on DL because of its accuracy and its increasing of some researcher using DL method past five years. Carvalho, et al [7] mentioned before 2013 only two articles about PdM because of its new technique of maintenance strategy, as result from 0,5 articles/year on 2009-2012 and increasing significantly to 11,3 articles/year on 2013-2018. The most frequent methods that using is RF, ANN, SVM, and k-means. Also, other researcher has vary ML methods can estimate Remaining Useful Life (RUL) recommended presented Long Short-Term Memory (LSTM) method for prognostic technique for aircraft fault prediction, because the model is capable to predict engine behavior correctly [8].

This article purpose is looking for the effective and optimal method to calculate PdM, specially on aircraft engine, and potential method that can apply on future research. This work also has given the comparison between articles in International and Indonesia institution

2. Systematic Literature Review

The survey has been conducted to review the literature based on article in trends for predictive maintenance on aircraft using machine learning. Increasing of interest on research for this area is

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important due to growth of knowledge and for industry. This survey's scope period 5 years between 2016 until 2021. To accomplish the purpose of this study, various of journal articles and conferences from maintenance strategy focused on Predictive Maintenance on aircraft engine to implemented on machine learning methods. The literature searching is used Google Scholar as primary sources and other such as IEEE Xplore for international articles, for Indonesia articles, literature searching used GARUDA and SINTA. Keyword for searching the article used:

1. "Predictive Maintenance".
2. "Predictive Maintenance on Aircraft".
3. "Predictive Maintenance using Machine Learning".
4. "Predictive Maintenance on Aircraft using Machine Learning".

The keywords are representative of this study to find out the current trends and challenges in this area of the research. Selection for this survey literature focused on the suitable method of machine learning to make prediction, the methods using based on the experiment and calculation and comparison from various methods. This survey also selected article journal on September 2021.

As systematical review from journal articles, the result of the searching was categorized from years between 2016 until 2021. The years of publication indicate the interesting of researcher about this topic is increase or decrease each year. This work survey aims to compare the origin of the journal publication based on institution that publish this topic (International or Indonesia), this comparison the interest of local researcher and trends. The categorization also compared different methods that using for predictive maintenance and machine learning for aircraft engine.

3. Recent Trends of Predictive Maintenance

The total research for literature survey was 35 articles and filtered from above criteria being 19 articles from International and from 3 Indonesia. The selection process is focusing on keywords mentioned before, and applying ML into PdM method in aviation industry or other industry.

In optimal way to applied predictive maintenance in any system, ML method which included DL is the best for make prediction with high accuracy result. After applied the filter in literature searching that matched with criteria that have made, the summary articles which divided in International and Indonesia group articles shows on table 1 and table 2. the year of publish the article shows in figure 1 that indicate the ML applied on PdM is new trend of work, because average of publishing article per year is only 3,7 articles from 2016-2021, and Indonesia institution in recent 1 year which is 2020 and 2021 published articles about it. Most of classify technique of ML using on articles while implemented it on PdM because of this method has high accuracy than regression technique.

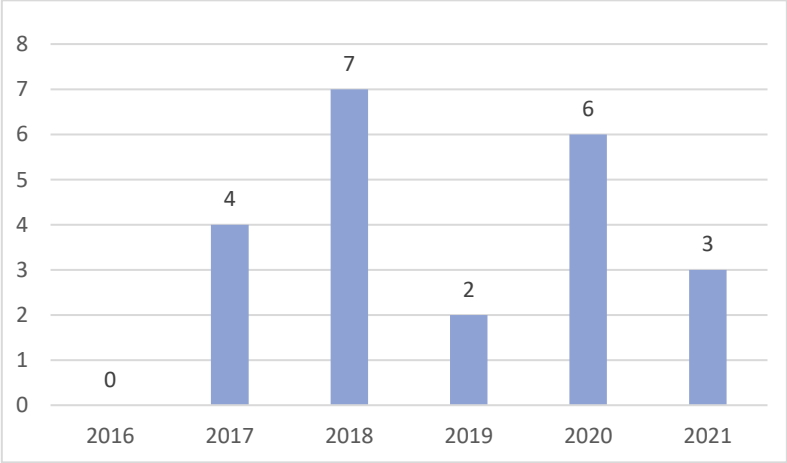

Figure 1. Number of articles in years

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RF is the most method used in literature systematic review, there 6 articles used it. LSTM method for prediction is frequently used in recent years (2019-2021) because of this method output is high accuracy and reliable to any cases in industry, especially on aviation. In international articles group, 6 articles research about applied of ML in PdM for aircraft engine, and 2 articles applied PdM on aircraft engine without ML method, and the rest of articles employed PdM and ML on other industry such as power plant, manufacture, and cooling system. In Indonesia institution, there is no article applied PdM on aviation industry had published until now which fulfil the criteria was made in this work, the most articles focus on manufacturing industry, and the methods used are linier regression, Random Forest (RF), and Support Vector Machine (SVM). This described in Indonesia the enthusiasm of PdM using ML is in low level, especially on aircraft engine or aviation industry.

Table 1. Summary of Recent Trends Predictive Maintenance International Research

References	Year	Methods	Description of Applied Predictive Maintenance
Hsu, et al [9]	2020	RF; DT; K-means fold	Statistical process to detect fault and ML predict maintenance needs on wind turbine which accuracy higher 90% could detect wind turbine failure state.
Amruthnath and Gupta [10]	2018	Principal Component Analysis (PCA); Gaussian Mixture Modelling (GMM); C-means; K-means Cluster Analysis	Monitoring the exhaust fan using vibrator sensor and divided to 3 are healthy warning, and fault condition using PCA and Cluster Analysis then predict the condition using ML, afterward T^2 method is high accuracy then other.
Bampoula, et al. [3]	2021	Long Short-Term Memory (LSTM); Autoencoder	LSTM-autoencoder employed to estimate RUL on rolling milling machine in high accuracy, but it has limitation on applied multiple neural networks to identify status RUL.
Bruneo and Vita [11]	2019	LSTM and Tunning hyperparameter	Using LSTM and tunning hyperparameter for Predictive Maintenance on jet engine which higher RMSE than other ML methods.
Cho et al. [12]	2018	Hybrid ML unsupervised and semi supervised	Smart factory with various machine operation without proper maintenance data solved the issues using hybrid machine learning calculate predictive maintenance.
Demidova [13]	2020	LSTM; GRU; RNN Hybrid (LSTM and GRU)	Employed one and two layers RNN, LSTM, and GRU neurons for calculate RUL for predictive maintenance on aircraft engine and accuracy above 90% using LSTM and GRU.
Hermawan, et al. [14]	2020	RF	Combined of predictive maintenance and monitoring applied on real industry 4.0 using ML with 95% overall accuracy
Gohel, et al [15]	2020	Support Vector Machine (SVM); Logistic Regression	Nuclear infrastructure is vital site and applied ML to make Predictive maintenance, because using SVM and LR have complete functionality for nuclear power plan infrastructure.
Chen, et al [16]	2020	Autoencoder; Cox Proportional Hazard (CPH); LSTM	Using PdM to calculate TBF using CPH and LSTM based on historical maintenance data on automobile.

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Kanawaday and Sane [17]	2017	Auto-Regressive Integrated Moving Average (ARIMA)	Employed ARIMA to forecast possible failure and quality defects from time series Slitting machine data on various sensors.
Ullah, et al. [18]	2017	Artificial Neural Network (ANN); Multilayer	Infrared thermal image used as monitoring electrical equipment, then applied ANN to classify the state of thermal condition from electrical equipment as predictive maintenance.
Butte, at al. [19]	2018	RF; Gradient Boosting Method (GBM) Deep Learning	Predictive maintenance employed on microelectronic manufacturing to solve issues of unplanned maintenance using various of ML
Xayyasith, et al [20]	2018	Decision Tree (DT); SVM; Discriminant Analysis (DA); Logistic Regression; KNN	ML applied to predictive maintenance on cooling system for hydraulic power plan which data collected from temperature sensor and historical maintenance. The result is SVM and DT better to make prediction other than ML methods using in this work.
Korvesis, et al. [21]	2018	Multiple instance Regression (MIR)	Developing alert system for upcoming failure on aviation as predictive maintenance using Multiple Instance Regression, and collected data from post flight report.
Urbano, et al. [22]	2018	Generalized Like-hood Ratio Test (GLRT)	Employed Predictive maintenance to detection and diagnose limit cycle oscillation on civil aircraft using GLRT method.
Behera, et al [23]	2019	GBT; RF	Applied ensemble tree ML method which is GBT and RF to estimate current health and RUL of turbofan engines in predictive maintenance. Both methods gain above 90% accuracy, and GBT more accurate than RF.
Mathew, et al [24]	2017	Liner Regression; DT SVM; RF; K-Nearest Neighbors (KNN); GBM; Deep Learning; Analysis of Variance (ANOVA); K-means	Comparing 10 different ML methods to calculate RUL for predictive maintenance of turbofan engine as result RF is lowest RMSE than other methods
Dangut, et al [25]	2020	Natural Language Processing (NLP); RF	Using hybrid ML by combined NLP and ensemble learning to solve irregular data pattern for calculate predictive maintenance which performed better than only ensemble methods, and this method 10% outperformed than synthetic minority oversampling technique
Panagiotis, et al [26]	2020	CNN; LSTM CNN and LSTM	Combined CNN and LSTM applied to predict maintenance which is calculating RUL from historical data. The accuracy of combined method reaching above 99%.

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Table 2. Summary of Recent Trends Predictive Maintenance Indonesia Research

References	Year	Methods	Description of Applied Predictive Maintenance
Suryadarma and Ai [27]	2020	Linier Regression	Predicting cooling system maintenance using linier regression which SCADA system collected real-time data from combination sensors
Andriani, et al. [28]	2021	RF and SVM	Labeling data which is providing by manufacture is costly task, but ML can solve this problem and the calculate the prediction, RF and SVM implemented to this action to forecast predictive maintenance.
Kusumaningrum, et al. [29]	2021	RF and SVM	Predicting RUL based on multi-sensors data and machine failure report ML can calculate the pattern and make prediction. With tunning optimal in Rf and SVM to apply predictive maintenance.

4. Potential Methods and Challenges for PdM on Aircraft Engines

As result of systematic literature review about implemented PdM on aircraft engines using ML, there are several methods of ML most frequent used: RF and LSTM. Both methods (RF and LSTM) can apply on regression and classify technique that the reasons why this method well known for most researcher to predicting. As aims of this work, implemented PdM on aircraft engine using ML method has potential to developing in few sectors such as combined proper method to create new method with high prediction accuracy, or make the variable on the data effective in tunning hyperparameter.

LSTM and GRU selected as the optimal and effective method to implemented PdM because both of method result high accuracy and minimum RMSE data. LSTM and GRU are the RNN base method appealing to the PdM domain due to the fact that both method excellent at learning from sequences, and it will allow the method to use time-series data that operating in longer period of time in past or historical data to detect failure patterns. As the advantages of LSTM and GRU, they have limitation that cannot deal with irregular time-series data, but to apply on PdM for aircraft engine is the advantage for both methods, because in the aviation industry the record data in regular form on time-series.

Hermawan, et. al. [14] on they work to calculate PdM using DL which is CLSTM (combination CNN and LSTM) have got accuracy rate more than 99%, but in this article only mentioned their result on accuracy rate, which the other evaluation result they cannot display such as precision, recall, and error percentage. On other hand, others have worked on RNN method which are GRU, LSTM, and combination both method resulting the LSTM and GRU demonstrate their high efficiency to solve classification problem for PdM on aircraft engine. Recent article also using machine learning system optimization of the algorithm for predictive maintenance [29].

In additional, the development of PdM strategy in any industry which employed ML we briefly can mention that it will change our future to more efficient in every sector. Moreover, in Indonesia, shows an opportunity to develop the PdM using ML method, especially on aircraft engine sector due to the high efficiency and accuracy rate of LSTM and GRU method [28-29].

There are some possibilities for the future work, they are including the combination of ML method with itself or other method, tunning hyperparameter to optimize the computation process, and implemented the result and calculation (Training and Test) on real-data as premier source, because most of research conducted to artificial data.

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5. Conclusions

The study of systematic literature review focused on PdM using ML method for aircraft engine is resulting PdM using ML is rather new topic which show the average publish article only 3,7 articles per year that fulfil our criteria. LSTM and GRU are the best for now to calculate PdM, especially on aircraft engine which the accuracy more than 99%. The interesting of this topic is low level in Indonesia, because there are only 3 articles published focusing on PdM using ML which fulfil our criteria, and there is no article focus on aircraft engine. Combination other ML method, tunning parameter, and using real-data is the future possible study that can be applied on ML method for PdM.

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