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Application of AI-based Predictive Maintenance for Industrial Processes

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Abstract: Modern industry is increasingly relying on digital technologies to optimize maintenance processes, reduce costs and ultimately increase productivity. Conventional maintenance models, such as corrective and preventive maintenance, often lead to unnecessary downtime and high operating costs. Predictive Maintenance (PdM), which is based on data analysis and artificial intelligence (AI), enables the timely detection of failures and the optimization of maintenance cycles and is therefore a key component of modern industry. With the advancement of artificial intelligence (AI) and machine learning, data analytics can accurately predict failures, thereby reducing the need for preventive and corrective maintenance in the form that was common before the application of AI. Predictive maintenance (PdM) is emerging as a key element of modern industry, enabling a significant reduction in downtime, an increase in operational efficiency and a reduction in maintenance costs. This paper explores the application of artificial intelligence, including machine learning (ML), deep learning (DL) and the Internet of Things (IoT) in predictive industrial maintenance, analyzes the key implementation challenges in implementation, considers the potential benefits for industrial systems and discusses the challenges and prospects for the further development of this approach.

Keywords: Artificial Intelligence (AI); Deep Learning (DL); Internet of Things (IoT); Machine Learning (ML); Predictive Maintenance (PdM)

1 INTRODUCTION

In the course of industrial development, the maintenance of industrial plants has evolved from reactive to preventive maintenance. Due to the strong development of digitalization and Industry 4.0, predictive maintenance is becoming the industry standard for efficient maintenance. The development and thus the application of artificial intelligence (AI), machine learning (ML) and database analytics such as failure history enables the prediction of failures before they occur from a different perspective, which ultimately reduces costs and increases the availability of production facilities [1]. Industrial production itself relies on the continuous functionality of machines and systems to ensure higher productivity and profitability.

However, breakdowns and unplanned downtime often pose a major problem to the ambitious targets, especially those of high mechanical availability, often above 95%, which ultimately causes significant financial losses and affects the availability and reliability of production processes. According to certain studies, unplanned downtime in industry can cause billions of dollars in losses every year, and no less than 82% of companies have experienced sudden, unplanned downtime in recent years [1].

Conventional approaches to maintenance models, such as reactive and preventive, have significant shortcomings. With reactive maintenance, maintenance measures are only carried out when a failure occurs, while preventive maintenance often includes maintenance measures that are not necessary, which ultimately increases maintenance costs, i.e. overall production costs. Accordingly, there is a growing need for smarter and more efficient maintenance strategies that can minimize these problems and thus contribute to various benefits of maintenance. Predictive maintenance (PdM) uses sensor input data for the necessary analysis, including Internet of Things (IoT) and AI algorithms, as well as Fuzzy Logic, Genetic Algorithms, which would actually have the function of predicting potential failures before they occur. Such activities are very important from the perspective of predictive maintenance itself, before a failure, breakdown or major downtime of the production process occurs. By implementing artificial intelligence models into the maintenance function, such as deep neural networks (DNN), multi-channels deep convolutional neural network (MC-DCNN), artificial neural network (ANN), convolutional neural networks (CNN) and recurrent neural networks (RNN), PdM provides the ability to estimate the probability of failure and influences the optimization of maintenance management. With the accelerated development of Industry 4.0 technology, predictive maintenance is becoming a fundamental tool for improving industrial processes, with a significant increase in mechanical availability and reliability. This paper provides an insight into the applications of AI in PdM, examines existing methods, presents the current challenges of modern industry and highlights future directions for the development of these technologies.

2 A BRIEF OVERVIEW OF THE EVOLUTION OF MAINTENANCE

The evolution of maintenance in industry can be divided into several broad key phases that have accompanied the development of industry itself, from reactive maintenance to predictive and smart maintenance, which is still used in industry today. In order to better understand the development of the maintenance process, a brief historical overview of the development of maintenance in industry is provided:

1) Reactive maintenance (before 1900)

Main feature: Repair after failure

Maintenance was most often conceived of as repair after a failure occurred. There was no basic systematic approach, but the production workers carried out the maintenance activities after a failure occurred. All production in terms of maintenance took place in the uncertainty of failure because the condition of the equipment and the risks of failure were unknown.

Example: Early machinery in the textile and mining industries, as mentioned, was only repaired when a failure occurred.

2) Preventive maintenance (1900)

Key feature: Scheduled inspections and replacement before failure occurs

With the development of industrialization and mass production (especially after the introduction of the assembly line in Ford factories), the importance of taking various measures to regularly inspect and replace parts that are worn out but have not yet been used up was recognized. Due to the technology that was in use at the time, this type of maintenance was not effective.

Example: Preventive maintenance measures are introduced in the aviation and automotive industries to reduce the number of breakdowns

3) Proactive maintenance (1950)

Key feature: Identification of the cause of failure of strategically important equipment

The development and application of risk and maintenance management methods, such as root cause analysis (RCA) and total productive maintenance (TPM), are slowly finding their way into effective failure management, i.e. effective maintenance management.

The goal of these tools is the timely detection of the causes of equipment failures that cause significant losses and to increase the reliability of production processes.

Example: Japanese factories use TPM in the automotive industry to increase production efficiency and reduce maintenance losses.

4) Predictive maintenance (1980)

Main feature: Use of sensors and data analysis in "offline" and "online" methods

Technological development of equipment and digitalization enable the use of various sensors, thermal imaging, ultrasound and vibration analysis to predict the condition of equipment, ultimately giving insight into the state of faults before they occur.

Example: Various manufacturing processes, process industries use vibration recording to perform analysis to detect irregularities in the exploitation of machinery.

5) Smart maintenance (2010)

Key feature: Artificial intelligence and IoT in modern industry

The application of Internet of Things (IoT) tools, machine learning and big data enables automated decisions in real time, which has an impact on predictive maintenance. Such approaches increase the reliability and mechanical availability of industrial processes.

Example: Industry 4.0 uses digital twins and AI algorithms to optimise machine maintenance in order to increase efficiency.

Maintenance approaches have evolved from simple repairs after a failure occurs to sophisticated systems that predict and prevent failures before they occur, increasing the reliability of production processes and reducing the costs caused by faults and breakdowns.

In summary, it can be concluded that maintenance strategies have developed in three main phases since the beginning of industrialization:

- **Reactive maintenance:** repairing equipment after a failure has occurred. This type of approach is very inefficient and often leads to long downtimes and high costs due to the need for quick maintenance and the procurement of spare parts [2].
- **Preventive maintenance:** Includes planned activities to check the condition of equipment and replace equipment parts at planned intervals. Although it improves reliability, it often results in unnecessary replacement of correct components that may still be in use, increasing operational maintenance costs [3].
- **Predictive Maintenance (PdM):** Uses AI technology and analysis of data collected from production processes to detect early signs of failure before a breakdown occurs, and ultimately optimizes maintenance based on the actual condition of the equipment [4].

The evolution of maintenance in the industry shows a clear path of industrial development from a simple, reactive approach to more advanced, sophisticated methods that enable greater reliability and efficiency in the production of process equipment. From post-failure repairs, through preventive and proactive methods, to the use of advanced sensors and data analytics, the industry is constantly evolving to reduce costs, increase productivity and manage and reduce unplanned downtime in production processes. This maintenance approach enables better control over the maintenance of production processes and lays the foundation for the further development of smart and autonomous maintenance systems in the future.

3 COMPARISON OF PREVENTIVE (PM) VS. PREDICTIVE MAINTENANCE (PdM)

The maintenance of industrial plants, especially complex plants such as those in the process industry, is usually based on various strategies to ensure their reliability, availability, safety and ultimately their cost-effectiveness. In most cases, the maintenance strategy defines two main approaches to maintenance, namely preventive and predictive maintenance. The maintenance strategy itself is not designed with just one maintenance approach due to the different types of systems and the varying complexity of the equipment.

3.1 Preventive Maintenance

The brief description of preventive maintenance (PM) already given actually implies the implementation of pre-planned, defined maintenance activities with the aim of preventing failures and reducing the frequency of unforeseen downtime. The activities listed include a series of planned maintenance actions in order to successfully perform maintenance, such as regular inspections of equipment, lubrication of equipment, replacement of parts and calibration of equipment, and are based on predefined time intervals or on the mean time between failures (MTBF) defined by the failure distribution. The overall preventive maintenance plans are defined by the maintainer, who uses various assessment tools such as risk matrices, failure distributions, failure history and the like.

Preventive maintenance can generally be divided into three parts for better perception:

Constant interval maintenance – is based on predefined time intervals, such as operating hours, and does not take into account the actual condition of the equipment. The logic of this approach is based on the assumption that an equipment or process component is expected to fail or malfunction after a certain period or hours of operation. Such defined maintenance measures are carried out before a failure occurs.

Age-dependent maintenance – equipment maintenance activities are carried out after a component has reached a certain age or a certain number of operating hours. This approach assumes that failures become more likely as the equipment ages or as operation progresses, which is the actual and expected sequence of maintenance. Therefore, certain equipment is replaced and repaired before a fault or failure occurs.

Imperfect maintenance – is a form of maintenance that usually does not always restore the system to its original state in a completely new state, but partially improves the condition of the component or system, i.e. its functionality and reliability. It can also be said that with this form of maintenance, the system is not at the full reliability level of the equipment, i.e. the component, but is in an intermediate state between failure and the state of full reliability. It should be noted that, according to the definition of imperfect maintenance, it is not possible to restore the original reliability in the service process – all maintenance is therefore imperfect. This method often leads to high maintenance costs and is not relevant for further processing when assessing the risk status, as it does not take into account the actual condition of the equipment.

3.2 Predictive Maintenance

Predictive maintenance (PdM) is certainly a more sophisticated concept, based on the continuous monitoring of the condition of the equipment using various diagnostic tools and techniques. Some of these are vibration analysis, thermography, oil analysis, ultrasonic testing and others. The main objective of such an approach is to predict faults that are present in the equipment and process but are not yet visible during operational use of the equipment. After identifying such faults in the early stages of their occurrence, corrective maintenance actions can be planned before the failure occurs.

Predictive maintenance can generally be divided into several parts:

Condition-Based Maintenance (CBM) – the continuous monitoring of key parameters or key equipment - helps to enable decisions based on the actual condition of the equipment or the system that ultimately constitutes the equipment. The main feature of this type of maintenance is that maintenance actions are only carried out when signs of system anomalies occur, rather than according to predefined time intervals as in preventive maintenance. The aim of this type of maintenance is to continuously monitor the actual condition of the equipment and only carry out maintenance measures when necessary. This maintenance approach optimizes costs and reduces unnecessary activities to replace parts that are still working.

Reliability Centered Maintenance (RCM) – a maintenance concept that focuses on the reliability of equipment by analyzing potential failures and their impact on the entire system. The most important steps in implementing this type of maintenance are identifying the function of the equipment, which includes defining the primary and secondary functions that this equipment must perform; next, recognizing the type of failure of the equipment, which is the function of analyzing how the equipment cannot perform the defined functions; next, determining the cause of the failure to identify the reason for the failure in depth; while the next step considers the evaluation of the consequences of the failure, e.g. on safety, environment, operating costs; while the last step is perhaps the most important because it defines the selection of a maintenance strategy based on the previous steps. The last step in the RCM is crucial as it determines for which equipment a maintenance strategy is defined; it classifies the equipment and assigns it the appropriate maintenance strategy, corrective, preventive, predictive or mixed strategies, strategy by reliability etc.

The main advantage of predictive maintenance over preventive maintenance ultimately lies in reducing the number of maintenance interventions, extending equipment life, knowing the condition of the equipment, achieving significant maintenance savings and increasing reliability and mechanical availability.

Preventive maintenance, as traditionally applied in maintenance management, comes up against certain limits when it comes to optimizing costs and resources. While predictive maintenance reduces downtime and increases availability, reliability and safety by making more efficient use of production facilities.

As modern industrial equipment requires significant mechanical availability, often exceeding 95%, which ultimately leads to higher reliability and has a direct impact on the reduction of operational potential that is not transformed into production impact, predictive maintenance becomes a dominant strategy over other applicable strategies in many manufacturing sectors as it offers various benefits, including a significant reduction in operating costs.

4 THE ROLE OF ARTIFICIAL INTELLIGENCE IN PREDICTIVE MAINTENANCE

Artificial intelligence and machine learning (ML) enable high-precision monitoring of equipment condition parameters and early detection of potential faults that actually indicate future failures based on the analysis of collected data, such as vibration records. The most important AI methods in maintenance include:

- **Machine learning (ML):** includes algorithms such as regression, classification and neural networks which analyze failure history and real-world data and detect early patterns that indicate the occurrence of failures [5].

- **Anomaly detection:** AI models analyze deviations from defined upper and lower limits in machine operation and signal potential failures before failures occur [6].
- **Remaining Useful Life (RUL) estimation:** Various AI models, especially with deep neural networks, enable a realistic estimate of how long a particular component will continue to function before maintenance is required or a failure occurs [7].

The application of artificial intelligence and machine learning significantly improves the efficiency of plant maintenance by enabling condition monitoring and prediction of failures. With the help of data analysis algorithms, AI systems detect defined deviations, predict the service life of components and enable timely interventions before a fault or failure occurs. Deep neural networks (DNN) and recurrent neural networks (RNN) have proven to be very effective in predicting failures and optimizing maintenance [8]. The application of AI models in predictive maintenance enables rapid identification of potential problems and optimization of priorities when performing maintenance in real time. This approach not only reduces costs and unplanned downtime, but also increases the reliability and productivity of industrial plants, making maintenance more proactive and intelligent.

5 INTEGRATING PREDICTIVE MAINTENANCE WITH INDUSTRY 4.0

The development of Industry 4.0 technologies enables new possibilities in the field of predictive maintenance, enabling more accurate and efficient analysis of industrial processes. Modern technologies such as the Internet of Things (IoT), 5G networks and digital twins enable the collection and processing of large amounts of data in real time, increasing the ability to predict potential failures and optimize the maintenance of production processes. The integration of these technologies with artificial intelligence and data analysis further increases the reliability and efficiency of industrial processes. Industry 4.0 technologies such as the Internet of Things (IoT), 5G networks and digital twins further enhance predictive maintenance as follows:

- IoT sensors enable the collection of various data, for example on temperature, vibrations and pressure, which serve as input data for AI algorithms based on which analyzes will be performed [8].
- 5G communication ensures fast data transmission in real time and enables faster response and processing of the data so that the information gains its true meaning [9].
- Digital Twins use real-time data to simulate the operation of industrial systems and predict future problems that can be eliminated in a timely manner [10].

The integration of predictive maintenance with Industry 4.0 technologies enables a positive transformation of traditional maintenance approaches into intelligent and automated systems that can respond in real time, bringing many benefits. By using IoT sensors for data collection, 5G networks for fast information transfer and digital twins for simulating and analyzing plant operations, the industry has the prerequisites for achieving greater efficiency and reducing unplanned downtime. This combination of technologies provides new possibilities for preventive maintenance, especially predictive maintenance, which we can freely call new generation maintenance, adapted to the requirements of modern production and modern industrial facilities.

6 ADVANTAGES AND CHALLENGES OF APPLYING AI IN PREDICTIVE MAINTENANCE OF INDUSTRIAL PLANTS

Maintenance using AI in PdM brings significant benefits, such as reduced downtime, lower maintenance costs and greater safety for production workers. It is certainly important to note the challenges that manufacturing faces when using such technologies, such as the need for high quality data, the complexity of implementation and the need for skilled labor [11].

Some of the benefits highlighted would be: reduced production equipment downtime and operational maintenance costs, increased worker safety, optimization of consumption of available resources, automated decision making based on quantitative data, significantly extended equipment lifespan with reduced cost of replacing consumable parts, while some of the challenges would be the following: integrating AI systems into existing industrial infrastructure, ensuring high quality data for analysis, lack of skilled professionals who can handle AI technologies, security challenges related to digitalization and cyber-attacks on industrial facilities that we are unfortunately experiencing [10].

The application of AI in industry can provide maintenance management staff with the equivalent of an experienced maintenance expert who continuously analyzes all the data collected from the equipment in operation, such as temperature, vibration records, torque, speed and other indicators of the condition of the equipment in operation. In this way, AI can predict and detect various deviations, warn employees in a timely manner and even provide useful insights based on the history of equipment failures using certain analytics.

The perception of the application of AI in maintenance can sometimes be confusing for employees, and after training, it contributes significantly to making informed assessments based on solid “tangible” evidence, and thus to the acceptance of AI “maintenance” employees. Artificial intelligence in predictive analytics transforms 'raw' data into actionable information on which appropriate maintenance decisions are made, usually in real time, before a failure occurs. For example, by analyzing equipment failures in the history of failures, a predictive model can predict future failure patterns, such as failure distribution and the like, which contributes to significant benefits.

7 CONCLUSION

The application of artificial intelligence (AI) in predictive maintenance brings significant benefits to industrial maintenance systems by enabling a reduction in operational maintenance costs, increasing the productivity of production processes and reducing unplanned downtime, which also impacts the bottom line. By using advanced machine learning algorithms, real-time sensor data and Industry 4.0 technologies, predictive maintenance enables accurate analysis of equipment condition and timely action before failures occur.

The application of the Internet of Things (IoT), 5G networks and digital twins in production processes improves the ability to predict and optimize maintenance itself, increasing the reliability of production systems. The advantages are many, but there are also challenges such as the need for high-quality data, the complexity of the implementation itself and the lack of qualified experts, which are often obstacles that must be overcome in order to fully exploit the potential of this technology.

The future of AI in maintenance probably lies in the further development of AI and IoT technologies, with PdM becoming even better, more precise, faster and smarter. The application of generative artificial intelligence (GAI) will enable deeper and more complex data analysis, while quantum computing will significantly accelerate analytical processes and predictions in maintenance. In predictive maintenance, the basis is to obtain data as soon as possible after the occurrence of anomalies and take corrective action before a malfunction occurs, while the future will certainly lie in autonomous robotic systems that perform inspection and repair activities independently, thus reducing the need for human intervention. It can therefore be concluded that AI is not just a tool for improving maintenance, but will shape the future of industrial production and enable fully automated, intelligent management of machines and available resources.

The advancement of artificial intelligence and digital technologies provides the opportunity to further automate and optimize the maintenance of production facilities, making the industry even more efficient, safe and resilient to unpredictable failures. Predictive maintenance based on artificial intelligence is becoming a key tool for modernizing industrial processes and ensuring sustainability and competitiveness in a dynamic industrial environment.

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