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Artificial Intelligence Applications in Predictive Maintenance of Mechanical Systems: A Critical Mini Review

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Abstract: **Artificial Intelligence (AI) has become one of the most influential technologies supporting predictive maintenance in modern mechanical engineering. By combining machine learning algorithms, sensor networks, and Industrial Internet of Things (IIoT) technologies, AI enables continuous equipment monitoring, early fault diagnosis, and accurate estimation of Remaining Useful Life (RUL). Compared with corrective and preventive maintenance strategies, AI-driven predictive maintenance significantly reduces unexpected failures, minimizes downtime, lowers maintenance costs, and improves equipment reliability. This mini-review summarizes recent developments in AI-based predictive maintenance, highlights major engineering applications, discusses current technical challenges, and identifies future research opportunities.**

Keywords: **Artificial Intelligence, Predictive Maintenance, Machine Learning, Mechanical Engineering, Industry 4.0, Condition Monitoring.**

1. INTRODUCTION

Industrial facilities increasingly depend on highly automated mechanical systems operating under demanding conditions. Unexpected equipment failures can lead to production interruptions, increased maintenance costs, safety risks, and reduced operational efficiency. Consequently, maintenance strategies have evolved from corrective maintenance toward intelligent predictive maintenance.

Predictive maintenance uses real-time operational data collected from sensors to determine the actual condition of machinery before failures occur. Recent advances in Artificial Intelligence, cloud computing, Industrial Internet of Things (IIoT), and big-data analytics have significantly enhanced predictive maintenance capabilities. AI algorithms can analyze large volumes of operational data and identify abnormal behavior that may indicate developing mechanical faults.

Mechanical engineers increasingly apply AI-based predictive maintenance to rotating machinery, bearings, pumps, compressors, turbines, HVAC systems, manufacturing equipment, and industrial production lines. These technologies contribute to improved asset reliability while reducing operational expenditure.

2. ARTIFICIAL INTELLIGENCE TECHNIQUES

Several AI algorithms have demonstrated excellent performance in predictive maintenance applications.

2.1 Artificial Neural Networks (ANNs)

Artificial Neural Networks are capable of identifying complex nonlinear relationships between operational parameters and equipment condition. ANNs have been successfully applied to fault diagnosis in bearings, pumps, turbines, and rotating machinery.

2.2 Support Vector Machines (SVMs)

Support Vector Machines provide reliable classification of mechanical faults using relatively small training datasets. Their robustness makes them particularly suitable for industrial condition monitoring.

2.3 Deep Learning

Deep learning models, including Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks, automatically extract meaningful features from vibration signals, acoustic emissions, thermal images, and sensor measurements. These models generally achieve higher diagnostic accuracy than conventional machine learning techniques.

Table 1. Comparison of Common Maintenance Strategies

Maintenance Strategy	Downtime	Maintenance Cost	Reliability
Corrective Maintenance	High	Low initially	Low
Preventive Maintenance	Moderate	Moderate	Moderate
AI-Based Predictive Maintenance	Very Low	Optimized	High

3. ENGINEERING APPLICATIONS

AI-driven predictive maintenance has become increasingly important across numerous mechanical engineering sectors.

Major applications include:

- Rotating machinery monitoring.
- Industrial pumps and compressors.
- Steam and gas turbines.
- HVAC equipment.
- Manufacturing production lines.
- Wind turbines.
- Railway mechanical systems.
- Aerospace propulsion systems.

Continuous monitoring enables maintenance activities to be scheduled before catastrophic failures occur, thereby reducing operational interruptions and extending equipment service life.

4. CRITICAL DISCUSSION

Artificial Intelligence has significantly transformed predictive maintenance; however, several engineering challenges continue to limit widespread industrial implementation.

The first challenge concerns data quality. AI models require large quantities of reliable operational data collected under different working conditions. Missing values, sensor failures, or noisy datasets can reduce prediction accuracy and increase false alarms.

A second challenge is model generalization. Algorithms trained using one machine or operating condition often perform poorly when applied to different equipment. Developing robust AI models capable of adapting to multiple industrial environments remains an active research area.

Cybersecurity is another growing concern. Predictive maintenance systems depend on Industrial Internet of Things (IIoT) communication, cloud computing, and wireless sensor networks. Unauthorized access or cyberattacks may compromise system reliability or disrupt industrial operations.

Finally, many advanced deep learning algorithms operate as black-box models, making engineering interpretation difficult. Explainable Artificial Intelligence (XAI) has therefore become an important research direction because maintenance engineers require understandable diagnostic results before making operational decisions.

Table 2. Engineering Challenges and Recommended Solutions

Engineering Challenge	Recommended Engineering Solution
Poor Data Quality	High-quality industrial sensors and data validation
Limited Model Generalization	Continuous model retraining and adaptive learning
Cybersecurity Risks	Secure communication protocols and encryption
High Computational Cost	Edge computing and cloud optimization
Limited Explainability	Explainable Artificial Intelligence (XAI) techniques

5. CONCLUSION

Artificial Intelligence has become one of the most promising technologies for predictive maintenance within modern mechanical engineering. By integrating machine learning, IIoT, cloud computing, and intelligent sensor networks, AI enables accurate fault diagnosis, reliable Remaining Useful Life (RUL) prediction, and optimized maintenance scheduling.

Compared with conventional maintenance strategies, AI-based predictive maintenance improves equipment availability, reduces maintenance expenditure, enhances operational safety, and increases industrial productivity.

Although challenges related to data quality, cybersecurity, computational complexity, and model interpretability remain, continuous advances in Artificial Intelligence and Industry 4.0 technologies are expected to accelerate industrial adoption. Future research should focus on explainable AI, Digital Twin integration, autonomous maintenance systems, and practical validation under real industrial operating conditions.

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