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COMPREHENSIVE REVIEW OF ARTIFICIAL INTELLIGENCE APPLICATIONS IN THE DIAGNOSIS AND PROGNOSIS OF SHIP POWER SYSTEMS

КОМПЛЕКСНИЙ ОГЛЯД ЗАСТОСУВАНЬ ШТУЧНОГО ІНТЕЛЕКТУ В ДІАГНОСТИЦІ ТА ПРОГНОЗУВАННІ ЕНЕРГЕТИЧНИХ СИСТЕМ СУДЕН

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Abstract. The maritime industry is grappling with significant pressures to enhance ship power plants' efficiency, reliability, and environmental sustainability. As vessels become more sophisticated, the traditional diagnostic and maintenance methods often fall short, unable to adequately address the complexities inherent in these advanced systems. This inadequacy can lead to delayed responses to wear and malfunctions, ultimately jeopardizing operational safety and increasing costs.

This study delves into the transformative potential of artificial intelligence (AI) in revolutionizing diagnostic and predictive capabilities within ship energy systems. By leveraging AI's advanced algorithms, we can process and analyze extensive datasets in real-time, enabling the development of accurate behavioral models that reflect the operational conditions of power plants. This analytical prowess facilitates early fault detection, allowing timely intervention before minor issues escalate into significant failures.

Implementing predictive maintenance strategies powered by AI can dramatically enhance the reliability of maritime power systems. These strategies help anticipate maintenance needs based on real-time data and optimize operational efficiency, resulting in substantial reductions in operational and maintenance costs.

Furthermore, the research highlights various key approaches for successfully integrating AI into maritime systems. This includes examining case studies that illustrate the practical applications of AI technologies, the challenges that may arise during implementation, and the training required for personnel to use these systems effectively. By discussing the benefits and potential hurdles of AI adoption, the study aims to provide a comprehensive understanding of the future landscape of the maritime sector, emphasizing the importance of continued advancements and innovation in this critical field.

Key words: Artificial Intelligence; Ship Power Systems; Predictive Maintenance; Fault Detection; Diagnostic Methods.

Анотація. Зараз морська галузь бореться зі значним тиском щодо підвищення ефективності, надійності та екологічної стійкості суднових енергетичних установок. У міру того, як судна стають все більш складними, традиційні методи діагностики та технічного обслуговування часто виявляються неефективними, не в змозі належним чином усунути складнощі, властиві цим передовим системам. Ця невідповідність може призвести до затримки реагування на знос і несправності, що в кінцевому підсумку ставить під загрозу експлуатаційну безпеку та збільшує витрати.

Це дослідження заглиблюється в трансформаційний потенціал штучного інтелекту (ШІ) у революції діагностичних і прогнозних можливостей у енергетичних системах суден. Використовуючи передові алгоритми штучного інтелекту, ми можемо обробляти й аналізувати великі набори даних у режимі реального часу, уможливлюючи розробку точних моделей поведінки, які відображають робочі умови енергокомплексів. Ця аналітична майстерність полегшує раннє виявлення несправностей, дозволяючи своєчасно втручатися до того, як незначні проблеми переростуть у значні збої.

Впровадження стратегій прогнозного технічного обслуговування на основі ШІ може значно підвищити надійність морських енергетичних систем. Ці стратегії допомагають передбачити потреби в технічному обслуговуванні на основі даних у реальному часі та оптимізувати ефективність роботи, що призводить до значного скорочення витрат на експлуатацію та технічне обслуговування.

Крім того, дослідження висвітлює різні ключові підходи до успішної інтеграції штучного інтелекту в морські системи. Це включає вивчення тематичних досліджень, які ілюструють практичне застосування технологій штучного інтелекту, проблеми, які можуть виникнути під час впровадження, і навчання, необхідне для персоналу для ефективного використання цих систем. Обговорюючи переваги та потенційні перешкоди впровадження штучного інтелекту, дослідження має на меті забезпечити повне розуміння майбутнього ландшафту морського сектору, підкреслюючи важливість постійного прогресу та інновацій у цій критичній галузі.

Ключові слова: штучний інтелект; суднові енергетичні установки; прогнозоване технічне обслуговування; виявлення несправностей; методи діагностики.

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Introduction. The application of artificial intelligence (AI) in the diagnosis and prognosis of ship power systems has gained significant traction over the past few years. This review synthesizes recent advancements in AI methodologies, mainly focusing on deep learning and machine learning techniques, which have been effectively employed to enhance ship power systems' reliability, efficiency, and predictive capabilities. The integration of these technologies is pivotal in addressing the complexities associated with the operation and maintenance of maritime power systems, which are critical for ensuring operational safety and efficiency.

One of the primary areas where AI has made substantial contributions is predictive maintenance (PdM) for ship propulsion engines. Traditional maintenance practices often rely on scheduled inspections, which may not accurately reflect the actual condition of the equipment. Recent studies, such as those by Park and Oh, highlight using machine learning algorithms, specifically principal component analysis and K-nearest neighbors, to establish abnormal data detection algorithms that facilitate predictive maintenance [3]. This approach allows for real-time monitoring and analysis of propulsion systems, thereby reducing downtime and maintenance costs. Forecasting potential failures before they occur is crucial in maritime operations, where unexpected breakdowns can lead to significant operational disruptions and financial losses.

Moreover, deep learning algorithms have emerged as powerful tools for diagnosing faults and predicting power outages in ship power systems. Rizvi's review emphasizes the limitations of traditional rule-based methods and statistical analyses, which often fail to capture the intricate dynamics of power systems [4]. By leveraging deep learning, these algorithms can automatically learn representations from vast datasets, improving the accuracy of fault detection and outage prediction. This capability is particularly beneficial in maritime contexts, where the operational environment is rapidly changing and uncertain.

Applying graph neural networks (GNNs) in power systems is another notable advancement. Liao et al. discuss how GNNs can effectively handle data represented in non-Euclidean domains, which is increasingly relevant in power systems where complex interdependencies among components [2]. This approach allows for a more nuanced understanding of power system dynamics, enabling better decision-making and operational strategies. Integrating GNNs with deep learning techniques has shown promise in enhancing the performance of various tasks, including transient stability assessment and anomaly detection in power systems.

In addition to predictive maintenance and fault detection, AI techniques have also been applied to load forecasting in ship power systems. Sun's research on intelligent grid power load type forecasting demonstrates the effectiveness of combining graph convolutional networks (GCNs) with sequence-to-sequence models and attention mechanisms [5]. This hybrid approach significantly improves the accuracy of load type predictions, which is essential for optimizing power distribution and ensuring the efficient operation of ship power systems. Accurate load forecasting allows for better resource allocation and can help prevent overload situations that may compromise system integrity.

Furthermore, the integration of deep learning with traditional physics-based models has been explored to enhance power system state estimation. Zou's work on power anomaly detection highlights the importance of utilizing deep learning networks to process large volumes of power system data, enabling the identification of anomalies that could indicate underlying issues [7]. This approach not only improves the reliability of power systems but also facilitates timely interventions, thereby enhancing overall operational safety.

The advancements in AI applications for ship power systems are not limited to predictive maintenance and load forecasting. The use of reinforcement learning (RL) has also gained attention for optimizing operational strategies in power systems. For instance, the work by Zhou et al. on intelligent economic dispatch using deep reinforcement learning illustrates how RL can be employed to optimize the management of power grids, thereby improving efficiency and reducing operational costs [6]. This approach is particularly relevant in maritime contexts, where the economic implications of power management are significant.

Moreover, the development of real-time deep learning frameworks for reliability modeling of power electronics converters has been explored. Baharani et al. present a comprehensive approach that integrates deep learning techniques for monitoring and assessing the reliability of power electronic devices in real-time [1]. This capability is crucial for ensuring the continuous operation of ship power systems, where reliability is paramount.

In summary, the last few years have witnessed significant advancements in the application of AI, particularly deep learning and machine learning, in the diagnosis and prognosis of ship power systems. These technologies have demonstrated their potential to enhance predictive maintenance, improve fault detection, optimize load forecasting, and refine operational strategies through reinforcement learning. The integration of these methodologies not only improves the reliability and efficiency of ship power systems but also contributes to the overall safety and sustainability of maritime operations.

Overview of Ship Power Systems Challenges. Modern ship power systems are complex assemblies that ensure the efficient operation of vessels by performing key functions related to energy production, distribution, and consumption. The efficiency and reliability of these systems directly impact shipping economics, environmental safety, and uninterrupted transportation. However, the unique conditions of marine environments create various challenges that complicate the management and maintenance of these systems [8].

One major issue is the wear and tear of equipment. Vessels often operate in high-temperature conditions and are subjected to vibrations, salt water, and other aggressive factors, accelerating the deterioration of power plant components. Critical elements such as engines, heat exchangers, and pumps frequently face failures in challenging situations, potentially leading to serious consequences for the ship and its crew.

Another significant problem is unexpected system failures. Traditional diagnostic methods often fail to identify hidden defects or predict their progression. This inadequacy can result in unscheduled ship stops, costly emergency repairs, and losses due to disruptions in transportation schedules.

Modern vessels have numerous sensors and measuring instruments that generate vast data. Unfortunately, this data often goes underutilized due to the limitations of traditional processing systems. Current diagnostic approaches mainly rely on routine maintenance practices or visual inspections, which are neither sufficiently accurate nor efficient for managing complex power systems.

Moreover, the absence of predictive tools for analyzing system states significantly hinders maintenance optimization. This increases operational costs and elevates the risk of accidents that could harm the environment. This concern is particularly pressing given the strengthening of international standards for the environmental sustainability of shipping [9].

In conclusion, ship power systems urgently require modern technologies that provide timely and accurate diagnostics, predict wear, and manage data effectively. Artificial intelligence, in particular, offers a promising solution to these challenges due to its capability to process large volumes of information, analyze complex patterns, and generate precise predictive models.

Advanced Insights: Utilizing Artificial Intelligence for Ship Engine Diagnostics. Ship engines serve as the pivotal elements of marine power plants, critical for ensuring the ship's safe and continual operation. Operating under demanding conditions—characterized by high loads, extreme temperatures, vibrations, and corrosive marine environments—ship engines are susceptible to malfunctions that can lead to significant repercussions, including unscheduled downtimes, financial setbacks, or potentially severe accidents.

Implementing artificial intelligence (AI) [10] in engine diagnostics can markedly enhance the efficiency of these processes. AI's capability to process and analyze substantial data volumes in real-time enables a spectrum of functions, ranging from early fault detection to automated diagnostics and estimations of remaining useful life for various systems.

A notable advantage of AI systems lies in their proficiency in anomaly detection within operational parameters, utilizing data from onboard sensors that monitor critical metrics such as vibration, temperature, pressure, rotational speed, and fuel consumption. By synthesizing these real-time parameters with historical performance data, AI can establish a baseline for normal operating conditions and pinpoint even minor deviations.

For instance, an elevated vibration amplitude may signal bearing wear or the formation of structural cracks, while atypical temperature profiles may indicate cooling or heat transfer issues. AI systems can detect such anomalies and categorize them based on severity, thus providing the crew with actionable insights for decision-making.

Traditional diagnostic methodologies often require extensive human interaction, inadvertently introducing the potential for human error. Conversely, AI can automate data analysis, minimizing reliance on subjective evaluations. Machine learning algorithms, trained on extensive datasets, allow real-time assessments of the engine's operational state [11].

This capability is particularly crucial for vessels engaged in prolonged voyages without immediate access to repair facilities. An AI-driven automated diagnostic system can give the crew precise reports on engine health, suggest remedial actions, or autonomously implement stabilization measures.

Furthermore, AI can facilitate predictions concerning the remaining lifespan of engines and their components through sophisticated predictive models. These models leverage historical wear data, operating conditions, and performance parameters to guide maintenance planning—not based on rigid schedules but rather on the actual condition of the equipment.

For instance, predictive algorithms can determine the timeframe in which engine components such as bearings, pistons, or valves may approach critical wear limits. This foresight allows crew members or ship operators to proactively obtain spare parts and schedule maintenance, reducing the risk of unexpected operational interruptions.

Integration with Existing Management Systems. AI can be incorporated into the modern control systems of ship power plants, enhancing their functionality. These integrated systems can perform multiple tasks simultaneously, including data collection and analysis, fault scenario modeling, report generation, and recommendations for the crew.

Additionally, the AI system can interact with other ship subsystems, such as automatic control, navigation, or emission control systems, ensuring the coordinated and uninterrupted operation of the entire complex.

The integration of AI into engine diagnostics and control processes contributes to the following:

– Reducing the number of emergencies

– Increasing the economic efficiency of the vessel

– Ensuring compliance with modern environmental standards

Overall, applying AI in the diagnostics of ship engines is a significant step toward developing intelligent energy systems that can self-learn, adapt to changes, and provide high reliability and efficiency [12].

Forecasting the technical condition of ship power systems. Forecasting the technical condition of ship power systems is crucial for ensuring reliability, safety, and economical operation. Traditional forecasting methods often rely on mathematical models that consider average values of equipment operating parameters or follow routine maintenance intervals, which do not reflect the actual condition of components. This outdated approach fails to provide the necessary level of accuracy.

Artificial intelligence significantly enhances prediction capabilities by utilizing data on the actual condition of equipment, operating conditions, and historical performance for precise analysis and forecasting [13].

Modern ship power systems have numerous sensors that record thousands of real-time operating parameters, including temperature, pressure, rotational speed, fuel consumption, and exhaust gas composition. By employing machine learning techniques, large volumes of data can be organized, analyzed, and tapped into to uncover hidden patterns. AI algorithms can construct predictive models to monitor how equipment characteristics change over time and estimate when a specific component will likely reach a critical state. This enables shipowners and crews to plan maintenance at optimal times, minimize unplanned repair costs, and enhance voyage safety by reducing the risk of accidents.

AI-based forecasting of equipment conditions can be implemented using several approaches. Machine learning algorithms, such as random forests, gradient boosting, and support vector machines, allow the system to be trained on historical data concerning component failures and wear. These models can yield highly accurate predictions, even when the available data has significant noise or incompleteness. Deep neural networks are beneficial in analyzing complex relationships between equipment parameters and are very effective for systems with multiple interconnected components, such as ship power plants. Neural networks can learn to predict future malfunctions based on subtle parameter changes that may not be obvious to human observers [14].

The concept of a digital twin involves creating a virtual model of the ship's energy system that operates in parallel with the system. Based on sensor data, this model is updated in real-time, allowing for the simulation of various operating scenarios and identifying potential risks. Applying AI to predict the state of energy systems offers numerous benefits, including reducing accidents through early risk identification, optimizing costs by transitioning from routine to predictive maintenance, enhancing environmental sustainability by optimizing engine performance, and improving overall efficiency since less downtime from unexpected breakdowns leads to increased operational effectiveness.

Some companies are already adopting AI-based forecasting systems [15]. Modern shipping companies utilize big data analysis platforms that integrate with power plant management systems. The outcomes of such technological implementations show significant reductions in accident rates, lower repair costs, and extended component life cycles. Therefore, leveraging AI to predict the technical condition of ship power systems is not merely a technological innovation but a strategic necessity for the shipping industry, which is dedicated to enhancing operational efficiency and safety.

Practical results and examples of AI application in diagnostics and optimization of ship power plants. The use of artificial intelligence (AI) technologies in ship energy represents a promising avenue for enhancing the efficiency of ship power plants, reducing maintenance costs, and improving navigation safety. This section presents specific examples of how AI is applied to diagnose and optimize marine engines and the outcomes of implementing these technologies.

AI technology allows for continuous monitoring of ship engine conditions in real time. Modern marine engines are equipped with numerous sensors that collect vast amounts of data regarding engine operation, including temperature, pressure, vibrations, and rotational speed. The application of machine learning (ML) and deep learning (DL) enables the processing of this data and the creation of predictive models to identify potential technical issues before they arise. For instance, neural networks can recognize patterns in the data indicating the likelihood of future wear or failure of specific engine components, such as pistons or turbochargers. This capability facilitates timely scheduled repairs and minimizes the risk of accidents [16].

Diagnostic systems for marine engines employ algorithms that consider multiple operational parameters. Such systems can analyze data at the component level, including the cooling, lubrication, and starting systems. In real-world applications, the implementation of AI can significantly lower maintenance and repair costs since breakdowns are identified early and can be addressed before escalating into serious issues (fig. 1) [4].

Using AI algorithms to predict the wear of marine engine components is crucial in optimizing maintenance schedules and reducing operating expenses. Machine learning algorithms analyze historical data concerning the condition of ship systems and account for fluctuations in external factors, such as changes in water temperature and wind speed, as well as the operating mode of the ship. Based on this analysis, forecasts are generated regarding when to replace or repair critical engine elements.

This approach prevents premature and delayed maintenance, lowering the costs associated with spare parts and crew working hours. To assess wear and tear, models based on neural networks are employed, analyzing complex relationships among various parameters of the ship's power systems. For instance, a model might identify a correlation between low fuel levels and elevated temperatures in the cooling system, signaling potential issues with heat exchange components. Disparity vessel downtime can be significantly reduced by minimizing the response time to these challenges [16].

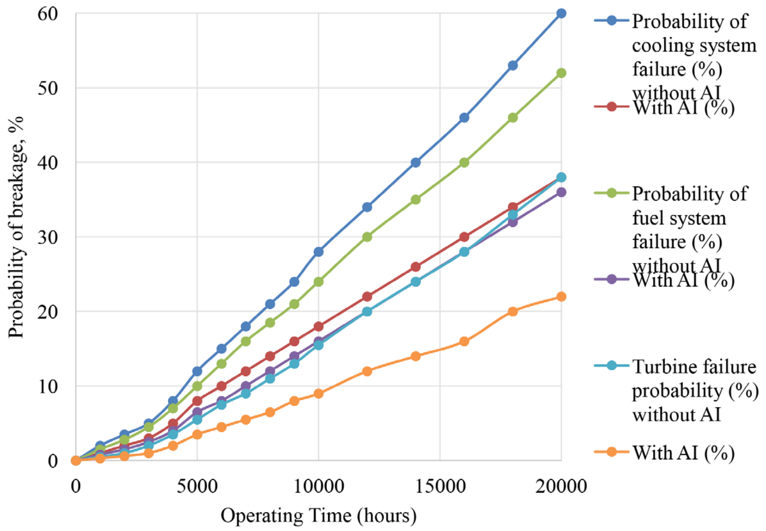

Fig. 1. Distribution of the probability of engine component failure (up to 20,000 engine hours) using AI

A primary objective of utilizing AI in marine energy is to decrease fuel consumption and minimize emissions of harmful substances into the environment. AI models enable the analysis of factors influencing fuel consumption and allow for automated adjustments to engine performance for optimal results. These AI-driven optimization systems consider weather conditions, vessel speed, payload capacity, and engine operational modes to find the best balance between speed, fuel efficiency, and CO_2 emissions. In practical applications, implementing such systems can lead to a 10-15 % reduction in fuel consumption, translating to substantial savings for large shipping companies.

The role of AI in curbing carbon emissions is particularly vital, especially given the pressing need to meet international environmental standards like MARPOL. AI algorithms ensure that systems are optimized concerning low emissions and reduced energy consumption. Consequently, applying AI not only conserves resources but also aids in achieving environmental objectives.

Challenges and Limitations in the Implementation of Artificial Intelligence in Marine Power Systems. Implementing artificial intelligence (AI) within marine power systems presents substantial opportunities for enhancing operational efficiency and reducing costs. However, this transformative process is accompanied by several challenges. One primary concern is the integration of AI technologies with existing ship power plants. Many vessels continue to operate with legacy systems that lack the capacity for requisite data collection and transmission, impeding the effectiveness of AI solutions. Consequently, upgrading these systems necessitates the installation of new sensors and advanced data collection mechanisms, which may entail considerable financial investments.

Moreover, the accuracy and reliability of AI algorithms pose another critical challenge. Inadequately configured systems carry the risk of erroneous diagnoses or misguided decisions, which can adversely affect the operation of power plants. Therefore, it is imperative to implement ongoing monitoring of these systems while conducting extensive testing under real-world conditions to ensure their reliability.

Equally important is the issue of cybersecurity. AI-enhanced ship power systems are susceptible to external threats, leading to severe repercussions, including system failures or losing control over vital components. Thus, developing and implementing robust cybersecurity measures are essential, alongside regular software updates, to mitigate potential cyber risks.

Prospects and Future Trends in the Development of AI in Marine Energy. The evolution of artificial intelligence technologies in maritime energy management catalyzes significant modifications in power plant operations, leading to cost reductions, enhanced efficiency, and improvements in environmental sustainability. Although the potential for AI application in this sector is vast, specific areas emerge as particularly promising for implementation in the foreseeable future.

One critical area of focus involves the integration of AI with emergent energy technologies, such as hydrogen fuel, biofuels, and advanced electrical systems. For instance, hydrogen represents a potentially transformative energy source, as its utilization can markedly decrease greenhouse gas emissions while improving the environmental performance of vessels. AI can optimize operations within such hybrid energy systems, allowing seamless transitions between various energy sources by varying operational conditions and vessel modes. The effective integration of alternative energy sources also necessitates enhancements in AI algorithms to ensure efficient real-time management.

Another promising avenue for AI application is predictive maintenance and technical assessment of energy systems. AI algorithms can analyze data from many sensors to identify early signs of malfunctions or emerging issues. Such monitoring systems continuously evaluate critical components within a ship's power plant, encompassing parameters like exhaust emissions, temperature, pressure, and fluid conditions.

AI systems can detect even minor deviations in engine performance, which may serve as preliminary indicators of potential failures, such as component degradation or cooling system malfunctions. Operators can proactively perform maintenance activities by predicting faults and generating timely alerts, thus minimizing financial losses and unintended vessel downtime.

Furthermore, AI algorithms can optimize maintenance expenditures by forecasting ideal operational conditions. This approach extends the lifespan of power plant components and reduces repairs and spare parts procurement costs.

Conclusions. Artificial intelligence (AI) in marine energy opens up new opportunities for enhancing maritime transportation's efficiency, safety, and environmental sustainability. AI optimizes the operation of ship power plants and facilitates the integration of innovative technologies that reduce emissions and conserve fuel. Additionally, it helps prevent serious breakdowns by allowing for timely detection of malfunctions.

The potential for AI in ship energy is associated with the incorporation of new energy sources, such as hydrogen, and improvements in algorithms for predicting technical conditions and service planning. Particularly, advancements in monitoring and diagnosing marine engine systems can significantly enhance the reliability and durability of power plants while reducing their environmental impact and achieving optimal operating costs.

Furthermore, implementing machine learning and big data analysis technologies enables the creation of adaptive forecasting systems that respond to changing navigation and environmental conditions. This ensures maximum efficiency for power systems and helps reduce maintenance and spare parts costs.

The future of ship power is closely linked to the development and application of AI technologies. AI has the potential to transform the entire structure of energy management on vessels, making them more resilient to changing operating conditions and supporting the sustainable development of the maritime industry. Therefore, integrating AI into ship power systems is essential for achieving higher efficiency, safety, and sustainability standards in marine transportation.

The most impactful application of AI in maritime technology is predictive maintenance, which facilitates early fault detection, enhances operational efficiency, reduces costs, and increases system reliability. By analyzing real-time data, AI can identify potential issues before they escalate, permitting timely intervention and minimizing failures. Through the prediction of maintenance requirements, AI-driven strategies optimize performance and significantly lower operational and maintenance expenses. Furthermore, the integration of AI into marine energy systems improves reliability, a crucial element for the safety and efficiency of maritime operations.

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