International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Review Article)

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AI-enhanced subsea maintenance for improved safety and efficiency: Exploring strategic approaches

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International Journal of Science and Research Archive, 2024, 12(01), 114–124

Publication history: Received on 20 March 2024; revised on 26 April 2024; accepted on 29 April 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.12.1.0766

Abstract

As the oil and gas industry increasingly explores deeper and more remote offshore sites, the maintenance of subsea infrastructure becomes paramount. The use of Artificial Intelligence (AI) in subsea maintenance offers promising solutions to enhance safety and efficiency in these challenging environments. This review explores strategic approaches to integrating AI into subsea maintenance operations. AI facilitates predictive maintenance by analyzing vast amounts of data collected from sensors and historical maintenance records. Machine learning algorithms can detect patterns and predict equipment failures before they occur, enabling proactive maintenance scheduling. This predictive capability reduces downtime and minimizes the risk of accidents by addressing potential issues before they escalate. AI-enabled autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) play a crucial role in subsea inspections and repairs. These AI-enhanced robots can navigate complex subsea environments, perform inspections, and execute maintenance tasks with greater precision and efficiency than human divers. By reducing the need for human intervention in hazardous environments, AI-driven AUVs and ROVs significantly improve safety. Furthermore, AI algorithms can optimize maintenance schedules based on factors such as equipment condition, environmental conditions, and operational requirements. By dynamically adjusting maintenance plans, operators can maximize equipment uptime while minimizing costs and risks. This proactive approach ensures that maintenance activities are conducted at the most opportune times, reducing the likelihood of unplanned downtime and improving overall efficiency. Moreover, AI facilitates condition-based maintenance strategies, where equipment health is continuously monitored in real-time. Sensors installed on subsea infrastructure collect data on factors such as temperature, pressure, and vibration, which is then analyzed by AI algorithms to assess equipment condition. By detecting early signs of degradation or malfunction, AI enables timely interventions, preventing costly breakdowns and ensuring optimal performance. In addition to predictive and condition-based maintenance, AI-driven analytics offer insights into operational performance and asset integrity. By analyzing data from various sources, including sensors, historical records, and operational logs, AI can identify trends, anomalies, and optimization opportunities. These insights enable operators to make data-driven decisions that enhance overall system reliability and efficiency. Strategic approaches to implementing AI in subsea maintenance require collaboration between technology providers, operators, and regulatory bodies. Establishing industry standards and guidelines for AI applications in subsea operations is crucial to ensure safety, reliability, and interoperability. Furthermore, investing in research and development to enhance AI algorithms and robotics technology is essential to unlock the full potential of AI in subsea maintenance. AI-enhanced subsea maintenance offers significant benefits in terms of safety and efficiency. By leveraging predictive analytics, autonomous robotics, and real-time monitoring, operators can optimize maintenance activities, reduce downtime, and minimize risks. Strategic approaches to integrating AI into subsea operations require collaboration, investment, and a commitment to advancing technology to meet the challenges of offshore environments.

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Keywords: Artificial intelligence; Maintenance; Safety; Efficiency; Strategic approaches

1. Introduction

The maintenance of subsea infrastructure is a critical aspect of the oil and gas industry, ensuring the reliability, safety, and efficiency of offshore operations (Olugu *et al*., 2022). Subsea equipment, including pipelines, wellheads, and control systems, is subjected to harsh environmental conditions and operational stresses, making regular maintenance essential to prevent failures, leaks, and environmental damage (Shafiee *et al*., 2020; Ani *et al*. 2024). This review provides an in-depth exploration of the strategic approaches to implementing Artificial Intelligence (AI) for improved safety and efficiency in subsea maintenance. Subsea maintenance is indispensable in the oil and gas industry due to several reasons: asset integrity, safety, environmental protection, operational continuity, regulatory compliance (Ferreira *et al*., 2020).

Artificial Intelligence (AI) refers to the simulation of human intelligence processes by computer systems (Sarker, 2022). AI algorithms can analyze vast amounts of data, identify patterns, and make decisions without explicit human intervention. AI can analyze historical maintenance data and real-time sensor data to predict equipment failures before they occur (Keleko *et al*., 2022). By identifying patterns indicative of impending failures, it enables proactive maintenance scheduling, reducing downtime and minimizing risks. AUVs and ROVs can perform inspections and maintenance tasks in subsea environments with greater precision and efficiency than human divers (McLean *et al*., 2020). These robots can navigate complex underwater terrain and execute tasks such as pipeline inspections, structural repairs, and valve maintenance. AI algorithms can optimize maintenance schedules based on factors such as equipment condition, operational requirements, and environmental conditions (Pinciroli *et al*., 2023). By dynamically adjusting maintenance plans, it ensures that maintenance activities are conducted at the most opportune times, maximizing equipment uptime and minimizing costs. AI enables condition-based maintenance strategies by continuously monitoring equipment health in real-time (Sharma *et al*., 2022). Sensors installed on subsea infrastructure collect data on parameters such as temperature, pressure, and vibration, which is then analyzed by AI algorithms to assess equipment condition (Sandhu *et al*., 2023). By detecting early signs of degradation or malfunction, it facilitates timely interventions, preventing costly breakdowns and ensuring optimal performance.

This review aims to explore strategic approaches to implementing AI for improved safety and efficiency in subsea maintenance operations. By examining various applications of AI, including predictive maintenance, autonomous robotics, optimization of maintenance schedules, and condition-based maintenance, this review will highlight how AI can enhance subsea maintenance practices. Furthermore, the review will discuss the importance of collaboration between stakeholders, establishment of industry standards, investment in research and development, and overcoming challenges to successfully integrate AI into subsea maintenance operations. Ultimately, the goal is to provide insights into how AI can be effectively utilized to ensure the integrity, safety, and efficiency of subsea infrastructure in the oil and gas industry.

2. Predictive Maintenance with AI

Predictive maintenance is an advanced maintenance strategy that utilizes data analysis and machine learning algorithms to predict when equipment failures are likely to occur (Ouadah *et al*., 2022). Unlike traditional maintenance approaches, which rely on scheduled inspections or fixed intervals for maintenance activities, predictive maintenance aims to identify signs of impending equipment failure before it happens. By analyzing data collected from sensors, historical maintenance records, and other sources, predictive maintenance enables proactive interventions to prevent unplanned downtime and optimize maintenance schedules (Pech *et al*., 2021; Omole *et al*., 2024). Artificial Intelligence (AI) plays a crucial role in predictive maintenance by analyzing large volumes of data to detect patterns and anomalies indicative of equipment degradation or impending failures. Predictive maintenance requires access to relevant data sources, including sensor data, maintenance records, equipment specifications, and environmental conditions. Sensors installed on subsea equipment continuously monitor parameters such as temperature, pressure, vibration, and corrosion levels, providing real-time data for analysis. Raw data collected from sensors may contain noise, outliers, or missing values, which need to be processed before analysis. AI algorithms preprocess the data by cleaning, filtering, and normalizing it to ensure accuracy and consistency (Maharana *et al*., 2022). AI algorithms extract meaningful features from the preprocessed data to represent equipment health and performance. These features may include statistical measures, frequency domain analysis, or domain-specific features relevant to subsea operations. Machine learning algorithms, such as supervised learning, unsupervised learning, or reinforcement learning, are trained using historical data to learn patterns indicative of equipment failures (Bao and Li, 2021). During training, the algorithm adjusts its parameters to minimize prediction errors and optimize performance. Once trained, the AI model can predict future equipment failures based on new data inputs. The model analyzes current sensor readings and compares them to learned patterns to identify deviations or anomalies that may signal potential failures. Based on the predictions generated by the AI model, maintenance recommendations are generated, indicating the likelihood of equipment failure and the recommended actions to be taken. These recommendations can include scheduling preventive maintenance, replacing components, or adjusting operational parameters to mitigate risks. Predictive maintenance offers several benefits for subsea operations: By predicting equipment failures before they occur, predictive maintenance minimizes unplanned downtime, ensuring continuous operation of subsea infrastructure and maximizing production uptime (Olowe and Adebayo, 2015; Yazdi, 2024). Predictive maintenance reduces the need for emergency repairs and costly equipment replacements by enabling proactive interventions. This results in significant cost savings compared to reactive maintenance approaches. By identifying potential equipment failures in advance, predictive maintenance helps mitigate safety risks associated with subsea operations (Jimenez *et al*., 2020). Proactive maintenance interventions prevent accidents and hazardous situations, ensuring the safety of personnel and the environment. Predictive maintenance optimizes the reliability and performance of subsea equipment by addressing issues before they escalate. This extends the lifespan of equipment and improves overall operational efficiency. Predictive maintenance provides valuable insights into equipment health and performance, enabling data-driven decision making. Operators can prioritize maintenance activities, allocate resources efficiently, and optimize operational strategies based on predictive analytics (Ong *et al*., 2021).

Shell's Prelude FLNG Project: Shell implemented predictive maintenance on its Prelude Floating Liquefied Natural Gas (FLNG) facility, located off the coast of Western Australia (Purcell and Longley, 2023). Using AI and predictive analytics, Shell monitors the health of critical equipment such as compressors, turbines, and pumps in real-time. By analyzing data from thousands of sensors, the predictive maintenance system identifies potential equipment failures and recommends proactive maintenance actions. This approach has helped Shell minimize downtime and optimize maintenance schedules, ensuring the reliability and efficiency of the Prelude FLNG facility. BP's Thunder Horse Platform: BP utilizes predictive maintenance on its Thunder Horse semi-submersible platform in the Gulf of Mexico (Zhao, 2022). AI algorithms analyze sensor data from various equipment, including blowout preventers, subsea pipelines, and production risers, to predict equipment failures and optimize maintenance activities. By implementing predictive maintenance, BP has reduced maintenance costs, improved equipment reliability, and enhanced safety performance on the Thunder Horse platform. Equinor's Mariner Field: Equinor implemented predictive maintenance on its Mariner Field, located in the UK North Sea (Singh *et al*., 2023). Using AI-driven analytics, Equinor monitors the condition of subsea equipment, including wellheads, control systems, and umbilicals, to predict maintenance needs and optimize operational efficiency. By proactively addressing potential equipment failures, Equinor has reduced downtime, increased production uptime, and improved safety performance on the Mariner Field. These case studies demonstrate the effectiveness of predictive maintenance in subsea operations, highlighting its role in optimizing asset performance, minimizing risks, and enhancing operational efficiency. By leveraging AI and predictive analytics, oil and gas operators can achieve significant benefits in terms of reliability, safety, and cost-effectiveness in subsea maintenance (Odili *et al*., 2024).

3. Autonomous Robotics in Subsea Maintenance

Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) are sophisticated robotic systems designed for underwater exploration, inspection, and maintenance tasks in subsea environments (Petillot *et al*., 2019; Adeleke *et al*., 2024). AUVs are self-propelled, untethered vehicles equipped with sensors, navigation systems, and propulsion systems, which operate independently, following pre-programmed missions or autonomously navigating underwater environments. They are designed for long-endurance missions and can reach depths ranging from a few meters to several thousand meters, and are equipped with various sensors, including sonar, cameras, and environmental sensors, to collect data on underwater topography, marine life, and environmental conditions (Eleftherakis and Vicen-Bueno, 2020). Remotely Operated Vehicles (ROVs) are tethered underwater vehicles controlled by operators from the surface using a cable connected to a control console, equipped with cameras, lights, manipulator arms, and sensors, allowing operators to perform detailed inspections and maintenance tasks. ROVs can operate at greater depths than AUVs and are commonly used for complex tasks such as pipeline inspections, subsea equipment installations, and repairs (Dalhatu *et al*., 2023). They are widely used in the offshore oil and gas industry, marine research, and underwater infrastructure inspections.

AI algorithms enable AUVs to navigate autonomously through complex underwater environments by processing sensor data and making real-time navigation decisions (Cai *et al*., 2023). Machine learning algorithms allow AUVs to learn from previous missions and adapt their navigation strategies based on environmental conditions, obstacles, and mission objectives. AI-driven path planning algorithms optimize the trajectory of AUVs and ROVs to efficiently cover the target area and avoid obstacles. These algorithms take into account factors such as current, depth, terrain, and mission objectives to generate optimal paths for navigation and inspection. AI algorithms enable AUVs and ROVs to recognize and classify underwater objects, such as pipelines, wellheads, and marine life, from sensor data. Computer vision techniques, combined with machine learning, allow AUVs and ROVs to identify and track objects of interest, enabling precise inspection and maintenance tasks (Macaulay and Shafiee, 2022.). AI-powered manipulation systems enable ROVs to perform complex tasks, such as valve operations, tool manipulation, and equipment repairs, autonomously. These systems use computer vision, sensor feedback, and machine learning to control manipulator arms and tools with precision in subsea environments. AUVs equipped with sensors and cameras can conduct autonomous inspections of subsea pipelines to detect corrosion, leaks, and structural defects. AI algorithms analyze inspection data in real-time to identify anomalies and prioritize maintenance interventions. ROVs equipped with manipulator arms and tools can perform maintenance tasks on subsea equipment, such as valve operations, bolt tightening, and component replacements. AI-driven manipulation systems enable ROVs to execute maintenance tasks autonomously, reducing the need for human intervention in hazardous environments. AUVs equipped with sonar and imaging systems can assess the structural integrity of offshore platforms, subsea structures, and underwater installations (Huy *et al*. 2023). AI algorithms analyze imaging data to identify cracks, corrosion, and fatigue damage, providing insights into the health of subsea structures. AUVs equipped with environmental sensors can monitor water quality, temperature, and marine life in subsea environments. AI algorithms analyze environmental data to assess the impact of offshore operations on marine ecosystems and identify potential environmental risks.

Autonomous robotics minimize the need for human divers to perform dangerous tasks in hazardous subsea environments, reducing the risk of accidents and injuries (Brett, 2022). AUVs and ROVs can operate continuously for extended periods, covering large areas and performing repetitive tasks with high efficiency. AI-driven automation reduces the time and resources required for subsea inspections and maintenance, improving operational efficiency. AI algorithms enable precise navigation, object recognition, and manipulation in subsea environments, ensuring accurate inspections and maintenance interventions (O'Byrne *et al*., 2020). Autonomous robotics reduce the cost of subsea maintenance by minimizing downtime, optimizing maintenance schedules, and eliminating the need for costly offshore interventions. Autonomous robotics enable proactive environmental monitoring and maintenance, helping to minimize the environmental impact of offshore operations and prevent pollution incidents. Autonomous robotics, enhanced by AI, offer advanced solutions for subsea maintenance, inspection, and monitoring. AUVs and ROVs equipped with AI-driven capabilities can autonomously navigate complex underwater environments, perform precise inspections, and execute maintenance tasks with efficiency and accuracy (Tosello *et al*., 2024; Chukwurah and Aderemi, 2024). By leveraging autonomous robotics, the oil and gas industry can improve safety, increase operational efficiency, and ensure the integrity of subsea infrastructure in challenging offshore environments.

4. Optimization of Maintenance Schedules with AI

Subsea equipment is critical for offshore operations, and any downtime can lead to significant production losses (Shafiee *et al*., 2020). Optimized maintenance schedules ensure that maintenance activities are conducted at the most opportune times, minimizing disruptions and maximizing equipment uptime. Efficient maintenance scheduling helps in reducing operational costs by avoiding unnecessary downtime and minimizing the need for emergency repairs. By optimizing maintenance schedules, operators can allocate resources more effectively, reducing maintenance-related expenses. Regular maintenance is essential for preserving the integrity and lifespan of subsea equipment. Optimized maintenance schedules ensure that equipment is serviced and maintained in a timely manner, preventing premature degradation and extending its operational lifespan. Well-planned maintenance schedules contribute to improved safety by reducing the likelihood of equipment failures and accidents. Proactive maintenance interventions mitigate risks associated with subsea operations, ensuring the safety of personnel and the environment. Regulatory bodies impose strict standards and regulations on subsea operations to ensure safety and environmental protection. Optimized maintenance schedules help operators comply with regulatory requirements by ensuring that equipment is maintained according to prescribed standards and guidelines (Vrana and Singh, 2021.).

Artificial Intelligence (AI) algorithms optimize maintenance schedules by analyzing various factors and making data-driven decisions to determine the most efficient maintenance strategies (Cheng *et al*., 2020). The process involves the following steps: data collection, data preprocessing, feature selection predictive modeling, optimization algorithms, and real-time adaptation.

AI algorithms consider the current health and condition of subsea equipment, as assessed by sensor data and predictive analytics. Maintenance schedules are adjusted based on equipment degradation, failure probabilities, and performance metrics. Maintenance schedules are tailored to meet operational requirements, taking into account factors such as production schedules, equipment availability, and downtime allowances (George *et al*., 2022). AI algorithms prioritize maintenance activities to minimize disruptions and maintain operational continuity. AI algorithms optimize maintenance schedules based on resource availability, including personnel, equipment, materials, and support vessels. Maintenance activities are scheduled to coincide with resource availability, minimizing delays and resource conflicts. Maintenance schedules are adapted to environmental conditions, such as weather, sea state, and visibility. AI algorithms consider environmental factors to ensure the safety and effectiveness of maintenance operations. Also optimized to minimize costs while meeting maintenance objectives. AI algorithms consider cost factors such as labor costs, equipment rental costs, material costs, and opportunity costs associated with downtime. By scheduling maintenance activities at the most opportune times, optimized maintenance schedules minimize downtime and maximize equipment uptime, ensuring continuous operation and production efficiency. Efficient maintenance scheduling helps in reducing maintenance-related expenses by minimizing the need for emergency repairs, overtime labor, and expedited shipping of spare parts. Cost savings are achieved through better resource allocation and reduced downtime. Optimized maintenance schedules contribute to extending the lifespan of subsea equipment by ensuring that maintenance is performed in a timely manner (Ferreira *et al*., 2020). Preventive maintenance interventions prevent premature degradation and reduce the frequency of costly repairs. Well-planned maintenance schedules improve operational efficiency by minimizing disruptions, optimizing resource utilization, and streamlining maintenance activities. Operations run smoother, and productivity is increased as a result. Optimized maintenance schedules enhance safety by reducing the risk of equipment failures and accidents. Proactive maintenance interventions mitigate safety risks, ensuring compliance with regulatory requirements and industry standards (Sonko *et al*., 2024). AI-driven maintenance scheduling enables data-driven decision making by providing insights into equipment health, maintenance needs, and operational requirements. Operators can make informed decisions to optimize maintenance strategies and allocate resources efficiently. Optimization of maintenance schedules with AI offers significant benefits in terms of efficiency, cost savings, and operational performance in subsea operations. By leveraging AI algorithms to analyze data, forecast maintenance requirements, and optimize scheduling decisions, operators can maximize equipment uptime, reduce maintenance costs, and enhance safety and compliance in challenging offshore environments (Ohalete *et al*., 2023; Adelani *et al*., 2024).

5. Condition-Based Maintenance Strategies

Condition-Based Maintenance (CBM) is a maintenance strategy that involves monitoring the condition of equipment in real-time to determine when maintenance should be performed (Teixeira *et al*., 2020). Instead of performing maintenance at fixed intervals or when equipment fails, CBM relies on data collected from sensors and other monitoring systems to assess the health and performance of equipment. By analyzing this data, maintenance activities are planned and executed only when necessary, optimizing maintenance efforts and reducing downtime (Olowe *et* al., 2017; Khalid *et al*., 2021). Artificial Intelligence (AI) plays a crucial role in enabling condition-based maintenance by providing advanced analytics and decision-making capabilities. The key roles of AI in CBM include: Analyze data collected from sensors, equipment logs, and other sources to assess equipment condition and predict potential failures. Machine learning algorithms can detect patterns, trends, and anomalies in the data, providing insights into the health of the equipment. Predictive maintenance by forecasting equipment failures based on historical data and real-time sensor readings. By analyzing patterns indicative of impending failures, AI algorithms can predict when maintenance should be performed to prevent breakdowns and optimize equipment performance. Detect anomalies in equipment behavior or performance, signaling potential issues that require attention. By comparing current data to normal operating conditions, AI can identify deviations that may indicate underlying problems, allowing for proactive maintenance interventions. Provides decision support for maintenance planning and scheduling by recommending appropriate actions based on the analysis of equipment condition and performance data (Sedghi *et al*., 2021). AI algorithms prioritize maintenance tasks, allocate resources efficiently, and optimize maintenance schedules to minimize downtime and maximize equipment uptime.

Sensors installed on equipment continuously monitor parameters such as temperature, pressure, vibration, and fluid levels (Javaid *et al*., 2021). These sensors collect real-time data, providing insights into the condition and performance of the equipment. Sensor data is collected and transmitted to a central monitoring system, where it is stored and analyzed. Advanced data acquisition systems ensure that data is captured accurately and in real-time, allowing for timely analysis and decision-making. AI algorithms analyze the collected data to assess equipment condition, detect anomalies, and predict potential failures. Data analysis techniques, such as statistical analysis, machine learning, and pattern recognition, provide insights into the health and performance of the equipment (Rajula *et al*., 2020). AI-driven diagnostic tools identify the root causes of equipment issues by correlating sensor data with known failure modes and patterns. These tools help maintenance teams understand the underlying causes of problems and take appropriate corrective actions. AI generates prognostic models that predict future equipment performance and maintenance needs based on current and historical data. These models forecast equipment degradation, remaining useful life, and failure probabilities, enabling proactive maintenance planning and scheduling.

CBM minimizes downtime by performing maintenance only, when necessary, based on the actual condition of the equipment (Acernese *et al*., 2021). By avoiding unnecessary maintenance activities, equipment downtime is reduced, and production uptime is maximized. It reduces maintenance costs by optimizing maintenance efforts and avoiding unnecessary repairs and replacements. By focusing resources on critical maintenance tasks, costs associated with labor, spare parts, and equipment downtime are minimized. Helps in extending the lifespan of equipment by identifying and addressing issues before they escalate. Proactive maintenance interventions prevent premature degradation and reduce the frequency of costly repairs, ensuring the long-term reliability and performance of equipment (Zhang *et al*., 2022). CBM enhances safety by reducing the risk of equipment failures and accidents. Proactive maintenance interventions mitigate safety risks associated with equipment malfunctions, ensuring the safety of personnel and the environment. It improves operational efficiency by optimizing maintenance schedules and resources. By performing maintenance only, when necessary, operational disruptions are minimized, and productivity is increased. Also enables data-driven decision making by providing real-time insights into equipment condition and performance. Operators can make informed decisions based on predictive analytics and diagnostic information, optimizing maintenance strategies and resource allocation. Condition-Based Maintenance strategies, enabled by AI, offer significant advantages over traditional approaches by providing real-time insights into equipment condition, predicting potential failures, and optimizing maintenance efforts. By leveraging AI-driven analytics and real-time monitoring systems, operators can maximize equipment uptime, reduce maintenance costs, and enhance safety and reliability in industrial environments (Olowe and Kumarasamy, 2021; Ohalete *et al*., 2023).

6. AI-Driven Analytics for Operational Insights

AI-driven analytics in subsea maintenance involve the use of advanced algorithms and techniques to analyze large volumes of data collected from various sources (Kirschbaum *et al*., 20220). These analytics provide valuable insights into equipment health, operational performance, and maintenance needs, enabling operators to make informed decisions and optimize maintenance strategies. The key components of AI-driven analytics in subsea maintenance include data collection, preprocessing, analysis, and decision support. Sensors installed on subsea equipment collect data on parameters such as temperature, pressure, vibration, and fluid flow rates. This sensor data provides real-time insights into equipment condition and performance. Historical maintenance records contain information about past maintenance activities, equipment failures, and repair histories (Pinto *et al*., 2020). Analyzing this data helps in identifying trends and patterns in equipment behavior. Operational logs record operational parameters, production data, and system status information. Analyzing operational logs provides insights into equipment usage, performance, and efficiency. Environmental data, including weather conditions, sea state, and water quality, is collected to assess the impact of environmental factors on subsea operations. Imaging and video data captured by cameras and sonar systems provide visual information about subsea equipment, structures, and marine life.

AI-driven analytics assess the health of subsea equipment by analyzing sensor data and identifying anomalies indicative of equipment degradation or malfunctions (Pagar *et al*., 2023). It predicts equipment failures and maintenance needs based on historical data and real-time sensor readings. Predictive analytics help in scheduling maintenance activities proactively, minimizing downtime and optimizing maintenance efforts. AI-driven analytics optimize equipment performance by analyzing operational data and identifying opportunities for efficiency improvements. Insights gained from analytics help in optimizing operational parameters and reducing energy consumption. AI algorithms detect faults and diagnose equipment issues by analyzing sensor data and identifying abnormal patterns. Diagnostic analytics help in identifying the root causes of problems and taking corrective actions. AI-driven analytics assess the impact of environmental conditions on subsea operations by analyzing environmental data (Hussain *et al*., 2024). Insights gained from analytics help in mitigating environmental risks and ensuring compliance with regulatory requirements. Data-driven decisions are based on real-time data and advanced analytics, ensuring accuracy and reliability. Relying on data-driven insights, operators can make informed decisions that lead to better outcomes. It enables proactive maintenance interventions based on predictive analytics. Identifying potential issues before they escalate, operators can prevent downtime and optimize maintenance efforts. Help in optimizing maintenance strategies and resource allocation, resulting in cost savings. Focusing resources on critical maintenance tasks and avoiding unnecessary repairs, operators can reduce maintenance costs. Contribute to improved safety by identifying safety risks and taking preventive measures. By analyzing operational data and identifying potential hazards, operators can mitigate safety risks and ensure the safety of personnel and the environment. Also helps in ensuring compliance with regulatory requirements and industry standards. Analyzing data and identifying areas of non-compliance, operators can take corrective actions to meet regulatory requirements and avoid penalties. AI-driven analytics provide valuable insights into equipment health, operational performance, and maintenance needs in subsea maintenance (Chelliah *et al*., 2023). By analyzing data collected from sensors, historical records, and operational logs, AI-driven analytics enable operators to make informed decisions, optimize maintenance strategies, and enhance safety and efficiency in subsea operations. Data-driven decision making is crucial for proactive maintenance, cost reduction, safety improvement, and regulatory compliance in subsea maintenance.

7. Strategic Approaches to Implementing AI in Subsea Maintenance

Collaboration between stakeholders, including operators, technology providers, and regulatory bodies, is crucial for the successful implementation of AI in subsea maintenance (Johansson *et al*., 2021). Operators of offshore facilities play a key role in driving the adoption of AI in subsea maintenance. They provide domain expertise, data, and operational insights necessary for developing effective AI solutions. Operators should collaborate with technology providers to define requirements, validate solutions, and integrate AI into existing workflows. Technology providers develop AI solutions tailored to the needs of subsea maintenance. They leverage expertise in AI, data analytics, and subsea engineering to develop innovative solutions that improve efficiency and reliability. Collaboration with operators helps technology providers understand specific challenges and requirements, ensuring that AI solutions meet industry needs (Arinze *et al*., 2024). Regulatory bodies oversee offshore operations and set standards and guidelines to ensure safety, environmental protection, and compliance. Collaboration with regulatory bodies is essential for establishing regulatory frameworks for AI applications in subsea maintenance. Regulatory bodies should work with operators and technology providers to develop guidelines for AI implementation, validation, and compliance.

The establishment of industry standards and guidelines is critical for ensuring the safe and effective implementation of AI in subsea maintenance. SDOs, such as the International Organization for Standardization (ISO) and the American Petroleum Institute (API), develop standards and guidelines for the oil and gas industry (Watkins *et al*., 2023). SDOs should collaborate with operators, technology providers, and regulatory bodies to develop standards specific to AI applications in subsea maintenance. Industry organizations and consortia should develop guidelines for AI applications in subsea maintenance. These guidelines should cover aspects such as data quality, model validation, cybersecurity, and ethical considerations. By following standardized guidelines, operators and technology providers can ensure the reliability and safety of AI solutions. Certification programs should be established to certify AI solutions for use in subsea maintenance, ensures that AI solutions meet industry standards and regulatory requirements. Certification bodies should work closely with operators, technology providers, and regulatory bodies to develop certification criteria and processes (Matus and Veale, 2022).

Investment in research and development (R&D) is essential for advancing AI technology and developing innovative solutions for subsea maintenance (Koroteev and Tekic, 2021). Public-private partnerships (PPPs) facilitate collaboration between government agencies, industry, and academia to fund R&D initiatives. PPPs provide funding and resources for research projects focused on developing AI solutions for subsea maintenance. These projects explore topics such as predictive analytics, autonomous robotics, and data-driven decision-making. Industry consortia bring together operators, technology providers, and research institutions to collaborate on R&D projects. Consortia pool resources and expertise to fund and conduct R&D initiatives focused on addressing common challenges in subsea maintenance (Guinn and Castille, 2021,). By sharing knowledge and best practices, consortia accelerate the development and adoption of AI solutions. Academic institutions conduct research on AI technologies and their applications in subsea maintenance. Universities collaborate with industry partners to address real-world challenges and develop cutting-edge solutions. Academic research contributes to the advancement of AI technology and the development of new algorithms, methodologies, and tools.

Data quality and availability are key challenges in AI implementation. Subsea environments pose challenges for data collection, and data quality may be compromised due to sensor limitations or environmental factors. Operators should invest in data collection systems and processes to ensure data quality and availability for AI applications. Cybersecurity is a significant concern in AI implementation, as AI systems may be vulnerable to cyberattacks (Guembe *et al*., 2022). Operators should implement cybersecurity measures to protect AI systems from unauthorized access, data breaches, and manipulation. This includes encryption, access control, and intrusion detection systems. AI implementation requires specialized skills and expertise. Operators and technology providers should invest in training programs to build the skills of personnel involved in AI development, deployment, and operation (Wang *et al*., 2022). Training programs should cover topics such as AI algorithms, data analytics, and cybersecurity. Ethical and regulatory considerations must be addressed to ensure the responsible use of AI in subsea maintenance. Operators and technology providers should adhere to ethical guidelines and regulatory requirements related to data privacy, transparency, and accountability. Regulatory bodies should develop guidelines for AI applications in subsea maintenance and ensure compliance with existing regulations (Amaechi *et al*., 2022). By addressing these challenges and barriers through collaboration, standards development, investment in R&D, and training, the industry can successfully implement AI in subsea maintenance. AI-driven solutions have the potential to improve efficiency, reliability, and safety in subsea operations, leading to significant benefits for operators and the industry as a whole (Olajiga *et al*., 2024).

8. Conclusion

In conclusion, the adoption of AI-enhanced subsea maintenance represents a significant advancement in the oil and gas industry, offering numerous benefits in terms of efficiency, safety, and reliability. By leveraging AI technologies, operators can optimize maintenance strategies, improve equipment uptime, and enhance operational performance in challenging subsea environments. AI-driven analytics and predictive maintenance enable proactive interventions, minimizing downtime and optimizing maintenance efforts. By predicting equipment failures and identifying safety risks, AI helps in preventing accidents and ensuring the safety of personnel and the environment. AI-driven maintenance strategies reduce maintenance costs by optimizing schedules, avoiding unnecessary repairs, and extending equipment lifespan. AI-driven analytics provide insights into equipment health and performance, allowing operators to address issues before they escalate and improve overall reliability. AI enables data-driven decision making by providing real-time insights into equipment condition, operational performance, and maintenance needs. To fully realize the benefits of AI in subsea operations, a strategic approach to implementation is essential. Operators, technology providers, and regulatory bodies must collaborate to adopt the following strategic approaches: Foster collaboration between stakeholders to define requirements, develop solutions, and establish industry standards and guidelines for AI applications in subsea maintenance. Invest in research and development initiatives to advance AI technology and develop innovative solutions tailored to the needs of subsea maintenance. Provide training programs to build the skills and expertise necessary for AI implementation, including AI algorithms, data analytics, cybersecurity, and ethical considerations. Establish industry standards and certification programs to ensure the reliability, safety, and compliance of AI solutions for subsea maintenance. Embrace a culture of continuous improvement to evolve AI-driven maintenance strategies and adapt to changing operational needs and technological advancements. The integration of AI with autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) will revolutionize subsea maintenance, enabling autonomous inspections, repairs, and maintenance tasks. Edge computing technology will enable real-time processing and analysis of sensor data at the source, reducing latency and enabling faster decision-making in subsea environments. Predictive analytics will become more sophisticated, leveraging machine learning and artificial intelligence to predict equipment failures with greater accuracy and reliability. Digital twin technology will enable operators to create virtual models of subsea assets, allowing for simulation, monitoring, and optimization of maintenance activities in real-time. Integration with the Internet of Things (IoT) will enable seamless connectivity between sensors, equipment, and AI-driven analytics platforms, facilitating data-driven decision-making and optimization of maintenance strategies. AI holds great promise for revolutionizing subsea maintenance, offering benefits such as improved efficiency, enhanced safety, and cost savings. By adopting strategic approaches to implementation and embracing emerging technologies, the industry can unlock the full potential of AI in subsea operations, paving the way for a safer, more reliable, and more efficient future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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