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Review

Remote Non-Destructive Testing of Port Cranes: A Review of Vibration and Acoustic Sensors with IoT Integration

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Abstract

Safe and efficient operation of port cranes is vital for maintaining the efficiency of global maritime logistics. However, traditional non-destructive testing methods face significant limitations in harsh port environments, such as periodic inspection intervals, restricted access to structural components, and a lack of real-time monitoring. This review explores the emerging paradigm of remote non-destructive testing through the integration of vibration and acoustic emission sensors with Internet of Things platforms. By enabling continuous, real-time monitoring, these sensor systems can detect early indicators of mechanical degradation, structural fatigue, and corrosion. This study synthesizes findings from over 100 peer-reviewed sources and identifies a significant gap in the application of these technologies to port cranes. Although vibration and acoustic emission sensors have been widely studied in various fields, their application to port cranes remains underexplored, presenting a novel and promising avenue for future research and practical applications. The unique operational demands and structural complexities of port cranes, coupled with their critical role in global trade logistics, make them ideal for leveraging these sensors in tandem with Internet of Things solutions. This integration not only overcomes the limitations of traditional non-destructive testing methods, but also offers substantial benefits, including enhanced safety, reduced inspection costs, and improved operational efficiency. This review concludes by proposing future research directions to enhance sensor performance, data analytics, and Internet of Things integration, paving the way for predictive maintenance strategies that increase operational uptime and improve safety in port crane operations.

Keywords: acoustic emission testing; vibration sensor; non-destructive testing; Internet of Things; real-time monitoring

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1. Introduction

In the intricate web of global trade and maritime logistics, port cranes have emerged as critical linchpins, ensuring the seamless and efficient transfer of cargo containers between ships and the shore. They are the unsung heroes of the supply chain and work tirelessly to meet the ever-increasing demands of international trade. These cranes are marvels of engineering and are composed of a sophisticated array of components, such as booms, jibs, cables, trolleys, and slewing bearings. Each component plays a vital role in the precise handling of heavy loads. The boom rises significantly from a robust base, providing the necessary height and reach, whereas the jib extends with remarkable accuracy. Cables and trolleys work in perfect harmony to lift and move cargo, and slewing bearings enable the crane to rotate precisely to align with ship positions [1]. A visual representation of the key structural and functional components of a modern ship-to-shore crane is provided in Figure 1 for clarity and reference.

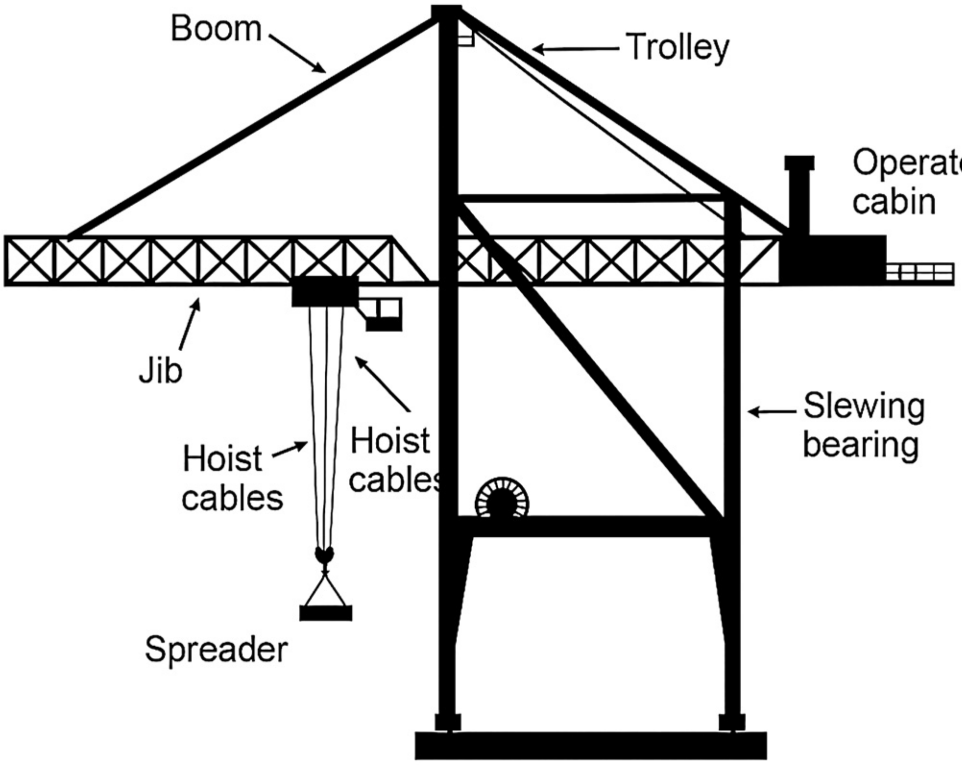

Figure 1. Key components of a modern ship-to-shore crane.

However, this complexity renders port cranes vulnerable to wear and tear. The relentless cycle of lifting heavy loads, the dynamic stresses of acceleration and deceleration, and corrosive marine environments gradually degrades their structural and mechanical integrity [2]. As international trade continues to expand and port operations intensify, the impact of crane downtime has become increasingly severe. Operational downtime in port cranes can impede cargo handling efficiency, leading to delays in port activities and broader disruptions across the logistics chain [3]. Therefore, implementing effective condition monitoring and maintenance strategies is essential to uphold the reliability and safety of crane operations.

Traditional non-destructive testing (NDT) techniques are typically periodic, manual inspections that detect surface or internal flaws in structural components. In contrast, structural health monitoring (SHM) employs permanently installed sensors to continuously track structural behavior and integrity over time. Remote non-destructive testing (RNDT) represents an emerging paradigm that merges the diagnostic precision of NDT with the continuous sensing of SHM, enhanced through Internet of Things (IoT) integration. In this context, the use of vibration and acoustic emission (AE) sensors, networked via IoT platforms, offers real-time insight into port crane health. Vibration sensors identify dynamic anomalies such as gear misalignment or bearing wear, while AE sensors detect stress waves associated with crack initiation or material degradation. Through IoT-enabled data acquisition and analysis, RNDT enables predictive maintenance, allowing port operators to intervene before minor faults evolve into critical failures or unscheduled outages.

A review of 100 journal articles shows that while vibration and AE sensors have been widely studied in various fields, their application to port cranes is still limited. Although a few studies have lightly touched on related topics, integrated research on applying these sensors to port cranes in conjunction with the IoT is still in its infancy. Given the current state of technology, combining vibration and AE sensors with IoT for port crane monitoring is not only novel, but also practical and feasible. This approach could significantly enhance the safety and reliability of port operations, reduce inspection costs, and improve operational efficiency, thereby providing substantial benefits to the port industry.

2. Port Cranes Overview

In the port operation system, port cranes serve as core equipment, and their stable operation is directly related to the material transfer efficiency of global trade. With the continuous increase in international trade volume, port operations have become busier, placing higher demands on crane performance and reliability. In this context, it is important to have an in-depth understanding of all aspects of port cranes.

At a fundamental level, port cranes are of various types, each with unique design, functions, and application scenarios. They jointly form the cornerstone of efficient port operation. Meanwhile, looking back on the development history of port cranes, we can clearly observe how technological progress has continuously driven innovation in this field, evolving from simple manual devices in the early days to highly complex and intelligent large-scale machinery. In the actual operation process, mechanical and structural defects have always been key factors affecting the safety and efficiency of port cranes. Conducting an in-depth analysis of these problems is an important prerequisite to exploring effective solutions.

2.1. Types of Port Cranes

In the vast tapestry of global maritime logistics, port cranes serve as the backbone of cargo handling operations, and each type is meticulously designed to meet specific operational demands. These cranes, which vary in their design, mobility, and operational requirements, are tailored to handle diverse cargo types and port layouts. Here, we provide an overview of the primary types of port crane:

- Ship-to-Shore Cranes (STSCs)—the largest and most iconic port cranes, serving as the primary interface between ships and the shore. These rail-mounted cranes feature telescopic or hinged booms, enabling them to reach container ships with lifting capacities exceeding 100 tons. High-profile STS cranes dominate major ports because of their ability to handle 24,000-TEU vessels with lifting heights exceeding 50 m and reach 25 container rows [4]. Their design has evolved to accommodate Panamax, Neo-Panamax, and Post-Panamax ships with critical advancements in structural integrity and energy efficiency [5,6].
- Rail-Mounted Gantry Cranes (RMGCs)—operate on fixed rails in container yards, stacking containers with precision. These electrically powered cranes are energy-efficient and widely used in automated terminals with lifting capacities of up to 50 tons [7]. Their rail-mounted design ensures stability during high-speed container transfers, rendering them ideal for intermodal terminals [8,9].
- Rubber-Tyred Gantry Cranes (RTGCs)—combine mobility with container stacking capabilities. Equipped with rubber tires, they can move freely across port yards, thereby offering flexibility in congested areas. Traditionally, diesel-powered, fully

electric variants have gained traction, reducing emissions by 36% [10]. These cranes are critical for ports requiring dynamic cargo handling [11–13].

- Automated Stacking Cranes (ASCs)—fully automated RMG cranes that eliminate human operators and improve throughput by 38% in large terminals [7]. These cranes use AI and IoT for real-time monitoring, enabling high-precision container stacking in dense storage yards [14–16].
- Mobile Harbor Cranes (MHCs)—diesel- or electric-powered cranes that can be relocated within ports, making them ideal for smaller terminals or bulk cargo handling [17,18]. Their telescopic booms and high lifting capacities (up to 144 tons) enhance their operational flexibility [19].
- Floating Cranes (FCs)—mounted on barges, handle heavy loads (up to 10,000 tons) in offshore environments or port construction projects [20,21]. These cranes are essential for lifting large components in areas inaccessible to land-based equipment [22,23].

2.2. Evolution Timeline of Port Cranes

The evolution of port cranes is intricate, interwoven with technological progress spurred by the ceaseless expansion of global trade, as well as the pursuit of higher efficiency and environmental sustainability. This timeline offers an in-depth exploration of the historical progression, emphasizing the landmark developments that have sculpted the contemporary port crane landscape.

2.2.1. Ancient to Medieval Periods (Pre-18th Century)

- Early Manual Lifting Devices (Pre-530 BC)—Long before the first written records, civilizations such as the Ancient Greeks, Egyptians, and those of the Mycenaean era had already employed basic pulley systems and winches. These simple yet effective mechanisms were crucial for constructing monumental structures and facilitating early port operation. For instance, the construction of massive structures in Tiryns, Mycenae, and the megalithic monuments of Mane in ancient Greece relied on such lifting techniques, although the exact crane-like devices used remain somewhat speculative [1].
- Written Records and Early Cranes (530 BC)—The first known written records of hoisting mechanisms in ports date back to 530 BC in Ephesus, Greece, in relation to the construction of the first Temple of Artemis. Although details are scarce, these records mark an important milestone in the documented history of port-related lifting technologies [1].
- Treadwheel Cranes (12th–18th Centuries)—By the 12th century, Europe saw the emergence of wooden wheel cranes. These cranes, operated by humans walking on a large wheel, can lift up to five tons. They became staples in medieval ports, enabling the loading and unloading of goods, although their operations were labor-intensive and relatively slow. Their design, with wooden gears and ropes, was a significant technological step forward at the time but was limited in terms of mobility and the weight they could handle [2].

2.2.2. Industrial Revolution Era (Late 18th to Mid-19th Century)

- Steam-powered crane introduction (Late 18th Century)—During the Industrial Revolution, the late eighteenth century saw the emergence of steam-powered cranes, which triggered a paradigm shift in port crane technology. Steam engines were introduced to replace the manual and animal power. In 1785, James Watt developed the first practical steam engine, not long before this technology was adapted for crane use. The introduction of steam-powered cranes increased the lifting capacity to approximately 20 tons, thereby significantly improving the efficiency of port operations. However, these cranes require stationary boilers, which limits their mobility, and their complex maintenance requirements are a drawback [2].

- Advancements in Structural Materials (1830s–1850s)—In 1834, the first cast iron crane was constructed. Cast iron offers greater strength than wood, thereby enhancing the durability of cranes. Subsequently, in 1851, more advanced steam-powered designs emerged, and iron and steel began to be widely used in crane structures. This further increases the load capacity and stability of the cranes [3].

2.2.3. Early 20th Century (1900–1950s)

- Electric Crane Adoption (early 1900s)—At the dawn of the 20th century, electric motors began to replace steam engines in cranes. This transition offers numerous advantages including smoother operation, higher reliability, and easier control. Electric cranes reduce the maintenance costs associated with steam engines such as boiler maintenance and coal handling. By 1910, many major ports in developed countries had started to incorporate electric-powered cranes into their operations, leading to increased productivity and a more stable power source for lifting heavy loads [2].
- Bulk Handling Innovations (1920s–1940s)—The 1920s–1940s saw significant advancements in bulk cargo handling. Hydraulic systems and grab buckets were introduced, and revolutionizing materials such as coal, ores, and grains were loaded and unloaded. These innovations increased the throughput of bulk cargo at ports, as hydraulic systems provided more precise control over the lifting and dumping of materials. For example, hydraulically operated grab buckets can be adjusted to pick up different amounts of bulk materials and improve the efficiency of handling various types of cargo [2].

2.2.4. Containerization Revolution (1950s–1970s)

- PACECO Container Crane Invention (1959)—In 1959, a game-changing event occurred in the port crane world. The Pacific Coast Engineering Company (PACECO) introduced the first high-speed container crane for Matson Navigation. This crane was a revolutionary design featuring all-welded box girders that provided enhanced structural integrity. With a lifting capacity of 27.5 tons, it can handle containers at a much faster rate than previously used cranes. The introduction of this crane reduced ship turnaround times from weeks to hours, setting a new standard for container handling globally and paving the way for the containerization revolution [24].
- Widespread Containerization Adoption (1960s–1970s)—By 1966, 16 PACECO cranes were operational in various ports, and containerization had begun to gain widespread acceptance. The standardization of containers has led to the development of specialized port cranes designed specifically for container handling. These cranes, including STS cranes, are essential for efficient port operations. The growth of container shipping has also spurred the development of larger container ships, which in turn require cranes with greater reach and lifting capacities [24].

2.2.5. Specialized Cranes for Larger Vessels (1970s–1990s)

- Panamax/Post-Panamax STSCs Development (1970s–1980s)—As container ships continued to grow, the cranes had to adapt. In the 1970s, Panamax cranes were developed to handle ships passing through the original Panama Canal. These cranes had a reach of 13 container rows and lifting height of approximately 38 m. In the 1980s, post-Panamax cranes were introduced for even wider vessels, extending their reach to 16 rows and increasing lifting capacity to 40–50 tons. Seismic design innovations were also incorporated to ensure the stability of large cranes in regions prone to high winds and earthquakes [25].

- RTGCs Introduction (1987)—In 1987, Valmet (later known as Kalmar) delivered the first batch of RTGCs to the Tanzanian port of Dar es Salaam. RTGCs have several significant advantages over their predecessors such as mobile gantry cranes. They have eight wheels, allowing them to stack containers in a 1 over 3 configurations, which increases the storage density in the container yards. With a lifting capacity of up to 41 tons and 400 horsepower, compared to the 22–30-ton capacity and 130-horsepower of mobile gantry cranes, RTGCs were better equipped to meet the high-productivity demands of modern ports [26].

2.2.6. Automation and Sustainability (1990s–2020s)

- ASCs debut (1990s)—In the 1990s, fully automated rail-mounted ASCs were debuted in European terminals, such as Rotterdam's ECT Delta Terminal. These cranes eliminate the need for human operators for certain container-handling tasks, enhance safety, and significantly increase the throughput of large terminals. The use of sensors, computer-controlled systems, and automated guidance systems allows ASCs to move containers with high precision and speed [8].
- Electric/Hybrid RTGCs Developments (1997–2005)—In 1997, Kalmar introduced the next generation of AC electric-powered RTGCs along with its own PLC software, which provided in-house electrical engineering capabilities. This shift towards electric power has reduced emissions and noise pollution. In 2005, Kalmar launched the E-One RTGCs, the first fully electric RTGCs without hydraulics. These electric and hybrid RTGs not only improve environmental performance, but also offer better energy efficiency, with some models reducing energy consumption by 30–50% compared to diesel-powered RTGCs [11,27].
- Energy-Saving RTGCs Retrofits (2007–2008)—In 2007, the Ministry of Transport issued Guidance on Energy Conservation and Emission Reduction in Ports. In response, the Water Transport Science Research Institute of the Ministry of Transport, Guangzhou Port Group Co., Ltd. (Guangzhou, China), and Shenzhen Jingsheng Textile Co., Ltd. (Shenzhen, China), initiated a project to retrofit RTGCs for energy efficiency. Through months of laboratory and field testing from 2007 to 2008, the retrofitted RTGCs achieved significant fuel savings of up to 40–65%. For instance, the Shanghai International Port Group retrofitted its RTGCs into hybrid diesel-battery RTGCs, reducing the fuel consumption by 65%. Additionally, in a Shanghai terminal, replacing diesel-powered RTGCs with electric RTGCs reduced the energy consumption by 54.9% and total energy costs by 29.7%. These results demonstrate the potential of retrofitted RTGCs to enhance the energy efficiency of existing port crane fleets [27]. Driven by green port initiatives, container terminal operators have replaced the environmentally and economically inefficient diesel-powered rubber-tyred gantry cranes with new or retrofitted electric cranes. For example, 57 RTGCs in Tianjin Port were converted to electric RTGCs over two years, reducing the unit energy consumption of yard cranes by nearly 80% [28].
- Hydrogen Fuel Cell RTGCs Testing (2025)—In April 2025, DP World completed the initial testing of a hydrogen fuel cell RTGCs at the Port of Vancouver. This marks a significant milestone in decarbonizing port operations. RTGCs, traditionally powered by diesel, are crucial for cargo handling but are major contributors to greenhouse gas emissions. At the DP World's Vancouver terminal, 19 RTGCs account for 50% of diesel consumption and generate over 4200 tonnes of CO_2 annually. The adoption of hydrogen technology promises to drastically reduce or eliminate this environmental impact. The tested RTGCs are currently undergoing field trials, as the DP World evaluates the feasibility of electrifying its global fleet of 1500 RTGCs. If the trials are

successful, the DP World may convert its 25 diesel-powered RTGCs to Vancouver and Prince Rupert to meet its zero-emission goals [29].

Figure 2 depicts the evolutionary timeline of port cranes from ancient times to the present.

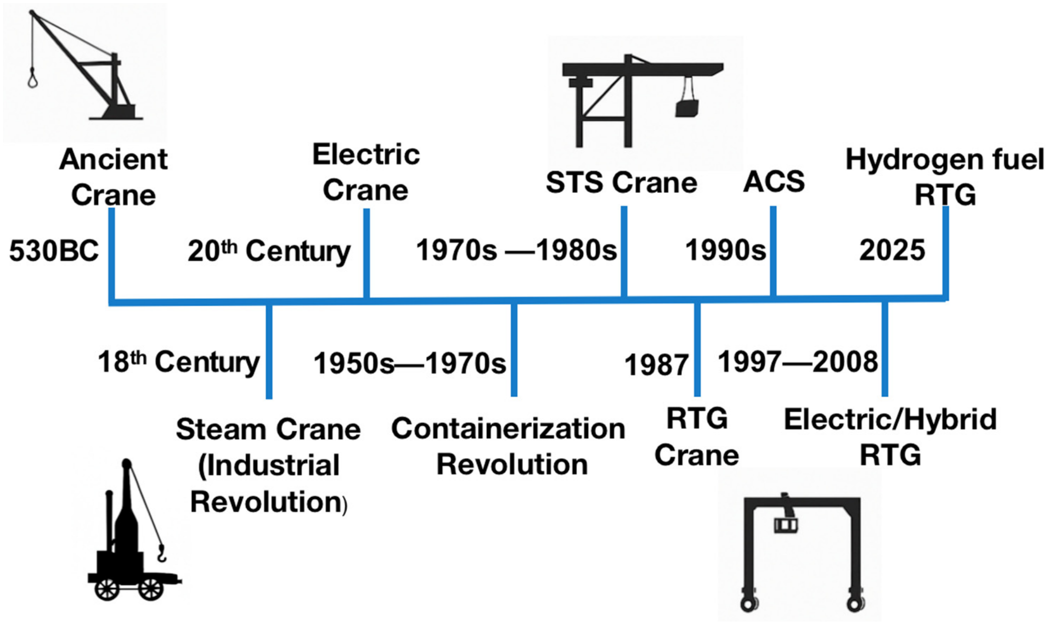

Figure 2. Evolution timeline of port cranes.

2.3. Mechanical and Structural Defects and Failures of Port Cranes

As critical equipment in port operations, port cranes are subjected to intense operational demands and harsh environmental conditions, making them susceptible to various mechanical and structural defects and failures. These defects and failures not only affect the operational efficiency of port cranes but also pose significant safety risks. Below is a detailed analysis of the common mechanical and structural defects and failures in port cranes.

2.3.1. Mechanical Defects

Mechanical defects are common in port cranes. Key components such as gears, bearings, and braking systems are prone to wear and tear owing to prolonged use under heavy loads and variable working conditions [30–33]. For example, repeated stress cycles can lead to cracks in gears or bearings [34,35]. As cracks propagate, they may cause gear tooth breakage or bearing failure, resulting in abnormal vibrations and noise, which in turn affect the crane's operational precision and stability [36–38]. Similarly, brake systems may experience reduced effectiveness owing to lining wear or hydraulic fluid degradation, increasing the risk of uncontrolled load lowering and posing severe safety hazards [39]. Mechanical defects can also be caused by insufficient preloading of bolts used in structural connections in cranes [40–43].

2.3.2. Structural Defects

Port cranes endure significant stress from lifting operations and environmental factors, such as wind and seismic activity, making them prone to structural defects. Common structural defects include metal fatigue, cracks in the structural framework, and boom and gantry deformation. Metal fatigue arises from cyclic loading, which leads to microscopic cracks that propagate over time [44–46]. If undetected, these cracks can grow, potentially causing structural components to fracture and compromising the integrity and stability of the crane. Additionally, the boom and gantry may deform owing to improper lifting operations or collisions, altering the crane load distribution and increasing the risk of accidents [47].

2.3.3. Impact of Defects and Failures

Mechanical and structural defects and failures of port cranes can cause numerous adverse effects. These include reduced operational efficiency, increased maintenance costs, shortened service life, and serious safety risks to personnel and equipment. For example, brake failure may lead to uncontrolled load lowering, whereas structural component fractures can cause crane collapse, resulting in significant casualties and property damage. Furthermore, these defects and failures may disrupt port operations, causing delays in cargo handling and economic loss [39,48].

Figure 3 shows the port crane failure caused by using a fishbone diagram.

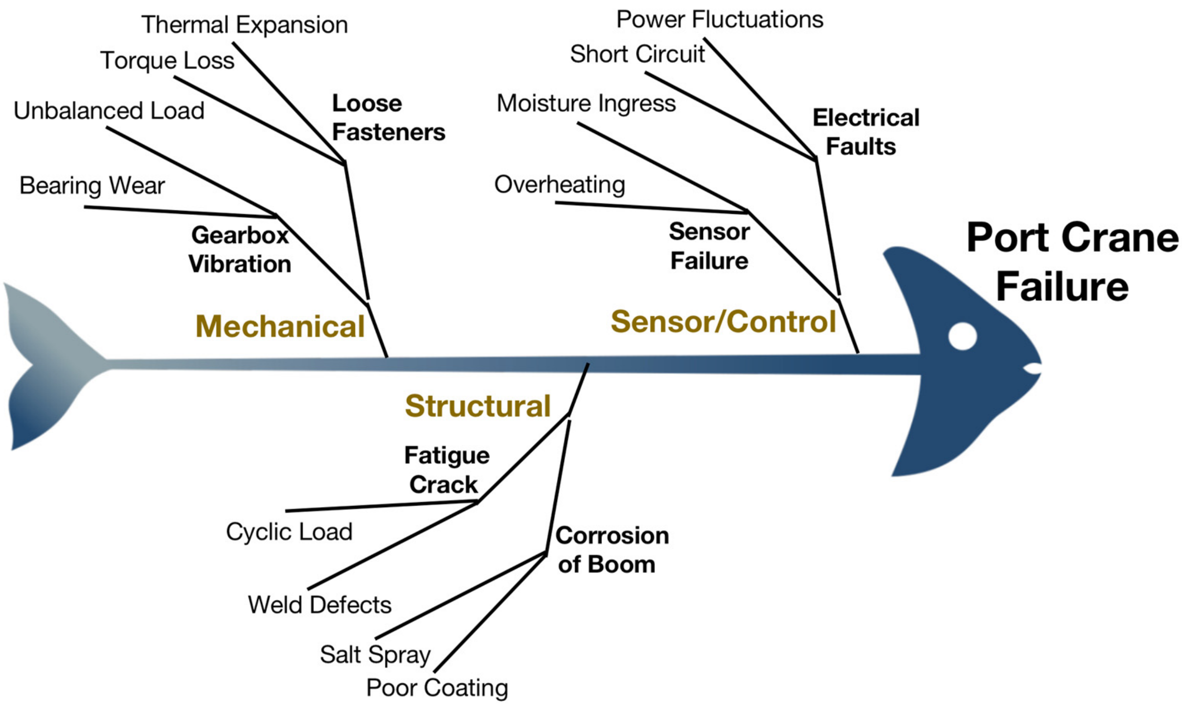

Figure 3. Fishbone diagram of port crane failure causes.

3. Current Non-Destructive Testing Practices for Port Cranes and Their Drawbacks

In the operation and maintenance system of port cranes, NDT is a vital tool for ensuring safe and reliable performance. Although traditional NDT methods have historically contributed valuable insights and operational safety, they are increasingly challenged by the growing complexity of modern port environments and the rising expectations for inspection efficiency and precision. These challenges have exposed several inherent limitations in conventional NDT approaches, prompting the need for smarter, more adaptive solutions.

These problems not only affect the accuracy and reliability of inspection results but also have a negative impact on the overall operational efficiency of the port. Therefore, it is of great significance to comprehensively and deeply explore the practical applications of traditional NDT methods and their disadvantages. This is not only helpful for accurately identifying the limitations of existing inspection methods but also provides a strong basis for exploring more efficient and advanced inspection technologies and methods.

3.1. Common Non-Destructive Testing Methods

NDT is critical for ensuring the safety and reliability of port cranes. Current NDT practices for port cranes involve various techniques, each with specific applications and limitations:

- Visual inspection (VI)—the most basic NDT method, in which inspectors visually examine a crane for signs of wear, corrosion, or damage. Although VI is simple and cost-effective, it is subjective and can detect only surface-visible defects. This requires the inspectors to have extensive experience and expertise. Liu et al. [49] highlighted that inspectors with years of experience are better equipped to identify signs of cracks or rust that may lead to damage in complex steel structures. Damage to container cranes often appears in critical structural areas, which are regions that are most prone to structural weaknesses owing to high loads, stress, and environmental factors. Gantry cranes, for instance, operate 24/7, 365 days a year and load and unload containers next to the sea. These working conditions accelerate material deterioration and necessitate more frequent inspections without prolonged downtime for maintenance because such downtime requires significant resources, time, and costs.
- Ultrasonic testing (UT)—uses high-frequency sound waves to detect internal flaws in a material [50]. It is commonly employed to inspect critical components such as welds, pins, and slewing ring bolts [51]. UT can detect subsurface defects and measure the thickness of a material [52]. However, skilled technicians are required to operate the equipment and interpret the results. In conventional UT, the tested component must typically be cleaned and prepared, and direct contact between the probe and the component is necessary, making the process time consuming. Chen et al. [53] indicated that UT is a widely used NDT method for detecting internal defects in steel structures but noted its limitations, such as the need for specialized personnel and component preparation [54].
- Magnetic particle testing (MPT)—used to detect surface and near-surface defects in ferromagnetic materials [55]. It is often applied to inspect components, such as crane hooks and pins. MPT can identify fine cracks but is limited to ferromagnetic materials. The tested component must be magnetized, and the testing environment should avoid magnetic interference [56]. Fonte et al. [57] pointed out that MPT is effective for detecting surface and near-surface defects in ferromagnetic materials but does not apply to non-ferromagnetic materials [58].
- Eddy current testing (ECT)—detects surface and near-surface flaws in conductive materials and is used to inspect components, such as structural welds, pressure vessels and piping [59–62].
- Radiographic testing (RT)—uses X-rays or gamma rays to inspect internal structures and can detect internal defects, such as cracks and porosity, in components such as welds [63–65]. RT provides intuitive image results but involves radiation safety hazards. The testing process is complex and time-consuming, and requires strict safety precautions [66,67].

Table 1 compares common NDT techniques used for port cranes. It focuses on four key aspects: the detection depth, material limitations, strengths, and limitations. This comparison is crucial, as it allows for a direct assessment of each technique's capabilities and constraints in the context of port crane inspection.

Table 1. Comparison of common non-destructive testing techniques for port cranes.

Technique	Detection Depth	Material Limitation	Strengths	Inspection Limitations
VI	Surface	None	Quick, low cost	Subjective, surface only
UT	Subsurface	All metals	Accurate, deep flaw detection	Needs coupling medium
RT	Deep	Most metals	High detail imagery	Radiation hazard, costly
MPT	Near surface	Ferromagnetic only	Quick for surface cracks	Limited to surface and magnetic materials

3.2. Drawbacks of Current NDT Practices

- Subjectivity and Human Factors—VI is highly subjective and depends on the inspector's experience and skills. Human factors can lead to missed detections or misjudgements. Liu et al. [49] pointed out that the subjectivity of VI results in significant variability in defect detection outcomes, influenced by the inspector's experience and skills.
- Limited Detection Capabilities—Some NDT methods can only detect surface or near-surface defects but cannot identify internal defects. For example, MPT and ECT are only effective for specific material types and defect locations.
- High Requirements for Component Preparation—Certain conventional UT and RT often require the tested component to be cleaned, paints removed, and surface prepared, thereby increasing inspection time and labor costs. Stanić et al. [68] indicated that the preparation of components for UT and RT is time-consuming and labor-intensive, impacting inspection efficiency [69].
- Safety Risks—RT involves radiation hazards, necessitating strict safety measures to protect inspectors and nearby personnel. The operation of the NDT equipment may also pose safety risks. Majumder et al. [70] emphasized the radiation hazards associated with RT and the need for stringent safety protocols during testing [71].
- Inconvenience and Low Efficiency—Traditional NDT methods often require inspectors to access hard-to-reach or elevated areas of the crane, increasing inspection difficulty and risk. Typically performed during scheduled shutdowns, these methods interrupt operations and reduce port efficiency [72].
- Lack of Real-Time Monitoring—Most current NDT methods are periodic inspections that cannot provide real-time information on the structural health of port cranes. Defects that develop between inspections may go undetected, potentially leading to sudden failures [73].

The limitations of current NDT practices underscore the need for more effective and efficient inspection methods. The integration of vibration and AE sensors with the IoT offers a promising solution. By enabling real-time continuous monitoring without frequent shutdowns, this approach can significantly enhance the safety, reliability, and operational efficiency of port cranes [74].

4. Vibration and Acoustic Sensors in Non-Destructive Testing of Port Cranes

Vibration sensors such as accelerometers and strain gauges are commonly used to monitor the dynamic responses of port cranes [75]. They can detect changes in the structural integrity caused by factors such as fatigue, corrosion, and impact. Acoustic sensors, including AE and ultrasonic sensors, can capture high-frequency acoustic signals generated by crack propagation, delamination, and other damage mechanisms [76,77]. These sensors can be strategically placed on port cranes to monitor their health continuously.

4.1. Vibration Sensors in Port Crane Monitoring

Vibration sensors are integral to RNDT of port cranes, enabling the detection of dynamic mechanical responses such as gear misalignment, bearing wear, or structural im-balance. These sensors support predictive maintenance by providing real-time data on operational integrity and fault development in crane systems. This section outlines the working principles, sensor types, and application relevance for port crane environments.

4.1.1. Working Principle of Vibration Sensors

Vibration sensors detect and measure the vibrations generated by the dynamic responses of structures. When external forces act on port cranes, structural vibrations occur, reflecting their dynamic characteristics and integrity [78,79]. Vibration sensors convert these mechanical vibrations into electrical signals for analysis. Common working principles include piezoelectric, capacitive, and strain gauge-based principles. Piezoelectric sensors generate electrical charges when they are subjected to mechanical stress. They exhibit high sensitivity and frequency response, making them suitable for dynamic vibration measurements. Capacitive sensors measure the capacitance changes caused by vibrations and offer high accuracy and stability. Strain-based sensors detect strains induced by vibrations and provide precise measurements of structural deformation. As Wong et al. [48] noted, vibration sensors can effectively monitor the dynamic responses of crane structures, providing valuable data for assessing structural health [80,81].

4.1.2. Types of Vibration Sensors

Piezoelectric vibration sensors are widely used in RNDT owing to their excellent performances [82,83]. They are simple in structure, require no external power, and exhibit good frequency response characteristics [84,85]. They can detect a wide range of vibration frequencies, making them suitable for various marine structures [86]. For example, piezoelectric sensors can detect vibrations caused by lifting and lowering operations in port cranes [85]. However, they are sensitive to temperature changes, which can affect the measurement accuracy. Temperature compensation techniques are often required to improve reliability.

Capacitive vibration sensors are known to have high accuracy and stability. They have low power consumption and good linearity. They can measure low-frequency vibrations with high precision [87]. In port cranes, capacitive sensors can detect vibrations caused by operational movement [88–90]. However, they are sensitive to environmental factors such as humidity and require complex circuits for signal conditioning. Proper sealing and circuit design are required to ensure their performance.

Strain gauge-based vibration sensors measure structural deformation by detecting resistance changes in the strain gauges [91,92]. They can be used in complex structures to measure local vibrations and deformations [93]. They can detect localized vibrations in port cranes with complex geometries. However, their installation is relatively difficult, and they are prone to damage. High-precision measurement circuits are required to ensure accuracy.

Dzioba et al. [47] highlighted the advantages and limitations of different types of vibration sensors in SHM, providing valuable insights for their selection and application in port cranes.

4.1.3. Performance Characteristics of Vibration Sensors

Sensitivity is a key parameter of vibration sensors. High-sensitivity sensors can detect weak vibrational signals. For example, piezoelectric sensors have high sensitivity for dynamic vibration measurements [94]. However, high sensitivity can lead to a lower measurement range. A balance between the sensitivity and measurement range is required.

Frequency response is the sensor's ability to respond to different vibration frequencies. The proper selection of vibration sensors with suitable frequency–response characteristics is crucial [95,96]. For crane booms, the sensors should cover the frequency range of the vibrations caused by lifting and lowering operations [97]. Vibration sensors used in RNDT for port cranes must accommodate a wide range of amplitudes, especially those generated during heavy lifting operations. A broad measurement range ensures accurate detection under varying load conditions.

Marine environments are harsh, and vibration sensors must have good stability and reliability to provide accurate and stable measurement results. Sensors made with high-quality materials and advanced manufacturing processes are more stable and reliable [98,99]. As Chen et al. [53] pointed out, the performance characteristics of vibration sensors directly affect their effectiveness in SHM. Therefore, the selection of vibration sensors with appropriate performance characteristics is critical for port crane maintenance.

Table 2 lists the numerical data on the sensitivity, frequency response, environmental adaptability, and cost for piezoelectric, capacitive, and strain gauge-based sensors. Piezoelectric sensors have high sensitivity and excellent frequency response, but moderate environmental adaptability. Capacitive sensors are accurate, costly, and humidity sensitive. Strain gauge-based sensors are low-cost but have weak environmental adaptability.

Table 2. Performance comparison of vibration sensor types used in RNDT.

Metric	Piezoelectric	Capacitive	Strain Gauge
Sensitivity	High	Medium	Medium
Frequency Response	Excellent	Good	Fair
Environmental Adaptability	Moderate	Poor	Weak
Cost	Moderate	High	Low

4.1.4. Application of Vibration Sensors in Port Cranes

Although vibration sensors have been extensively applied in various industries, their use in port crane maintenance is relatively new. However, several studies have begun to explore their application in port cranes. Tran et al. [4] conducted a comparative study of nonlinear static and time-history analyses of typical Korean STSCs. Their research highlighted the importance of vibration monitoring for assessing the dynamic performance and structural integrity of port cranes.

Jo et al. [6] developed key performance indicators for ship-to-shore crane performance assessment in container terminal operations. Their study indicated that vibration sensors provided valuable data for evaluating the operational efficiency and safety of port cranes. Additionally, Liu et al. [49] emphasized that vibration sensors can detect signs of structural damage in port cranes, such as fatigue cracks and corrosion, by analyzing vibration signals. These studies demonstrate the potential of vibration sensors in port crane maintenance and provide a foundation for further research and applications in this field [49].

The integration of vibration sensors with IoT marks a significant leap in the realm of port crane monitoring, enabling continuous, real-time surveillance of these critical machines [100,101]. Unlike traditional inspection methods that rely on periodic check-ups, this innovative approach provides a constant stream of data for detecting minute vibrations that may signal the early stages of mechanical degradation, such as incipient gear wear or bearing defects [102,103].

However, fully capitalizing on this technology presents several formidable challenges. Sensor installation and calibration are particularly difficult because of the complex, dynamic structure of port cranes and the harsh maritime environment in which they operate [104]. High humidity, salt-laden air, and intense vibrations can interfere with the sensor readings, necessitating regular recalibration. Data transmission and processing also pose hurdles; the vast amount of information generated requires robust communication networks and an efficient edge-to-cloud computing infrastructure to ensure a timely analysis. Moreover, interpreting the data accurately requires sophisticated algorithms and machine-learning models, as distinguishing between normal operational vibrations and those indicative of emerging faults remains a complex task.

To fully unlock the potential of vibration sensors in port crane maintenance, future research efforts should focus on three key areas. First, developing sensors with enhanced environmental resilience and self-calibration capabilities would significantly improve reliability. Second, advancements in data analytics, such as the application of deep learning for pattern recognition in vibration data, can lead to more accurate fault diagnosis. Finally, enhancing IoT platforms to support seamless integration of multiple sensor types and real-time data sharing among various stakeholders in the port ecosystem is crucial for the widespread adoption of this technology.

4.2. Acoustic Emission Sensors in Port Crane Maintenance

AE sensors are powerful tools in NDT and can detect acoustic emissions generated by materials under stress or deformation. These sensors are crucial for monitoring and assessing the structural integrity of materials and components in various industrial applications. Below is a detailed discussion of the working principles, types, applications, and performance characteristics of port crane maintenance.

4.2.1. Working Principle of Acoustic Emission Sensors

AE sensors detect the acoustic waves generated by materials during stress or deformation. These acoustic emissions are caused by microstructural changes within the material, such as crack propagation, dislocation movement, or phase transformation. When an acoustic wave reaches the sensor, it converts the mechanical wave into an electrical signal, which can then be amplified, processed, and analyzed. There are two main types of AE sensors based on their working principles: piezoelectric transducers and fiber-optic sensors. Piezoelectric transducers generate electrical charges when they are subjected to mechanical stress. When an acoustic wave reaches a piezoelectric transducer, it generates an electrical signal proportional to the amplitude and frequency of the wave.

Fiber-optic sensors detect AEs by measuring changes in the properties of optical fibers caused by acoustic waves. These changes are then converted into electrical signals for further analysis. In addition, Güemes et al. [105], AE sensors are based on the physical principle that elastic waves are generated within a material when stress fields are redistributed. This makes AE testing an inherently in-process method, owing to the need for stress redistribution. This technique is commonly used in machining for tool condition monitoring because acoustic signals, such as rake face pitting and flank face abrasion, are generated through changes to the condition of the tool.

Research has shown that AE testing can be used to monitor the condition of a tool and simultaneously detect anomalous surface features generated on the workpiece surface [105]. This is owing to the large redistribution of stress fields associated with these examples of severe plastic deformation.

Figure 4 presents the acoustic emission signal pattern in crack propagation. By analyzing these patterns, engineers and researchers can gain a deeper understanding of how cracks initiate, grow, and become unstable.

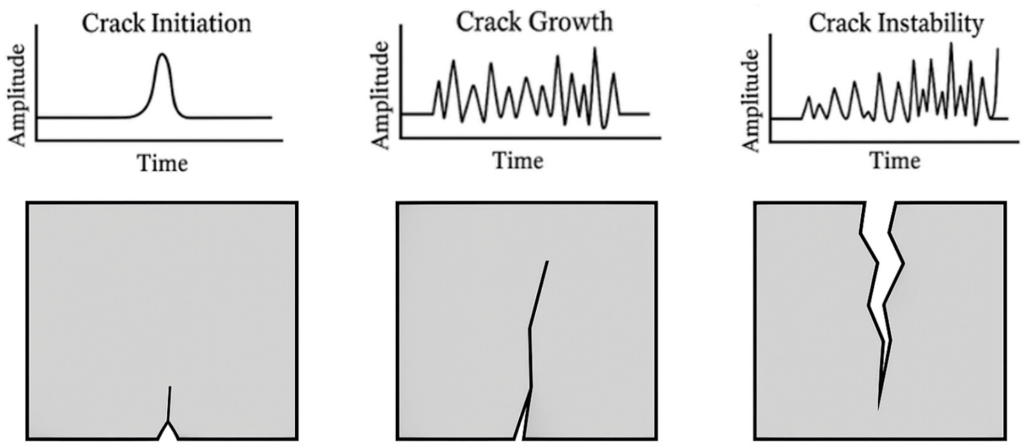

Figure 4. Acoustic emission signal pattern in crack propagation.

4.2.2. Types of Acoustic Emission Sensors

Piezoelectric transducers are widely used in AE testing, owing to their high sensitivity, wide frequency response, and good stability. They convert mechanical stress into electrical signals via the piezoelectric effect, typically using ceramic materials such as lead zirconate titanate or quartz crystals [106,107]. These sensors are widely used in AE systems owing to their high sensitivity, broad frequency response, and fast reaction time.

Fiber-optic sensors offer several advantages over piezoelectric sensors, particularly in environments with high electromagnetic interference (EMI). These sensors operate based on fundamental optical principles, typically interferometry or intensity modulation, whereby AEs induce strain or pressure variations in the optical fiber. These disturbances alter the phase, amplitude, or polarization of light propagating through the fiber, which can be measured and converted into an electrical signal by photodetectors.

Common configurations include Fabry–Pérot interferometers and fiber Bragg gratings (FBGs), which are highly sensitive to dynamic strain and pressure changes [108–110]. In the case of FBG-based AE sensors, an acoustic wave causes a shift in the Bragg wavelength, which can be monitored for real-time damage assessment. These systems are inherently immune to EMI, chemically inert, lightweight, and capable of multiplexing multiple sensors along a single optical line [111,112]. This makes them ideal for harsh or constrained environments such as shipyards, offshore platforms, nuclear plants, and high-voltage port crane systems.

Their high bandwidth and spatial resolution enable early detection of damage phenomena such as crack propagation or delamination in complex structures, which may otherwise go unnoticed using conventional sensors.

As mentioned in a study by Calabrese and Proverbio [113], the integration of AE testing with IoT enables continuous real-time data collection and monitoring. Pressure vessels, for example, can be embedded with sensors that provide continuous real-time data, alerting operators to minute stress changes indicative of crack initiation or wall thinning [113].

4.2.3. Performance Characteristics of Acoustic Emission Sensors

The sensitivity of the AE sensors is a critical parameter that determines their ability to detect weak acoustic signals. High-sensitivity sensors can detect low-amplitude acoustic emissions, which are essential for identifying the early signs of damage. However, a high sensitivity may also make the sensors more susceptible to noise interference. Therefore, a balance between sensitivity and noise immunity is necessary.

The frequency response of AE sensors refers to their ability to respond to different frequencies of acoustic emissions. Different materials and damage mechanisms generate acoustic emissions in different frequency ranges. The selection of sensors with appropriate frequency response characteristics is crucial for accurate detection and analysis.

The measurement range of the AE sensors refers to the amplitude span of the acoustic emissions that they can detect. A wide measurement range enables detection of both low- and high-amplitude acoustic signals, making these sensors versatile for multiple applications. However, a broader range may sometimes compromise resolution at lower amplitudes, necessitating trade-offs based on the use case.

Stability and reliability are critical performance factors, especially in long-term, unattended monitoring applications. AE sensors must maintain consistent performance despite varying environmental conditions, such as humidity, temperature, or vibration. These attributes are typically achieved through the use of high-grade materials and precision manufacturing processes.

As noted in the study by Hassani and Dackermann [114], compared with classic AE instruments, the IoT AE equipment system has the characteristics of long-term stable automatic operation, low cost, small size, and the ability to realize online, remote, and unattended AE monitoring and detection. It also features software that automatically analyzes and rates the results according to standards, eliminating the need for technicians to rate them [114].

4.2.4. Applications of Acoustic Emission Sensors in Port Cranes

AE sensors play a crucial role in the SHM systems of port cranes. They enable the continuous, real-time assessment of critical components, such as crane booms, cables, and support structures. For example, in port cranes, AE sensors detect microcracks caused by cyclic loading during lifting operations [115,116]. They can also monitor stress-induced failures during operations. Corrosion is a significant concern in port cranes because it can compromise the integrity of structural components.

AE sensors detect stress-wave emissions from corrosion activity, aiding predictive maintenance and structural integrity testing. They can identify pitting corrosion, stress-corrosion cracking, and general corrosion in various components of the port cranes [117]. Furthermore, with the increasing use of advanced materials and complex components in port cranes, there is a heightened need for NDT methods such as AE testing. These materials often exhibit unique failure modes such as delamination and fiber breakage. AE sensors detect faults in crane components such as lifting cables, slewing bearings, and boom structures. For instance, they can identify delamination and fiber breakage in composite boom structures during operation [118,119].

The case study of the Red Sea Gateway Terminal highlights how IoT, machine learning, and artificial intelligence can be leveraged for real-time condition monitoring and fault prediction in super Panamax quayside container cranes. This integration enhances crane reliability, reduces inspection efforts, increases the mean time between failures, and boosts the uptime and availability. Autonomous crane monitoring, fault detection, and prediction contribute to saving maintenance team time and enhancing the overall reliability. The critical components monitored included motor DE-NDE bearing blocks, gearbox input, intermediate and output shafts, and drum supports. The AE sensors integrated with IoT achieved 83% accuracy in fault prediction and 19% improvement in overall reliability based on increased mean time between failures [120].

4.3. Integration with IoT for Remote Monitoring of Port Cranes

The role of the IoT in remote monitoring has revolutionized monitoring and management of various systems, including port cranes. By connecting devices and sensors to the Internet, the IoT enables seamless collection, transmission, and analysis of data in real time. In the context of port cranes, IoT provides a centralized platform for data storage and processing, allowing engineers and technicians to remotely access and analyze sensor data. This capability is particularly valuable, given the remote and inaccessible locations of port cranes. IoT facilitates the implementation of automated monitoring systems that can trigger alerts when abnormal conditions are detected, significantly enhancing the efficiency and effectiveness of maintenance operations.

4.3.1. Vibration Sensors in IoT-Based Remote Monitoring of Port Cranes

Vibration sensors play a crucial role in monitoring the structural health of the port cranes. When integrated with IoT, these sensors can provide continuous and real-time data on the dynamic response of cranes to various stimuli such as lifting operations and environmental factors. It applies as follows:

- Data collection and transmission—Vibration sensors, such as accelerometers and strain gauges, are strategically placed on critical components of port cranes. These sensors convert mechanical vibrations into electrical signals that are then amplified and conditioned. The data is collected by IoT-enabled data acquisition systems, which can be located on the crane itself or at a nearby monitoring station. The data is transmitted over wireless or wired networks to a central IoT platform. Wireless networks, such as Wi-Fi, Bluetooth, and cellular networks, are often preferred in marine environments because of their flexibility and ease of installation.
- Data Processing and Analysis—Once the vibration data reaches the IoT platform, it undergoes processing and analysis. Cloud and edge computing can also be used for data processing. Cloud computing offers virtually unlimited storage and computational resources but may introduce latency issues. Edge computing processes data closer to the source, reduces latency, and enables faster response times. The processed data is analyzed using various algorithms and techniques to detect patterns, anomalies, and trends. Machine learning algorithms can be trained to identify the early signs of structural damage or mechanical failure based on historical data and predefined thresholds.
- Automated Monitoring and Alerts—IoT platforms enable the implementation of automated monitoring systems that trigger alerts when abnormal conditions are detected. For example, if the vibration levels exceed predefined thresholds, the system can automatically send alerts to engineers and technicians via email, SMS, or mobile applications. These alerts provide valuable time to investigate and address potential issues before they escalate to catastrophic failure. Automated monitoring systems can also generate reports and dashboards, thereby providing a comprehensive overview of the structural health of the port cranes.

4.3.2. Acoustic Emission Sensors in IoT-Based Remote Monitoring of Port Cranes

AE sensors are another vital component of the remote monitoring of port cranes. These sensors detect acoustic emissions generated by materials under stress or when they undergo deformation or damage. The technique is applied as follows:

- Data Collection and Transmission—AE sensors, such as piezoelectric transducers and fiber-optic sensors, are placed on or near monitored structures. These sensors detect high-frequency acoustic emissions generated by microstructural changes within a material, such as crack propagation or dislocation movement. The detected signals are converted into electrical signals and transmitted to IoT-enabled data acquisition systems. Like vibration sensors, data is transmitted over wireless or wired networks to a central IoT platform.

- Data Processing and Analysis—AE data collected by the AE sensors is processed and analyzed on the IoT platform. Cloud and edge computing can be used for data processing. The analysis of AE data involves the identification and classification of emission sources. Signal processing techniques, such as time-frequency analysis and wavelet transform, are used to extract features from the AE signals. Machine learning algorithms can then be applied to classify signals and determine whether they are indicative of structural damage or other issues.
- Automated Monitoring and Alerts—IoT platforms also enable automated monitoring of systems for AE sensors. When abnormal AE activity is detected, the system can trigger alerts to notify engineers and technicians. These alerts can help prioritize inspections and maintenance activities, ensuring the timely identification and resolution of potential issues. Automated monitoring systems can also integrate data from multiple sensors, including vibration and AE sensors, to provide a more comprehensive assessment of the structural health of the port cranes.

The integration of IoT in the remote monitoring of port cranes has revolutionized the way we ensure their safety and reliability. With growing demand for real-time data and proactive maintenance, IoT-based monitoring systems are rapidly gaining traction in modern port operations, although widespread adoption remains in progress. However, this system is complex and involves multiple components such as sensors, data acquisition units, communication networks, and data analysis platforms.

Figure 5 depicts the IoT-based remote monitoring architecture for the port cranes. This diagram provides a visual roadmap of how vibration sensors, AE sensors, and other components work together within the IoT framework. It helps us understand how data are collected from sensors on port cranes, transmitted through various networks, processed on edge or cloud platforms, and finally used to generate alerts and inform maintenance decisions. By visualizing this architecture, we can better appreciate the seamless flow of information that enables the efficient remote monitoring of port cranes.

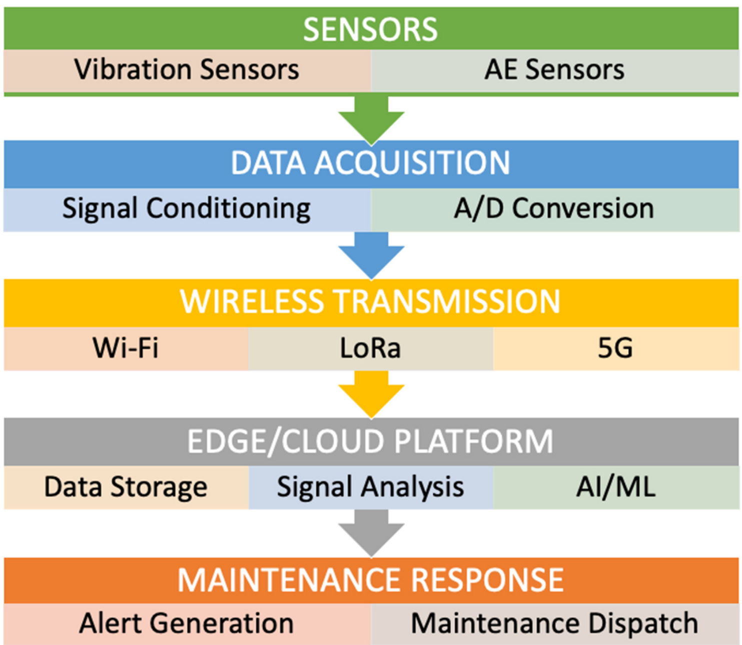

Figure 5. IoT-based remote monitoring architecture for port cranes.

5. Summary and Discussion

As research on remote NDT technology for port cranes progresses, it is crucial to systematically summarize and discuss relevant achievements. Through research on the application of vibration and acoustic sensors integrated with IoT in the inspection of port cranes in the previous chapters, we obtained a wealth of information. This integrated technology has shown significant advantages in improving inspection efficiency and enabling real-time monitoring. However, in an actual application process, it inevitably faces several challenges and limitations.

Comprehensively summarizing these research results can clarify the current development status of the technology and its practical value in the field of port crane inspection. An in-depth discussion of the existing problems helps to identify the directions for technological improvement and provides clear ideas for subsequent research. This not only promotes further optimization of the technology but also facilitates its wide application in the port industry, thereby enhancing the safety and reliability of the entire port operation.

5.1. Summary

The application of vibration and AE sensors in port crane monitoring has shown substantial potential for enhancing structural integrity assessment and operational safety. Vibration sensors, such as MEMS accelerometers, piezoelectric sensors, and strain gauges, can detect dynamic mechanical responses, misalignments, and early structural fatigue. AE sensors, on the other hand, are well suited for identifying crack initiation, corrosion propagation, and weld defects through transient elastic wave detection. However, challenges regarding environmental exposure (e.g., salt, moisture), signal noise, power consumption, and data integration persist. Therefore, the choice of sensor technology must be based on specific application requirements, environmental constraints, and system integration capabilities. To consolidate the technical understanding, Table 3 summarizes the key characteristics of commonly used vibration sensors applicable to port crane monitoring.

Table 3. Comparison of vibration sensor types for crane applications.

Sensor Type	Sensing Principle	Frequency Range	Sensitivity	Power Source	IoT Compatibility	Application Notes
MEMS Accelerometer	Capacitive/ Piezoelectric	0.1–5000 Hz	Low to Moderate	Low Power/ Battery	High	Compact, ideal for mobile crane arms
Piezoelectric Sensor	Piezoelectric effect	1–10,000 Hz	High	Wired/Passive	Moderate	Good for high-frequency mechanical faults
Triboelectric Sensor	Contact electrification	1–2000 Hz	Moderate to High	Self-powered	High	Energy harvesting with vibration data
Strain Gauge	Resistance change	Static–500 Hz	Moderate	Wired	Low	Best for structural stress monitoring

Although vibration sensors are instrumental in capturing mechanical anomalies such as imbalance or misalignment, AE sensors complement this approach by detecting high-frequency stress waves generated from crack propagation, corrosion, and weld degradation. Table 4 further expands this comparison by detailing AE sensor types best suited for port crane monitoring applications.

Table 4. Comparison of AE sensor types for remote monitoring of port cranes.

Sensor Type	Peak Frequency Range	Operating Bandwidth	Application Suitability	IoT Integration Capability
Narrowband Piezoelectric	100–300 kHz	Narrow	Crack initiation, fatigue detection	Moderate (wired systems)
Broadband Piezoelectric	100–1000 kHz	Wide	Corrosion, weld defect, delamination detection	High (supports edge analytics)
Wireless AE Node	100–500 kHz	Configurable	Remote real-time SHM	Very High (BLE/Wi-Fi enabled)

5.2. Challenges and Limitations

Although the integration of vibration and AE sensors with IoT shows great potential in the remote monitoring of port cranes; to achieve its widespread application and efficient operation, a series of complex challenges and limitations need to be addressed. These issues cover multiple key aspects, such as sensor performance, IoT integration, and data processing, posing obstacles to practical implementation and long-term stable operation of the technology.

Deeply analyzing these challenges and limitations not only helps to accurately locate bottlenecks in technological development but also provides a basis for formulating targeted solutions. Only by properly addressing these issues can the advantages of the remote monitoring system be fully utilized, the safety and reliability of port crane operation be enhanced, and the process of intelligent port operation and maintenance be promoted.

5.2.1. Vibration Sensor Challenges

- Environmental vulnerability: Marine environments present high humidity, salinity, and temperature fluctuations, all of which can impair sensor accuracy and durability. Sensor corrosion is a major concern, necessitating the use of protective housing and robust sealing strategies.
- Installation and calibration complexity: Appropriate sensor placement is crucial for accurate signal acquisition. However, installation on large, geometrically complex structures, such as STSCs or RTGCs, is logistically demanding. Calibration procedures are equally labor-intensive and require periodic readjustments to maintain the measurement integrity.
- Data management constraints: Vibration sensors produce voluminous time-series data, posing challenges for data transmission, especially in areas with limited wireless coverage, and require efficient preprocessing and filtering algorithms to extract actionable insights.

5.2.2. Acoustic Emission Sensor Challenges

- Signal-to-noise ratio—AE sensors are highly sensitive to environmental and mechanical noises. Differentiating genuine acoustic emissions from background noise is nontrivial and requires advanced filtering and denoising algorithms.
- Localization accuracy and sensor placement—The diagnostic effectiveness of the AE testing is influenced by sensor positioning relative to the emission source. Incorrect placement can lead to signal attenuation or misclassification, particularly in multi-material or composite components.

- Interpretation complexity—The acoustic signals generated by microstructural changes can be difficult to interpret without advanced pattern recognition or machine learning tools. False positives and negatives remain a concern in early-stage deployment.

5.2.3. IoT Integration Challenges

- Data security and privacy—Port cranes are often critical for national security and economic interests. Ensuring the security and privacy of the data collected from the sensors is paramount. The implementation of robust encryption protocols, secure authentication mechanisms, and access control measures can help protect data from unauthorized access and cyber threats.
- Data management and storage—The large volume of data generated by vibration and AE sensors requires efficient data management and storage solutions. Cloud storage offers scalable and cost-effective storage options; however, it is essential to implement proper data organization and retrieval mechanisms to ensure quick access to relevant data.
- Network connectivity and reliability—Port environments pose challenges to network connectivity. Ensuring reliable and consistent network connectivity is crucial for transmitting sensor data. Using redundant network connections, satellite communication, and edge computing can help mitigate connectivity issues.
- Sensor calibration and maintenance—Vibration and AE sensors require regular calibration and maintenance to ensure accurate and reliable data collection. Developing automated calibration procedures and implementing remote maintenance capabilities can help reduce the need for manual intervention and minimize downtime.
- Data analysis and interpretation—The analysis and interpretation of data from vibration and AE sensors can be complex because of the high volume and variability of the data. Advanced data analysis techniques, such as machine learning and artificial intelligence, can help automate the analysis process and improve the accuracy of structural issues detection.

5.3. Comparison of Traditional and IoT-Based Non-Destructive Testing

Traditional NDT methods such as VI, UT, MT, and RT have long served as the backbone of port crane maintenance. These techniques, however, are inherently constrained by their periodic nature, dependency on manual labor, and inability to offer real-time diagnostic insights. In contrast, IoT-enabled RNDT systems leverage continuous sensor-based monitoring, edge/cloud data processing, and AI-driven analytics to overcome many of these limitations.

Table 5 presents a structured comparison between traditional and IoT-based NDT approaches across key operational and technical parameters. The comparison is based on recent literature and practical implementation trends in the maritime, energy, and manufacturing sectors. Each parameter has been selected based on its relevance to port crane applications and its impact on inspection reliability, safety, and cost-effectiveness.

Compared to conventional practices, IoT-integrated systems offer broader inspection coverage, reduced dependence on manual inspection teams, and improved predictive maintenance capabilities. Moreover, the ability to collect and analyze data in real-time enhances safety by minimizing the need for personnel to physically access hazardous areas, such as high crane structures or confined mechanical spaces.

Table 5. Comparative analysis of traditional NDT and IoT-based NDT for port cranes.

Parameter	Traditional NDT	IoT-Based NDT	Reference
Inspection Mode	Periodic, manual	Continuous, remote	[73,114]
Coverage Scope	Localized, point-based	Wide area, sensor-networked	[104,121]
Detection Accuracy	Operator-dependent, variable	Algorithm-enhanced, consistent	[105,122]
Personnel Dependency	High (skilled inspectors needed)	Low (remote monitoring and AI-assisted)	[70,102]
Cost Efficiency	High labor and equipment costs	Higher setup cost, but reduced long-term O&M costs	[120,123]
Safety	Risky for inspectors (e.g., heights)	Safer (less need for physical access)	[72,113]
Real-Time Capability	No	Yes	[119,124]

5.4. Future Research Directions for Port Crane Monitoring

To further enhance the integration of vibration and AE sensors with IoT for the remote monitoring of port cranes, the following several research directions should be prioritized:

- Development of next-generation sensors—Research on nano-enabled, self-powered, or bioinspired sensor materials could yield devices with enhanced sensitivity, environmental resistance, and energy efficiency.
- Hybrid NDT frameworks—Integrating vibration and AE sensors with complementary NDT techniques (e.g., thermal imaging and guided wave testing) may provide a holistic and redundant diagnostic framework for critical crane components.
- AI-driven predictive maintenance—Continued exploration of AI models for anomaly detection, pattern recognition, and lifecycle prediction enhances system autonomy and decision accuracy.
- Self-sustaining monitoring systems—The incorporation of energy harvesting technologies, such as piezoelectric or thermoelectric generators, could eliminate the need for manual sensor recharging or replacement, thereby improving system sustainability.
- Standardization and interoperability—Establishing international standards for RNDT sensor calibration, data formats, and IoT communication protocols would accelerate technology adoption and cross-system integration in global port operations.

To provide a clear overview of the current limitations and prospective advancements in the field, Table 6 summarizes the key research gaps identified in this review, along with recommendations for future research directions. These gaps span sensor integration, data processing, durability in marine environments, and adoption of intelligent systems for predictive maintenance. Addressing these areas is essential to accelerate the deployment of robust, IoT-enabled remote NDT frameworks for port crane infrastructure.

Table 6. Identified research gaps and future research directions.

Category	Current Limitation/Gap	Future Research Direction
Sensor Integration	Lack of harmonized multi-sensor data fusion	Develop unified platforms integrating AE, vibration, and thermal sensors
Real-Time Data Processing	High latency and poor edge processing in harsh marine environments	Use AI-driven edge computing and real-time analytics platforms
Energy Sustainability	Battery-dependent wireless sensor nodes for cranes	Implement self-powered sensors (e.g., piezoelectric, triboelectric)
Environmental Durability	Sensor degradation due to salt spray, humidity, and vibration	Develop corrosion-resistant, encapsulated sensor casings
Standardization	Absence of unified IoT protocols or NDT communication standards in port environments	Create standardized, ISO-aligned frameworks for IoT-based crane monitoring
Predictive Maintenance	Current systems reactive; minimal use of predictive analytics	Integrate machine learning for early damage prediction and remaining life estimation
UAV and Mobile Platforms	Limited use in automated crane inspections	Expand UAV-assisted visual/NDT inspection with AI-based defect detection

6. Conclusions

The integration of vibration and AE sensors with IoT platforms marks a transformative shift in the NDT paradigm, advancing it toward a remote, intelligent, and predictive framework. Unlike traditional NDT, which relies on periodic, localized inspection, RNDT enables continuous monitoring of structural health through embedded sensor systems and real-time data analytics. This evolution is particularly significant for port cranes, which face extreme mechanical stress, corrosive environments, and operational constraints that make conventional inspection methods insufficient.

This review consolidates insights from over 100 peer-reviewed studies and demonstrates that, while vibration and AE sensors have been widely adopted in other industrial sectors, their deployment in port crane applications remains limited but promising. The reviewed technologies show clear potential for early detection of mechanical degradation, crack propagation, and corrosion. Furthermore, the convergence with IoT platforms al-lows for seamless data transmission, cloud-based analysis, and automated maintenance alerts, offering reduced downtime, enhanced safety, and improved cost-efficiency.

Despite these advantages, challenges such as sensor durability in marine environments, data interpretation complexity, and standardization of multi-sensor systems per-sist. Future research must prioritize the development of corrosion-resistant and self-powered sensors, AI-enhanced signal analysis, and interoperable IoT protocols tailored for heavy-lifting equipment. Importantly, the alignment of RNDT technologies with predictive maintenance frameworks and digital twin architectures will play a pivotal role in building smarter, safer, and more resilient port infrastructure in the Industry 4.0 era.

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Abbreviations

The following abbreviations are used in this manuscript:

AE	Acoustic emission
AI	Artificial intelligence
ASCs	Automated Stacking Cranes
CNC	Computerized Numerical Control
ECT	Eddy current testing
EMI	Electromagnetic interference
FBGs	Fiber Bragg gratings
FCs	Floating Cranes
IoT	Internet of Things
MEMS	Micro Electro-Mechanical Systems
MHCs	Mobile Harbor Cranes
MPT	Magnetic particle testing
NDT	Non-destructive testing
PACECO	Pacific Coast Engineering Company
RMGCs	Rail-Mounted Gantry Cranes
RNDT	Remote non-destructive testing
RT	Radiographic testing
RTGCs	Rubber-Tyred Gantry (RTG) Cranes
SCADA	Supervisory Control and Data Acquisition
SHM	Structural health monitoring
STSCs	Ship-to-Shore Cranes
UAVs	Unmanned aerial vehicles
UT	Ultrasonic testing
VI	Visual inspection

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