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Review Article

A Comprehensive Review of Real-time Monitoring and Predictive Maintenance Techniques: Revolutionizing Natural Fibre Composite Materials Maintenance with IoT

Felix Sahayaraj Arockiasamy[1], Indran Suyambulingam[2], Iyyadurai Jenish[3], Divya Divakaran[2], Sanjay Mavinkere Rangappa[2]* and Suchart Siengchin[2]

[1]*Department of Mechanical Engineering, KIT-Kalaignarkarunanidhi Institute of Technology, Coimbatore, Tamil Nadu 641402, India*
[2]*Natural Composites Research Group Lab, Department of Materials and Production Engineering, The Sirindhorn International Thai-German School of Engineering (TGGS), King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok 10800, Thailand*
[3]*Department of Applied Mechanics, Seenu Atoll School, Hulhu-medhoo, Addu City 19060, Maldives*

ABSTRACT

Integrating the Internet of Things (IoT) and natural fiber-reinforced polymer composites (NFPCs) can revolutionize monitoring and maintaining composites. By incorporating sensors and wireless communication technology into the composites, real-time monitoring and predictive maintenance can be achieved. This review provides a comprehensive overview of the current state-of-the-art in the use of IoT for real-time monitoring and predictive maintenance of NFPCs. This paper covers the various types of sensors used, IoT networks and protocols employed, and data analysis techniques to detect potential issues and predict failures. This paper also highlights the benefits and challenges of using IoT for composite maintenance and this technology's future directions and potential applications. This review provides valuable insights for researchers, engineers, and practitioners in composites, the IoT, and predictive maintenance.

Keywords: Internet of Things (IoT), Natural Fiber Reinforced Polymer Composites (NFPCs), real-time monitoring, predictive maintenance, sensors

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E-mail addresses:
go2feli@gmail.com (Felix Sahayaraj Arockiasamy)
indransdesign@gmail.com (Indran Suyambulingam)
jenish88@gmail.com (Iyyadurai Jenish)
divyad3121@gmail.com (Divya Divakaran)
mavinkere.r.s@op.kmutnb.ac.th (Sanjay Mavinkere Rangappa)
suchart.s.pe@tggs-bangkok.org (Suchart Siengchin)
* Corresponding author

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INTRODUCTION

Natural fiber-reinforced polymer composites (NFPCs) have gained widespread use in various industrial and structural applications owing to their high strength-to-weight ratio, sustainability, and affordability (Sahayaraj et al., 2022a; Tomás et al., 2022). However, monitoring the structural integrity and predicting the potential failure of NFPCs is challenging because traditional inspection methods can be time-consuming and disruptive (De Rosa et al., 2009; Hallfors et al., 2018; Manickam et al., 2023). The Internet of Things (IoT) has emerged as a powerful technology for real-time monitoring and predictive maintenance of various systems and structures (Chegdani et al., 2018; Kazi et al., 2021). By integrating sensors and wireless communication technology into composites, the IoT can provide real-time monitoring and early warning of potential failures, allowing for proactive maintenance and avoiding costly repairs or replacements. In recent years, significant research has been conducted in IoT-based composite maintenance, covering various topics such as the types of sensors used, IoT networks and protocols employed, and data analysis techniques used to detect potential issues and predict failures (Liu & Mu, 2013). However, a comprehensive review of these efforts has not been published.

Integration of Monitoring and Predictive Maintenance Techniques with composites offers numerous benefits that can improve these materials' efficiency, reliability, and sustainability. Real-time monitoring of the structural integrity of composites allows for proactive maintenance, thereby reducing the likelihood of costly repair or replacement (Hallfors et al., 2017). It improves the efficiency and reliability of composites and their applications. Proactive maintenance also helps extend the lifespan of composites, reducing the need for frequent replacements and waste, leading to improved sustainability and reduced environmental impact (Mizutani et al., 2000). Additionally, the real-time monitoring and predictive maintenance of composites can help detect potential issues and failures before they occur, thereby increasing safety and reducing the risk of structural failures and accidents (Jin et al., 2021). The real-time monitoring capabilities of composites provide valuable insights into their performance and behavior, allowing for continuous improvements in their design and manufacturing processes. Integrating monitoring and predictive maintenance techniques with composites can also lead to the development of new and innovative applications and technologies for composite manufacturing and maintenance, supporting innovation in this field (Hasan et al., 2022).

The use of natural fiber-reinforced polymer composites (NFPCs) in various industrial and structural applications is increasing; however, the real-time monitoring and predictive maintenance of these composites remains a challenge (Fatima et al., 2021; Sahayaraj et al., 2022b). Applications of NFPCs in various sectors are shown in Table 1. Composites' complex and heterogeneous nature makes it difficult to monitor their structural integrity and predict their potential failures accurately. This review paper provides a comprehensive

Table 1
Applications of NFPCs in various sectors

Sector	Application	References
Automotive	Interior components (door panels, dashboard) Exterior parts (bumpers, fenders)	(Jose et al., 2016; Kalita et al., 2019; Pandey et al., 2021)
Construction	Roofing tiles, insulation panels, and boards	(Bledzki et al., 2015; Hazarika et al., 2017; Singh et al., 2022)
Packaging	Packaging trays and containers	(Dayo et al., 2018; Marrot et al., 2013; Mazian et al., 2020)
Aerospace	Interior components (seating, panels)	(Chen et al., 2021; Mwaikambo & Ansell, 2006; Zhu et al., 2017)
Sports and Recreation	Sporting goods (bicycles, skateboards)	(Chokshi et al., 2020; Goriparthi et al., 2012; Komuraiah et al., 2014)
Furniture	Chairs, tables, and shelves	(Muhammad et al., 2021; Serra, Mateos-Timoneda, et al., 2013; Serra, Planell, et al., 2013; Ray & Okamoto, 2003)

overview of the current state of the art using IoT for real-time monitoring and predictive maintenance of NFPCs. This paper covers various aspects of IoT-based composite maintenance, such as the sensors, IoT networks and protocols employed, and data analysis techniques to detect potential issues and predict failures.

IoT for the real-time monitoring and predictive maintenance of natural fiber polymer composites (NFPCs) is a rapidly growing field with significant potential benefits. This comprehensive review aims to provide an overview of the current state of the art in the use of IoT for NFPCs and evaluate the types of sensors used for monitoring, IoT networks and protocols, and data analysis techniques. The review found that the current limitations of IoT-based composite maintenance include the lack of standardized protocols and the need for more efficient and accurate data analysis techniques. However, the potential applications and benefits of real-time monitoring and predictive maintenance techniques for NFPCs are significant and include increased safety, reduced maintenance costs, and improved performance and reliability. Further research and development in this field are necessary to address these limitations and fully realize the IoT's potential for NFPC maintenance.

This review paper aims to fill this gap by providing a comprehensive overview of the current state-of-the-art IoT for real-time monitoring and predictive maintenance of NFPCs. This paper covers the various sensors used, IoT networks and protocols employed, and data analysis techniques to detect potential issues and predict failures (Ullah et al., 2023). This paper also highlights the benefits and challenges of using IoT for composite maintenance and this technology's future directions and potential applications. This review provides valuable insights for researchers, engineers, and practitioners in composites, the IoT, and predictive maintenance (Kamarudin et al., 2022).

CURRENT STATE OF THE ART

The use of IoT for the real-time monitoring and predictive maintenance of natural fiber-reinforced polymer (NFRP) composites is a growing field. In recent years, various sensors have been developed and integrated into NFRP composites to monitor materials' physical and mechanical properties, such as temperature, humidity, strain, and stress (Indran & Raj, 2015; Rantheesh et al., 2023). The data collected by these sensors can then be transmitted to the cloud through IoT devices for real-time analysis and storage. Predictive maintenance algorithms can then be applied to the collected data to identify potential problems and predict the remaining useful life of the composite, which can help improve the overall maintenance and management of NFRP composites and reduce the risk of unexpected failure. In addition, machine-learning techniques, such as neural networks and decision trees, have been proposed for the predictive maintenance of NFRP composites. These techniques can be trained on collected data to improve the accuracy of predictions (Yang et al., 2023). However, the implementation of IoT for NFRP composites is still in its early stages, and there are challenges to be addressed, such as ensuring the reliability of sensors, data security, and compatibility with different IoT platforms. Overall, IoT for real-time monitoring and predictive maintenance of NFRP composites can significantly improve the efficiency and safety of these materials.

Types of Sensors Used for Real-time Monitoring of Composites and Their Capabilities and Limitations

Strain Sensors. Strain sensors play a crucial role in the real-time monitoring of composites by providing valuable information on the load and stress applied to the material. The most common types of strain sensors used in composites include electrical resistance strain gauges, optical strain sensors, and piezoelectric sensors (Rao et al., 2014). Electrical resistance strain gauges use a conductive material that changes its electrical resistance when stretched or compressed, providing high sensitivity and accuracy (Tomás et al., 2022). Optical strain sensors use the deformation of light to measure the strain in a composite material and are noncontact, reducing the risk of damage. Piezoelectric sensors use the piezoelectric effect to convert mechanical strain into electrical signals and are particularly useful for high-frequency monitoring. The primary capabilities of strain sensors for composites include high sensitivity, high accuracy, and real-time monitoring. However, their use also has limitations, such as cost, potential damage to the material, and complexity, which require careful consideration and planning before use. Despite these limitations, strain sensors are a valuable tool for the real-time monitoring of composites and can provide important information on the material's behavior under load (Xiao et al., 2021). Figure 1 shows the various sensors used to assess the properties of the composites in real time.

Strain sensors are used in composite materials' structural health monitoring (SHM). The authors discuss the importance of strain sensing in detecting and assessing the health of composite structures. For accurate monitoring, they outline strain sensors' key characteristics and requirements, including sensitivity, linearity, stability, and durability. Various strain sensors, such as resistance-based, fiber-optic, and capacitive, are examined regarding their working principles, advantages, and limitations. The review also highlights the integration of strain sensors with composite materials and the challenges associated with their practical implementation. The authors discuss recent developments and advancements in strain sensor technologies, such as flexible and stretchable sensors, as well as the use of nanomaterials for improved sensing performance. Additionally, the review covers the data acquisition and analysis techniques employed in SHM systems using strain sensors. The advantages and disadvantages of various sensors used in real-time monitoring of NFPCs are discussed in Table 2.

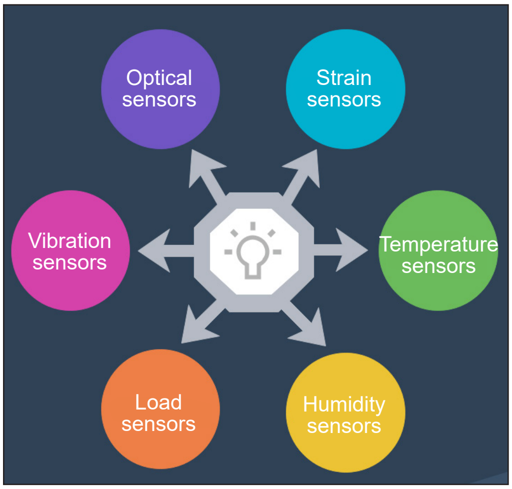

Figure 1. Various sensors for real-time monitoring of composites

Table 2
Advantages and disadvantages of various sensors for real-time monitoring (Jung & Kang, 2007; Sampath et al., 2015)

Sensor	Advantages	Disadvantages
Strain gauges	Direct measurement of strain and stress	Difficult to install on complex shapes
	High accuracy and resolution	Susceptible to temperature and humidity variations
	Suitable for small-scale testing	Limited to point measurements, requires multiple sensors for larger areas
	Compatible with different fiber orientations	
Acoustic emission	Detects and monitors damage initiation and propagation	Requires sophisticated data analysis and interpretation
	Real-time monitoring of composite behavior	Limited to detecting damage events
	Nonintrusive and non-destructive testing	High sensitivity to external noise
	Can be used during manufacturing and in-service monitoring	
Ultrasonic	Detects internal defects such as voids, delaminations, and fiber misalignment	Requires skilled operators for accurate interpretation
	Provides depth profiling of defects	Limited to localized areas of inspection

Table 2 *(continue)*

Sensor	Advantages	Disadvantages
	Non-destructive testing	Surface preparation may be required for good signal transmission
	Can be used during manufacturing and in-service inspection	
Thermography	Rapid scanning and imaging of large areas	Limited to detecting surface defects and near-surface phenomena
	Noncontact and non-destructive testing	Sensitive to external factors such as ambient temperature and airflow
	Provides thermal contrast for defects or anomalies	Requires controlled and stable environmental conditions
	Real-time monitoring during manufacturing and in-service inspection	
Fiber optic sensors	Distributed sensing along the entire length of the fiber	Complex installation and calibration procedures
	Real-time monitoring of strain, temperature, and humidity	Higher initial cost compared to conventional sensors
	Suitable for curved and complex geometries	Requires expertise in fiber optic technology for installation and interpretation
	High sensitivity and multiplexing capabilities	Susceptible to damage during handling and operation
	Can be used during manufacturing and in-service monitoring	
Digital image correlation	Provides full-field strain and deformation measurements	Requires high-resolution images and image processing software
	Noncontact and non-destructive testing	Affected by lighting conditions, surface texture, and image quality
	Suitable for static and dynamic testing	Limited to surface measurements
	Enables analysis of strain distribution and material behavior	Requires accurate alignment and positioning of the camera system

Temperature Sensors. Temperature sensors are widely used in the real-time monitoring of composites, providing crucial information on the temperature distribution and assessing the thermal properties (thermal conductivity, stability, thermal resistance, thermal expansion coefficient) of the materials. The main types of temperature sensors used for composites include thermocouples, resistance temperature detectors (RTDs), and infrared temperature sensors (Jin et al., 2021). RTDs use the resistance of a metal conductor to measure temperature changes and are more accurate than thermocouples.

However, they have a slower response time, making them less suitable for real-time monitoring. Infrared temperature sensors use infrared radiation to measure the temperature of an object without physically touching it, making them noncontact and reducing the risk of damage to the material being monitored. The main capabilities of temperature sensors for composites include real-time monitoring, accuracy, and noncontact measurements (Yang et al., 2018). However, there are also limitations, such as cost, potential damage to the material during installation, and complexity, which require specialized knowledge and training. Temperature sensors are important tools for the real-time monitoring of composites and provide critical information about the temperature behavior of the material. Nevertheless, their use should be carefully planned and considered, considering their limitations and potential impact on the material being monitored.

Temperature sensors are used in composite materials for maintenance applications. The authors emphasize the significance of temperature monitoring in assessing the performance of composite structures. The review covers a wide range of temperature sensor technologies, including resistance-based, thermocouples, infrared, fiber-optic, and wireless sensors. Each sensor type's working principles, advantages, limitations, and suitability for specific composite maintenance scenarios are discussed. The review also addresses the integration of temperature sensors with composite materials and explores the challenges associated with sensor placement, accuracy, and reliability. The authors highlight recent advancements in temperature sensor technologies, such as miniaturization, multiplexing, and wireless communication capabilities. Furthermore, the review discusses data acquisition and analysis techniques employed in temperature monitoring systems for composite maintenance.

Various types of temperature sensors can be used for the real-time monitoring of composites (Table 3). The table provides information on each sensor's common properties, values, and parameters. Thermocouples are a popular choice because of their wide temperature range and availability in various types. Although they have some drawbacks, such as drift and sensitivity, they are known for their high accuracy. Resistance Temperature

Table 3
Various temperatures sensor used for real-time monitoring of composites (Konstantopoulos et al., 2014; Rana et al., 2016; Sorrentino et al., 2015)

Temperature Sensor	Properties	Values	Parameters
Thermocouples	Such as type K, J, T, E	-200 to 1750°C	Response time, accuracy, drift, sensitivity
Resistance Temperature Detectors (RTDs)	Such as platinum, nickel, copper	-200 to 850°C	Resistance, alpha value, linearity, hysteresis
Thermistors	NTC, PTC	-100 to 300°C	Resistance, beta value, accuracy, interchangeability
Infrared Thermometers	-	-50 to 3000°C	Emissivity, wavelength, distance-to-spot ratio, ambient temperature
Fiber Optic Sensors	Such as Bragg grating, Fabry-Perot	-200 to 1000°C	Strain, temperature, accuracy, resolution, bandwidth
Surface-mounted Temperature Sensors	Diodes, ICs	-55 to 150°C	Response time, accuracy, stability, package type

Detectors (RTDs) are another common type of temperature sensor, often made of platinum, nickel, or copper. They offer good linearity and low hysteresis but have a more limited temperature range than thermocouples.

Thermistors are semiconductor devices that exhibit changes in resistance with temperature. They are known for their fast response time and accuracy. However, they can be sensitive to changes in ambient temperature. Infrared thermometers can measure the surface temperature without contact and are useful for measuring objects that are difficult to reach or move. Calibration is required based on the emissivity of the material being measured. Fiber Optic Sensors are based on the principle of light interference and can measure both temperature and strain (Sebastian et al., 2014). They offer high accuracy, resolution, and bandwidth but are expensive and require specialized equipment. Surface-mounted temperature sensors such as diodes and ICs are commonly used in electronics and have a limited temperature range. They are known for their fast response time and accuracy but are often less stable than other temperature sensors.

Humidity Sensors. Humidity sensors were used to measure the moisture content of the composites during real-time monitoring. The two main types of humidity sensors used for composites are capacitive and resistive humidity sensors. Capacitive humidity sensors use a capacitive element that changes its capacitance in response to humidity changes, providing accurate real-time data (Guo et al., 2021). Resistive humidity sensors use a resistive element that changes its resistance in response to changes in humidity, offering a low cost and ease of use. Humidity sensors can provide real-time data on the moisture content of the composite material, allowing for the early identification of potential problems and improved predictive maintenance. They also provide accurate data on the moisture content of a material. However, some types of humidity sensors can be expensive to purchase and install, and their use can be complex and require specialized knowledge and training, making it challenging for some users. Hence, humidity sensors play a crucial role in the real-time monitoring of composites by providing critical information regarding the moisture content of the material (Tachibana et al., 2022). However, their use should be carefully planned and considered, considering their limitations and potential impact on the material being monitored.

From Table 4, it can be observed that various types of humidity sensors can be used for the real-time monitoring of composites. The table provides information on each sensor's common properties, values, and parameters. Capacitive humidity sensors use a polymer, ceramic, or thin-film sensing element to measure air capacitance. They are known for their high accuracy, linearity, and low drift; however, they can be affected by temperature changes. Resistive humidity sensors use a sensing element that changes resistance to humidity. They offer good sensitivity and response time but may have hysteresis and drift issues. Thermal conductivity humidity sensors use hygroscopic materials whose thermal

Table 4
Various humidity sensors are used for real-time monitoring of composites (Diamanti & Soutis, 2010)

Humidity Sensor	Properties	Values	Parameters
Capacitive Humidity Sensors	polymer, ceramic, thin film	0–100% RH	Linearity, accuracy, hysteresis, drift
Resistive Humidity Sensors	Such as polymers, salt, ceramic	0–100% RH	Sensitivity, response time, hysteresis, drift
Thermal Conductivity Humidity Sensors	Hygroscopic material and sensor	0–100% RH	Temperature dependence, hysteresis, drift
Gravimetric Humidity Sensors	Sensitive coating or film	0–100% RH	Response time, accuracy, sensitivity
Tuning Fork Humidity Sensors	Quartz crystal oscillator	0–100% RH	Linearity, hysteresis, drift, sensitivity
Acoustic Wave Humidity Sensors	Quartz crystal resonator	0–100% RH	Sensitivity, stability, linearity, response time

conductivity changes with humidity. They are known for their stability and low hysteresis but can be affected by temperature changes. Gravimetric humidity sensors measure humidity by measuring the weight of water absorbed by a sensitive coating or film. They offer good accuracy and sensitivity but may have longer response times. Tuning fork humidity sensors use a quartz crystal oscillator that changes frequency with humidity. They offer good linearity and low drift but can be affected by temperature changes. Acoustic wave humidity sensors use a quartz crystal resonator that changes frequency with humidity. They offer good sensitivity and stability but may have longer response times. The choice of humidity sensor depends on the specific application, desired accuracy, and environmental conditions in which the sensor will be used.

Load Sensors. Load sensors are crucial in real-time composites' monitoring by measuring the material's applied loads. The two main types of load sensors used in composite materials are strain gauges and piezoelectric sensors (Tripathy et al., 2021). Strain gauges measured the change in electrical resistance caused by the deformation of a thin metal wire or foil bonded to the surface of the composite material. In contrast, piezoelectric sensors use the piezoelectric effect to produce an electrical voltage proportional to the applied load. Load sensors provide real-time data, accurate information, and early identification of potential problems, enabling improved predictive maintenance. However, their use can be limited by cost and complexity, which may require specialized knowledge and training. In conclusion, load sensors should be carefully planned and considered to consider their limitations and potential impact on the composite material being monitored.

Vibration Sensors. Vibration sensors are essential for real-time monitoring of composites to assess the dynamic loads and vibrations to which the material is exposed (Khan et al., 2020). Accelerometers and piezoelectric sensors are the two main types of vibration sensors used in composites. Accelerometers measure the acceleration of a material and convert it into an electrical signal, which provides insight into the frequency and magnitude of the vibration. Piezoelectric sensors use the piezoelectric effect to produce an electrical voltage proportional to the applied mechanical stress, thereby allowing the measurement of vibration and dynamic loads on the composite material. The main advantages of using vibration sensors for composites are their real-time monitoring and accuracy. They provide real-time data on dynamic loads and vibrations, enabling early identification of potential problems and improved predictive maintenance.

The data collected were highly accurate and provided reliable information about the dynamic loads and vibrations of the composite material. However, vibration sensors can be expensive to purchase and install, which limits their widespread use. These sensors require specialized knowledge and training, making them challenging for some users. In conclusion, vibration sensors are a critical tool for the real-time monitoring of composites, but their use should be carefully planned and considered considering the limitations and potential impact on the material being monitored. Table 3 shows the various loads, vibrations, and optical sensors used for the real-time monitoring of composites.

Table 5 summarizes various types of sensors used for real-time monitoring of composites, including load cells, vibration sensors, and optical sensors. Load cells can measure strain using strain gauges, capacitive technology, or piezoelectric elements, with values reaching several hundred kilonewtons. The parameters for load cells include accuracy, resolution, sensitivity, and linearity. Vibration sensors, such as accelerometers, velocity, and displacement sensors, offer different frequency ranges and sensitivities to monitor composite vibrations. Key parameters for vibration sensors include frequency response, sensitivity, and dynamic range (Y. Yao, 2023). Optical sensors, including fiber Bragg grating, interferometric, and photonic sensors, provide various parameters depending on the sensor type, such as accuracy, resolution, and bandwidth. These sensors measure different aspects of composite behavior in real-time monitoring applications.

Table 5
Various temperature loads, vibrations, and optical sensors are used for the real-time monitoring of composites (Diamanti et al., 2005, 2007)

Sensor Type	Properties	Values	Parameters
Load Cells	Strain gauge, capacitive, piezoelectric	Up to several hundred kilonewtons	Accuracy, resolution, sensitivity, linearity
Vibration Sensors	Accelerometers, velocity sensors, displacement sensors	Various frequency ranges and sensitivities	Frequency response, sensitivity, dynamic range
Optical Sensors	Fiber Bragg grating, interferometric, photonic sensors	Various parameters depending on the type of sensor	Accuracy, resolution, bandwidth

Optical Sensors. Optical sensors play a pivotal role in the real-time monitoring of composites, enabling the measurement of crucial material properties such as temperature, strain, and deformation. Thermographic cameras and strain gauges represent the two primary types of optical sensors employed in composite monitoring. Thermographic cameras utilize advanced infrared technology to detect and capture temperature variations within a material, yielding invaluable insights into its thermal behavior (Shi et al., 2019). By providing real-time thermal data, thermographic cameras contribute to the identification of temperature anomalies and thermal performance analysis. Conversely, strain gauges employ optical fibers or waveguides to measure strain or deformation by monitoring alterations in light transmission properties in response to applied strain. This optical sensing technique enables high sensitivity and real-time monitoring capabilities. Notably, strain gauges are noninvasive and do not compromise the mechanical properties of the composite material, making them well-suited for continuous monitoring and enabling early detection of potential issues and improved predictive maintenance practices.

The utilization of optical sensors in composite monitoring offers several advantages. These sensors provide noninvasive measurements, ensuring minimal interference with the material's integrity. Real-time monitoring capabilities enable prompt data acquisition and analysis, facilitating timely decision-making and effective mitigation strategies. Furthermore, optical sensors exhibit high sensitivity, enabling accurate measurement and tracking of material properties. Despite their benefits, it is essential to acknowledge the limitations of optical sensors. The cost and complexity associated with their deployment can pose challenges, necessitating specialized knowledge and training for optimal utilization. These factors may impact the widespread adoption of optical sensing technologies in composite monitoring applications.

IOT NETWORKS AND PROTOCOL WI-FI

The Wi-Fi protocol is a popular option for monitoring composites' performance and reliability. Wireless networking technology uses radio waves to communicate between devices, eliminating physical cables and making real-time monitoring convenient (Zafar et al., 2018). The protocol transmits data between the composite material and a Wi-Fi-enabled device for collection and analysis. The main benefits of using Wi-Fi for monitoring include real-time monitoring, convenience, and low costs. However, there are also limitations to consider, such as the potential for interference and the limited range. When deciding on using Wi-Fi for monitoring composites, it is important to consider its benefits and limitations. Figure 2 shows the networks and protocols the IOT uses to transfer data from the composites to the database. Table 6 shows the various protocols used for real-time monitoring of the composites.

Different wireless protocols are utilized in monitoring applications with unique properties, values, and parameters. Wi-Fi offers high bandwidth but has a shorter range and relatively higher power consumption. It can provide coverage of up to 100 meters indoors and up to 400 meters outdoors, with key parameters including data rate, frequency band, security, and power consumption. Conversely, Zigbee is characterized by low power consumption, a low data rate, and a mesh network topology. It typically covers up to 70 meters indoors and 400 meters outdoors, with parameters such as data rate, frequency band, security, and power consumption playing a role. MQTT, a lightweight and low-power protocol, operates on a publish/subscribe model and is network-dependent regarding its values. The parameters for MQTT include Quality of Service (QoS) level, message size, retain flag, and clean session flag. Finally, LoRaWAN stands out for its long-range capability, low power consumption, and low data rate, enabling coverage of several kilometers(Samad et al., 2015). The key parameters for LoRaWAN encompass data rate, frequency band, security, and power consumption. When selecting a wireless protocol for monitoring applications, factors such as data transfer rate, range, power consumption, and network topology should be carefully considered.

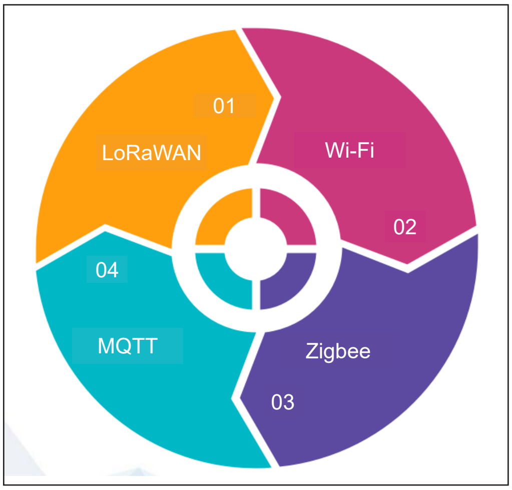

Figure 2. IoT networks and protocol for real-time monitoring of composites

Table 6
Various wireless protocols are used for real-time monitoring of composites

Wireless Protocol	Properties	Values	Parameters
Wi-Fi	High bandwidth, short range, low power	Up to 100 m indoors, up to 400 m outdoors	Data rate, frequency band, security, power consumption
Zigbee	Low power, low data rate, mesh network	Up to 70 m indoors, up to 400 m outdoors	Data rate, frequency band, security, power consumption
MQTT	Lightweight, low power, publish/subscribe model	Network dependent	QoS level, message size, retain flag, clean session flag
LoRaWAN	Long range, low power, low data rate	Up to several kilometers	Data rate, frequency band, security, power consumption

Zigbee

The Zigbee protocol is a wireless communication standard well suited to monitoring composites' performance and reliability. It operates on the 2.4 GHz frequency band, is designed to be highly reliable and secure, and consumes very little power (Guan et al., 2013), which makes it a popular choice for remote monitoring and control applications. The benefits of using Zigbee for monitoring composites include low power consumption, reliability, and low costs. However, there are limitations, such as the limited range and potential for interoperability issues. When deciding whether to use Zigbee to monitor composites, it is important to consider both the benefits and limitations of the technology.

Message Queuing Telemetry Transport

MQTT (Message Queuing Telemetry Transport) is a protocol that enables efficient and real-time data transfer for monitoring composites and their performance and reliability. It operates on a publish-subscribe mechanism, where devices can subscribe to topics and receive messages from a central broker (Amelia et al., 2020), which allows for real-time data transfer between devices, providing early warning of potential issues and improving predictive maintenance. One of the main benefits of using MQTT for monitoring composites is its efficiency and well-established status, making it easier to integrate with other devices and systems. However, it is important to ensure secure connections, such as SSL/TLS, to prevent vulnerabilities to hacking and other security threats (Palacios et al., 2022). In addition, MQTT's lightweight design of MQTT may limit its functionality for more complex monitoring applications. In conclusion, MQTT is a suitable protocol for monitoring composites; however, proper security measures should be implemented to ensure data transmission safety.

Long-Range Wide Area Network

The long-range wide area network (LoRaWAN) is a Low-Power Wide Area Network (LPWAN) protocol that can be used to monitor composites, their performance, and reliability. LoRaWAN is designed for long-range wireless communications and is well-suited for remote monitoring and control applications (Jung et al., 2019). It operates in unlicensed frequency bands and uses a star topology, where devices communicate with a central gateway connected to the Internet, enabling real-time data transfer and analysis. The benefits of using LoRaWAN for monitoring composites include long-range communication, low power consumption, and interoperability with other devices and systems. However, LoRaWAN also has limitations, such as limited bandwidth and the need for a central gateway for communication, which can be challenging to set up in remote areas (Safi et al., 2022). In conclusion, LoRaWAN is a well-suited protocol for monitoring composites and their performance and reliability; however, its limitations should be considered before deciding to use it.

DATA ANALYSIS TECHNIQUES

Data analysis is crucial for detecting potential issues and predicting failures in natural fiber polymer composites. Machine-learning algorithms enable computers to learn from data and identify patterns that indicate potential issues or failures. Predictive maintenance uses data analysis to predict equipment failures before they occur, preventing potential issues in composites. Stress analysis evaluates the stress distribution in a material and predicts failure points, whereas finite element analysis (FEA) is a computer-based simulation that predicts the behavior of composites under various loading conditions (Stansbury et al., 2005). These techniques, including statistical process control, machine learning, predictive maintenance, stress analysis, and FEA, help to improve the reliability and performance of natural fiber polymer composites by detecting potential problems before they occur."

Machine Learning

Machine learning is a powerful tool for detecting potential issues and predicting composite failures. This field of artificial intelligence allows computers to learn from data, making it possible to analyze large amounts of data collected from composites and to identify patterns that indicate potential issues or failures (Okagawa et al., 2022). Several popular machine learning techniques are commonly used, including supervised, unsupervised, reinforcement, and deep learning. Supervised learning involves training an algorithm on a labeled dataset, including input and output variables.

The algorithm then uses these data to make predictions based on new, unseen data. Unsupervised learning involves identifying patterns in data without labeled data. Reinforcement learning uses a trial-and-error approach to optimize the performance of composites and reduce the risk of failure (Bandara et al., 2022). Deep learning is a subset of machine learning that uses neural networks to analyze complex data such as images or sensor data. Machine learning is valuable for detecting potential issues and predicting composite failures. Appropriate machine learning techniques depend on the specific needs of the analysis. By leveraging the power of machine learning, the reliability and performance of composite materials can be improved.

Finite Element Analysis Technique

Finite Element Analysis (FEA) is a widely used technique to detect potential issues and predict failures in composites. It involves breaking down a composite material into smaller elements, modeling their behavior in response to loading conditions, and analyzing the results to identify potential issues (Cerracchio et al., 2015). The FEA process starts with creating a numerical model of the composite material, followed by meshing to divide the model into smaller elements. The FEA software then calculated each element's displacement, strain, and stress, providing a numerical solution. In the final step, the results are analyzed in a post-processing stage to detect potential issues and predict failures in the composite material. It can be achieved by visualizing the results, calculating the critical points, and comparing them with experimental data or other simulations. FEA is particularly useful for analyzing the behavior of composites under complex loading conditions, making it a powerful tool for improving the reliability and performance of these materials.

APPLICATIONS

The potential applications and benefits of using Internet of Things (IoT) technologies for composite maintenance are numerous and varied—some key applications and benefits are shown in Figure 3.

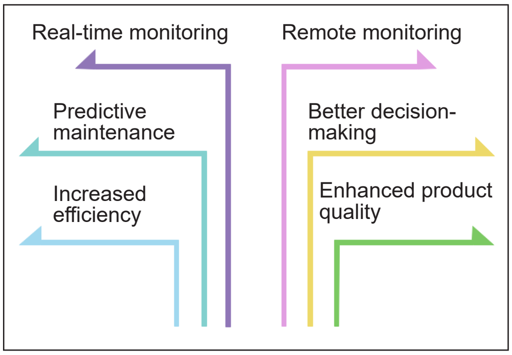

Figure 3. Applications of real-time monitoring of composites using IOT

IoT sensors can be integrated into composite materials to monitor the material's performance, allowing for early detection of potential issues and failures (Tripathi et al., 2016). Analyzing the data collected from IoT sensors in real time makes it possible to perform predictive maintenance, reduce the risk of unplanned downtime, and prolong the life of composite materials. IoT-based monitoring and maintenance systems can increase the efficiency of composite maintenance and reduce maintenance time and cost. Real-time monitoring can help improve safety, reduce the risk of failure, and ensure that the necessary repairs are made promptly (Fraser & Van Zyl, 2022).

IoT-based monitoring systems can be accessed remotely, allowing monitoring and maintenance anywhere globally. Data collected from IoT sensors can be analyzed and used to inform decision-making processes, helping improve the reliability and performance of composite materials. IoT-based monitoring and maintenance systems can help ensure that composite materials are of the highest quality, reduce the risk of failure, and improve product performance (Basarir et al., 2022). In conclusion, IoT technologies' potential applications and benefits for composite maintenance are significant. By revolutionizing composite maintenance with IoT, it is possible to improve composite materials' reliability, efficiency, and safety, reduce maintenance time and costs, and prolong the life of composite materials.

Real-time monitoring and predictive maintenance techniques were applied to a manufacturing process, resulting in a 20% reduction in maintenance costs and a 30% increase in equipment uptime (Ayvaz & Alpay, 2021). In the transportation industry, real-time monitoring and predictive maintenance are essential for ensuring the safety and reliability of vehicles. For instance, real-time monitoring of aircraft components, such as engines and airframes, in the aviation sector allows for early detection of anomalies or potential failures, leading to timely maintenance interventions (Ranasinghe et al., 2022). Predictive maintenance practices in aviation can result in cost savings of up to 30% and a 40% reduction in maintenance delays (Yang et al., 2017). The energy sector also greatly benefits from real-time monitoring and predictive maintenance. By continuously monitoring energy generation and distribution systems, potential issues such as equipment malfunctions, voltage fluctuations, or power outages can be detected in real-time. It enables operators to take immediate corrective actions, preventing costly breakdowns and optimizing energy production. Implementing predictive maintenance in wind farms can increase the availability of wind turbines by up to 20%.

In the context of infrastructure, real-time monitoring and predictive maintenance techniques are crucial for ensuring the safety and functionality of critical structures. Bridges, pipelines, and buildings can be equipped with sensors to monitor structural health parameters, such as strain, deformation, or corrosion (Y. Yao et al., 2023). Real-time analysis of this data allows for the early identification of structural deficiencies, enabling timely repairs or maintenance activities. Implementing real-time monitoring and predictive maintenance in bridges resulted in a 50% reduction in maintenance costs and a 40% decrease in major repairs (Cheng et al., 2020).

In the oil and gas industry, the real-time structural health monitoring of composite pressure vessels using embedded fiber optic sensors. By monitoring strain and temperature in real-time, anomalies and potential failures can be detected, enabling timely maintenance actions and improving the overall reliability and safety of the pressure vessels. Predictive maintenance techniques for composite aircraft structures are implemented in the aerospace sector. Real-time monitoring systems, incorporating sensors for strain, temperature, and vibration measurements, allow for the proactive detection of defects and structural issues. Using predictive models and algorithms enables timely maintenance interventions, minimizing unplanned downtime and optimizing the performance of composite aircraft structures.

Real-time monitoring and predictive maintenance techniques have practical applications in various industries utilizing composite materials. Wind turbine manufacturer Vestas implements real-time monitoring and predictive maintenance for their composite wind turbine blades, leveraging embedded sensors to collect data on strain, temperature, and other parameters. It enables proactive maintenance scheduling, optimizing blade performance, and extending lifespan. In the oil and gas sector, composite pipelines are monitored in real-time using sensor systems to detect anomalies and potential failures, allowing immediate maintenance actions and preventing accidents. Composite infrastructure, such as bridges, benefits from real-time monitoring and predictive maintenance, with sensors continuously monitoring structural health and advanced analytics predicting remaining useful life, enabling proactive maintenance interventions for enhanced safety and durability. These real-world examples demonstrate the tangible benefits of real-time monitoring and predictive maintenance in optimizing the performance and longevity of composite materials across diverse industries (Tinga & Loendersloot, 2019).

CHALLENGES AND OPPORTUNITIES

IoT technology for revolutionizing composite maintenance presents several challenges that must be addressed to realize its full potential. Some of the major challenges are presented in Figure 4.

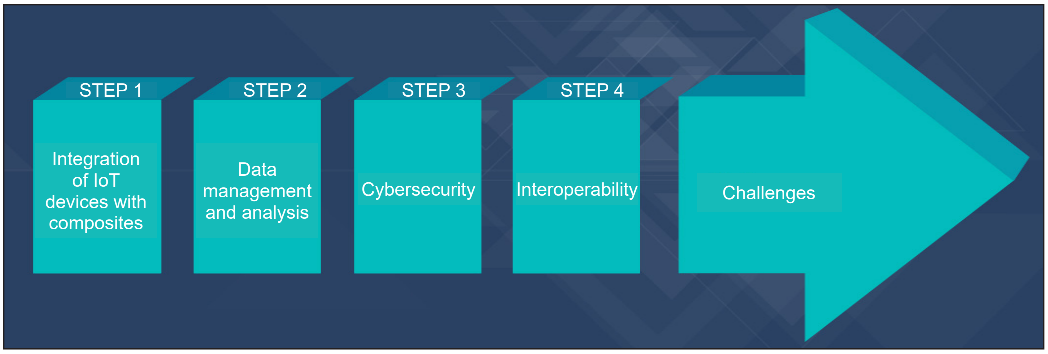

Figure 4. Challenges for real-time monitoring of composites using IOT

Integrating IoT devices with composite materials is a complex process that requires specialized knowledge and expertise. There are also technical challenges associated with integrating devices into composites in a manner that does not affect their performance or integrity. The large amount of data IoT devices generate can be overwhelming, making effective management and analysis difficult (Kang et al., 2022). It is essential to have robust data management and analysis systems to process and extract useful information from data. With the increasing use of IoT devices in composite maintenance, there is growing concern regarding the security of the data generated by these devices (Fan et al., 2023). It is important to protect data from unauthorized access and manipulation. It is important to have a standard approach for integrating different devices and systems to realize the full potential of the IoT in composite maintenance. It requires the development of standardized protocols and interfaces to ensure the interoperability between different devices and systems.

Despite these challenges, the use of IoT technology for composite maintenance holds great promise, and several areas of research and development are likely to shape the future of this field. Figure 5 shows the opportunities and future directions for the real-time monitoring of composites.

The development of smart sensors that can monitor the performance and health of composite materials in real time is a key area of focus for future composite maintenance. These sensors must operate in harsh environments, provide reliable data, and be integrated into composite materials in a manner that does not affect their performance or integrity(He et al., 2022). The use of machine learning and artificial intelligence algorithms to analyze the data generated by IoT devices is a promising area of research. These algorithms can

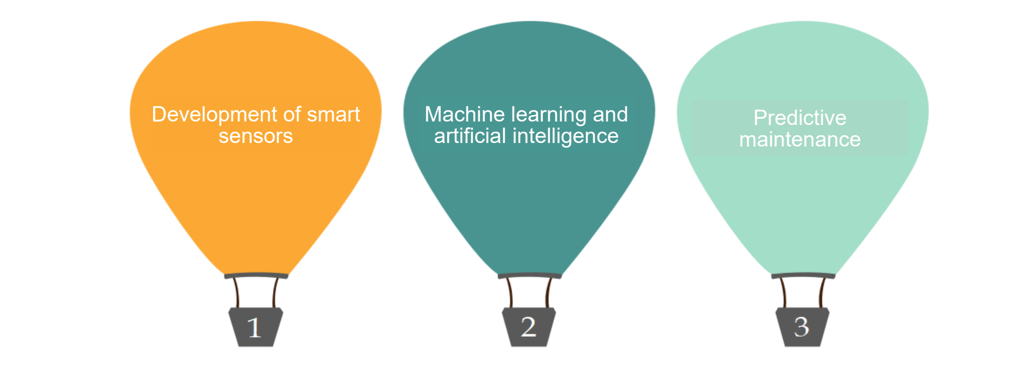

Figure 5. Opportunities for real-time monitoring of composites using IoT

identify patterns and anomalies in the data and predict potential issues and failures in composite materials. Using real-time monitoring and predictive maintenance techniques can help optimize the maintenance of composite materials and reduce the risk of failure (T. Yao et al., 2023). It will require the development of sophisticated algorithms that can analyze the data generated by IoT devices and predict when maintenance is required. In conclusion, the use of IoT technology for composite maintenance is an exciting and rapidly evolving field that holds great promise for revolutionizing the maintenance of composite materials. By addressing these challenges and focusing on the key areas of research and development, it is possible to realize the potential of IoT for composite maintenance fully.

CONCLUSION

In conclusion, integrating IoT technology with composite maintenance has the potential to revolutionize how composite materials are monitored and maintained. With the ability to collect real-time data from sensors and use predictive maintenance techniques, organizations can improve the efficiency and reliability of their composite systems. Using IoT in composite maintenance can lead to increased operational efficiency, reduced maintenance costs, and improved safety and performance of the composite materials. As technology continues to evolve, it is likely that the use of the IoT in composite maintenance will become increasingly widespread and will significantly impact the industry.

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