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APPLICATION OF CONDITION-BASED MONITORING IN ENHANCING MECHANICAL SYSTEM RELIABILITY AND PROACTIVE STRUCTURAL DAMAGE DETECTION

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Abstract

Technologies, processes, and systems are not immune to failure, which is why robust monitoring systems are crucial to ensure their continued functionality and safety. An interdisciplinary approach that combines engineering, data science, and material science allows for more comprehensive measurement and analysis, enabling better decision-making and more accurate predictions of performance. The integration of these technologies leads to increased safety, reduced human error, and significant cost savings by preventing costly repairs and downtime. Continuous monitoring helps in avoiding catastrophic failures, allowing for early detection of issues before they escalate. Additionally, it opens opportunities for improving the design of mechanical systems and structures, optimizing the organization of maintenance. By reducing human impact and enhancing safety, these monitoring systems offer a more secure and efficient operation. Furthermore, through advanced predictive analytics, the remaining service life can be estimated, facilitating more effective planning. The development of such smart, intelligent mechanical systems and structures promises a future where maintenance is proactive rather than reactive, creating a safer, more sustainable environment for both operators and systems by leveraging advanced sensors, Internet of Things, data analytics, and adaptive technologies for real-time monitoring and damage detection.

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Introduction

Today's technologies, processes or systems, despite using modern methods and techniques, are not excluded from the possibility of damage or failure, i.e. to guarantee flawless and reliable functionality. For this reason, monitoring the condition of structures is extremely important in engineering applications from various fields. Monitoring the condition of structures defines the condition of the structure by assessing it, but there is also the possibility of predicting the remaining service life (GOPALAKRISHNAN et al. 2011). Predicting the remaining service life of a structure is critical for planning repairs or replacements, which helps to ensure safety and optimal performance. The successful development and implementation of processes for monitoring the condition of structures involves an understanding of various disciplines, such as mechanics, materials, electronics, modeling and computer engineering. The basic idea in monitoring the condition of structures is to provide the possibility of adequate measurement and analysis, as well as the ability to periodically or continuously, often autonomously, monitor for the needs of condition evaluation. Regular monitoring can prevent damage from growing to dangerous levels, as it allows for early detection of issues. By reducing reliance on human judgment and enabling proactive maintenance, it can also reduce the chances of human error. Moreover, cost savings arise from conducting planned maintenance rather than reactive repairs, which often tend to be more expensive and disruptive.

Damage to a mechanical structure refers to any deviation from its intended geometric shape or changes in the material properties (RAMANAMURTHY, CHANDRASEKARAN 2011, BLANKE et al. 2006) that compromise its integrity and alter the dynamic characteristics of the structure. Damage means an unauthorized change in at least one characteristic of the system, deviating from the standard operating state (SIMANI et al. 2002). It can also refer to an unexpected change in the function of the mechanical system, not necessarily caused by physical disturbances (CHEN, PATTON 1999). Damage typically leads to a decrease in performance, functionality, or safety, potentially resulting in system failure. If not addressed, this can eventually lead to complete failure, disrupting the functionality of the structure and possibly leading to catastrophic consequences. Therefore, identifying and understanding damage early is critical to preventing these failures. In contrast to damage, the consequences of a defect in mechanical systems and structures are usually more serious with a tendency to interrupt the performance of the required functions in a given operating mode, or an error as a periodic irregularity in the fulfillment of the desired function of the system (ISERMANN 2005). When it comes to the source of damage, mechanical systems and structures are also exposed to the influence of the external environment that can contribute to a change in the structural parameters themselves. Structures are often exposed to a range of environmental factors that can contribute to the degradation of materials or the physical properties of a structure. These factors include temperature fluctuations, humidity, wind, chemical exposure, or even natural disasters like earthquakes or floods.

The block diagram in Figure 1 illustrates the flow of a feedback control system comprising several components, each with a specific role in maintaining the desired performance of a dynamic system. The dynamic system is vulnerable to external disturbances, such as environmental changes, unexpected loads, or vibrations, as well as structural damage, which might arise from material fatigue, degradation, or other physical failures. The control unit processes both the input command and the feedback from the sensor to generate a precise control signal for the actuator. The actuator is responsible for converting the control signal, which is generated by the control unit, into a physical action that directly influences the dynamic system. However, actuators are not flawless, they may experience defects that will reduce their efficiency which can affect their ability to perform correctly. The sensor monitors the output of the dynamic system and sends this information back to the control unit. This feedback is essential for ensuring the system operates as intended. However, sensors can also experience defects, calibration errors, signal noise, or complete failure, which can compromise the accuracy of the feedback they provide. In mechanical systems and intelligent structures, damage can occur as a result of a failure in equipment, sensors and actuators, or an error in control units. These types of failures may not involve visible physical damage to the structure, but they can still cause the system to behave in unintended ways, potentially compromising safety, efficiency, or functionality (VENKAT et al. 2003). For example, a sensor failure might cause a system to misinterpret the structural load, triggering incorrect maintenance actions or even leading to unsafe operational conditions. Damage occurs at various stages throughout the service life of a structure, and its unforeseen onset can lead to catastrophic consequences, including threats to human lives. The critical importance of damage detection drives the continuous development of more efficient technologies and the application of effective engineering solutions for detecting, locating, quantifying, and predicting damage at the earliest possible stage.

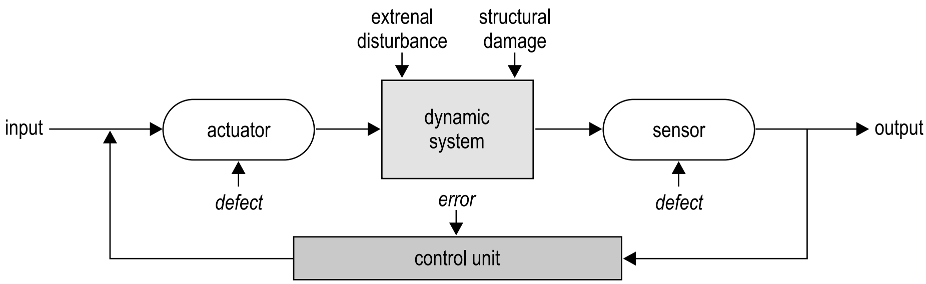

Fig. 1. Damage, defect and error in mechanical systems and structures

In following, Section *Condition monitoring systems* explores the role of monitoring systems and their capacity for proactive damage detection, highlighting the impact on reducing failures that can be costly and lead to unplanned downtime. In addition, the maintenance costs and reliability of systems with and without monitoring are compared, demonstrating the advantages of real-time data analysis in making maintenance decisions. Various methods and techniques are used for damage detection and analysis, as discussed in Section *Methods and implementation of monitoring systems*. The approach can be passive or active, with each offering different levels of damage detection and characterization, and it also delves into the different methods and techniques for damage detection, categorizing them into destructive and non-destructive evaluation techniques, as well as further distinguishing between global and local methods. Global methods are further divided into model-based approaches and signal-based approaches, offering tailored solutions depending on the needs of the system. Section *Intelligent monitoring systems* is dedicated to intelligent monitoring and Internet of Things (IoT), the real-time damage detection by using interconnected sensors to monitor and assess the condition of mechanical systems and structures. Section *Advantages of smart structural systems* is dedicated to the benefits of smart condition monitoring, which are far-reaching, from reducing maintenance costs to improving reliability and security, while Section *Conclusion* is dedicated to the conclusion.

Condition monitoring systems

A system that utilizes advanced diagnostic techniques to accurately assess and monitor the structural health of critical components is vital for maintaining the functionality and safety of the system. The adoption of such systems significantly reduces the need for traditional, labor-intensive inspections, instead relying on continuous, real-time monitoring through embedded sensors and data acquisition systems. This shift towards condition-based maintenance is a result of the integration of smart materials such as piezoelectric sensors (Djidrov et al. 2017) and fiber optics (Zakirov, Giyasova 2022), and the application of predictive algorithms (Ho et al. 2021) for damage detection, location, and quantification. Ongoing research in structural health monitoring explores the use of these technologies to offer a constant representation of structural integrity, helping engineers predict the remaining service life and identify when repairs or replacements are needed. The evolution of these intelligent monitoring systems, including diagnostic systems (Fig. 2) is driven by the increased demand for smart structures, advanced sensor integration, and the ability to transmit large volumes of data in real-time, enabling informed decision-making in maintenance and management. By collecting and analyzing large amounts of data, these systems

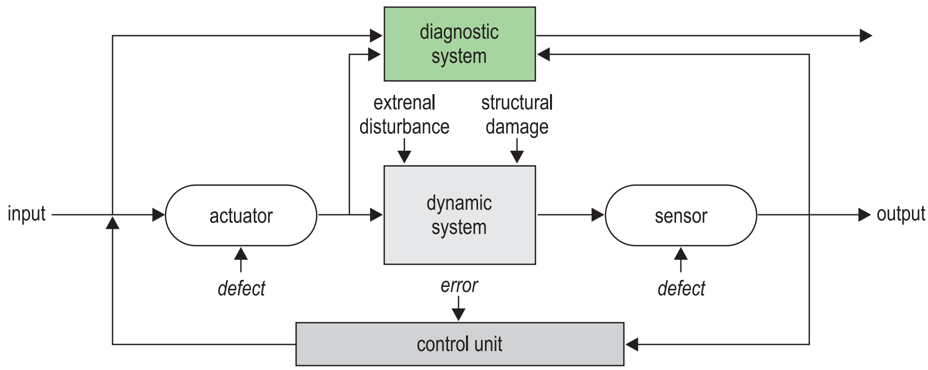

Fig. 2. Intelligent monitoring systems and damage detection

help detect issues early, predict potential failures, and support decision-making in maintenance and management, ultimately improving the safety, efficiency, and longevity of the monitored structures.

Modern structures, characterized by complexity and constantly exposed to the need for greater efficiency, combined with financial and safety constraints, are a challenge not only in their production, but also in their use. Material selection, design and safety factor must often be combined to create safe, lightweight structures with low maintenance costs. If damage occurs to a part of the structure, rapid detection is necessary to have enough time for adequate repair or replacement, in order to ensure the safety of the structure and the system in which it is embedded. The economic motivation for such systems is large and mainly concerns end users (Fig. 3), i.e. for structures with monitoring systems, the benefits are constant maintenance costs and reliability, as opposed to the increase in maintenance costs and decrease in reliability in use in the classic case of structures without monitoring systems (BALAGEAS et al. 2010). This demonstrates the long-term benefits of such systems in preserving structural quality and reducing operational expenses.

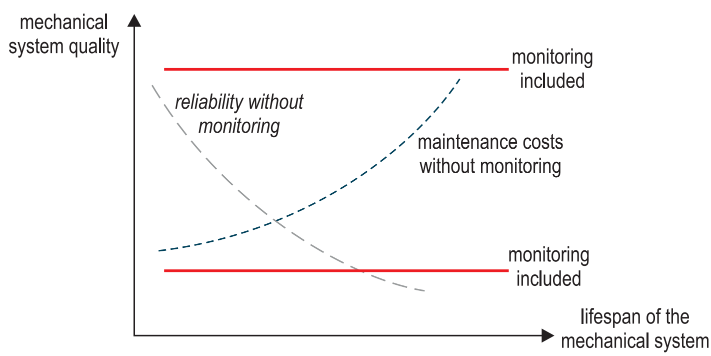

Fig. 3. Maintenance costs and reliability with and without monitoring systems

Methods and implementation of monitoring systems

Monitoring the health of a structure can be implemented passively or actively (STASZEWSKI et al. 2009). Figure 4 presents possible scenarios when conducting an experiment on a mechanical structure equipped with sensors and actuators, and in an environment where external influences may contribute to changes in the state and physical parameters that need to be monitored. In passive monitoring, the state of the structure is observed and evaluated using built-in sensors, without any external stimulation. This type of monitoring is commonly seen in acoustic emission detection techniques (SAEEDIFAR et al. 2019). In active monitoring, sensors and actuators are used. The actuator generates a stimulus, and the sensor monitors the structure's response. For example, piezoelectric devices can be used, with one transducer acting as an acoustic emission detector and another emitting ultrasonic waves. The piezoelectric effect enables these devices to convert electrical signals into mechanical stress, and vice versa. By generating and registering the emitted signals, information about potential damage can be obtained from the interaction between the signals and the damage within the structure (WANG, CHANG 2000). Active testing methods can help detect both sudden and slow-developing damage in materials. These damages can be caused by various processes such as corrosion, delamination, or fatigue (ETXANIZ et al. 2023).

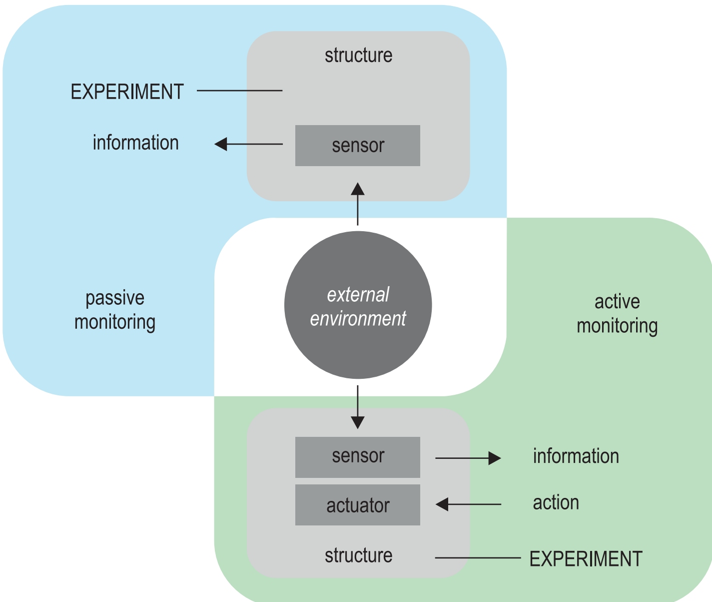

Fig. 4. Possibilities for conducting a monitoring experiment

The wide variety of mechanical structures and systems necessitates the development of diverse techniques, methods, and algorithms for effective health monitoring. Monitoring systems are typically classified based on the level of damage detection and characterization (RYTTER 1993). At Level 1, the system confirms the presence of damage without specifying its location. Level 2 involves identifying the precise location of the damage. Level 3 provides a more detailed analysis, quantifying the extent of the damage. At Level 4, the system estimates the remaining service life of the structure, considering the current state of damage. As advancements in smart materials, such as self-healing alloys with memory effects, progress rapidly, the classification is being extended to include Level 5, where structures have the ability to autonomously repair damage (ZHANG et al. 2020, DE BELIE et al. 2018) and restore their functionality. Detection, localization, and assessment focus on identifying the presence, location, and extent of damage, which primarily involve techniques like identification, modeling, and signal processing. This includes data acquisition, analysis, and interpretation to detect and characterize damage. These processes are fundamentally rooted in signal processing, algorithms, and modeling approaches to ensure accurate identification without false positives. Prediction deals with predicting the remaining service life of a structure. It involves more complex analysis related to material fatigue, fracture mechanics, and design assessment. Prediction requires the integration of statistical methods, probabilistic modeling, and advanced material science techniques to estimate how long the structure will function safely before requiring repair or replacement. The self-healing capability represents the highest level of sophistication. It requires advanced materials such as smart or self-healing alloys and the integration of multiple techniques, including real-time monitoring and autonomous repair mechanisms. This is still an emerging field, combining materials science, advanced diagnostics, and system control. While significant progress has been made in each level, there are still technical and methodological challenges to overcome in improving the accuracy, sensitivity, and reliability of these systems, particularly in the early detection of damage and in integrating advanced self-healing capabilities.

Damage detection techniques and analysis

The change in dynamic characteristics during vibration of a structure (RYCHLIK, LIGIER 2017) is the basis for developing methods and techniques that are applied in condition monitoring in order to quickly and effectively, but also economically detect damage. The main dynamic characteristics of a structure are oscillation frequency, damping rate and oscillation modes (DJIDROV et al. 2014). These parameters are related to the physical characteristics of the structure, such as mass and stiffness (JAROSZEWICZ, ŁUKASZEWICZ 2018).

Changes in physical characteristics due to damage can also manifest themselves as changes in dynamic characteristics. In the case where this relationship can be represented by a linear dependence, the effect of damage on mechanical systems can be classified as linear, otherwise nonlinear. The frequency response method is used for detecting damage in composite materials (KESSLER et al. 2002) by analyzing shifts in their dynamic behavior, while the mode shape method can be applied for identifying damage in plate-like structures (ZHONG, YANG 2016) by observing changes in their vibration mode shapes. In addition, the strain energy method can be applied to fixed-end beams and three-story frames (MORADI POUR et al. 2015).

Methods and techniques related to the detection and analysis of damage in mechanical structures can be broadly divided into destructive and non-destructive evaluation techniques (TOWSYFYAN et al. 2020). Depending on the structure being examined, non-destructive techniques are grouped into global and local, both of which use the response of the structure as an indication of an external excitation that may be intentional or naturally induced. Global techniques involve examining the structure when it is excited by low frequencies, in order to cause it to oscillate at its natural frequencies and obtain the fundamental modes of oscillation. This is followed by an analysis to determine damage in mechanical structures by obtaining information about changes in dynamic parameters: natural frequencies, damping, and modes of oscillation. Global methods typically rely on a small number of the first few modes of oscillation, natural frequencies and mode shapes, which makes them less sensitive to detecting local damage. This limitation arises because global methods focus on the overall behavior of the structure, and local damage may not significantly affect the global modes. To address this, local examination techniques have been developed, such as those based on the propagation of ultrasonic waves, acoustic emissions, electromagnetic methods, radiographic methods, laser testing, and liquid penetrant testing, among others (STEPINSKI et al. 2013).

While local techniques are highly effective in detecting damage in specific parts of a structure, they are best applied to individual components or regions. These methods are not practical for comprehensive condition monitoring of large, complex structures, as they often require detailed, time-consuming inspections of individual parts and are not well-suited for continuous or large-scale monitoring (LOH 2011). Global methods can be divided into two main categories: model-based and signal-based methods (BADIHI et al. 2022). Global techniques such as model-based methods can be used to assess the structural integrity of an aircraft stabilizer structure (SAKARIS et al. 2017) by comparing actual measurements with predicted models to detect damage. Also, these techniques are applied to the composite tail structure of an aerial vehicle (ARAVANIS et al. 2021), and in the case of a steel-concrete composite slab (FANG et al. 2020). Signal-based methods use the relationship between the measured response of the structure to external excitation to identify potential damage. These methods analyze the signals in the time, frequency, or time-frequency domains. Signal-based methods are most commonly applied in damage detection in rotating machinery, where changes in the vibration signals can indicate faults like imbalance, misalignment, or bearing damage. Signal-based methods can be used for damage detection by utilizing piezoelectric transducers in a case of pipeline (TORRES-ARREDONDO et al. 2015) to identify or cracks, or to monitor structural integrity of a multi-story steel frame (BEHESHTI AVAL et al. 2020), and also as method for fault identification in a variable displacement hydraulic axial-piston pump (CASOLI et al. 2019). However, while signal-based methods can detect the presence of damage, they often require additional techniques or information to accurately localize the damage and assess its extent.

Over the past few years, extensive analytical, numerical, and experimental research has been conducted on various mechanical structures, including slender and surface-planar elements made of different materials. The most commonly applied methods are model-based, which use a predefined set of parameters to define the structure under investigation and its corresponding damage representation. In this approach, the damage state is determined by analyzing the changes in the values of the parameters associated with the structure's model (KOTHAMASU et al. 2006). In Figure 5, a global model-based method for monitoring the condition of a structure is schematically presented. It begins with

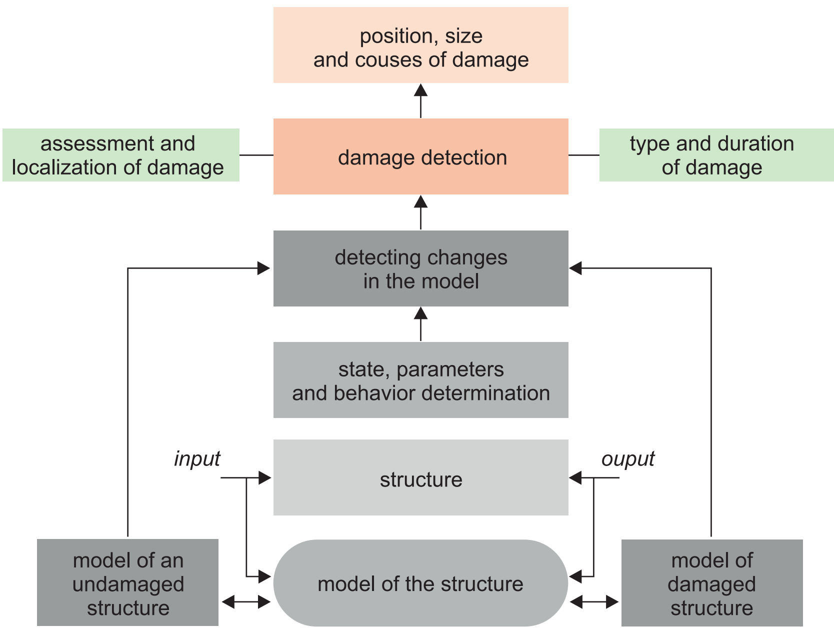

Fig. 5. Model-based method for monitoring

the input, which drives the structure, and the output as the system response, which also may be influenced by additional noise. The structure is analyzed through three models: the undamaged structure as baseline healthy state, the model of structure which reflects the model of real-time state and the damaged structure which represents the potential damage scenarios. The system utilizes various estimators to evaluate the structure's condition. A state estimator monitors the structure in real time, a parameters estimator identifies changes in physical parameters, and a behavior estimator is dedicated to captures the dynamic properties. This allows collectively to be identified the discrepancies between the current and undamaged models, feeding into a module for detecting structural changes. If changes are identified, the model moves towards damage detection, where the current structural model is compared to the damaged structure model. Once damage is recognized, the system determines its characteristics, including the type of damage and the time of occurrence. Finally, in the damage assessment and localization phase, the model provides a detailed evaluation, identifying the position, size, and cause of the damage, ensuring comprehensive damage monitoring and analysis.

The methods based on the model and analysis of dynamic characteristics are classified into several groups, and the most often used in the systems for monitoring the condition of structures are methods based on the change of dynamic parameters, methods for detecting the frequency response function, methods for analyzing the oscillation modes, methods for determining the energy in the oscillation modes, methods based on finite elements. Methods based on the global behavior of the structure allow the detection, isolation and analysis of damage due to changes in the dynamic characteristics during oscillation. These techniques are based on the idea that the characteristics of the model such as the frequency, oscillation mode and damping of the structure can be determined as a function of the physical properties. In addition, if damage occurs in the mechanical structure, this can be recognized as changes in the physical properties that cause changes in the characteristics of the model of the same structure.

While finite element method (FEM) provides detailed simulations, it can be computationally expensive, especially for large structures. Consequently, to reduce the computational time compared to FEM, Artificial Intelligence (AI) approach can be utilized for monitoring and damage detection. Because dynamic behavior of a structure can be used as input variables, the location and the severity of damage can be obtained as output through training and testing to detect damage, i.e. using patterns in the data learned during training and testing phases. In the case of lightweight plates machine learning and deep learning techniques can be implemented for damage detection (TAVARES et al. 2021). Through *K*-means clustering, rolling contact fatigue can be studied and model the wear and fatigue damage (BINI CHIESA et al. 2018). In case of wind turbine condition monitoring (FENG et al. 2023), the use of kernel density estimation, deep neural networks, and the sequential probability ratio test leads to multivariate anomaly detection approach that enhances data accuracy, models complex relationships, and detects early anomalies in wind power generation. Classifier for detecting cracks and damages in structures from images is based on convolutional neural networks (GULGEC et al. 2019). This can overcome the effects of noise caused by lighting, shadow, reflections, blur in visual and image processing techniques.

Intelligent monitoring systems

The process of evaluating the state of mechanical structures and systems is a complex task. Monitoring systems are also part of complex processes, influenced by many factors over time. Traditional wired methods are being replaced by IoT-based real-time wireless sensors. Because data from the sensors is stored on cloud-based platforms, leads to real-time analysis that will contribute to early detection of issues such as cracks, corrosion, deterioration or damage and system faults, i.e. towards smart and predictive maintenance. IoT operates on the internet or local networks, and many IoT devices are assigned unique IP addresses to communicate and share data over the internet and reaching a data center. Physical objects are equipped with sensors, tags with small microchips or barcodes in order to enable collection and sharing of data, while each object has a unique identity allowing it to be tracked and monitored. These objects operate in environments where they communicate and work together automatically. The integration of all these devices into the information network is made possible through intelligent software interfaces, allowing everything to work together (TOKOGNON et al. 2017). This leads towards the creation of smart environment and things, i.e. smart monitoring system for detecting changes in the state of the mechanical structures and systems in real-time. Therefore, it is necessary to include smart sensors, that is piezoelectric material as sensor (ABDELGAWAD, YELAMARTHI 2017), fiber optic sensors (JO et al. 2018), radio frequency identification (RFID) (AONO et al. 2016) and micro electromechanical system (MEMS) sensors (DI NUZZO et al. 2021). Figure 6 illustrates a smart system designed for data acquisition, processing, and communication using a central processing unit as the central hub and cloud servers.

The structural parts are equipped with piezoelectric devices that serve as sensors and actuators. These transducers generate signals that are processed through analog-to-digital converters (ADC) for digitizing sensor data and, and through digital-to-analog converters (DAC) to provide analog actuation outputs. The digitized data and signals are temporarily stored in buffers, which act as intermediaries to ensure smooth data flow and synchronization between the

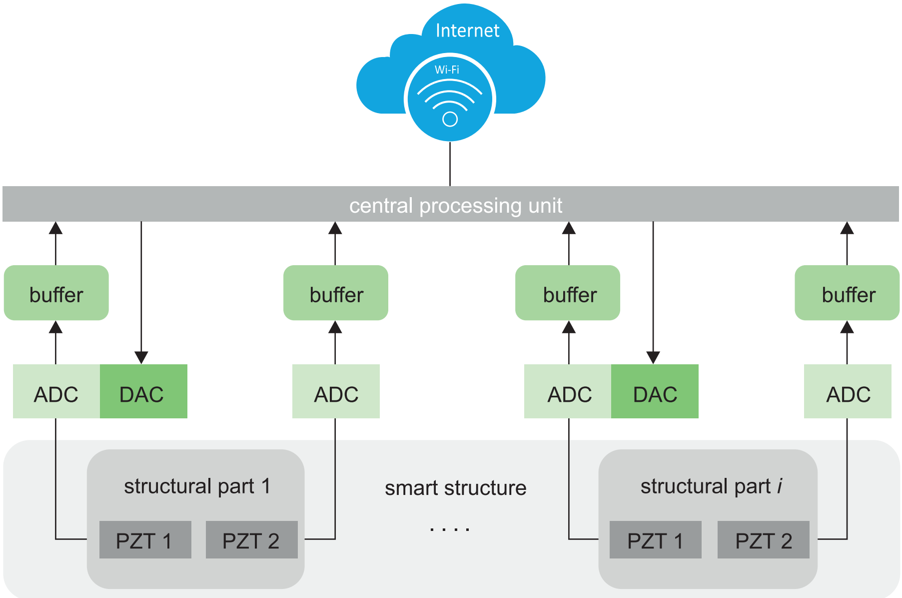

Fig. 6. IoT-based real-time system for smart structural monitoring

hardware and the central processing unit. Acting as the system's computational core, the central processing unit collects and processes data from all connected structure parts, and it is used for running algorithms for real-time analysis, control, or storage. Additionally, the central processing unit is connected to the Internet via Wi-Fi, therefore enabling remote monitoring, control via a web interface, and data transmission to cloud servers. This system is scalable, allowing for multiple structural parts to be integrated seamlessly, and to achieve an IoT-based real-time system for smart structural monitoring.

Advantages of smart structural systems

While monitoring systems are able for evaluating the health of structures, their application is hindered by the practical and economic challenges of installing and maintaining sensor networks, whether wired or wireless. To implement these methods effectively that requires a large number of sensors to gather enough data and installing such networks, can be with high-priced because requires significant effort, both financially and in terms of labor, for the sensors' installation and maintenance. Wireless sensors solve the problem of wiring by eliminating the need for physical connections (SOFI et al. 2022), making the system more flexible and easier to install. However, wireless data transfer can be complicated, because many sensors can be involved and needs the data from different sensors to be correctly synchronized. Furthermore, wireless sensors need to be powered, and maintaining a power supply for numerous sensors on a large-scale structure is a challenging task. Despite the advancements in wireless technology, sensors measure vibrations only at specific points, not continuously across the entire structure, which limits the ability to understand the detailed condition of a bigger mechanical structure. Therefore, the limitations in sensor coverage and the complexity of managing data reduce the effectiveness in identifying and assessing localized structural damage. While current sensors for measuring displacement, both contact and non-contact types, are effective in certain situations, they each have limitations, such as high cost, installation complexity, limited measurement range, and accuracy issues. The alternatives are vision-based sensing techniques, which utilize cameras and advanced computer vision algorithms (FENG, FENG 2021). They are emerging as a solution that could overcome many of these challenges, providing an efficient and cost-effective method for large-scale monitoring. However, besides advantages such as non-contact monitoring and the ability to measure multiple points on a surface, their accuracy can be impacted by factors like environmental and weather conditions, or lighting conditions and camera motion.

The benefits of monitoring the condition of structures via smart systems are presented in Figure 7. Optimal use of the structure is achieved through monitoring, which enables engineers to evaluate its current condition and make necessary adjustments to its use or maintenance, ensuring the structure operates as efficiently as possible throughout its service life. Reduction of downtime is achieved by detecting issues early through condition monitoring, allowing for proactive maintenance scheduling and minimizing unexpected downtime.

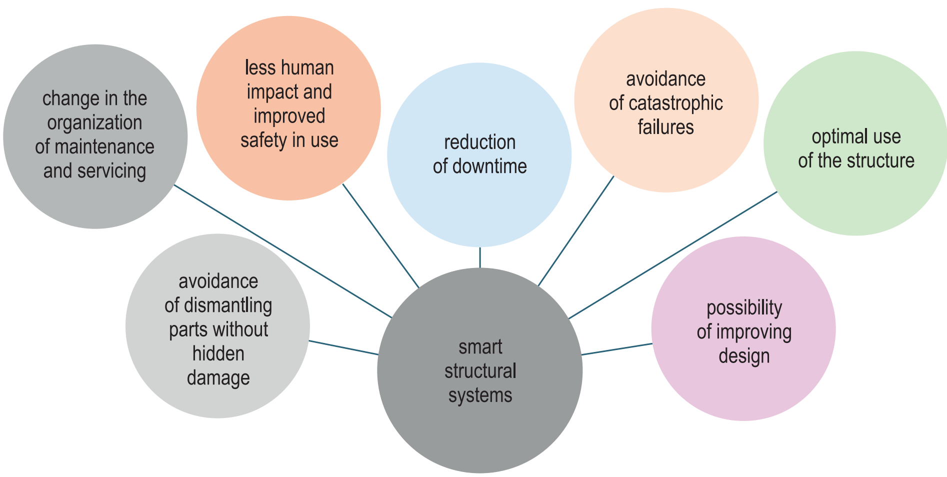

Fig. 7. Benefits of monitoring the condition with smart system

As a result, the structure can remain in operation for longer periods without significant interruptions. Avoidance of catastrophic failures is possible through regular monitoring, which helps identify potential weaknesses or damage before they become critical, preventing costly, dangerous, or even life-threatening failures. The possibility of improving the design of the structure arises from the data collected through condition monitoring, which provides insights into how the structure performs over time and can inform future design improvements for new structures or guide retrofitting of existing ones. A change in the organization of maintenance and servicing occurs with condition-based monitoring, which enables a more informed and efficient approach. Rather than relying on fixed schedules, maintenance can be adjusted based on the actual condition of the structure, allowing for more precise and effective interventions. Additionally, avoidance of dismantling parts without hidden damage is possible through condition monitoring, which identifies whether parts of a structure are still in good condition or require replacement. This helps prevent unnecessary dismantling or replacement of functional components, reducing waste and costs. Also, the benefit is the less human impact, and improved safety in use are achieved with autonomous or semi-autonomous monitoring systems, which reduce the need for human intervention and minimize the risk of human error. By detecting potential issues early, the system also enhances overall safety, ensuring the structure remains safe for use.

Conclusion

The interaction between damage and system performance is crucial to understand. Structural integrity, performance, and functionality are interdependent. When damage occurs, the system's ability to perform as expected can diminish. In many cases, even minor damage can lead to a significant reduction in performance, requiring timely intervention to prevent further degradation. Monitoring and detecting damage early on, whether through visual inspection, sensor systems, or predictive modeling, are essential steps in ensuring that a mechanical structure or system continues to function safely and efficiently throughout its service life. The goal is not just to identify the damage but to assess its potential impact on the system's performance, and to predict future behavior, which could prevent unexpected failures and ensure the system remains within safe operational limits.

Damage, defects and errors in mechanical systems and structures can significantly affect their performance, safety and lifespan, therefore, in this paper is presented intelligent monitoring system, which include a diagnostic system as key role in early detection, enabling timely repairs and minimizing downtime. For these reasons, maintenance costs tend to decrease when these monitoring systems are installed, as they enable more accurate condition-based maintenance, rather than time-based interventions. Additionally, to reduce the computation time compared to traditional methods such as FEM, an approach using artificial intelligence is proposed, in order to enable faster damage detection and prediction. In addition, IoT-based real-time monitoring systems are presented, enabling smart, continuous assessment of structural health, thus providing a better and more accurate way of making decisions for the overall longevity of the mechanical structure or system.

Understanding the nature of damage and how it can affect both the physical structure, and the operational functionality of mechanical systems is essential for maintaining safety, efficiency, and performance. Whether due to physical degradation or failure in monitoring systems, damage can have far-reaching consequences that go beyond ordinary structural changes. Proactively identifying and addressing damage, whether through routine inspections, advanced sensors, Internet of Things or AI with predictive algorithms, is key to extending the lifespan of mechanical structure or systems and minimizing the risks associated with failures.

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