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Application of Unmanned Aerial Vehicles Integrated with Infrared Thermography System to Investigate the Health of Heritage Buildings

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Abstract

The application of Unmanned Aerial Vehicles (UAVs) / drones in various industries has been on the rise in recent years, and these are making a significant impact is in the field of Investigation of Health of Heritage Buildings (IHHB). IHHB is a critical aspect of maintaining the safety and integrity of heritage infrastructure, such as old bridges, old buildings, and old dams. Traditionally, this process has been labor-intensive, time-consuming, and often dangerous for the personnel involved. However, with the advent of UAVs / drone technology integrated with Infrared Thermography (IRT), the process of inspecting and monitoring the health of heritage buildings has become more efficient, cost-effective, and safer. UAVs / Drones integrated with IRT offer numerous advantages over traditional methods of IHHB, such as accessibility, speed, and accuracy. UAVs / drones are Equipped with high-resolution cameras and sensors, which capture detailed images and data of structures, even in hard-to-reach areas. This enables Engineers and Inspectors to assess the condition of a structure without the need for scaffolding, cherry pickers, or other cumbersome equipment. Furthermore, UAVs / drones can cover large areas in a relatively short amount of time, allowing for quicker identification of potential issues and more efficient allocation of resources for repairs and maintenance. In addition to visual inspections, UAVs / drones can also be equipped with advanced sensors and technologies to detect various structural issues. For example, thermal imaging cameras can identify areas of heat loss or moisture ingress, while LiDAR (Light Detection and Ranging) sensors can create detailed 3D models of structures for further analysis. These technologies enable Inspectors to not only identify visible defects but also uncover hidden issues that may not be apparent through traditional inspection methods. Despite the numerous advantages that UAVs / drones offer in the field of IHHB, there are also several challenges that need to be addressed to fully realize their potential. One of the primary concerns is the regulatory environment surrounding drone operations. In many countries, strict regulations govern the use of drones, particularly in urban areas or near critical infrastructure. Another challenge is the need for skilled operators and analysts to effectively utilize UAVs / drone technology for IHHB. While UAVs / drones can capture vast amounts of data and images, interpreting this information requires specialized knowledge and expertise. This highlights the importance of training and education in the field of UAVs / drone-based IHHB, as well as the development of software and tools to assist in data analysis and interpretation. Data security and privacy are also significant concerns when using UAVs / drones for IHHB. The sensitive nature of the data collected, particularly in the case of critical infrastructure, necessitates robust security measures to protect against unauthorized access or tampering. Additionally, the use of drones in urban environments raises privacy concerns, as they may inadvertently capture images or data of private property or individuals. Addressing these issues is essential to building public trust and ensuring the responsible use of UAVs / drones in IHHB applications.

Keywords: UAV, IRT, SHM, IHHB, LiDAR.

1. Introduction

Inaccessible surfaces or the requirement to install a large number of sensors limit the affordability of traditional contact-based sensors. Recent advances in non-contact measurement technology were made possible with UAVs, namely, drones. UAVs are aircraft without pilots, crews, or passengers. Rapid developments in control theory, computing capabilities, robotics, communications, and automation technologies provide the platform for the wide variety of applications of UAV technology in IHHB systems. UAVs are now equipped with lightweight cameras to take pictures and estimate the structure's global and local health. Most UAVs are composed of a navigation system with visual servoing, a global positioning system (GPS), and a vision system typically consisting of an out-of-the-box camera (e.g., an infrared camera, optical sensor, or laser detection and ranging (LADAR)). A navigator on the ground can control the aircraft remotely by controlling its in-flight data acquisition and post-flight image processing. Recent UAV applications include traffic monitoring, construction inspections, surveying, and health monitoring of roads, bridges, pipelines, and buildings, particularly in the transportation sector. In addition to reducing workplace accidents, UAV sensors reduce logistics and working hours. Compared to satellite images, they provide excellent temporal and spatial resolution, making them suitable for monitoring inaccessible areas. UAV sensors can provide 3D information about structures which can be used for large-scale system monitoring and management. Ortiz et al. [1] studied the use of UAVs for heritage site surveillance. An algorithm called CornerHarris was applied by Cho et al. [2] to detect cracks using UAVs. The researchers used Haar-like features and converted color images to greyscale to identify the damage. UAV-based crack detection of a concrete bridge was investigated by Reagan et al. [3]

In vision sensors, cameras are typically used to capture images and determine various characteristics of an object, including its position, orientation, and surface composition. Vision-based sensors do not require physical contact with the object or long-wired transmission networks providing benefits in cost reductions, ease of use, a wide range of applications, and improved reliability. A critical difference between image inspection systems and these sensors is that the camera, light, and controller are integrated into one device, simplifying installation and operation. In the last few years, vision-based sensors have been studied for their use in system identification. Despite presenting a significant step forward in innovation, some challenges exist, providing an exciting opportunity for further research. Lighting in the workspace, for example, may limit the measurement accuracy with the tracked object needing repositioning. As a result, modal parameter estimation may be inaccurate due to the incorrect mapping of the reference system. Sony et al. [4] used vision-based sensors for crack detection in real-life networks applying algorithms that can isolate the tracking point regardless of the picture's luminosity. Helfrick et al. [5] investigated using stereo cameras to detect damage caused by curvature changes in 3D digital image correlation (DIC). According to Huňady et al., [6], a Q450 Dantec dynamics camera was used to estimate the damping of steel plates at 1000 frames per second. Using video recordings, Yang and Yu [7] developed a vision-based method to monitor vibrations such as velocity and displacement.

The presented article having the application of infrared thermography in section 2, section 3 describes the need of Heritage Building Health Monitoring (HBHM) System, section 4 details Data Analysis available for SHM system, section 5 explains the future direction in the research area of SHM and followed by conclusion.

2. Infrared Thermography in IHHB

Infrared technologies were first discovered in the early 19th century. In infrared testing, temperature changes on the surface of an object are monitored over time using thermographic technology [8 - 11]. Through an infrared detector, infrared thermography maps thermal patterns on an object's surface in a non-intrusive and contactless manner. Surface images with pronounced thermal patterns are produced indicating not only the surface but also subsurface irregularities. As is shown in Figure 1, a typical infrared thermography system comprises the following components: an IR radiometer, energy source, control panel, and data processor. A comprehensive review paper on this topic can be found in [12] for readers interested in the topic. In the following, we address the advantages and limitations: Advantages: Affordable and fast operation; real-time implementation; compatible with a variety of materials; damage visualization; single-sided inspection; safe procedure (non-ionizing radiation). Disadvantages: Delicate equipment, unsuitable for field testing; the precision is affected depending on the specimen geometries and complexities; restrictions are imposed due to the expense and accessibility of excitation sources in the field; computing power and algorithms determine the processing time for data; identifying cracks will require higher automation from footage; offshore structures may have difficulty implementing the application.

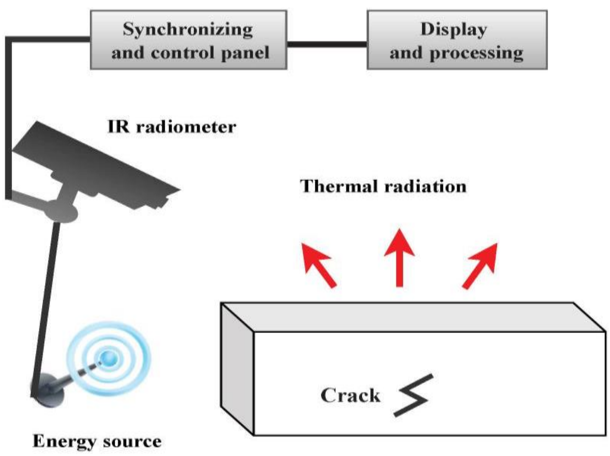

Figure 1. Working Mechanism of Infrared Thermography System

Currently, two different types of infrared technology exist [8,13]: (i) infrared technology that detects infrared radiation and (ii) technology that transmits information via infrared radiation (called wireless infrared technology). The first type of infrared technology utilizes sensors that convert infrared radiation into usable information. Thermal imaging is a typical example of infrared technology. Since heat releases infrared radiation, the source of the heat can be identified using infrared radiation detection technology. Thermal imaging cameras can collect data about different temperatures (such as infrared radiation levels) and convert them into heat-mapping images that are invisible to the naked eye. Military and civilian industries use thermal imaging cameras for a variety of purposes. Since infrared light can pass through thick areas of dust and cloud, astronomers have developed tools that detect infrared radiation in space, enabling them to study aspects of the universe that are not visible to the naked eye.

The corresponding infrared sensors are electronic instruments that detect specific characteristics of their surroundings by either emitting or detecting infrared radiation. They are capable of detecting motion and measuring the heat being emitted by objects. Three laws govern the physics behind infrared sensors:

1. Planck's Radiation Law: Radiation is emitted by every object at a temperature T not equal to 0 Kelvin.

2. Stephan Boltzmann Law: The total energy emitted by a black body at all wavelengths is proportional to its absolute temperature.

3. Wein's Displacement Law: Different objects emit different wavelength spectra at different temperatures.

The infrared sensors can be active or passive [14] and can generally be divided into thermal and quantum infrared sensors. Thermal infrared sensors use infrared energy as a heat source. They do not require cooling but have slow response times and low detection capabilities. No relationship exists between their photosensitivity and their wavelength capabilities. Quantum infrared sensors, on the other hand, offer higher detection capabilities and faster response times. Since photosensitivity depends on the wavelength, quantum detectors need to be cooled for highly accurate measurements.

Wireless infrared technology uses infrared radiation to transmit data and commands rather than detect them. An example of wireless infrared technology is a TV remote control. A remote's infrared sensor transmits a signal to a TV's sensor, which sends a command to the television (for example, turning it on or turning up the volume). Wireless infrared technologies can be classified as directed or diffuse. Infrared lasers transmit information through directed technologies, but the receiver and the source must be unobstructed. Infrared light disruption technology can be used to detect whether a predefined threshold has been crossed. With diffuse infrared technology, the transmitted beam is scattered, making it more difficult to block. The TV remote is an example of diffuse infrared wireless technology: it will work as long as it is used in the same room. Further examples of wireless infrared technology are intrusion detectors, home entertainment control systems, robot control systems, medium-range, line-of-sight laser communications, cordless microphones, headsets, modems, and printers.

Three main methods of active infrared thermography NDT exist: optical infrared thermography [15], ultrasonic infrared thermography [16], and microwave thermography [17]. Heinz et al. [18] examined infrared thermography (IRT) for analyzing steel rope failures. A thermal imaging camera recorded the relationship between temperature increase and force increase. The research found that when the temperature rises, the steel rope's minimum load capacity decreases by 43.01%, as monitored by a thermo-camera. The thermo-camera's mounting affected the accuracy of the measurements. In [19], Deane et al. aimed to examine the effectiveness and challenges of NDT using active IRT to inspect aerospace-grade composite samples, using the signal-to-noise ratio (SNR) as a performance parameter to compare uncooled and cooled thermal cameras. Both types of cameras were compared using seven different SNR definitions to determine whether a lower-resolution uncooled IR camera could meet NDT standards. Using active IR thermography to evaluate coating thickness is a common technique for NDT of materials. To demonstrate the feasibility of this method, Moskovchenko et al. [20] described a one-sided thermal NDT procedure that employed apparent effusivity as a quantitative method for evaluating coating thickness. The proposed algorithm determined a threshold value of apparent effusivity based on specific coating-on-substrate structures. Swiderski [21] investigated the possibility of using IR thermography methods to detect defects in ballistic covers made from carbon fiber-reinforced composites used in military vehicles. An overview of IRT fault diagnosis for renewable and sustainable energy (RSE) systems is presented in [22].

Recently proposed matched filter-based non-periodic infrared thermographic approaches have become increasingly popular for various NDT methods, including pulse-based and mono-frequency excited modulated lock-in thermography. These approaches lead to superior test resolution and sensitivity for detecting hidden defects in the test material over pulse-based and mono-frequency excited modulated lock-in thermography. As a result, pulse compression favorable techniques are more economical and reliable than conventional pulse-based thermographic techniques because they can be implemented in moderate experimentation times compared to mono-frequency lock-in thermographic techniques. Dua et al. [23] demonstrated the advantages of pulse compression favorable frequency-modulated thermal wave imaging for identifying flat bottom holes in polymers. To demonstrate how IRT and ANN can be combined, Chulkov et al. [24] trained and verified a neural network to determine defect depth in infrared thermographic NDT using ten different sets of input data. The input data sets included raw temperature data, polynomial fitting, principal component analysis, Fourier transforms, and other parameters. With polynomial fitting in logarithmic coordinates and further computation of the first temperature derivatives, a minimum error of 0.02 mm for defects in CFRP at depths from 0.5 to 2.5 mm was achieved. One of the novel IRT techniques is atomic force microscopy-based infrared spectroscopy (AFM-IR) [25]. AFM-IR detects localized thermal expansion in a sample caused by the absorption of infrared radiation using the tip of an AFM probe. The combination of AFM-IR and infrared spectroscopy can thus provide the spatial resolution of AFM along with chemical analysis and compositional imaging capabilities.

3. Heritage Building Health Monitoring (HBHM) System

Initially, Structural Health Monitoring (SHM) started attracting attention in the research community in the 1980s and was first applied in offshore platforms and aerospace structures. Over the following decades, SHM gained further popularity in research as well as asset management, and SHM systems have been implemented to monitor various types of structures, such as bridges, wind turbines, buildings, pipelines, or railway tracks [26]. Several authors have described the concept of SHM in terms of its aims. Here are a few examples:

- In SHM, existing civil structures are characterized to identify and detect structural defects [27].
- SHM involves continuously interrogating sensors installed within a structure to extract characteristics indicative of the structure's current state [28].
- In SHM, different parts of the structure are continuously diagnosed and assembled as a whole so that the entire structure can be diagnosed continuously [29].

SHM systems should meet the following requirements: being affordable; able to continuously assess a system; capable of adapting to environmental changes; able to detect diverse types of damages; robust to measurement noise and ambient loads. In general, SHM involves two major processes (a) sensing and (b) data analysis. Typical components of an SHM system are the sensory system (active or passive), data acquisition and signal conditioning, data transfer and storage mechanisms, data management, signal processing, and data interpretation. Figure 2 illustrates the general schematic of an SHM system.

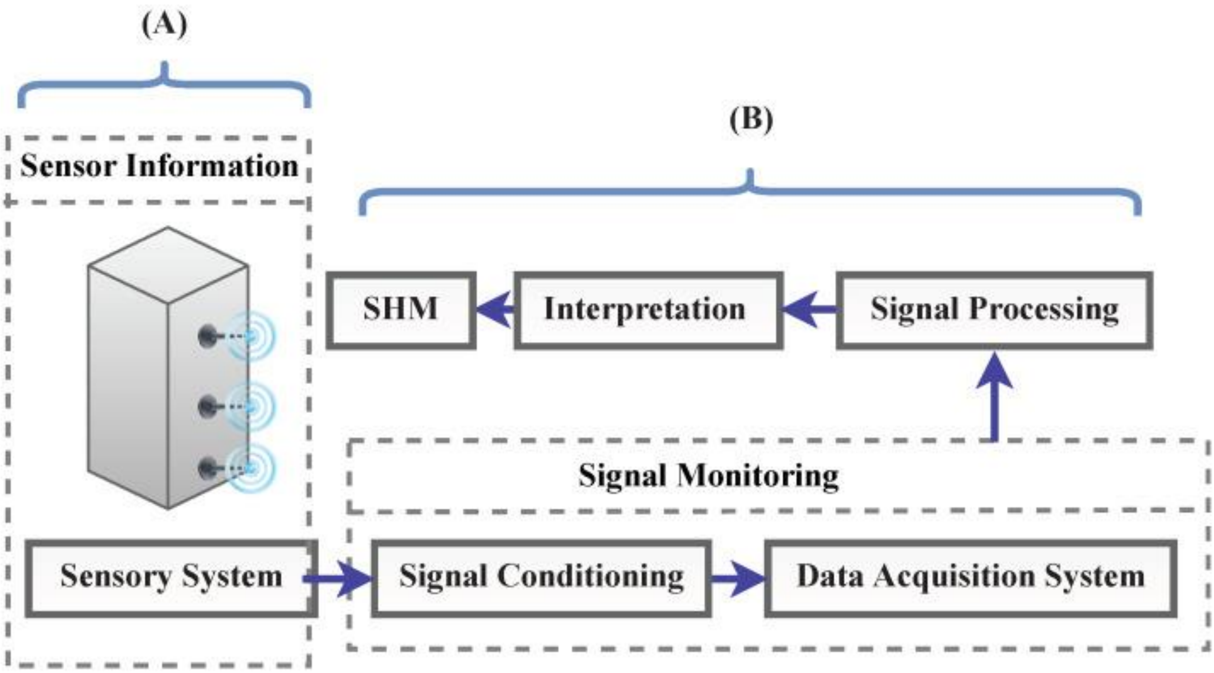

Figure 2. Building blocks of common SHM system - (a) Sensor & (b) Data Analysis System

3.1. Benefits of SHM System

The implementation of SHM technologies can have many benefits and improve several aspects of civil structure management and design, including the following:

i. Active safety monitoring and control: Alert systems can inform asset managers if prescribed limits are exceeded, such as when abnormalities in load or responses occur, ensuring human and structure safety.

ii. Environmental monitoring: Site-specific environmental conditions such as wind and temperature can be evaluated.

iii. Improved structure assessment: The reliability and accuracy of structural assessments can be improved based on up-to-date structural response data.

iv. Optimization of maintenance: An optimal inspection, maintenance, and repair schedule can be determined on an "as needed" basis when indicated by monitoring data, resulting in cost reductions.

v. Real-time safety assessments can be performed during normal operations or immediately following extreme events.

vi. Assumptions and parameters related to the structure design can be validated, resulting in improvements in future specifications and guidelines.

vii. Future performance can be predicted based on past and current monitoring data.

Human safety is the most obvious advantage. Disasters such as bridge collapses have motivated much research on SHM strategies. If employed as an early warning system related to safety problems, SHM strategies can be highly beneficial, even at a minimum level, e.g., detecting damage or strength degradation. Furthermore, an automated SHM system can assess the safety of inaccessible areas, which may otherwise remain hidden from visual inspection. Implementing sophisticated SHM systems may also lead to other benefits, such as policy changes. Currently, routine inspections and maintenance of civil structures are implemented at specific intervals following standard procedures. This time-based approach implies that unexpected failures between scheduled inspections may be overlooked, leading to life-threatening situations. On the other hand, civil structures may be subjected to unreasonably conservative inspection schedules resulting in unnecessary costs. The economic impact can be even more significant if structural components are replaced as part of routine maintenance, where even healthy components are renewed. Since SHM is aimed at continuous monitoring, and structural maintenance is condition-based, SHM strategies may solve both sides of this problem. In addition to reducing downtime for routine maintenance, condition-based maintenance schedules can reduce emergency maintenance downtime. Consequently, this would benefit safety, structure operation, the economy, and the environment [30].

3.2. Enivronmental and Operational Conditions (EOCs) Effect

Civil engineering structures are typically subjected to changing EOCs, which can impact the structural parameters and responses. Since SHM systems capture time-variant data, these EOCs can heavily affect measurement signals. Hence, a significant challenge of SHM systems is their sensitivity to EOCs parameters. Various SHM techniques have been proposed to determine the extent and location of damage in in-service structures considering the effects of EOCs variations [31]. Environmental factors include temperature, humidity, wind, seismic actions, settlement, and scouring. Operational factors include highway, traffic, railway, ship impact, and permanent loads. Changing EOCs may have more significant impacts on structures than damage-induced changes. Neglecting these influences may affect the accuracy of damage detection and lead to incorrect conclusions. Thus, sensors that are robust to EOCs variations can be highly advantageous in reliably and accurately detecting damage in structures. Table 1 lists typical EOCs affecting civil infrastructure and sensors suitable for measuring EOCs in SHM systems. An important aspect of damage identification methods is the selection of attributes that discriminate between damaged and healthy structures. In SHM, these features are commonly constructed from the dynamic properties of structures (e.g., modal properties), known as vibration-based approaches. However, a structure's modal properties are sensitive to both damage and EOCs variations. Any change in EOCs alters the structural stiffness and mass, which affect the modal properties and hence can be mistaken for damage. Figure 3 illustrates the influence mechanisms of various EOCs on modal properties.

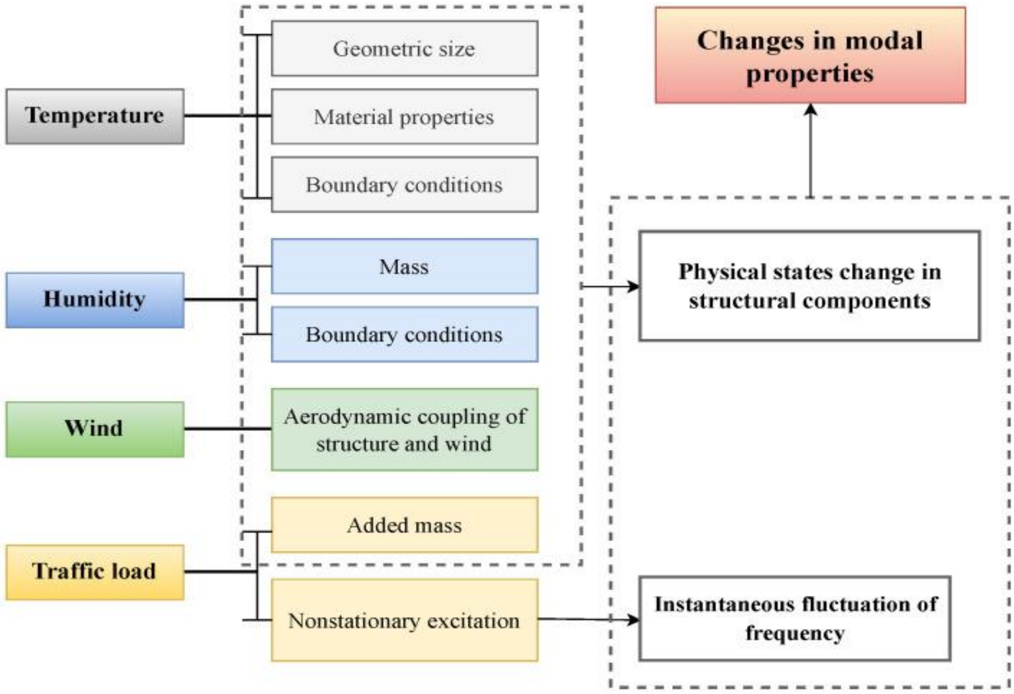

Figure 3. Influence mechanisms of EOCs on modal properties

Table 1. Typical EOCs and suitable sensors for SHM systems

Tpye of EOCs	Suitable Sensors for SHM systems
Wind	Ultrasonic and propeller anemometers
	Barometers
	Visibility and precipitation sensors
	Hygrometers
Temperature	Temperature sensors
	Fiber optic sensors
	Thermocouples
Seismic and ship impacts	Servotype accelerometers
Settlement	Settlement sensors/systems
	Liquid leveling system
Scouring	Scouring sensors/systems
Corrosion	Hygrometers
	Corrosion cells
	Gas concentration detectors
	Temperature sensors
Highway traffic	Dynamic weigh-in-motion stations
	Static/dynamic strain gauges
	High-definition video cameras
Railway traffic	Static/dynamic strain gauges
	High-definition video cameras

3.3. Sensing Systems for SHM

For the design of a suitable sensing system, essential requirements need to be identified. A typical SHM system comprises a network of sensors that measure different structural quantities. The sensor measurements reflect either the structural behavior or external factors, such as environmental or operational conditions, that can influence the sensor readings or behavior of the system. The measured sensor data should be sensitive to damage to allow direct correlations to the structure's health state and be used for system identification. Examples of conventional sensors used for SHM systems are strain gauges, temperature gauges, accelerometers, and fiber optic-based sensors [32].

The following sensing system characteristics need to be taken into account to design a suitable sensing network:

- Monitoring objectives;
- Sensor types, numbers, and placements;
- Sensor measurement characteristics;
- Sensitivity, bandwidth, and dynamic range;
- Continuous or periodic sampling intervals;
- System installation constraints;
- Power demands;
- Data transmission;
- Telemetry, data acquisition, and storage system;
- Excitation source (for active sensing);
- Memory and processor requirements;
- Resilience of the system in the case of malfunctions;
- Data Analytics.

To select sensors that adhere to the system requirements and restraints, specific sensor characteristics need to be considered, including (1) sensitivity to damage, (2) sensitivity to noise, (3) sensitivity to EOCs variations, (4) sensitivity to chemical influences (5) sensitivity to mechanical influences, (6) measurement accuracy, (7) error-proneness and (8) cost. Most SHM systems consist of a network of multiple sensors, constituting either homogeneous or heterogeneous sensors. A sensor network presents several advantages, such as:

- Increasing the robustness of the intended measurements;
- Enhancing the system's robustness and reliability;
- Reducing uncertainty in the monitoring results in systems.

A more significant number of low-precision measurements is typically preferred to a smaller number of high-resolution measurements. However, dealing with measurements from many sensors implicates several disadvantages, including the following: (1) The management and analysis of the large volume of recorded data is challenging, (2) the extended sensor network is more prone to environmental effects, and (3) the large volume of data exchange increases the power consumption in the sensor network. Hence, there is always a trade-off between the number of network sensors and the amount of information gathered for an application.

4. Data Analysis for SHM System

In any SHM system, the analysis of measurement data is the second essential process for capturing structural characteristics using sensory systems. The recorded raw data typically undergoes a process of data acquisition, signal conditioning, data transfer, data storage, signal processing, and data interpretation for damage detection. Many data analysis approaches and algorithms have been developed and are constantly further advanced depending on the type of sensors and measured data. The fast-growing field of data science, with rapid advances and innovations in artificial intelligence (AI) and data mining, led to a transformation and renewal of data analysis methodologies for SHM, while data analysis techniques, such as traditional signal processing, are applied to datasets to execute and test models and hypotheses, regardless of the amount of data, AI methods, such as deep learning, are used to uncover hidden patterns in large volumes of data [33]. The following sections present an overview of recent developments in signal processing techniques and the application of deep learning, the most progressive AI technology, in SHM systems.

4.1. Signal Processing Methods in SHM

Complex processes characterize the structural response to time-variant loading, and hence, one of the most challenging aspects of SHM is the extraction of damage features via signal processing [34]. A signal processing algorithm for SHM must be able to deal with noise and complexities embedded in the measurement signal while identifying the features of interest. The objective of signal processing is defined as [35]: the extraction of features from the recorded data for (1) identification of the status of the system (damaged or healthy), (2) localization of damage, (3) quantification of damage, and (4) identification of the damage type. Several methods and mathematical models have been proposed to analyze signals from sensor systems associated with the time-frequency or time-frequency domain. Some examples of signal processing techniques include Kalman Filter (KF), statistical time series (STS) models, fast Fourier transform (FFT), wavelet transform (WT), short-time FFT (SFFT), S-transform (ST), Hilbert transform (HT), fast ST (FST), Hilbert-Huang transforms (HHT), blind source separation (BSS) and multiple signal classification (MUSIC). System characteristics can be determined by employing these techniques, and damage features derived [36].

5. Future Directions

we summarize the most important future research directions as follows:

- The newest generation of sensing systems incorporates recent innovations in sensor technologies such as intelligent materials, active sensing, wireless data transfer, and deep learning, while some of these novel techniques have been applied to real structures, many have only been studied under research conditions, and they must be further explored in real-life environments for their benefits and challenges to be fully assessed and understood.
- NDT and SHM of components exposed to high temperatures (>650 °C) is a field of increasing importance. Their implementation, however, poses significant challenges due to the harsh high-temperature environments. The development of advanced sensors suitable to these environments is, therefore, an essential field of future research.
- Despite significant progress in sensing developments, many challenges remain demanding further research efforts. The next generation of smart structures is aimed to incorporate smart materials with embedded sensing power that consume only little energy or are self-powered, resist noise and environmental variations, and are cost-effective and eco-friendly.
- Novel vision-based sensors need to be insensitive to light conditions, demanding the development of improved algorithms for image processing.
- Self-sensing materials are an exciting field of research investigating strategies such as embedding fiber-optic and piezoceramic sensors in a structure's critical components. Future research directions are aimed at developing self-sensing materials that are able to instantly identify any material changes induced by damage in the nano- or microstructure.

- Further research is needed in the field of deep learning algorithms as potential replacements or additions to traditional data analysis approaches for intelligent pattern recognition for damage identification and classification.
- Big data-driven product design is a hot topic with many ongoing developments and applications related to the Internet of things (IoT).
- Digital twin technology, which analyzes sensor data using AI algorithms, is a cutting-edge technology linking the physical and virtual worlds. More research is needed to exploit the capabilities of digital twin technology fully.
- Existing sensor technologies, such as cameras, microphones, inertial measurement units, etc., are widely used for various applications, but their high-power consumption and battery replacement remain a concern. Further developments are needed on self-powered sensors, such as using triboelectric nanogenerators (TENGs) that provide a feasible platform to realize self-sustainable and low-power systems.

6. Conclusion

In conclusion, the application of UAVs / drones integrated with ITR in IHHB holds great promise for improving the efficiency, safety, and accuracy of inspections and assessments. As technology continues to advance, UAVs / drones are likely to play an increasingly important role in maintaining the integrity of our built environment. However, to fully harness the potential of UAVs / drone-based IHHB, it is crucial to address the challenges related to regulation, workforce development, and data security and privacy. By overcoming these obstacles, UAVs / drones can revolutionize the way we monitor and maintain our infrastructure, ultimately contributing to a safer and more resilient society.

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