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Defect Detection Using Thermography Camera Techniques: A review

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Abstract

Individuals across different industries, including but not limited to agriculture, drones, pharmaceuticals and manufacturing, are increasingly using thermal cameras to achieve various safety and security goals. This widespread adoption is made possible by advancements in thermal imaging sensor technology. The current literature provides an in-depth exploration of thermography camera applications for detecting faults in sectors such as fire protection, manufacturing, aerospace, automotive, non-destructive testing and structural material industries. The current discussion builds on previous studies, emphasising the effectiveness of thermography cameras in distinguishing undetectable defects by the human eye. Various methods for defect detection, including temperature analysis and image processing algorithms, are thoroughly presented. The factors contributing to the effectiveness of thermography cameras are explored, along with their advantages over traditional inspection methods. The literature review highlights the diverse applications of thermography cameras in fault detection. The review highlights the remarkable transformation brought by thermal camera technology in mechanical system fault detection, leading to improved maintenance practices. These cameras can detect unseen irregularities, enable non-invasive testing and support hands-on system maintenance, making them indispensable tools for ensuring mechanical systems operate efficiently, reliably and safely. With the continuous advancement of technology, the integration of Industry 4.0 and IoT technologies will further enhance the capabilities of thermal cameras, ensuring elevated performance across different domains. In electrical systems, thermal cameras allow for the early identification of faults, enabling proactive maintenance to mitigate risks. Additionally, by assessing structural integrity, thermal cameras can detect thermal and insulation inefficiencies, leading to improved energy efficiency.

Keywords: *Thermography camera; defect detection; temperature analysis; image processing*

1. Introduction

A thermal image camera (TIC) is a type of imaging device designed to detect and capture infrared radiation emitted by objects, subsequently converting this thermal energy into a visible image. TICs operate by measuring the thermal energy emitted from objects within their field of view. The amount of infrared radiation emitted increases proportionally with the temperature of an object, resulting in a corresponding increase in the brightness of the object as observed in the thermal image. This technology has a wide range of applications across diverse industries, such as manufacturing and building inspection. However, the literature reveals that many researchers have approached this subject from various perspectives. One crucial aspect of remote structural monitoring is the application of machine learning (ML) for detecting fatigue damage in glass–epoxy composites through thermal imaging. This technique plays a key role in remote structural monitoring, providing a reliable method for the safety evaluation and optimisation of composite structures and components [1]. However, the precise characterisation of fatigue-induced damage hotspots, encompassing their dimensions, morphology, spatial distribution, hysteresis-induced thermal effects and subsurface temperature profiles, through the application of surface thermal imaging techniques, continues to pose remarkable challenges in current research. The objective was to assess the theoretical accuracy of hotspot characterisation using an ML model trained on artificially generated thermal images derived from 3D finite element models with increasing levels of complexity. Incorporating fatigue damage as an inherent heat source has been shown to effectively mitigate the impact of thermal image noise and other uncertainties related to heat transfer. The study demonstrates that ML can effectively and precisely retrieve the heat influx, depths and geometry of the heat source from the initial thermal images of composite materials. The prediction accuracies achieved ranged from 85% to 99%. The study also analysed the impact of variations in the size of the training set and image resolution on the level of prediction error. The results presented make a substantial contribution towards the development of precise and effective techniques for detecting fatigue damage in fibre composite materials remotely. In [2], two deep learning methodologies were examined for the purpose of restoring initial temperature profiles from thermographic images in the context of non-destructive material testing is examined. Initially, a deep neural network (DNN) was trained in an end-to-end manner, where the surface temperature measurements were directly inputted into the DNN. Subsequently, the surface temperature measurements were transformed into virtual waves, a novel concept in thermography, which were subsequently utilised as input for the DNN. A data generation system is devised and a dataset comprising 100,000 synthetic images depicting temperature measurements are produced to demonstrate the efficacy of the aforementioned techniques. Various model-based reconstruction techniques, such as Abel transformation, curvelet denoising and synthetic aperture focusing methods, were examined in time and frequency domains to establish an appropriate baseline. These methods are considered to be state-of-the-art in the field. Furthermore, a tangible model was generated to facilitate assessment of entirely novel real-life data. According to the findings of multiple experiments, the end-to-end as well and hybrid approaches exhibited superior performance compared to the baseline in terms of reconstruction accuracy. The end-to-end methodology, in particular, exhibited superior computational efficiency and demanded minimal domain expertise. The utilisation of the hybrid approach necessitated a substantial amount of expertise in the relevant field and incurred higher computational costs compared to the end-to-end approach. The use of virtual waves has been proven to be a crucial aspect in simplifying the intricate process of end-to-end reconstruction. Consequently, superior reconstructions were achieved with the same number of training samples compared to the traditional end-to-end methodology. Furthermore, this approach facilitated the implementation of more condensed network structures and the integration of pre-existing knowledge, such as sparsity and non-negativity. The technique presented is particularly suited for non-invasive, two-dimensional examinations, specifically in scenarios where the amplitudes along objects remain constant, as in the case of metallic wires. In [3], a deep thermal imaging model was explored to investigation its application in close-range automated recognition, aimed at enhancing the understanding of people and universal technologies within their surroundings. The study employed a low-cost mobile thermal camera to collect thermal textures, which were then classified into distinct material types using a deep neural network. This approach proved highly effective in the absence of ambient light sources or direct material contact. Additionally, the use of a deep learning network eliminated the need for manually designing a feature set for various materials. The performance of the system was assessed based on its capability to identify 32 distinct material types across indoor and outdoor settings. The methodology employed yielded recognition accuracies exceeding 98% in a sample of 14,860 images depicting 15 indoor materials and exceeding 89% in a sample of 26,584 images depicting 17 outdoor materials. However, the discussion of the potential real-time applications of this technology in human–computer interaction applications and its prospective avenues for further development is also observed. In [4], the researchers introduced a neural network based on deep learning and region convolution for detecting obscured objects. The identification of buried objects in thermal images involves using a region of interest selection technique with a bounding box. The experimental findings indicate that thermal images of buried objects exhibit temperature fluctuations due to changes in the heat-carrying capacity of the surrounding soil. The neural network approach proposed in this study demonstrated a 90% accuracy rate in predicting the locations of buried objects in thermal images. This method has the potential to be applied to land mine detection through thermal image processing techniques. The conditions of machines and other systems can be realised by creating and classifying features that summarise the measured signal attributes. At present, professionals within their specialised domains formulate these characteristics using their expertise. Thus, the efficacy and utility of the system are contingent upon the expertise of practitioners in the relevant fields of physics or statistics. Additionally, if new and supplementary circumstances arise, specialists must incorporate innovative feature extraction techniques. In the study presented in [5], the authors explored a technique from the sub-discipline of feature learning, namely deep learning, using convolutional neural networks (CNNs), to address the limitations of traditional feature engineering. The goal was to assess the feasibility and methodology of using deep learning techniques to automatically evaluate the operational state of machinery through the analysis of infrared thermal video data. This goal demonstrated the effectiveness of the proposed system in detecting various conditions in rotating machinery with high accuracy (95% and 91.67% for machine fault detection and oil level prediction, respectively) using infrared thermal data. Notably, the system does not require extensive knowledge of the underlying physics, which may simplify the condition monitoring process using intricate sensor data. Additionally, the use of trained neural networks enables the identification of important areas within infrared thermal images that are associated with particular conditions, potentially yielding novel physical insights. In [6], researchers introduced a thermal imaging process for assessing the electrical equipment status. They explored a broader range of anomalies compared to other thermographic surveys. Numerous fault conditions have been determined to cause considerable heat dissipation, whilst some fault conditions have been found to result in even lower levels of heat dissipation compared to that of normal equipment. These conditions indicate a complex segmentation challenge. A pre-processing procedure, where the data is segregated into two discrete categories based on the thermal condition of the equipment, specifically denoted as the ‘cold’ and ‘hot’ states, is implemented to address this issue. Subsequently, the segmentation process is conducted through the implementation of random forest and AdaBoost classifiers, employing a sliding window technique, whilst considering interpretable ML principles. Furthermore, a novel collection of infrared images, featuring transformers and three-phase induction motors, has been generated. The method under consideration was evaluated using an identical dataset, resulting in outcomes that are currently unparalleled. The implementation of deep learning for automatic damage detection necessitates a comprehensive data repository that encompasses intricate pavement conditions. The presented study introduced a novel model for detecting surface damage by fusing thermal and RGB images. In [7], researchers investigated how detection outcomes are impacted by input data and network configurations across thermal, MSX, fused image and RGB systems. The findings indicate that the accuracy of damage detection in the fused image can reach up to 98.34%. Additionally, the use of an augmented dataset improved the stability of the detection model, resulting in a precision of 98.35%, recall of 98.34% and F1-score of 98.34%. In [8, 9], researchers introduced a deep learning model that integrates TIC for detecting humans trapped in emergency situations, such as smoky fires, where visibility is notably reduced. The instantaneous results can be communicated to command centres as valuable data, enabling prompt rescue operations and ensuring the safety of firefighters before engaging in hazardous, smoke-filled fire scenarios. The application of deep learning methodologies, supported by comprehensive datasets that incorporate intricate pavement characteristics, has been proven effective in quickly identifying pavement deterioration. Additionally, the use of low-cost infrared imaging technology, coupled with deep learning methodologies, has been shown to be an effective means for detecting pavement damage, particularly in cases where temperature variations are present. Previous studies using pavement data collected under sunny conditions and analysed through the SA-ResNet deep learning methodology achieved a predictive accuracy of 96.47%. In [10, 11], researchers focused on applying deep learning frameworks to datasets containing photographs taken during winter and summer sunny conditions to compare the predictive sensitivity, recall and precision scores. The findings of these studies indicate that moderate-resolution IR-T imaging cameras perform more reliably in summer than in winter conditions, as they yield higher predictive accuracy during warmer months. The studies also recommended the use of these cameras in such conditions due to their cost-effectiveness. Researchers in objective studies [12, 13] explored automatic variations in cognitive evaluation tasks between a healthy control (HC) and a mild Alzheimer’s disease (AD) group to detect the condition in real time. Group differences were also examined using an artificial intelligence (AI) model based on thermal infrared imaging (IRI) technology. Using IRI technology, the researchers conducted non-invasive observations of autonomic activity and its associated thermoregulatory manifestations without affecting the psychophysiological state of the participants, thereby facilitating free communication with physicians. In this regard, overdependence on human experts is likely to be diminished.

2. Applications

Thermal cameras have proven to be effective tools for detecting defects across various industries. Their capability to gather and visualise the thermal energy generated by objects allow them to identify defects that may not be visible to the human eye. An overview of the application of thermal cameras in defect detection, as presented in Figure 1, is introduced in detail in the following subsections.

Mechanical systems	Bearing faults and Misalignments
	Worn-out parts
	Inadequate lubrication
Electrical systems	loose connections
	overloaded circuits
	overheating components
Structural materials	edifices
	overpasses
	conduits
Manufacturing and quality control	fissures
	separation
	spaces
Non-destructive testings	cracks
	voids
	inclusions
Pipeline inspections	leaks
	blockages
	irregularities
Fire protection	thermal signatures
	irregularities
Automative and aerospace industries	engines
	exhaust systems
	brakes

Fig. 1. Defect detection-based thermal camera applications

2.1 Mechanical Systems

Thermal imaging technology plays a crucial role in identifying anomalies in mechanical systems and equipment. Detecting temperature variations can help identify issues such as bearing faults [14], misalignments [15], worn-out parts [16] and inadequate lubrication [17]. Timely detection of these defects can notably enhance the maintenance process. Mechanical systems are essential in a variety of industries, including manufacturing and aerospace. Ensuring optimal performance and minimising downtime are essential factors for achieving efficient operation in these sectors. This phenomenon is due to any potential defect in mechanical components, which can lead to a corresponding failure in the operational processes, ultimately affecting the overall efficiency and reliability of the system. Consequently, the use of thermal cameras has become an effective tool for non-destructive testing (NDT) of defects in mechanical systems [18]. The capability of thermal cameras to sense the temperature on the exterior of mechanical components allows them to detect potential defects at an early stage [19]. In addition, thermal cameras can continuously monitor and record the temperature of mechanical components whilst they are in operation. This capability enables the identification of heat-related issues caused by many factors such as wear and friction. Standard cameras cannot detect these temperature variations. Thus, the importance of thermal cameras in detecting defects in mechanical system components is widely considered. The reliability and longevity of mechanical systems are noticeably improved when mechanical issues are promptly identified and proactive maintenance strategies are implemented. Insights gained from thermal imaging allow for effective preventative maintenance, enabling the timely servicing or replacement of components before they approach critical failure levels. The incorporation of thermal cameras within the framework of Industry 4.0 and the Internet of Things (IoT) [20] introduces novel opportunities for identifying faults in mechanical systems. Intelligent and predictive maintenance systems can be developed by combining thermal imaging, sensor data and advanced analytics. These systems possess the capability to predict potential failures, optimise maintenance schedules and facilitate data-driven decision-making for the management of mechanical assets.

2.2 Electrical Systems

Electrical systems play a crucial role in numerous industries, including energy generation, delivery and circulation. Detecting defects in these systems is essential for identifying potential issues such as damaged interconnections [21], strained circuitry [22] and heat-generating components [23]. Thermal cameras are invaluable tools in preventing electrical malfunctions, improving energy efficiency and ensuring the reliability and safety of electrical systems. By identifying areas of elevated temperature, these cameras help pinpoint potential failures before they lead to more substantial problems [24]. All the thermal information obtained by thermal cameras can be recorded, allowing it to be monitored offline for onboard digital twin applications as well as for offline digital twin systems [25]. Hence, the application of thermal cameras is now recognised as a viable technique for detecting and diagnosing defects in electrical systems, thereby promoting preventive maintenance and minimising the likelihood of failures. The timely recognition of such defects enables immediate reconditioning measures, thereby preventing potential damage to equipment, electrical fires or interruptions in the power supply [26]. The application of a proactive approach advantageously reduces downtime and maintenance costs but also increases the operational lifespan of electrical equipment. Along with reducing potential risks, thermal imaging also facilitates the identification of electrical components operating at high temperatures. Furthermore, thermal cameras play a crucial role in the examination of electricity delivery and energy optimisation within electrical systems. By optimising energy consumption, these cameras substantially contribute to cost reduction, energy waste minimisation and overall improvement in the sustainability of electrical systems. During quality control and inspection processes, thermal cameras are invaluable tools. The incorporation of thermal imaging, sensors and advanced analytics can enhance smart supervision systems. These systems possess the capability to consistently evaluate the condition and operational efficiency of electrical components, detect deviations from normal behaviour and trigger notifications or automated actions as required. The incorporation of this technology improves the effectiveness of maintenance operations, reduces the likelihood of human error and enables the implementation of a predictive maintenance strategy.

2.3 Structural Materials

Buildings are constructed using various structural materials, which may develop defects under certain conditions. Ensuring the safety of these buildings depends on detecting and addressing these defects [31]. Thermal imaging technology is extensively used to identify defects in structural materials across different types of structures, including buildings [27], bridges [28] and pipelines [29]. By monitoring and investigating temperature changes on the surface, detecting issues such as leaks, moisture and structural deficiencies becomes practicable [30]. Thus, thermal inspections serve as a valuable tool for evaluating structural integrity, detecting hidden flaws and expediting timely repairs or maintenance activities. Researchers have widely utilised thermographic cameras for inspecting structural materials to identify obscure faults in the human eye. Thermal cameras can help detect air breakthroughs or unfit insulation due to their capability to collect and detect energy emitted from surfaces of structural materials. The collected thermal variations are indicators of heat dissipation or absorption that may increase structural material discomfort. Thermal cameras have facilitated insulation maintenance to improve thermal conditions and energy efficiency by detecting heat leaks. Individuals using thermal cameras can detect numerous building faults. For instance, they can help identify damaged insulations that lead to uneven temperature distributions, high cooling and heating costs and energy loss. Therefore, thermal cameras can help individuals offer regular building updates to enhance energy-saving effectiveness and cost reductions. Individuals also find thermal cameras essential in detecting breakthrough moisture. Structural materials contain water, thereby increasing their potential for corrosion, mould emergence and drop, which negatively impact buildings' safety. With thermal imaging technology embedded into thermal cameras, individuals can detect temperature variations caused by moisture infiltration, helping to mitigate potential risks. Typically, these temperature variations serve as a precaution for potential moisture breakthroughs, giving building managers or maintenance teams the opportunity to address the issue before it escalates. Thermal camera imaging is also highly effective for detecting structural issues such as delamination, gaps or cracks in buildings. Thus, temperature variations in buildings serve as indicators of hidden faults that require immediate attention to prevent potential hazards, including fatalities. The above information regarding thermal cameras is a crucial resource for professionals in the inspection and structural engineering fields. Such information can help in assessing the severity of faults within buildings, enabling the development of effective strategies for reinforcement and repair to meet safety and structural integrity standards.

2.4 Manufacturing and Quality Control

Different industrial players have applied thermal imaging technology to improve product process efficiency and meet quality control requirements. The technology helps manufacturing companies to produce quality goods, minimise waste and promote sustainable manufacturing operations, thereby meeting the requirements. With this technology, manufacturing firms can detect faults sufficiently early to avoid compromising customer satisfaction [32]. Production and quality control in companies have been substantially improved through thermal imaging technology, which offers non-destructive and non-contact methods for inspection. [33]. Using this technology in cameras gives them the capability to detect temperature variations, which are key indicators of hidden irregularities that might affect product quality [34]. Thermal cameras can detect hidden material flaws, including but not limited to insufficient bonding, cracks, delamination and porosity, by evaluating temperature fluctuations. If such faults are left unattended, then the performance and quality of products are more likely to be notably compromised, lowering customer satisfaction. Therefore, the use of thermal cameras in the manufacturing sector aims to provide quality assurance and verification [35].

By examining thermal patterns using these cameras, firms can assess compliance, uniformity and consistency of products before they are released into the market for consumption. Thermal imaging aids firms in detecting discrepancies in meeting desired quality standard by assessing variations in thermal signatures. This information is crucial because it allows entities to plan training programmes that raise awareness of compliance with quality standards, ensuring customer satisfaction and increased profits. In contrast, physical measurements or visual examinations used in conventional testing require disassembly and destructive sampling, methods that are associated with high material wastage and elevated costs [36]. With thermal cameras, non-destructive and non-contact testing can be performed on various materials and products without compromising their structural integrity.

2.5 Non-Destructive Testing

Non-destructive testing (NDT) widely employs thermal imaging cameras to identify faults, including material cracks, inclusions or voids, without causing damage to the products. Industries such as automotive, manufacturing and aerospace have adopted NDT techniques to ensure that their products meet safety and quality standards. These techniques are crucial in ensuring that the structures and materials produced are safe, reliable and of high veracity [37]. By using these techniques, companies can evaluate product components without the need for disassembly or causing damage. Thermal cameras have become increasingly recognised in the NDT field as valuable tools due to their non-invasive and non-contact inspection capabilities, allowing for the detection of temperature fluctuations that indicate potential issues. These cameras use thermal imaging technology to identify anomalies such as separations, fractures, foreign materials and empty spaces [38, 39]. Defects are often associated with varying thermal characteristics compared to the surrounding environment, creating detectable thermal variations that can be identified using thermal imaging technology. Thermal cameras are also useful for studying material homogeneity, density and composition by analysing temperature distributions across surfaces, thereby helping to identify faults. In the field of NDT-related welding inspection, thermal cameras play an important role in evaluating weld joint quality by assessing thermal variations along the material. These variations can reveal possible faults, such as cracks, minimal fusion or porosity. Inspectors in this field benefit from thermal imaging because it helps them detect temperature deviations in welded materials, highlighting the quality of the welding process.

2.6 Pipeline Inspection

Pipeline systems are considered critical infrastructures for loading different fluids across long distances, including water, gas and oil. Therefore, pipeline safety must be consistently maintained to limit potential issues such as leaks [40]. Particularly, thermal cameras are used to inspect pipelines to find leaks or defects by monitoring the temperature distribution along the pipeline. Thermal inspections make it easier to identify problems, thereby improving the integrity and condition of pipeline systems [41, 42]. Notably, using thermal cameras to inspect pipelines is an effective technology for monitoring defects and ensuring the safe functioning of these systems. The flow of fluids within the pipeline leads to temperature fluctuations on the pipe's surface. Thermal cameras are capable of detecting deviations in temperature and providing visual guidance to potential leakage points. The obtained data enables personnel to expeditiously detect and identify leaks, facilitating prompt repairs. Hotspots may also indicate other issues in pipelines, such as the presence of localised fluid obstructions [43]. This information assists operators in identifying possible problematic regions and implementing appropriate remedial steps, such as investigating fluid flow problems, to prevent them from escalating into more substantial difficulties. Thermal cameras are essential tools for monitoring and inspecting corrosion and erosion regions in pipelines [44]. Over time, corrosion and erosion can weaken the strength of pipe walls, posing a risk to the overall structural integrity of the pipeline. With the timely identification of thermal fluctuations, individuals can detect faults early and formulate maintenance strategies to address and prevent progressive failures. Scholars have found thermal cameras beneficial in assessing the structural integrity of pipeline coatings. These coatings often protect pipes from corrosion and other forms of damage. However, coatings may deteriorate over time due to the effect of mechanical issues (stress) or environmental conditions. In these circumstances, thermal cameras become crucial tools, as they assess temperature variations caused by coatings faults (such as inadequate coverage or delamination). Using temperature deviation visualisations, individuals can identify specific areas on pipes or walls where coatings have been compromised, allowing for targeted evaluations and repairs to maintain the protective integrity of the coatings. Inspecting insulated or underground pipes is made more efficient and non-intrusive with thermal cameras, which are capable of identifying hidden problems. Integrated thermal imaging technology detects thermal fluctuations on the exterior of pipes or their insulation, helping to locate faults, leaks or hot spots. The data collected from thermal cameras can be used for continuous monitoring of the conditions of pipes, eliminating the need for excavation or disassembly.

2.7 Fire Protection

Fire is a significant hazard to humans, animals, birds, tangible assets and the surrounding environment. The early detection of fire is vital because it expedites effective suppression and management of associated fire incidents. The enhancement of fire alarm systems and fire prevention instruments may be realised through their integration in environments characterised by substantial heat generation. Thermal imaging cameras are used inside fire protection systems to detect thermal irregularities, facilitating the rapid identification and control of flames. Thermal cameras are increasingly becoming recognised as essential tools in fire detection systems due to their capability to provide improved capabilities for early fire detection. The identification of temperature variations becomes possible by using thermal imaging technology, possibly serving as an indicator of fires [45]. In contrast to traditional smoke or flame detectors, thermal imaging technology assumes control over the identification of fires via the detection of heat fluctuations. This capability facilitates early detection before the sight of flames or smoke, which, in turn, enables fast response, including actions such as departure, putting out fires and control measures, reducing the likelihood of fire spread. Thermal cameras have shown notable use in the identification of fires that exhibit no apparent smoke or arise in environments with restricted visual perception [46]. The aforementioned characteristic provides thermal cameras with distinct advantages in situations where relying only on smoke detection may be inappropriate, such as in large open rooms, factories or high places. Additionally, thermal cameras provide continuous fire detection during the day and night. Furthermore, in contrast to human operators, thermal cameras are advantageous due to their resistance to tiredness or oversights, facilitating continuous monitoring of the area of interest for temperature irregularities. The continuous monitoring system ensures rapid identification and resolution of fires, even in situations where human supervision is impractical. Thermal cameras allow individuals to acquire thermal images to use in identifying the amount and the exact location of a fire to guide the actions of emergency responders towards improved fire suppression efforts.

2.8 Automotive and Aerospace Industries

The aerospace and automotive industries are increasingly adopting thermal cameras in detecting defects. These cameras can identify faults in the engine, the braking system, the exhaust system and other components. Through routine thermal inspection in the two industries, safety and performance have been improved as maintenance costs have been minimised. The sectors remain strict on surveillance and assessment of procedures to ensure safety is prioritised and commodities are effective and reliable. The thermal imaging technology on thermal cameras allows individuals to capture temperature fluctuations, indicating suboptimal functioning or irregularities linked to engines [47]. Thermal cameras also use embedded thermal imaging technology to monitor the cooling and exhaust systems of the engine to detect parts with high temperatures, leaks and other areas of concern to guide the maintenance team towards performing timely procedures to promote safety. Data from such evaluations assists engineers in assessing engine performance and efficiency. Thermal cameras have also been widely applied in thermal analysis and mapping of the aerospace and automotive industries [48]. These cameras can visualise temperature variations, allowing for the generation of thermal maps of various systems and components, including the propulsion, electrical and braking systems. Thermal maps allow engineers to study heat distribution to various systems and components, thereby identifying areas of concern and those with a high risk of overheating. Such collected data serves as the starting point for the optimisation of component designs, heat dissipation and thermal insulation and thermal veracity. The thermal cameras help identify and assess automotive and aerospace malfunctions. The thermal imaging technology aids the cameras in identifying temperature irregularities, which could indicate additional problems. The industry players also use the TIC to detect problems such as defective wiring, malfunctioning sensors and overheating of electrical connections. Using their non-invasive capability, thermal cameras rapidly identify faults, thereby diminishing operational interruptions and augmenting maintenance procedures. Thermal cameras equally help ascertain thermal and human comfort in the automotive and aerospace design domains. They also use thermal imaging technology to assess temperature distributions and thermal and human comfort levels within vehicle or aircraft cabins. Such information is vital in optimising air conditioning, ventilation and heating systems to ensure comfortability and safety of humans in those cabins, increasing their satisfaction. Human factors are also examined using thermal cameras in the cockpit design and seating areas to optimise ergonomic designs of the aerospace and automotive interiors and enhance comfort.

3. Thermographic Cameras Effectiveness

Thermographic cameras, which have been applied across numerous domains, have been proven effective. As shown in Figure 2, various factors that contribute to the effectiveness of thermographic cameras are explored in this section, and their benefits over conventional inspection approaches are clarified.

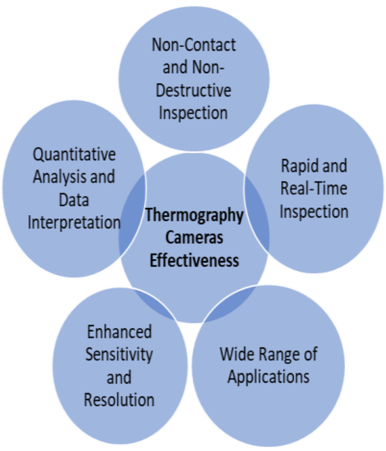


Fig.2. Thermographic camera factors

A major benefit of thermography cameras lies in their non-destructive and non-contact assessment capability. They can record various thermal patterns and temperature fluctuations without having direct contact with the item being examined. In contrast, conventional inspection techniques require close contact with the item or material under investigation. Notably, thermography cameras are useful in understanding the faultiness of sensitive and fragile constructions or materials because their non-destructive nature guarantees that the item would remain undamaged. These cameras have made it possible to conduct real-time and rapid inspections to identify abnormalities in items or materials [49]. In the contemporary market, the latest thermography cameras are faster at collecting data and offer high-resolution thermal image capabilities due to advancements in technology. With these capabilities, operators and other inspectors can quickly identify problems in materials, accelerating the pace of inspections and facilitating prompt resolution of issues. Some industrial processes and operations, especially in dynamic contexts, require real-time monitoring to detect anomalies. In these cases, thermography cameras are invaluable because they provide continuous, real-time monitoring. These cameras have found widespread use across different domains, including environmental monitoring, electrical inspections, medicinal applications, building inspections and mechanical system diagnostics. They are useful in these fields due to their capacity to help individuals detect varying thermal patterns and temperature changes, raising the curiosity of wanting to investigate systems and materials further for abnormalities, inefficiencies or defects. Resolution and sensitivity have been enhanced in the current thermography cameras, guaranteeing thorough and precise system and material evaluations. Owing to their increased sensitivity, the cameras can record thermal variations per minute, improving their capability to aid in the identification of small abnormalities. Based on their superior resolution, thermography cameras capture detailed and accurate thermal images of thermal patterns and temperature distribution in systems and materials. The resolution and sensitivity of the thermograph cameras determine their capability to assess problems in various applications. These cameras have become increasingly popular in fault detection because they support quantitative and qualitative analyses [50].

Individuals have found the cameras excellent in using refined image processing software and algorithms to transform thermal images into useful data (thermal gradients or readings). Through quantitative analysis, thermal cameras can accurately and impartially detect thermal variations, enabling more informed decision-making. Their capability to read and analyse data in real time allows them to efficiently identify problems and guide individuals in pinpointing their root cause.

4. Defect Detection Techniques

Many industrial players conduct thorough investigations to identify defects in their systems and materials using various approaches, including but not limited to image processing algorithms and temperature analysis. The advancement of thermography camera technology, its superior resolution and its capability to integrate imaging modalities have been key topics of discussion. Through its non-destructive techniques, thermal cameras offer considerable advantages in identifying defects in various constructions and materials. The following section highlights and elaborates on the common thermography defect detection techniques.

4.1 Active Thermography

Active thermography is known to apply external energy sources, such as heat, to trigger a thermal reaction in materials under investigation. This approach is widely used because it helps discover underlying faults that the human eye may overlook. Lock-in and pulsed thermography are two commonly applied active thermography methods [51]. In pulsed thermography, a material's surface is exposed to a heat pulse, and the thermograph camera records the reaction. Thermal responses occur due to changes in the heat transmission mechanism caused by abnormalities. Normally, inclusions, delamination and voids can be identified from thermal images taken before and after the heat pulse. In lock-in thermography, the modulation frequency is synchronised with the thermography camera's capture rate whilst applying a controlled light or heat source to the targeted substrate. This approach enhances flaw detection by isolating the thermal response of the faults from the background noise. The approach is vital for identifying underlying faults in metallic structures, such as concealed corrosion or fractures.

4.2 Passive Thermography

Passive, ambient or natural thermography relies on thermal variations in materials to identify faults without an external energy source. The technique applies the surface temperature variations to determine material faults. This approach is often used in electrical inspections, quality control and building inspections [52]. The method applies thermal contrast analysis in examining surface thermal variations to identify faults in materials. The different faults, such as cavities, hotspots or fractures, which are linked to distinct temperature changes and can be identified from thermal images, help analyse materials and draw conclusions. Thermal contrast analysis is commonly used in electrical connection inspections to identify overheating components and in building inspections to detect moisture incursion. Infrared imaging is a widely used passive thermography technique that captures images of temperature variations in materials. This technique relies on detecting temperature fluctuations to identify faults such as thermal bridging, air leaks and insulating gaps. This method is particularly effective for moisture detection, building energy audits and insulation assessments due to its superior spatial resolution.

4.3 Combined Techniques

In some cases, passive and active thermography techniques can be combined to ensure thorough fault detection. When combined, the two approaches aid in detecting a greater variety of flaws, thereby increasing the precision of defect characterisation. Transient thermography merges the benefits of passive and active thermography techniques by introducing a heat pulse and recording the consequent thermal reaction of materials.

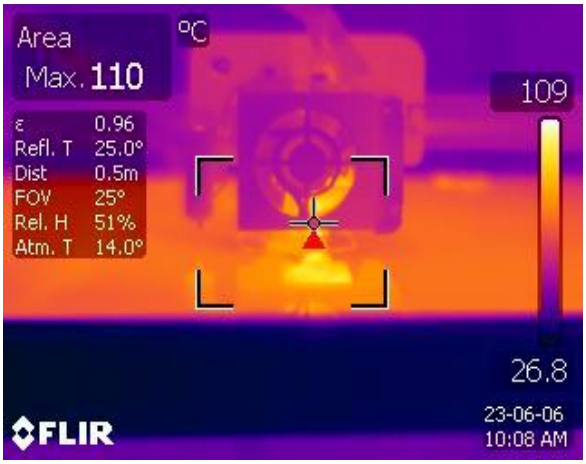
The combined method is commonly used in inspecting composite materials, evaluating aerospace components and inspecting concrete structures to identify subsurface and surface faults. Vibrothermography is employed to capture thermal images whilst inducing vibrations in materials. Flaws in materials often affect their thermal reactivity, resulting in varying thermal patterns. For composite materials, coatings and adhesives, vibrothermography can easily detect bonding/debonding/delamination. Table 1 displays a comparison of the thermography techniques.

Table 1
Main features of thermographic camera techniques

Thermography techniques	Method	Key features	Applications
Active Thermography	Uses an external energy source (heat or light) to induce a thermal reaction in the material.	Pulsed Thermography: Brief heat pulse to surface, records thermal response for flaw detection. - Lock-in Thermography: Synchronises camera with modulated heat or light source for improved flaw detection.	Finding underlying flaws such as delamination, voids or inclusions.
Passive Thermography	Relies on detecting natural or ambient temperature fluctuations in the material without an external energy source.	Thermal Contrast Analysis: Examines surface temperature changes to identify thermal differences caused by defects. - Infrared Imaging: Measures material surface temperature variations for abnormality detection.	Quality control, building inspections, electrical inspections, moisture detection, insulation evaluations and energy audits.
Combined Techniques	Integrates active and passive thermography methods to enhance flaw identification capabilities.	-Transient Thermography: Uses brief heat pulse and records subsequent thermal reaction over time for comprehensive analysis. - Vibrothermography: Utilises thermal imaging with induced vibrations to detect flaws.	Inspection of composite materials, testing of aerospace components, assessing concrete structures and specific fault identification in structures or materials.

5. Discussion

Thermographic cameras have numerous benefits compared to traditional inspection methods across different industrial domains. This section discusses the key findings and implications of using thermographic cameras for defect detection, as well as potential challenges and areas for future research. Thermographic cameras possess various advantages that substantially enhance their effectiveness in detecting defects. Thermographic cameras facilitate non-invasive and contactless examinations, thereby safeguarding the structural soundness of the scrutinised entity whilst offering remarkable revelations regarding its state. This advantage is of considerable importance, especially when dealing with delicate or sensitive materials and structures. Thermographic cameras offer efficient and instantaneous defect detection capabilities in real time. The rapid capture of temperature variations and thermal patterns using this technology facilitates the prompt detection and evaluation of defects, resulting in reduced inspection durations and facilitating the timely implementation of corrective measures. Figure 3 depicts the thermal image obtained by an FLIR T335 camera at the workshop of the Ministry of Higher Education, University of Baghdad, automated manufacturing department of a 3D printer's heater whilst the 3D printer is running. Notably, the temperature range of the obtained region is between 26.8 °C and 109 °C. Another example of the capability of a thermal image to monitor high temperatures, as shown in Figure 4, is obtained using an FLIR T335 camera at a workshop of the Ministry of Higher Education/University of Baghdad/automated manufacturing department, which was used whilst the furnace was running and the temperature of the obtained region ranged between 35.6 °C and 263 °C.



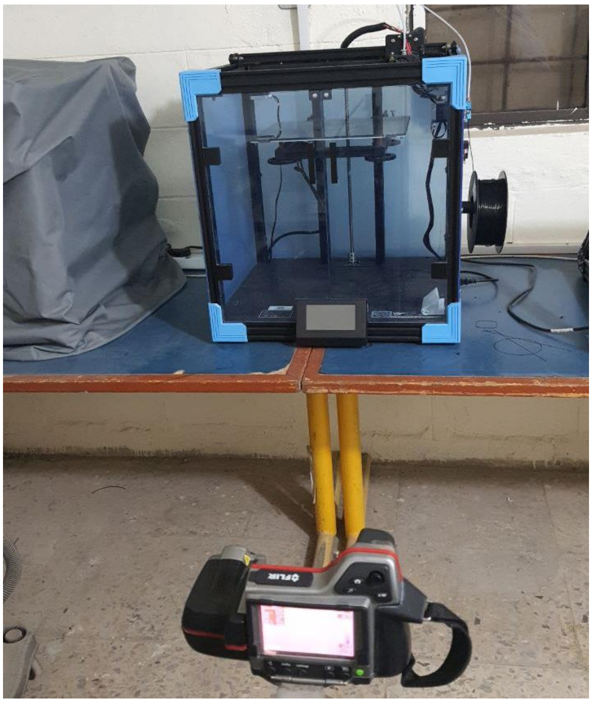


Fig. 3. Capturing thermal image of 3D printer heater

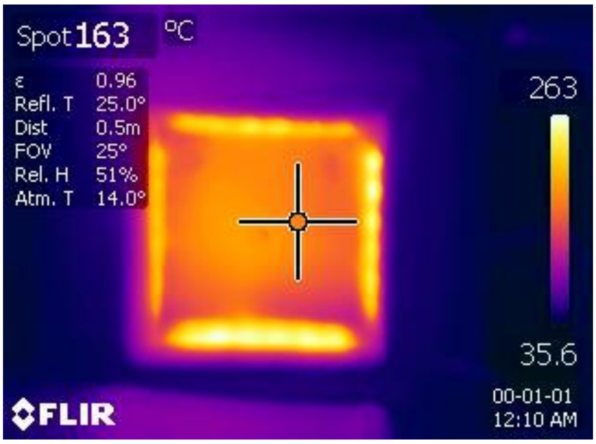


Fig. 4. Capturing thermal image of furnace

Online weld quality monitoring is realised using thermal image analyses to automatically identify defects. The temperature variance was computed for each row and column. Figure 5 displays the variance plot. The temperature variance was computed for each individual pixel in the row and column. The resulting values are presented in the provided figure. These statistical graphs facilitated the identification and localisation of anomalies.

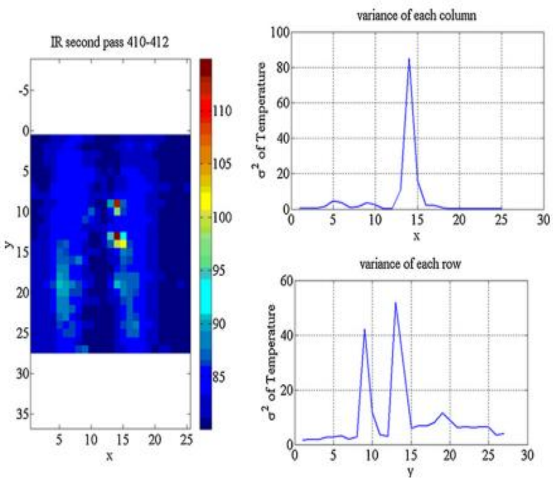


Fig. 5. Variation in a thermogram frame [53]

Figure 6 illustrates the contrast between a thermograph picture of a healthy induction motor and a thermograph image of a damaged induction motor. These differences allow for the application of an analysis. The video underwent analysis using the commercial programme FLIR ResearchIR MAX to extract the temperatures within the specified zones. Considering the high volume of data in the video (30 frames per second), an analysis was conducted on a per-minute basis, assuming that the temperature remains constant without abrupt changes. Two different supply frequencies, 40 and 60 Hz, were used to examine their behaviour. These frequencies were programmed or set up in the frequency inverter. The zones were examined, and the graphs were generated, as shown in Figure 6.

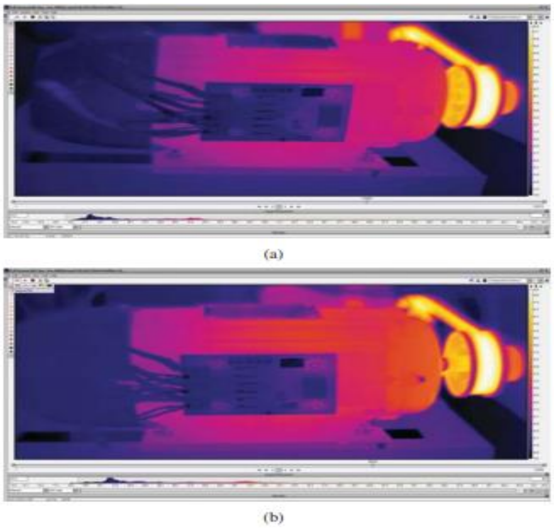


Fig. 6. Thermograph image of the induction motor: (a) No defect; (b) Damaged [54]

Steel fracture detection often relies on vision-based methods. Identifying any surface imperfections becomes possible when analysing the images captured by the camera. Photographic images are inherently limited in their capability to appropriately reveal the interior aspects of things. As presented in Figure 7, fractures in steel sheets can be identified by integrating CNNs with infrared thermal imaging.

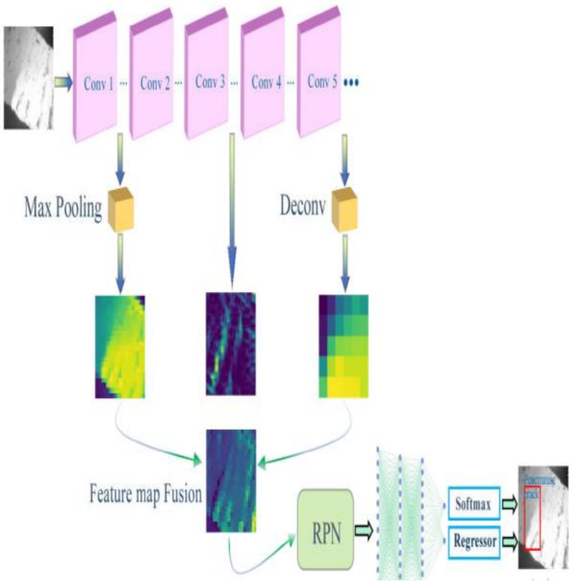


Fig. 7. Convolutional neural networks with infrared thermal imaging [55]

Thermographic cameras have demonstrated their versatility as multifaceted instruments, exhibiting utility across diverse industries, including manufacturing, construction, electrical systems and aerospace. The adaptability of thermographic cameras to various materials, structures and types of defects is emphasised by their versatility. The progress in thermographic camera technology has resulted in enhanced sensitivity and resolution, facilitating the identification of minimal temperature fluctuations and the augmentation of the precision and intricacy of thermal images. Such an improvement is crucial because it will elevate fault detection and characterisation in systems and materials. Thermographic cameras are beneficial in detecting and characterising system or material faults. However, recognising and addressing the limitations of these cameras is crucial. The emissivity and reflective properties of materials under investigation impact the effectiveness of the thermographic camera to a large extent. Surfaces with low emissivity and high reflectivity are likely to alter thermal patterns, diminishing the capability of the camera to assist in fault detection. Remedial actions (using emissivity correction methods or anti-reflective coatings) are required under such circumstances. Thermal image interpretation requires appropriate analysis techniques and expertise. During thermal image interpretation, the camera settings, environmental conditions and material properties must be considered to attain precise and accurate fault detections and characterisations. Substantial data could be extracted from the thermal images by applying sophisticated software and algorithms. The standardisation and calibration of thermographic cameras are crucial in ensuring that defect detection achieves high precision and is satisfactorily dependable. Regular camera calibration and strict compliance with standardised protocols are necessary to achieve high result compatibility and consistency. The development and implementation of industrial-wide measures and standards to guide defect detection and thermographic camera calibration are critical in ensuring reliable and consistent inspection results. Future research should focus on prioritising camera resolution in various aspects. Advancements in image processing methods are expected to augment the fault detection capabilities of thermographic cameras. Similarly, the advancement of algorithms to facilitate automatic flaw detection, quantitative image analysis and image fusion is expected to optimise the accuracy and precision of flaw detection. Integrating thermographic cameras into X-rays or visual inspections is expected to provide complementary and comprehensive flaw detection capabilities. Further investigations into different inspection methods could help improve the reliability and precision of fault identification. Various materials exhibit varying response characteristics due to distinct thermal properties. Further research in the development and advancement of flaw detection through thermographic cameras is also expected to improve methodologies aimed at addressing specific material needs, thereby improving their efficiency. Inspection process optimisation can be released by understanding the thermal properties of materials and tailoring them to an appropriate flaw detection technique. Performance evaluations in real-world situations are critical in assessing the effectiveness of the flaw detection methodology when thermographic cameras are adopted. In this regard, a comprehensive field testing and validation experiment should be implemented. The experiment should consider the different types of flaws; cameras should be tested using various materials and in different environmental conditions. This experiment is expected to elucidate the suitability and barriers to thermographic camera use in studying real-world defect situations. Thermal data interpretation and the potential avenues for ensuring automated abnormality detection have been reviewed. The literature review has contributed to the field of thermographic camera technology and its techniques, emphasising the need for additional research aimed at improving the availability and effectiveness of the NDT approach. The thermal camera applications highlighted in this review revealed the application of thermal imaging technology for detecting flaws in systems and materials in different industrial domains, as shown in Table 2. Thermal cameras are crucial in proactive maintenance, achieving enhanced product quality and improving safety across diverse sectors by effectively detecting thermal irregularities and identifying concealed flaws.

Table 2
Summary of the applications of thermal cameras in **defect detection**

Application	Description
Electrical Systems	Detects loose connections, overloaded circuits and overheating components in electrical systems
Mechanical Components	Identifies defects such as bearing faults, misalignments and inadequate lubrication in machinery
Structural Materials	Detects heat leaks, moisture intrusion and insulation deficiencies in buildings and structures
Manufacturing and Quality Control	Identifies defects such as cracks, delamination and voids in products during manufacturing processes
Non-Destructive Testing (NDT)	Detects defects such as cracks, voids or inclusions in materials without damaging the inspected object
Pipeline Inspection	Identifies leaks, blockages and temperature anomalies in pipelines, ensuring their integrity
Fire Protection	Detects heat sources and anomalies for early fire detection and prevention
Automotive and Aerospace Industries	Detects faults in critical components, optimising performance and improving safety

Table 2 summarises various thermal camera applications in the fault detection domain. Specific domains where this technology has been applied, along with the types of faults it has been used to detect, have been highlighted. Various industries have demonstrated the efficacy of thermal cameras in detecting flaws. These cameras have been utilised in detecting and displaying thermal energy emissions from materials, which helps in identifying various flaws. Various findings regarding the use of thermal cameras in flaw detection have been documented. They provide supplementary capabilities for evaluating temperature variations to detect defects such as excessive heat, insulation inefficiencies, structural defects and leakages. Individuals can use thermal cameras to identify flaws and direct their actions to reduce them, thereby enhancing the overall reliability and accuracy of systems. Through contactless and non-invasive approaches, thermal cameras can detect flaws without damaging systems or materials. As such, they help avoid direct physical contact with the materials under inspection, preventing interference with ongoing activities that could jeopardise performance and accuracy. Moreover, the NDT capabilities embedded in thermal cameras allow for the evaluation of crucial structural components whilst conserving their integrity. With thermal cameras, individuals and entities can detect flaws earlier, facilitating proactive approaches towards timely and continuous maintenance. Such proactive approaches help minimise costly downtime and breakdowns. Prompt fault detection is essential because entities have the opportunity to implement focused repairs, thereby enhancing financial savings, minimising potential safety risks and addressing minimal productivity. Different industrial domains, including but not limited to pipeline inspection, electrical systems, mechanical components, manufacturing and structural materials, have witnessed thermal camera applications. The adaptability of the systems requires firms to identify faults across different environments to tailor specific assessments and action points towards addressing the faults for enhanced productivity. Thermal cameras support various technology integrations, such as 3D imaging, AI and image processing algorithms, augmenting the capabilities of defect detection. Such integrations ensure the cameras perform automated fault detection, improving the precision and accuracy of the results. The use of thermal cameras to detect faults is a critical starting point for improving the safety and reliability of materials and systems across different industrial domains. They play a vital role in accident prevention, preserving structural integrity and mitigating risks by identifying various hazards, such as structural weaknesses, electric faults and mechanical failures, which could worsen if left unattended.

6. Conclusions

Different industries have applied thermal cameras to detect material or system defects. Through the use of non-destructive properties, hidden fault discovery and improved detection accuracy and performance, industries have realised reduced maintenance costs, substantial financial savings, heightened safety and reliability. Future research into defect recognition algorithms and advancements in thermal camera technology is expected to further enhance the capabilities of thermographic cameras, expanding their application in fault detection. The advantages of using thermographic camera-based defect detection are evident across a wide range of applications. Mechanical systems have revolutionised flaw detection and maintenance across industries using thermal cameras. Thermal cameras can detect early anomalies, enable non-destructive testing and facilitate predictive maintenance, making them essential tools for improving the dependability, security and effectiveness of mechanical systems. The integration of technologies such as the IoT and Industry 4.0 can further improve defect detection and asset management. This integration will improve mechanical systems across industries. Thermal cameras in electrical systems have also revolutionised defect detection, preventive maintenance and risk reduction. They can identify flaws, assess structural soundness and improve energy conservation in structural materials. Additionally, these cameras reveal heat leaks, moisture intrusions, insulation issues and other irregularities. In manufacturing and quality control, they help identify defects, monitor processes and ensure quality. Thermal imaging technology reduces waste and promotes sustainable manufacturing due to its non-destructive nature. In NDT, thermal cameras help identify defects and corrosion and can execute structural evaluations and material analyses. They can also detect leaks, hotspots, corrosion, buried or insulated pipelines and examine coating integrity. Thermal cameras in fire detection systems improve fire detection, especially in low-smoke or low-visibility environments. In the automotive and aerospace industries, they are useful for engine and component testing, thermal mapping and analysis, fault detection and diagnosis, composite material inspection, thermal comfort and human factors. Pulsed and lock-in thermography can detect subsurface defects. However, passive thermography methods such as thermal contrast analysis and infrared imaging can identify surface defects, and transient and vibro-thermography can help detect a wide range of defects. The next steps should include advanced image processing, alternative inspection methods, material-specific approaches and extensive field testing and validation. Overall, focusing on these areas can improve the defect detection capabilities of thermographic cameras, making them useful across industries.

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اكتشاف العيوب باستخدام تقنيات كاميرا التصوير الحراري: مراجعة الأدبيات

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الخلاصة

بسبب التقدم في تكنولوجيا مستشعرات التصوير الحراري, تستخدم الكاميرات الحرارية في مختلف المجالات، بما في ذلك على سبيل المثال لا الحصر، الزراعة والطائرات بدون طيار والأدوية والتصنيع، ومن أجل تحقيق أهداف مختلفة تتعلق بالسلامة والأمن. في هذه الدراسة سيتم استكشاف الأدبيات الحالية بعمق لتوضيح تطبيقات كاميرات التصوير الحراري في اكتشاف الأخطاء في مجموعة واسعة من التطبيقات، مثل الحماية من الحرائق، والتصنيع، والفضاء والسيارات، والاختبارات غير المدمرة، وصناعات المواد الإنشائية. تتوسع المناقشة الحالية حول نتائج الدراسات السابقة، مع التركيز على فعالية كاميرات التصوير الحراري في التمييز بين العيوب غير القابلة للاكتشاف من خلال الرؤية البشرية. تم عرض طرائق مختلفة للكشف عن العيوب، بما في ذلك تحليل درجة الحرارة وخوارزميات معالجة الصور، بدقة. ثم تمت دراسة العوامل التي تسهم في فعالية كاميرات التصوير الحراري وتوضيح مميزاتها عند مقارنتها بطرائق الفحص التقليدية. أشارت هذه الدراسة إلى التحول الكبير الذي أحدثته تقنية الكاميرا الحرارية في اكتشاف أخطاء النظام الميكانيكي لتحسين الصيانة . نظرًا لأن هذه الكاميرات يمكنها تحديد المخالفات غير المرئية والسماح بالاختبارات والصيانة العملية للنظام، فقد تطورت لتصبح أدوات لا غنى عنها لضمان عمل الأنظمة الميكانيكية بكفاية وموثوقية وبقائها آمنة. واشارت الدراسة ايضا انه يمكن تحسين التكنولوجيا الكاميرات الحرارية بشكل أكبر من خلال الجمع بين تقنيات الصناعة 4.0 وإنترنت الأشياء، مما يضمن أداءً مرتفعًا للنظام الميكانيكي عبر المجالات المختلفة. عند استخدامها في الأنظمة الكهربائية، مكنت الكاميرات الحرارية الأفراد من تحديد الأخطاء للتخطيط للصيانة المبكرة التي ترمي إلى تخفيف المخاطر. بفضل قدرتها على تقييم السلامة الهيكلية، يمكن للكاميرات الحرارية تحديد أوجه القصور في الحرارة والعزل، مما يؤدي إلى تحسين كفاية استخدام الطاقة .