Exploring the Diverse Applications of Thermal Cameras: A Comprehensive Review

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ABSTRACT

Thermal imaging technology, well-known to many through its relation with infrared or thermal cameras, has become a game changer in various industries due to its ability to capture the heat rays that are released by objects and then form that heat into images. In this paper the authors discusses the numerous uses of thermal imaging paying special emphasis to its application in industrial activities, security systems, structural health assessment, dullness management, healthcare, ecology, farming, and navigation. Preventive and diagnostic uses of thermal cameras have been justified in applications because of their effectiveness in monitoring heat signatures. The review seeks to understand how thermal imaging systems are progressing with technology and we are being increasingly used in various sectors. In addition, it speaks about the global tendencies encouraging the use of this technology and gives several forecasts for the development of this area. From improving security and productivity to facilitating the research of eco and medical problems, in this article thermography as a technology defined many modern solutions for difficult issues is discussed.

Keywords: Thermal cameras, Infrared imaging, Applications, Security, Building inspections.

1 Introduction

The foundations of thermal imaging technology date back to the processes of infrared radiation detection. It has now become one of the elements which underpin innovation. Nevertheless, thermal cameras in most cases have the ability to see and depict heat that any given object radiates. The increasing use of thermal cameras spans a variety of industries, such as thermal scanning, thermal scanning, thermal imaging, thermal imaging, and medical devices. The military first adopted this technology in the mid-20th century, but thermal cameras were bulky, expensive, and mostly used in specific sectors. However, the reasonable evolution of sensor technologies and data processing allowed expansion of the use and availability of the devices. The primary focus of this paper is to assess the evolution, technological principles and primary elements of the thermal imaging systems. It also addresses the use of the technology in different industries including the improvement it has brought to diagnosis, monitoring, and maintenance of various systems. Additionally, it provides findings on the development progress, possible upcoming trends and applications of thermal imaging, emphasizing its position in the provision of solutions to global problems such as environmental issues, health care and enhancement of industrial productivity.

In the late nineteenth to early twentieth century, science started investigating why and how people utilized infrared light which resulted into the establishment of thermal imaging also referred to as infrared imaging. The development of thermal imaging systems took new strides during the Cold War thanks to the increased combat functional demand for targeting, surveillance and night sight

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equipment. The first generation of thermal camera appeared to be oversized, overpriced, and designed for the aerospace and security industries. The reason for the functioning of the thermal camera is the radiation sensibility. All objects with a temperature higher than zero radiate heat in the form of infrared rays. Hotter objects appear brighter than cooler ones or cooler ones appear darker, on the thermographic temperature sensing mode which images any radiation. The camera sensor captures infrared radiation and transforms it into an electrical form, which is then employed to popularize thermal imaging. Figure 1 shows the components of thermal camera capturing.

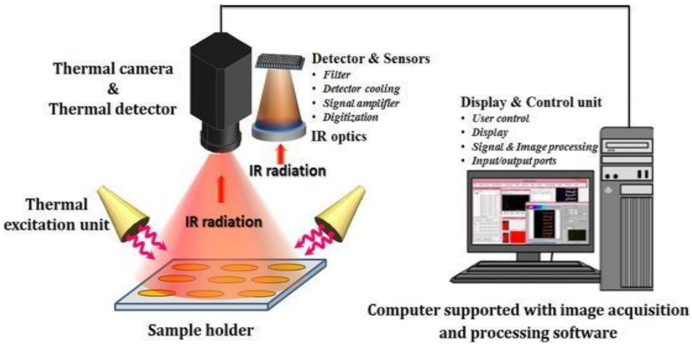

Figure 1 Components of Thermal Camera Capturing

Thermography and machine learning (ML) technology has achieved many remarkable things in different areas. Wilson et al. (2023) provide an updated version of the recently published works emphasizing the function of ML for thermal image processing in relation to tasks such as object detection or medical diagnosis [1]. Altay and Velipasalar (2022) focus on the task of pedestrian detection using thermal cameras, and demonstrate the improvement of deep learning methods under conditions with obscured visibility [2]. Hong et al. (2022) examine the usage of thermal cameras in education and prove that their application helps students visualize and understand concepts such as heat transfer better[3]. Fung et al. (2021) propose a low-cost, remote on-call system for monitoring human body temperature in the form of remote thermal imaging which became relevant during the COVID-19 pandemic[4]. As for the healthcare domain, Pandey et al. (2022) present a deep learning-based thermal imaging technique for pressure ulcer detection and utilize thermal images for accurate delineation of the wounds [5]. Finally, Rahmat et al. (2023) utilize thermal imaging and histogram classification to separate fertile from non-fertile chicken eggs, thereby improving poultry farming [6]. Nonetheless, there is still ongoing this kind of promising studies, there are many challenges such as the availability of data sets and the sensitivity of the environmental factors when it comes to ML where the next focus is transferring the dry technology concepts to the real world by enhancing social systems

2 Working Principle of Thermal Camera

Thermal cameras work based on the fact that objects generate thermal radiation. Thermal radiation refers to infrared emission from any object with a temperature above absolute zero, i.e., -273.15 degrees centigrade or 0 degrees Kelvin. Hotter objects appear white, while colder ones appear black on the thermal imaging camera temperature map. This is how the thermal cameras work. It is the same ray detection by other types of cameras that sensor detects invisible infrared radiation that is then turned into thermal imaging through electric signals. Figure 2 shows the working of the thermal camera. Thermal cameras consist of several key components, including:

I. Infrared Detector: This is the sensor that acquires the infrared energy that objects emit. Microbolometers and photonic detectors are two popular types of infrared detectors.

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II. Optics: A thermal camera's optics focus the infrared spectrum onto the detector array, yielding clear precise thermal images.
III. Signal Processing System: Signal processing algorithms get occupied by thermal cameras to adjust temperature ranges, create image quality, and perform any other photo processing tasks.
IV. Display Unit: Real-time thermal image monitoring is possible through the merged display unit or interface found on the immense majority of thermal cameras.
V. 5. Additional Features: Thermal cameras can have functionality including temperature monitoring, picture capturing, and connectivity for data migration, depending on the use purpose.

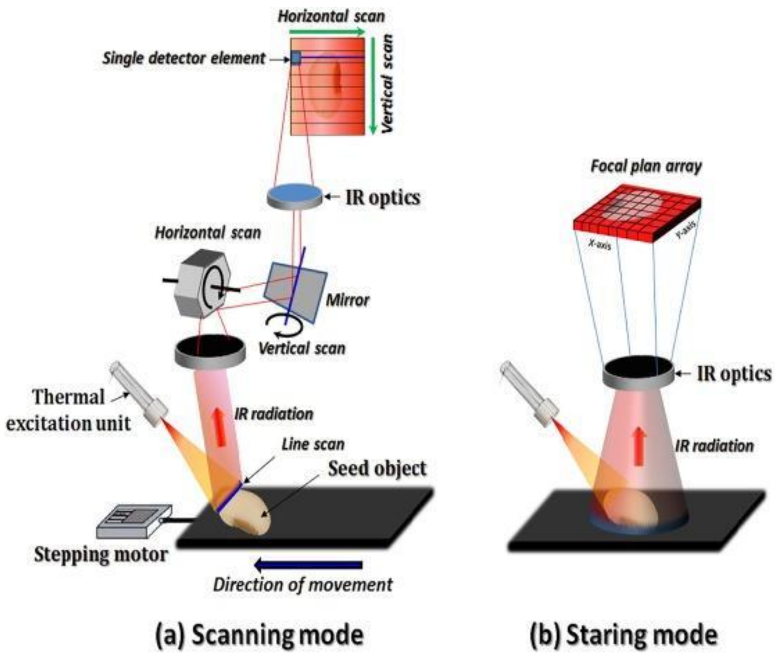


Figure 2 Working of Thermal Camera

3 Importance of Thermal Imaging in Various Industries

Thermal imaging—made realistic by thermal cameras—is essential for many distinct companies because it offers crucial data about variations in temperature, thermal patterns, and defects. It has importance in several fields.

3.1 Building Inspections and Energy Audits

Due to construction heat loss, insulation or energy inefficiencies in a structure, thermal imaging technology finds vast use in building check-ups and energy audits. More importantly, thermal cameras enable the detection of structural issues in a building such as energy inefficiency and excessive energy consumption Among these non intrusives, the most commonly used tools are thermographic inspection methods, which allow the reconstruction of the entire thermal envelope of a building's exterior walls, roofs, windows, and doors where energy is lost or is wasted Thermal imaging not only is useful in locating a structural defect but also to check moisture penetration and the growth of mold which greatly reduces the energy efficiency of a building Thermal imaging helps to find hidden deficiencies such as insufficient insulation coverage, air infiltration, and thermal bridges, which may not be detected by visual inspection [1].In renovation projects, this is critical because it helps the owners of the buildings to know which areas would benef it from which energy saving investments. Energy auditors with thermal images can facilitate repairs and upgrades so that energy costs are reduced and the building comfort is boosted. Also because of energy audit, the thermal energy image ensures that building satisfy the necessary performance standards Along with residential and commercial properties, its application extends to industrial facilities where significant energy losses are incurred due to inefficient processes or loose-fit equipment. In which scan the building's exterior using a thermal camera and a drone during surveys to examine the interior elements as well as the exteriors. A series of thermal pictures of the monitored object obtained by specialized equipment are processed through tagging soft using temperature range changes and determining the defective zones. This techniques based on facts gives perfect diagnostic and helps in seeking specific measures to improve energy efficiency.

During inspections, thermal imaging helps building inspectors in determining areas of thermal vulnerability or points of air incursion leaks which compromise the integrity of the building envelope. Comparisons are made between the inside and outside temperature using thermal cameras and such areas are attacked where there is a loss of heating or cooling air thus wastes energy expenditures on heating or cooling up that zone. Figure 3 shows the image captured by thermal camera.

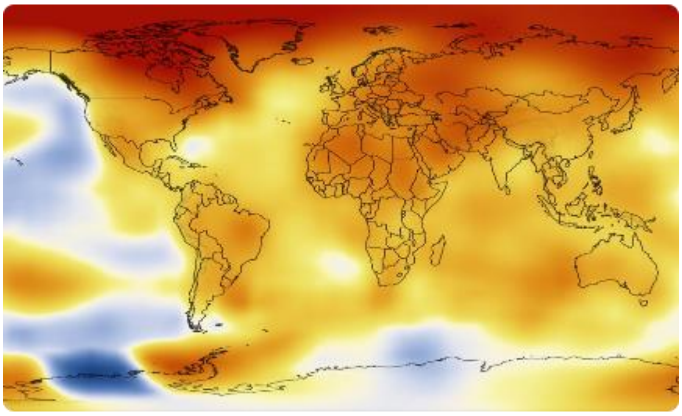


Figure 3 Image Capture by Thermal Camera

3.2 Perimeter Security

Apart from basing their attention on just external factors, facilities and borders also need perimeter security to guide against breaches by unauthorized persons and other intrusions. The thermal imaging effect has distinct advantages in opposing perimeter security threats in that it renders possible detection of a threat in difficult conditions and lighting stress. Here's the application of thermal imaging in perimeter security. Figure 4 shows the image of perimeter security.

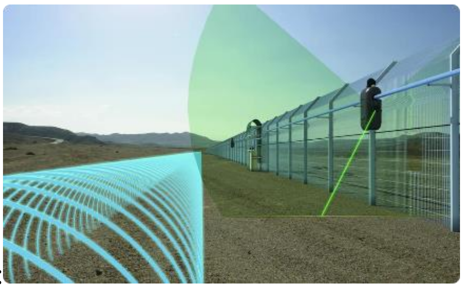
:

Figure 4 Perimeter Security

The strategic deployment of vertical and tilt thermal cameras is done along the boundary of a secured perimeter for monitoring any omissions occasioned by fence, wall or any barricades through inaccurate. Those types of cameras pick focus on the body temp of the mankind or warm things which makes it easy to distinguish people in the dark or in bad weather as well. Thermal cameras are held in a position to be able to sweep a field and so prevail upon the perimeter and barriers being monitored to continue getting intrusion detection alerts in real time. In contrast with visible light cameras, these thermal imaging cameras guarantee reliable monitoring, irrespective of the time of day and lighting conditions because irrespective to visible light cameras, the thermal imaging cameras do not rely on the light of the day. Such thermal imaging cameras allow covering and monitoring of large areas very well covering a whole perimeter with small sized deviation from the target area. And therefore this broad coverage is quite useful for the security staff, since today these borders as well as industrial sites or other important facilities can be controlled with fewer camera installations, and therefore less workforce and money are required. This also applies to the thermal imaging technology if the cause of alarm was activated by environmental conditions consisting of moving arms, flying papers, changing lighting intensity and so forth. With excessive mobility focused on warmth, thermal technologies insure minimal false alarms and actual physical penetrations alert reliably in time which constrains the actions of real threats.

Thermal imaging systems can be integrated with current security systems, including video management software, alarm systems, and access control solutions. The integration allows for easy operation, centralized monitoring, and automatic response actions based on detected intrusions, enhancing overall security effectiveness. Advanced thermal cameras equipped with high-resolution detectors and long-range lenses can detect intruders at considerable distances from the perimeter. Long-range detection skills enable security personnel to identify potential threats early, allowing for early response measures to prevent breaches and security incidents.

3.3 Low-Light Surveillance

Challenging as it may be, low-light environments are not suited for the standard visible light cameras which often offer reduced visibility and do not assure safety. [2]. Fortunately, thermal imaging is very effective in low-light surveillance as it enables reliable observation and detection of activities within such scenarios. Figure 5 shows the image captured in low light.

Figure 5 Image capture in low light

3.4 Electrical Fault & Hotspot Detection

Within building electrical systems, thermal imaging is applied to locate electrical faults such as overloaded wires, disconnections, and defective appliances. Thermal imaging features integrate electrical abnormalities through the identification of unusual temperature variations that might lead to a disaster, equipment failure, fire, etc. Thermal imagers are well adept at identifying hot spots – areas on surfaces such as electrical appliances which consist of circuits, connections, and equipment that operate at abnormal heat levels. Hot spots are areas prone to over resistance, short circuits and loose connections where high levels of heat are generated, a fire hazard and a risk to the apparatus. Figure 6 shows the identification of hotspots.

Figure 6 Hotspot

The critical overheating problems in electric circuits are detected at the earliest by thermal imaging because it heeds the temperature change even before the damage that is visible to the human eye occurs. Thermovision is used in the identification of zones with increases in temperature and hotspots on electric elements, which enable actions to be taken in time to avoid equipment failures, downtimes and safety issues.When there is a loose electrical connection, there is friction which produces heat which leads to overheating of the joint, arcing, and fire hazards due to the 'spark'. Thermal imaging works better in detecting loose connections by photo-thermally monitoring areas of increased temperature which are precursors of electrical failure and damage to equipment. Circuit overloads predispose the likelihood of a rise in the temperature of the circuit elements and risk insulation materials degrading which has susceptibility to electrical fires. Thermal imaging devices notice changes in temperatures, sometimes along the electrical conductors and other regions and structures in which currents flow and exceeds limits which have been set during the design of the system [3]. In electrical systems phase imbalance creates a situation whereby some phases carry a greater electrical load than others causing overheating, motor burnouts and equipment utilization damage. Occurrence of phase imbalance in thermal imaging is analyzed by identifying temperature difference across phases making corrective balancing measures feasible.

Also, thermal imaging is used to detect overheating and possible faults in the electrical distribution systems such as switchgear, panels, transformers and busbars. Thermal imaging is implemented on electrical equipment from a safe distance allowing visual inspection of equipment conditions without physically contacting them or taking them out of service. Data from thermal imaging is primarily used for preventive maintenance planning as such faults can be anticipated or existing problems redistributing resources for repair tasks based on the risk and damage they pose. Through thermal imaging, the maintenance department can, in turn, find the right time to carry out repairs, modifications or replacements on the equipment thus ensuring minimal downtimes and reduced chances of breakdown.

4 Industrial Maintenance and Predictive Maintenance

By ensuring industrial maintenance and predictive maintenance, it has been noted that there reliability, efficiency and safety on industrial equipment and machinery. In these maintenance activities, thermal imaging is used to locate defects in industrial equipment, monitor its condition and prevent unforeseen risks Machinery health monitoring is very important because it defines the reliability, efficiency and safety of equipment and machinery utilized in the industry. Among the techniques or tools that are used in machinery health monitoring, the most distinguished is the thermal imaging technology, focusing on the temperature, mechanical stress and operational aspects of machinery.

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Inspection of electrical equipment is important and can be performed to attain safety, efficiency, and reliability of electrical systems in industrial, commercial, and residential areas. Thermal imaging technology is rather very applicable for electrical equipment inspection aimed at observing temperature changes, faults in the electrical equipment, and in avoiding any condition that may bring about breakdowns of these handled equipment or cause some safety problems. A preventive maintenance strategy focuses on anticipating the points of machine or equipment that may fail, reducing interruption of work, and increasing the usage duration of industrial machines and electrical apparatus. Preventive thermal imaging program implementation empowers quicker preventive maintenance by introducing fast assurance of defect presence, temporal observation of faults in the system during work, and analysis of the data and a majority of factors fostering concentration of future activities at a certain maintenance point.

5 Medical Imaging and Diagnostic Applications

Thermal imaging technology has become a common tool in the monitoring and diagnosis around the medical field of interest. Despite this, it is not usually referred to as a primary imaging modality in the same bracket as X-rays, CT scans or MRIs, it is a useful addition that has distinct advantages in specialty situations. Thermal imaging utilizes the detection of temperature variation on the body surface and anatomical places as the main feature of its imaging. This may be helpful in assessing the area and the amount of inflammation or other physiological changes. These temperature patterns may assist in the diagnosis of conditions caused by infections, it can also assist in determining cognitive activity, and therefore thermal imaging uses include the diagnosis of peripheral vascular disorders, arthritis and chronic pain syndromes. It is also gaining in popularity in the diagnosis of breast cancer where tumors give an unusual vascular warming skin surface signal. In wound management thermal images help to assess the progression of the wound healing process and detect areas with blood flow insufficiency. This is critical for diabetic patients at risk of developing wounds that do not heal and ulcers. Moreover, it has a broad application in sports medicine for assessment of musculo-skeletal sprains, for the quick assessment of muscular strains in the tissues and controlling the inflammation stage and the entire healing process in sports people. Since then, fever screening with thermal imaging has been recognized as an effective method of assessing whether an individual's core body temperature is raised, as a screening tool for a variety of infectious diseases like flu, COVID-19 or many other febrile diseases [4]. Thermal imagers are employed in various scenarios to detect fever in people and carry out febrile control strategies. Fever screening and thermal imaging levers the burden of control measures with infection prevention efforts as follows:

5.1 Non-contact Temperature Measurement and Rapid Screening of Large Groups

By using thermal weapons sights, it is possible to take temperature measurements without contact. This means that the threat of cross-contamination is minimized and there is no need to crowd over the persons being screened. This type of intervention is most useful in crowded places like airports, clinics, offices or when there are public functions. Thermal imaging offers an efficient means of screening several people simultaneously to ascertain the department of public health's interventions within the turbid regions. At airports or any other location where there are large populations, measuring temperatures with thermal camera systems helps to identify fever early within a population to enable early isolation of infected individuals

5.2 Early Detection of Fever and Integration with Access Control Systems:

Usually, the thermal imaging systems are used for purposes of fever screening even when the patients do not cough or sneeze. Those areas of the body that are imaged and have elevated temperature could be masked for further evaluation and isolation of suspected illness to help tackle infectious diseases. Thermal imaging systems can be integrated with access control systems to automate fever screening processes and restrict entry to individuals with elevated temperatures. Integrated solutions utilize thermal cameras to scan individuals' temperatures at entry points, triggering alarms or access denial for individuals with fever, thereby enhancing infection control measures.

5.3 Enhanced Situational Awareness and Monitoring of Quarantine and Isolation Facilities:

Thermal imaging helps in increasing people's knowledge concerning the situation by detecting people based on the heat they emit and the differences in their temperatures in real-time. Thermal image camera technology detects changes in temperature, which enables the screeners to scan the audience, look for feverish people, and carry out the necessary measures to avoid further spread of the disease. Thermal scanning is also carried out in self-isolation or quarantine detection centers to assess compliance with fever surveillance principles and to identify the development of general and specific infectious diseases at an early stage. Use of thermal monitors in the quarantine areas makes it easier for medical personnel to keep track of patients' temperature changes and administer aid as soon as an increase in body temperature is detected.

5.4 Disease Diagnosis and Monitoring

Thermal imaging systems have potentials in diagnosing and monitoring the progression of disease processes in various specialties of medicine [5]. Even though it is not possible to use thermography alone for the diagnosis of every condition, it is still, however, a great asset and an adjunct to usual diagnostic tools and aids in tracking changes in the pathology of some diseases

6 Agricultural Applications

There are various applications of thermal imaging technology in agriculture to include crop stress identification, management of resources such as irrigation, disease, and pest management, and environmental assessments. Since thermal imaging detects different temperatures along various parts of the field, it allows for real time assessment of the crops to locate regions that are under water deficiency, or have diseases or lack vital minerals. This makes it possible to apply measures such as enhanced irrigation or fertilizer application so that resources are not wasted. It also makes possible the efficient application of irrigation by indicating areas that require excessive irrigation, or areas with drought such that water application is effective, especially in areas where water shortage is a problem. One more important application is the monitoring of cropland to look for pests since thermal imaging can show pest infestations even before they lead to large scale crop damage. This kind of detection enables farmers to take measures in good time which inhibits the spread of most pests. This also means that broad-spectrum pesticides are not so much needed thus making the agricultural practices greener. Besides looking after the crops, thermal imaging is also applied for soil evaluation in order to locate fields that are too moist or trapped in poor drainage that can be a hindrance to the crop yields.

Thermal imaging technology enhances the surveillance and management of crops, which assists farmers in diagnosing the health of crops, identifying particular stress factors, and increasing the yield of crops. Capturing thermal data with thermal imaging helps farmers determine the need for irrigation, pest control to sustain crop production among other factors. For livestock animals, thermal imaging technology provides a wide range of capabilities for health and welfare assessment which provides producers and veterinarian with advanced non-invasive options for screening health, stress, and management problems [6].

7 Research and Development

Thermal imaging technology plays a crucial role in research and development across various fields, providing scientists, engineers, and innovators with powerful tools for data acquisition, analysis, and experimentation. Thermal imaging is of great importance in the various stages of R&D in most, if not all, fields providing scientists, engineers and other innovators useful instruments for collecting, analysing, and disseminating information. Figure 7 shows the rays at different wavelength and frequencies. The use of thermal imagining technology is common in ecological monitoring activities as it helps determine the changes in temperature, the behaviour of the ecosystem, and other environmental phenomena.

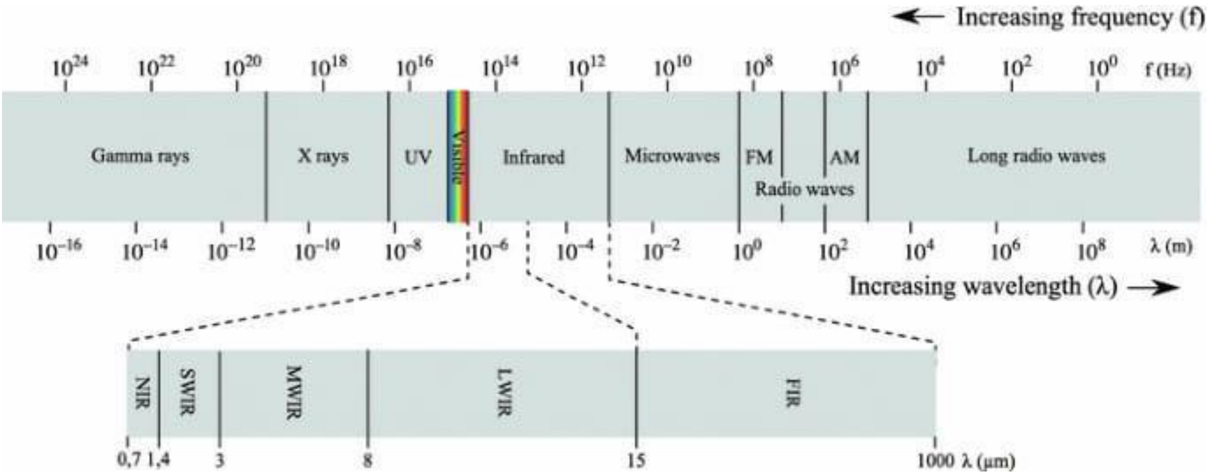

Figure 7- Rays at different frequency and wavelength

8 Future Trends and Emerging Applications

Thermal imaging technology is being augmented and ushering in new solutions and opportunities in various industries and fields. A few of the upcoming trends include future of thermal imaging and its potential new employments. It is made possible to carry out advanced image processing, automated surveillance of images for the presence of defects, and implementation of prognostic maintenance through the fusion of thermal imaging and artificial intelligence (AI) and machine learning methods. AI systems of thermal imaging are capable of studying thermal data, detecting possible hazards, and making rapid assessments that can aid decision-making for manufacturing, infrastructure surveillance and healthcare. The evolution of miniaturization and sensor technology leads to the creation of small, compact and light weight thermal imaging units which can be worn on the body. Thermal cameras which are worn on the body have the advantages of being used while on the move, hands free and worn on areas that can be monitored in real time using the thermal camera for applications in personal protection, leisure and medical purposes, hence creating new markets. Thermal cameras in multispectral and hyperspectral imaging extend the types and numbers of camera especially the thermal cameras making the materials to be more predictive and capable of chemical and environmental assessment. The application of multispectral and hyperspectral thermal imaging is also seen in agriculture, food safety and industrial inspection, where imaging objects that need to be analysed from a spectroscopic approach in terms of safe block and product determination.

Photon-counting detectors and quantum sensors improve the sensitivity, resolution, and speed of thermal imaging systems, allowing for effective imaging in dim environments as well as fast- imaging scenarios. Thermal cameras with photon count enumeration techniques are also beneficial in improving the images quality, enhancing the images colour and contrast levels and reducing the noise in the images for scientific, astronomy as well as defence applications, thereby extending the capabilities of thermal imaging. Thermography combined with consumers AR and MR platforms makes it possible not only to visualize the internal structures of products but also to overlay spatial context and enhance the understanding of a certain situation. Applications of AR/MR-enhanced thermal imaging systems unleash the possibilities for the development of user-friendly interfaces, data visualization, and the possibility of real-time annotations for the needs of industrial maintenance, construction, or emergency situations. The innovation of 3D thermal imaging and depth-sensing technology facilitates the acquisition of spatially resolved thermal data, making volumes contours, depth profiles, and 3D diagrams of thermal imaging possible. 3D imaging and sensing of heat have uses in robots, self-driving cars, and combinations of the real world with computerized graphics where there is a need to perceive depth as well as the location of objects with the ability to interact with them. Climate changes and any other variations require the judicial approach, for which thermal imaging and its networks can be employed. In particular, thermal imaging systems enable the monitoring of the temperature changes, the transformation of the land cover, and the state of the ecosystems on the local and global levels.

9 Conclusion

Thermal imaging technologies have affected our perception, analysis and behaviour with respect to the environment. Originally created as military instrument, later on thermal imaging has been steadily incorporating into various industries demonstrating its wide application fields, effectiveness and further development opportunity. During this journey, we have explored the vast number of different layers of thermal imaging and the ways it can enrich us. Enhancing surveillance and security capabilities, modern agricultural techniques, monitoring more biological environments that are wildlife, diagnosing more medical conditions with thermal imaging, the world continues to change perennially towards better. In addition, we typically go even further and have researched new trends and applications into which thermal imaging is expanding. As devices undergo artificial intelligence integration, shrink in size, and multi and hyperspectral imaging becomes a growing trend, there are other thermal technology solutions expected to emerge and reach new heights. Looking ahead, there is no doubt that thermal imaging will become a key weapon in the fight against many global challenges, including climate change, environmental and social problems, and health issues. This technology allows for the revelation of insights that would otherwise be inaccessible, for the promotion of creativity and the improvement of the world.

10 Declarations

10.1 Competing Interests

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

10.2 Publisher's Note

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