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THERMAL IMAGING PROCESS AND ITS APPLICATIONS: A SURVEY

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ABSTRACT

Thermal camera was originally developed as a surveillance and night vision tool for the military, but recently the price has dropped, significantly opening up a broader field of applications. These types of cameras are passive sensors that capture the infrared radiation emitted by all objects with a temperature above absolute zero. Deploying this type of sensor in vision systems eliminates the illumination problems of normal greyscale and RGB cameras. In this paper provides an overview of the current applications of thermal camera as include animals, agriculture, buildings, gas detection, industrial, and military applications. Moreover, it also use of detection, tracking, medical imaging and recognition of humans.

Keywords: Thermal camera, Infrared radiation, Thermal Imaging, Computer Vision

I. INTRODUCTION

Thermal imaging systems have been rapidly growing during the last couple of decades, research and development in automatic vision systems. The Visual cameras, capturing visible light in greyscale or RGB images but some disadvantages to use these cameras as the colours and visibility of the objects depend on an energy source, such as the sun or artificial lighting. The main challenges are therefore that the images depend on the illumination, with changing intensity, colour balance, direction, etc. and nothing can be captured in total darkness. To overcome some of these limitations and add further information to the image of the scene, other sensors have been introduced in vision systems. These sensors include 3D sensors [1, 2, and 3] and near infrared sensors [4]. Some of the devices are active scanners that emit radiation, and detect the reflection of the radiation from an object. As the use of active infrared cameras, which illuminate the scene with near infrared and capture the radiation of both the visible and the near infrared electromagnetic spectrum. These types of active sensors are less dependent on the illumination and the stereo vision cameras are passive 3D sensors, but as they consist of visual cameras, they also depend on the illumination.

The described sensors indicate that some of the disadvantages of visual cameras can be eliminated by using active sensoring. However, in many applications, a passive sensor is preferred. In the mid- and long- wavelength infrared spectrum, radiation is emitted by the objects themselves, with a dominating wavelength and intensity depending on the temperature. Thereby they do not depend on any external energy source. Thermal cameras utilize this property and measure the radiation in parts of this spectrum. Figure 1 shows an example of the same scene captured with both a visual and a thermal camera.

The thermal image is shown as a greyscale image, with bright pixels for hot objects.T he humans are much easier to distinguish in the thermal image, while the colours and inanimate objects, like chairs and tables, are invisible.

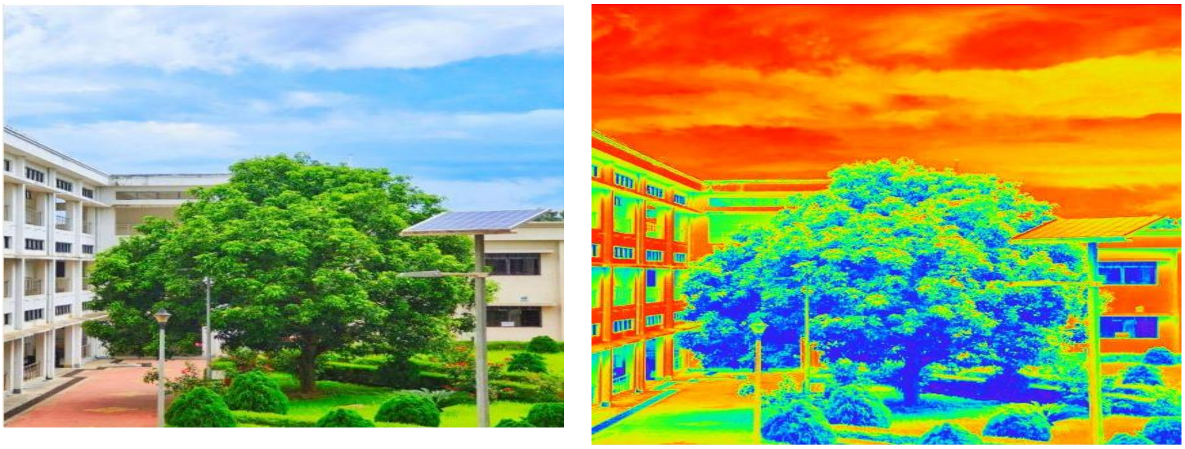

Fig. 1: Visible and thermal image of the same scene.

A special detector technology is required to capture thermal infrared radiation. Originally it was developed for night vision purposes for the military, and the devices were very expensive. The technology was later commercialized and has developed quickly over the last few decades, resulting in both better and cheaper cameras. This has opened a broader market, and the technology is now being introduced to a wide range of different applications, such as building inspection, gas detection, industrial appliances, medical science, veterinary medicine, agriculture, fire detection, and surveillance. This wide span of applications in many different scientific fields makes it hard to get an overview. This paper aims at providing exactly such an overview and in addition provides an overview of the physics behind the technology.

II. THERMAL RADIATION

Infrared radiation is emitted by all objects with a temperature above absolute zero. This is often referred to as thermal radiation. This section will go through the source and characteristics of this type of radiation.

II. A. ELECTROMAGNETIC SPECTRUM

Infrared radiation lies between visible light and microwaves within the wavelength spectrum of 0.7-1000μm as illustrated in Figure 2. The infrared spectrum can be divided into several spectral regions. There exist different sub-division schemes in different scientific fields, but a common scheme is shown in Table 1 [5]. The mid-wavelength and long-wavelength infrared are often referred to as thermal infrared (TIR) since objects in the temperature range from approximately 190 K to 1000 K emit radiation in this spectral range.

Division Name	Abbreviation	Wavelength
Near-infrared	NIR	0.7- 1.4 μm
Short-wavelength infrared	SWIR	1.4-3 μm
Mid-wavelength infrared	MWIR	3-8 μm
Long-wavelength infrared	LWIR	8-15 μm
Far-infrared	FIR	15-1000 μm

Table 1: Infrared sub-division.

The atmosphere only transmits radiation with certain wavelengths, due to the absorption of other wave-lengths in the molecules of the atmosphere. CO2 and H2O are responsible for most of the absorption of infrared radiation [6]. Figure 3 illustrates the percent- age of transmitted radiation depending on the wave- length, and states the molecule that is responsible for the large transmission gaps.

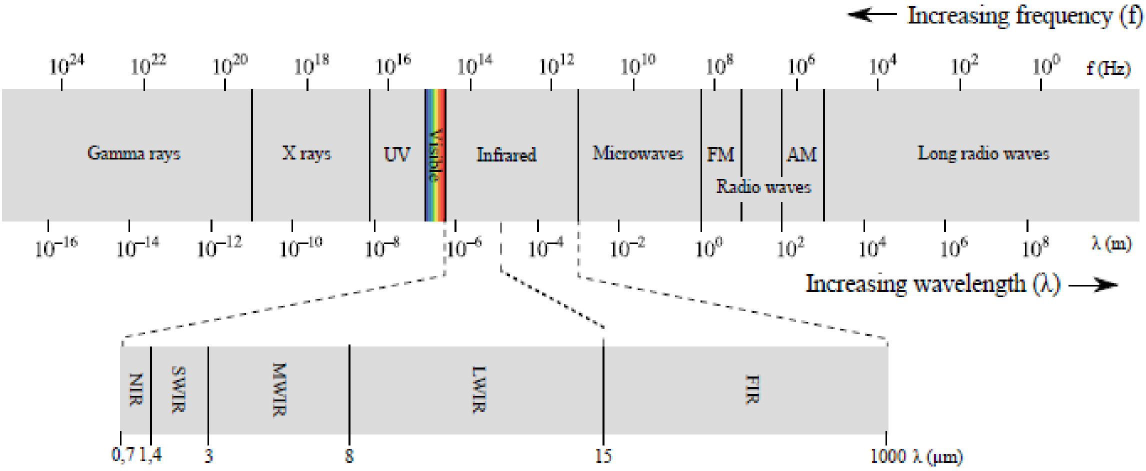

Fig. 2: The electromagnetic spectrum with sub-divided infrared spectrum.

Due to the large atmospheric transmission gap between 5-8 µm, there is no reason for cameras to be sensitive in this band. The same goes for radiation above 14 µm. A typical spectral range division for near-infrared and thermal cameras is shown in Table 2.

Short-wavelength infrared	SWIR	0.7-1.4 µm
Mid-wavelength infrared	MWIR	3-5 µm
Long-wavelength infrared	LWIR	8-14 µm

Table 2 Infrared sub-division for cameras.

II. B. EMISSION AND ABSORPTION OF INFRARED RADIATION

The radiation caused by the temperature T of an object is described by Planck's wavelength distribution function [7]:

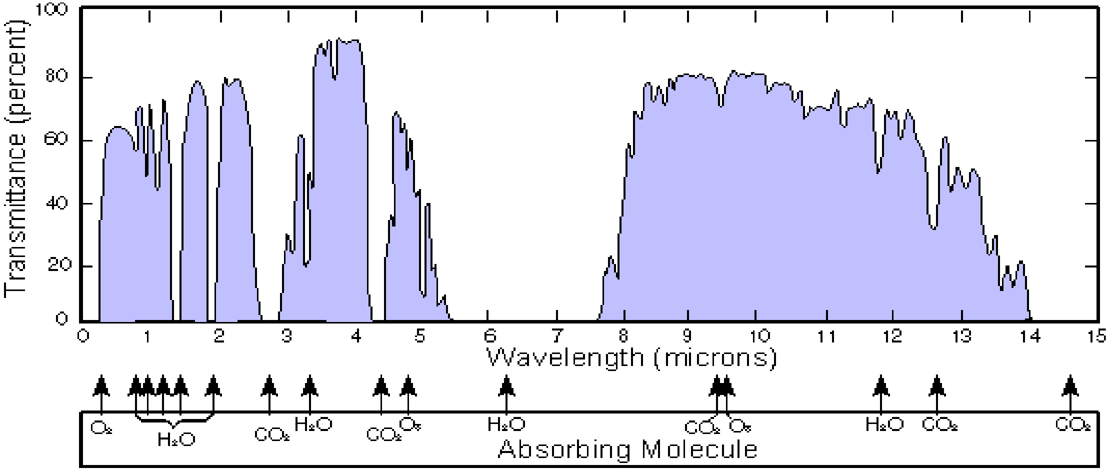

Fig. 3 : Atmospheric transmittance in part of the infrared region [7].

$$I(\lambda, T) = \frac{2\pi hc^2}{\lambda^5 \left(e^{hc/\lambda k_B T} - 1\right)}, \qquad (1)$$

where λ is the wavelength, *h* is Planck's constant (6:626 X 10^{34} *Js*), c the speed of light (299; 792; 458m/s) and k_B Boltzmann's constant (1:3806503 X 10^{-23} *J/K*).

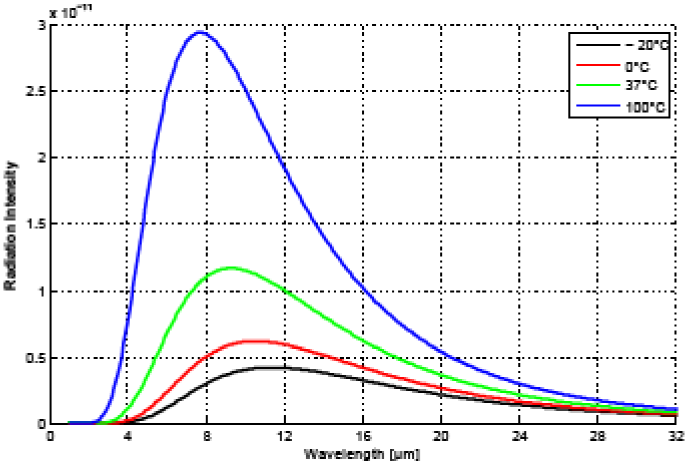

Fig. 4: Intensity of black body radiation versus wavelength at four temperatures.

In figure 4, the intensity peak shifts to shorter wavelengths as the temperature increases, and the intensity increases with the temperature. For extremely hot objects the radiation extends into the visible spectrum, e.g., as seen for a red-hot iron. The wavelength of the intensity peak is described by Wien's displacement law [8]:

$$\lambda_{max} = \frac{2.898 \times 10^{-3}}{T}. \qquad (2)$$

Planck's wavelength distribution function, Equation 1, describes the radiation from a black body. Most materials studied in practical applications are assumed to be so called grey bodies, which have a constant scale factor of the radiation between 0 and 1. This factor is called the emissivity. For instance, polished silver has a very low emissivity (0.02) while human skin has an emissivity very close to 1 [9]. Other materials, such as gases, are selective emitters, which have specific absorption and emission bands in the thermal infrared spectrum [6]. The specific absorption and emission bands are due to the nature of the radiation, as described in the next section.

II.C. ENERGY STATES OF A MOLECULE

The energy of a molecule can be expressed as a sum of four contributions [8]: electronic energy, due to the interactions between the molecule's electrons and nuclei; translational energy, due to the motion of the molecule's centre of mass through space; rotational energy, due to the rotation of the molecule about its centre of mass; and vibrational energy, due to the vibration of the molecule's constituent atoms:

$$E = E_{el} + E_{vib} + E_{rot} + E_{trans....}: \qquad (3)$$

The translational, rotational, and vibrational energies contribute to the temperature of an object. The possible energies of a molecule are quantized, and a molecule can only exist in certain discrete energy levels. Figure 5 illustrates the relation between the electronic, vibrational, and rotational energy levels. The contribution from the translational energy is very small and is not included in this illustration.

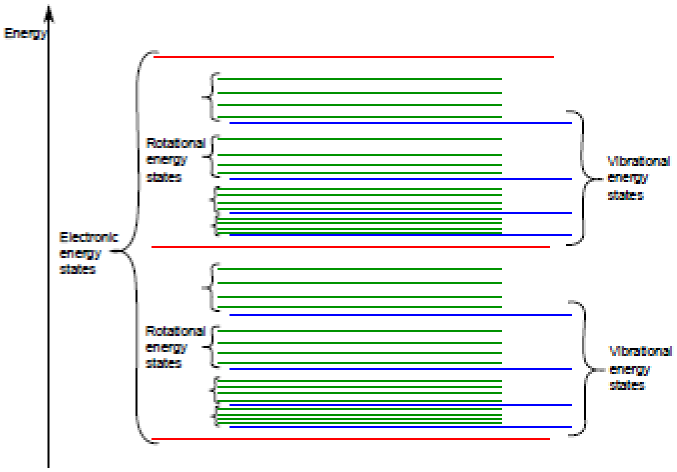

Fig. 5: Simplified illustration of the electronic, vibrational, and rotational energy states. Each line illustrates a discrete energy level that the molecule can exist in.

III. THERMAL CAMERAS

Thermal Cameras Although infrared light was discovered by William Herschel around 1800, the first infrared scanning devices and imaging instruments were not build before the late 1940s and 1950s [10]. They were built for the American military for the purpose of night vision. The first commercial products were produced in 1983 and opened up a large area of new applications. The measurement instruments available today can be divided into three types: point sensors, line scanners, and cameras.

III. A. CAMERA TYPES

Infrared cameras can be made either as scanning devices, capturing only one point or one row of an image at a time, or using a staring array, as a two-dimensional infrared focal plane array (IRFPA) where all image elements are captured at the same time with each detector element in the array. Today IRFPA is the clearly dominant technology, as it has no moving parts, is faster, and has better spatial resolution than scanning devices [10]. Only this technology is described in the following. The detectors used in thermal cameras are generally of two types: photon detectors or thermal detectors. Photon detectors convert the absorbed electro-magnetic radiation directly into a change of the electronic energy distribution in a semiconductor by the change of the free charge carrier concentration.

Thermal detectors convert the absorbed electromagnetic radiation into thermal energy causing a rise in the detector temperature. Then the electrical output of the thermal sensor is produced by a corresponding change in some physical property of material, e.g., the temperature dependent electrical resistance in a bolometer [6]. The photon detector typically works in the MWIR band where the thermal contrast is high, making it very sensitive to small differences in the scene temperature. Also with the current technology the photon detector allows for a higher frame rate than thermal detectors. The main drawback of this type of detector is its need for cooling. The photon detector needs to be cooled to a temperature below 77 K in order to reduce thermal noise. This cooling used to be done with liquid nitrogen, but now is often implemented with a cryocooler. There is a need for service and replacement for the cryocooler due to its moving parts and helium gas seals. The overall price for a photon detector system is therefore higher than a thermal detector system, both its initial costs and its maintenance. A thermal detector measures radiation in the LWIR band and can use different detector types, which will be described in the next section.

III. B. THERMAL DETECTOR TYPES

Uncooled thermal detectors have been developed mainly with two different types of detectors: ferroelectric detectors and micro-bolometer. Ferroelectric detectors take advantages of the ferroelectric phase transition in certain dielectric materials. At and near this phase transition, small fluctuations in temperature cause large changes in electrical polarization [11]. Barium Strontium Titanate (BST) is normally used as the detector material in the ferroelectric detectors.

A micro-bolometer is a specific type of resistor. The materials most often used in micro-bolometers are Vanadium Oxide (VOx) and Amorphous silicon (a-Si). The infrared radiation changes the electrical resistance of the material, which can be converted to electrical signals and processed into an image. Today it is clear that micro-bolometer have more advantages over the ferroelectric sensors and the VOx technology has gained the largest market share. First of all, micro-bolometers have a higher sensitivity. The noise equivalent temperature difference (NETD), specifying the minimum detectable temperature difference, is 0.039 K for VOx compared to 0.1 K for BST detectors [11]. Micro-bolometers also have a smaller pixel size on the detector, allowing a higher spatial resolution. Furthermore, BST detectors suffer from a halo effect, which can often be seen as a dark ring around a bright object, falsely indicating a lower temperature [11]. An example of the halo effect is shown in Figure 6.

Fig. 6: Thermal image showing bright halo around a dark person [12].

III. C. THE LENS

Since glass has a very low transmittance percentage for thermal radiation, a different material must be used for the lenses. Germanium is used most often. This is a grey-white metalloid material which is nearly transparent to infrared light and reflective to visible light. Germanium has a relatively high price, making the size of the lens important. The f-number of an optical system is the ratio of the lens's focal length to the diameter of the entrance pupil. This indicates that a higher f-number reduces the price of the lens, but at the same time, when the diameter of the lens is reduced, a smaller amount of radiation reaches the detector. In order to maintain an acceptable sensitivity, uncooled cameras must have a low f-number. For cooled cameras, a higher f-number can be accepted, because the exposure time can be increased in order to keep the same radiation throughput. These properties of the lens cause the price for uncooled cameras to increase significantly with the focal length, while the price for cooled cameras only increases slightly with the focal length. For very large focal lengths, cooled cameras will become cheaper than uncooled cameras [13].

III. D. CAMERA OUTPUT

Modern thermal cameras appear just like visual video cameras in terms of shape and size. Figure 7 shows an example of a thermal network camera.

Fig. 7: Example of an uncooled thermal camera, AXIS Q1921.

The data transmission typically takes place via USB, Ethernet, FireWire, or RS-232. The images are represented as grey-scale images with a depth from 8 to 16 bit per pixel. They are, however, often visualized in pseudo colours for better visibility for humans. Images can be compressed with standard JPEG and video can be compressed with H264 or MPEG [14]. Analogue devices use the NTSC or PAL standards [15]. Some handheld cameras are battery-driven, while most of the larger cameras need an external power supply or Power over Ethernet. The thermal sensitivity is down to 40 mK for uncooled cameras and 20 mK for cooled devices. The spatial resolution of commercial products varies from 160 x 120 pixels to 1280 x 1024 pixels, and the field of view varies from 1^0 to 58^0 [73,52,7, 50].

IV. APPLICATION AREAS

The ability to `see' the temperature in a scene can be a great advantage in many applications. The temperature can be important to detect specific objects, or it can provide information about, e.g., type, health, or material of the object. This section will survey the applications of thermal imaging systems with three different categories of subjects: animals and agriculture, inanimate objects, and humans.

IV.A. ANIMALS AND AGRICULTURE

IV.A.A. ANIMALS

Warm-blooded animals, such as humans, try to maintain a constant body temperature, while cold-blooded animals adapt their temperature to their surroundings. This property of warm-blooded animals makes them stand out from their surroundings in thermal images. Warm-blooded animals can warm their body by converting food to energy.

To cool down, they can sweat or pant to lose heat by water evaporation. The radiation of heat from animals depends on their insulation, such as hair, fur, or feathers, for example. The temperature distribution over the body surface can be uneven, depending on blood-circulation and respiration. In the studies of wild animals thermal imaging can be useful for diagnosis of diseases and thermoregulation, control of reproductive processes, analysis of behaviour, as well as detection and estimation of population size [16].

Diseases will often affect the general body temperature, while injuries will be visible at specific spots, e.g., caused by inflammations. Thermal imaging has thereby been proven to work as a diagnosis tool for some diseases of animals. In [17] it was observed that the temperature in the gluteal region of dairy cattle increases when the animal becomes ill and this could be detected in thermal images prior to clinical detection of the disease. If the observed animals are wild, the method of examining for a disease should be without contact with the animals. In [18] thermal cameras are used for detecting sarcoptic mange in Spanish ibex. Although conventional binoculars have higher sensitivity over a greater distance, thermal cameras can give indication of the prevalence of the disease in a herd.

Thermal imaging could also be used to detect diseases among other wild animals, in [19] it is found that rabies can be detected in raccoons by observing the temperature of the nose.

IV.A.B. AGRICULTURE AND FOOD

Thermal imaging systems have various applications in the agriculture and food industry. They are suitable in the food industry due to their portability, real time imaging, and non-invasive and non-contact temperature measurement capability [20]. In food quality measurement, it is important to use a non-destructive method to avoid waste. The two papers [21] and [22] review the use of thermal imaging in the agriculture and food industry, including both passive thermography (measuring the temperature of the scene) and active thermography (adding thermal energy to an object, and then measuring the temperature).

IV.B. INANIMATE OBJECTS

Inanimate objects do not maintain a constant temperature. Their temperature depends on both the surrounding temperature, and the amount of added energy that generates heat. Thermal images of inanimate objects depict the surface temperature of the scene. But even in a scene in equilibrium, differences in the image can be observed due to different emissivities of the observed surfaces. Thus thermal imaging can be used for analyzing both temperature and material.

IV.B.A. BUILDING INSPECTION

Thermal cameras have been used for years for inspecting heat loss from buildings, and special hand-held imaging devices have been developed with this application in mind. Figure 8 shows an example of a thermal image of a building.

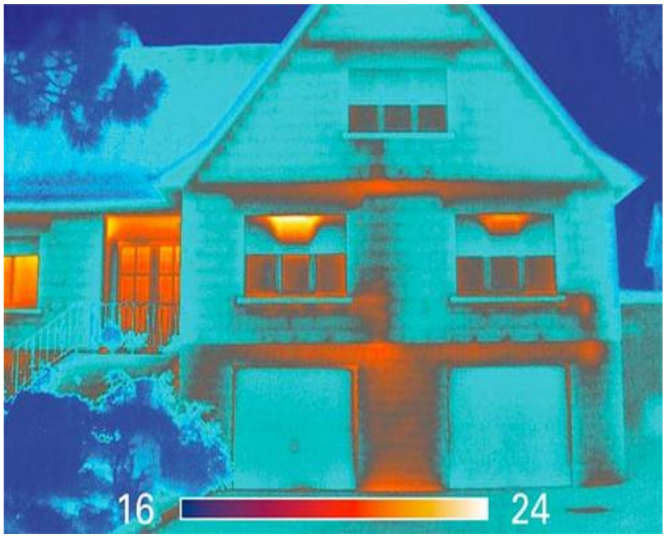

Fig. 8: Thermal image of a building, showing a higher amount of heat loss around windows and doors [23].

Normally the inspection of buildings requires manual operation of the camera and interpretation of the images to detect heat loss, e.g., as described in [24]. More automatic methods are also being investigated. In [25], an Unmanned Aerial Vehicle (UAV) is used for inspection of buildings, and the system automatically detects the heat loss from windows. Another system has been proposed, which automatically maps the images to a 3D model, eliminates windows and doors, and detects regions with high heat loss on the facade [26, 27,28]. A thermal system has also been proposed for detecting roof leakage [29]. Besides the detection of heat loss, thermal imaging has also been used to detect other problems behind the surface: [30] proves that thermal imaging can be used to detect debonded ceramic tiles on a building finish. Termites can also be found by inspection with a thermal camera, as they produce unusual heat behind the surface in buildings [31].

IV.B.B. GAS DETECTION

Gasses are selective emitters, which have specific absorption and emission bands in the infrared spectrum, depending on their molecular composition. By using instruments able to measure selectable narrow infrared bands, it is possible to measure the radiation in the absorption band of a specific gas. As the radiation is absorbed by the gas, the observed area would appear as a cool cloud (usually dark) if the gas is present.

IV.B.C. INDUSTRIAL APPLICATIONS

In most electrical systems, a stable temperature over time is important in order to avoid system break-downs. Sudden hot spots can indicate faulty areas and connections, e.g., in electric circuits and heating systems.

Thermal imaging can be applied as a diagnosis tool for electrical joints in power transmission systems [32], and for automatic detection of the thermal conditions of other electrical installations [33]. It can also be used to evaluate specific properties in different materials. Therefore [34] proposes a system that compares the thermal images to a simulated thermal pattern in order to find a diagnosis for the object. For more complicated objects, a 3D model is generated. In [35] uses thermal imaging for measuring the molten steel level in continuous casting tundish.

IV.B.D. FIRE DETECTION AND MILITARY

Automatic systems for detecting objects or situations that could pose a risk can be of great value in many applications. A fire detection system can be used for mobile robots. In [36] proposes a system using a pan-tilt camera that can operate in two modes, either narrow field of view or wide field of view using a conic mirror. Fires are detected as hot spots, and the location is detected in order to move the robot to the source of fire. In [37] proposes a hybrid system for forest fire detection composed of both thermal and visual cameras, and meteorological and geographical information, while [38] proposes a handheld thermal imaging system for airborne fire analysis.

In [39] present a gunfire detection and localization system for military applications. Gunfire is detected in mid-wave infrared images and validated by acoustic events. The detected gunfire is mapped to a real-world location. In [40] proposes using thermal imaging for mine detection. Depending on circumstances such as the ambient air temperature and soil moisture, mines can be detected using the assumption that the soil directly above the mine heats or cools at a slightly different rate than the surrounding soil. In [41] uses the same idea in their system. They spray cold water over the surrounding soil, and capture the temperature distribution of the cooling soil with a thermal camera. In [42] presents the idea of using thermal imaging for detecting snipers. The muzzle ash, the bullet in light, and the sniper body can be detected.

IV.B.E. DETECTION AND TRACKING OF HUMANS

Detection of humans is the first step in many surveillance applications. General purpose systems should be robust and independent of the environment. The thermal cameras are here often a better choice than a normal visual camera. In [43] proposes a system for human detection, based on the extraction of the head region and [44] proposes a detection system that uses background subtraction, gradient information, watershed algorithm and A* search in order to robustly extract the silhouettes. Similar approaches are presented in [45, 46], using Contour Saliency Maps and adaptive filters, while [47] presents a detection method based on the Shape Context Descriptor and Adaboost cascade classifier. A common detection problem is that the surroundings during summer are hotter than or equal to the human temperature. In [48] tries to overcome this problem by using Mahalanobis distance between pixel values and edge orientation histograms. In [49,50] use automatic thresholding and a sorting and splitting of blobs in order to detect and count people in sports arenas, shows in Figure 9.

Fig. 9: Example of humans playing handball. Top image: Original thermal image. Bottom image: Binarised image with all persons marked with a red dot. [49]

Thermal cameras are very useful for the surveillance and detection of intruders, because of their ability to `see' during the night. For trespasser detection, classification is often based on temperature and simple shape cues. The other work aims to identify humans using pattern recognition to detect the human head [51]. In [52] uses thresholding, and then a validation of each blob, to determine if it contains one or more persons. In [53] proposes a real time detection and tracking system with a classification step based on a cascade of boosted classifiers. Thermal sensors can be used in systems for the detection of fall accidents or unusual inactivity, which is an important safety tool for the independent living of especially elderly people. [54] proposes a system that uses a low resolution thermal sensor. The system gives an alarm in case of a fall detected or in the case of inactivity over a long time period. In [55] a fall detection system for bathrooms is proposed, using a thermal sensor mounted above the toilet. Analysis of more general human activity has also been performed. In [56] presents a system that distinguishes between walk and run using spatio-temporal information, while [57] estimates the gait parameters by fitting a 3D kinematic model to the 2D silhouette extracted from the thermal images. In [58] different sports types are classified by the detected location of people over time. [59] proposes a system for analyzing the posture of people in crowds, in order to detect people lying down. Thermal cameras are very popular in the research of pedestrian detection, due to the cameras' independence of lighting changes, which means that it will also work during the night, when most accidents between cars and pedestrians happen. One of the car-based detection systems is proposed in [60], where they present a tracking system for pedestrians. It works well with both still and moving vehicles, but some problems still remain when a pedestrian enters the scene running.

IV.B.F. FACIAL ANALYSIS

Face detection is the first step in many applications, including face recognition, head pose analysis, or even some full person detection systems. Since the face is normally not covered by clothes, a thermal camera can capture the direct skin temperature of the face. In [61] and [62] propose head detection systems based on a combination of temperature and shape. Face recognition using thermal cameras eliminates the effects of illumination changes and eases the segmentation step, but it can also introduce some challenges due to the different heat patterns of a subject, caused by different activity levels or emotions such as anxiety. One of the very early approaches is neural networks [63]. In [64, 65] compare the use of thermal images in face recognition to visual images using appearance based methods. The thermal images yield better results than visual images here. The recognition of common facial expressions is another task of great interest. Neural networks have also been used as an early approach here [66].

IV.C. MEDICAL ANALYSIS

The details regarding physiological processes using skin temperature distributions is provided by thermal imaging systems. These distributions can be due to blood perfusion. High resolution cameras are used to observe minute variations in temperature in the medical field. The information of standard anatomical investigation is further enhanced by thermal imaging [67]. The medical applications of IR thermography are reviewed in Lahiri et al. [68] and Ring and Ammer [69]. This technique enables the detection of malignant tumors at a very early stage as described in [70]. Many other medical conditions can be studied from thermal imaging, e.g. the behavior of the ciliary muscle of eye [71], superficial temporal artery pulse [72], and facial vasculature [73]. Tissue related risks for diabetic patients [74] and sports persons can also be detected by thermal imaging. Thermal imaging can be used to invigilate and understand communication from people with motor impairment.

V. IMAGE FUSION

Visual cameras and thermal cameras have both advantages and disadvantages in computer vision applications. Since the limitations of the different technologies are independent, and often do not occur simultaneously, it can be beneficial to combine these different types of images.

The most common combination of cameras is thermal and visual. This is due to the low price and well-known characteristics of visual cameras and the ensuing advantages of augmenting colour with temperature.

The main challenges are how to align and fuse the different image modalities. There is not necessarily any relation between brightness level in the different spectra, thus many mutual information alignment methods are not appropriate [75]. Automatic alignment techniques that rely on the correlation between edge orientations are presented in [76, 77], and a method that calculates the homography from automatically detected key points is presented in [78]. Fusion can take place at different levels of the processing, often described as pixel level, feature level, or decision level [79]. In pixel level fusion, the images need to be spatially registered, as discussed above, so that the same pixel positions of all images correspond to the same location in the real world. The images are then combined pixel-by-pixel using a fusion algorithm.

Methods for fusing visible and infrared videos are discussed in [80] and [81], where the two images are aligned and combined using an overlay image with the heat information. In [75] two fusion methods are compared, one named a general fusion model (pixel level) and the other method named a combination module (feature level). The combination module has the best performance tested over six sequences. In [82] proposes a combination of curvelet and wavelet transforms, as well as a discrete wavelet packet transform approach for fusing visual and thermal images.

Face detection and face recognition have been thoroughly investigated and standard methods exist using visual cameras. However, illumination changes still have a negative impact on the performance of these systems [83]. Research has been conducted on whether these problems could be overcome by extending the systems with a thermal sensor. In [84] shows a significant improvement by fusing the visible and thermal images in a time-lapse experiment. Work has been done on face recognition using pixel-level fusion [85, 86, 87], feature-level fusion [88], and decision-level fusion [89, 90, 91]. In [92] proposes fusion on both pixel and decision-level, while [93] tests two different fusion schemes. They all report an improved performance when fusing the different image modalities.

VI. DISCUSSION & CONCLUSION

Although the price of thermal cameras is still significantly higher than the price of comparable visual cameras, the hardware cost is continuously falling and the diversity of cameras is becoming wider. Simple sensors, such as the cheap pyroelectric infrared (PIR) sensor, have for many years been applied as motion detectors for light switch control, burglar alarm, etc. Although no image can be provided by this type of sensor, it can be sufficient for detecting a moving human or large animal. Moving towards thermal cameras, infrared array sensors can read temperature values in a coarse image. These sensors make it possible to analyze the movement, e.g. direction and speed, and can be used for instance in entrance counting systems.

The wide range of cameras opens up for a great diversity of applications of thermal cameras. Each research field has specific needs for, e.g., resolution, field of view, thermal sensitivity, price, or size of the camera. It is therefore expected that the diversity of cameras available will become even larger within the next few years, not only focusing on high-end cameras.

Thermal imaging has found use in two different types of problems: the analysis of known subjects and the detection of unknown subjects. In the first problem, both the subjects and their location in the image are known, and the properties of the subjects can be analyzed. The results could be the type of material, condition, or health. The methods used here are often simply the registration of the temperature or even a manual inspection of the images. If computer vision methods are used, often they are just simple algorithms, such as thresholding and blob detection. For the second problem, either the type of objects or their locations in the image are unknown. The most important step in this type of problem is normally the detection and classification of objects.

The goal here is more often to design an automatic system, e.g., for the detection or tracking of specific objects. More advanced computer vision algorithms can be applied here in order to design a robust and automatic system.

Methods for both analysis of known subjects and detection of unknown subjects are rapidly expanding due to the lower prices and greater availability of thermal cameras. In the case with known subjects, thermal cameras could be viewed as an alternative to a non-contact thermometer. In the last case, the thermal camera is seen more as an alternative to a visual camera, and therefore currently of greater interest from a computer vision point of view. However, the general trend in modern society is the implementation of automation.

The usual disadvantages of changing illumination and the need for active lighting in dark conditions are eliminated with the thermal sensor. Moreover, in the case of surveillance, the use of thermal imaging does not raise as many privacy concerns as the use of visual imaging does. However, new challenges often appear with a new type of sensor. For thermal imaging the lack of texture information can be a disadvantage in some systems, and reflections of the thermal radiation can be a problem in surfaces with high reflectance.

In order to overcome some of these challenges it can be advantageous to combine thermal images with other image modalities in many applications. A few pre-calibrated thermal-visual camera set-ups exist today [94, 95], and it is expected to see more of these combined systems in the future. This survey has shown that thermal sensors have advantages in a diversity of applications, and the fusion of different sensors improves the results in some applications. For the future development of vision systems, a careful choice of sensor can open up both new applications as well as alternative features for improving the performance of current applications.

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