THERMAL IMAGING AND ITS APPLICATION IN IRRIGATION WATER MANAGEMENT

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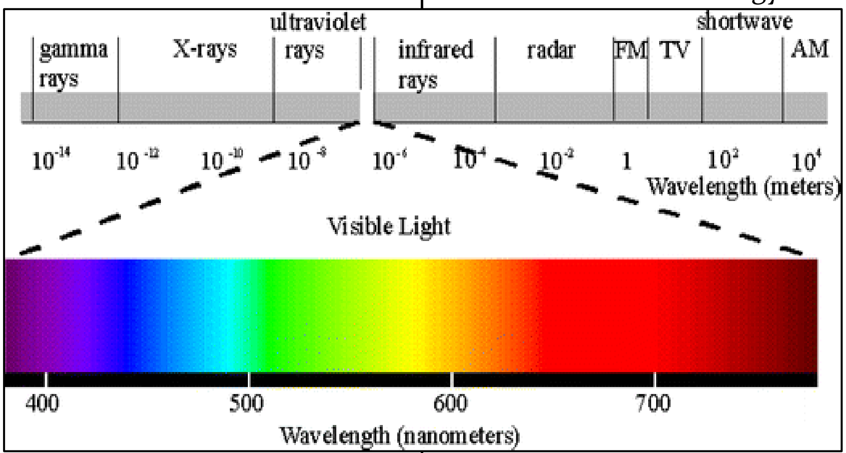
Process of capturing and creating an image of an object by using infrared radiation emitted from the object representing the temperature is called thermal imaging. Thermal imaging is the technique of using the heat given off by an object to produce an image of it or to locate it. All objects above the absolute zero temperature (0 K) emit infrared radiation as a function of their temperature. The infrared energy emitted by an object is known as its heat signature. In general, the hotter an object is, the more radiation it emits. The amount of radiation emitted by an object increases with temperature; therefore, thermography allows one to see variations in temperature. Thermal imaging is all about converting that infrared light into electric signals and creating an image using that information. A thermal imager (also known as a thermal camera) is essentially a heat sensor that is capable of detecting tiny differences in temperature. The device collects the infrared radiation from objects in the scene and creates an electronic image based on information about the temperature differences. Because objects are rarely precisely the same temperature as other objects around them, a thermal camera can detect them and they will appear as distinct in a thermal image. Works in environments without any ambient light and can penetrate obscurants such as smoke, fog and haze.



History

The underlying technology of the thermal imaging cameras was first developed for the military. However, the invention of the thermal camera is related to the history of thermography which began in 1960 by Sir William Herschel an astronaut who discovered infrared light. Both infrared radiation and visible light are part of the electromagnetic spectrum, but unlike the visible light, Infrared radiation cannot be perceived with human eyes directly.

Thermal Imaging Systems

Infrared thermal imaging system comprises of thermal camera equipped with infrared detectors, a signal processing unit and an image acquisition system, usually a computer. The infrared detectors absorb the infrared energy emitted by the object and convert it into an electrical impulse. The electrical impulse is sent to the signal processing unit which translates the information into thermal image. Most of the thermal imaging devices scan at a rate of 30 times per second and can sense temperature ranging from −20 to 1,500 °C, but the temperature range can still be increased by using filters (Meola & Carlomagno 2004). Detectors are the most important part of thermal imaging system which converts the radiant energy into electrical signals proportional to the amount of radiation falling on them. There are two types of detectors: thermal and photon detectors. In thermal detectors, infrared radiation heats up the detector element resulting in temperature rise, which is taken as a measure of the radiation falling on the object. In photon detectors, incident radiation interacts at an

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atomic or molecular level with the material of the detector to produce charge carriers that generate a voltage across the detector element or a change in its electrical resistance. The various types of photon detectors used are cadmium mercury telluride (CMT), indium antimonide, platinum silicide, and Quantum well devices. Among the two types, photon detectors provide greater sensitivity than thermal detectors (Willimas, 2009).

Thermal imaging devices can be classified into uncooled and cooled. Uncooled thermal imaging device is the most common one and the infrared detector elements are contained in a unit that operates at room temperature. They are less expensive but their resolution and image quality tend to be lower than the cooled device. In the cooled thermal imaging device, the sensor elements are contained in a unit which is maintained below 0 °C. They have a very high resolution and can detect temperature difference as low as 0.1 °C but they are expensive. Cooled thermal imaging devices are used in military and aerospace applications. An infrared imaging system is evaluated based on thermal sensitivity, scan speed, image resolution, and intensity resolution.

Thermal Imaging Cameras

A thermal imaging camera consists of five components: an optic system, detector, amplifier, signal processing, and display. The two most important factors are the detector resolution and the thermal sensitivity. The detector resolution describes the number of pixels. The most common resolutions are 160 x 120, 320 x 240 and 640 x 480 pixels. A 320 x 240 detector produces an image composed of 76,800 pixels. Since each pixel has a temperature associated with it that is 76,800 temperature data points. Higher resolutions also produce visibly clearer images. Thermal sensitivity is the smallest temperature difference the camera can detect. A sensitivity of 0.05° means the camera can distinguish between two surfaces with only a five-hundredths of a degree temperature difference. Another important factor to consider is the thermal imaging camera's temperature range. The range tells what the minimum and maximum temperatures are that the camera can measure (-4°F to 2200°F is typical). To obtain the best thermal image to analyse, there are four adjustments that can be made to most cameras: focus, emissivity setting changes, reflective temperature setting changes and thermal tuning.

Image Processing

Image processing is any form of signal processing for which the input is an image, such as a photograph or video frame and the output may be either an image or a set of characteristics or parameters related to the image.

Applications

Agriculture, Medicine, Industries, Building Construction, Health care, Veterinary Thermal Imaging, Night vision and Targeting, UAV Surveillance, Food Processing, Surveillance in security, law enforcement and defence etc. In Agriculture, Thermal imaging has been successfully adopted for studying plant physiology, irrigation scheduling, and yield forecasting in agricultural fields. Likewise maturity evaluation, detection of bruises in fruits and vegetables, detection of spoilage in agricultural produces by microbial activities, and detection of foreign materials are the potential post-harvest operations to use thermal imaging.

Reviews on Crop Water Stress using Thermal Imaging

Canopy temperature and transpiration from leaves are closely related. Therefore, water deficit stress in plants could be effectively identified using temperature data from the canopy. Canopy temperature measurement using thermal infrared remote sensing is mostly used to study plant water relation. The plant water relation is directly dependent on stomatal conductance. The reason behind this

relationship is that the leaf temperature is determined by the rate of transpiration from the leaf.

The transpiration is a continuous process. When leaf water is evaporated due to transpiration, a substantial amount of energy is required to convert each mole of liquid water to vapour and this energy is taken away from the leaf in evaporating water, making the leaf cool (Jones *et al*. 2009). If there is water deficit in the ground, the plant closes its stomata to stop loss of water. These physiological changes determine the temperature of the plant. It means that low leaf temperature is due to open stomata in leaf whereas high leaf temperature will be an outcome of closed stomata. Crop water content is quantified using direct sensing of plant water stress parameters like leaf water potential, stem water potential (Matese *et al*. 2018) and relative water content (Krishna *et al*. 2019) etc. Soil-based experiments for water stress detection were reported as erroneous and were not found to be the representative. Mostly, crops are irrigated by applying water to the whole field uniformly. Lack of uniformity among plants, enhance the chances of reduced yield.

Table 1: Various studies on Applications of thermal imaging in 'Irrigation Water Management

Sela *et al.*, (2007)	Thermal imaging for estimating and mapping crop water stress in cotton	This study developed models for estimating and mapping leaf water potential (LWP) in cotton fields using thermal and visible images of cotton canopies. The models were based on the crop water stress index (CWSI) calculated from canopy temperatures and showed good correlation with measured LWP. The LWP-CWSI model was used to generate LWP maps of plots with different water status. These findings suggest the potential for using precision irrigation to promote water-saving in cotton fields.
Gontia and Tiwari, (2008)	Development of crop water stress index of wheat crop for scheduling irrigation using infrared thermometry	This study developed a relationship between canopy-air temperature difference and vapor pressure deficit for non-stress conditions of winter wheat crops to calculate the crop water stress index (CWSI) for irrigation scheduling. Linear relationships were found between canopy-air temperature difference and VPD, and the CWSI was calculated for three irrigation schedules. The established CWSI values can be used to monitor plant water status and plan irrigation scheduling for wheat crops.

Vadivambal and Jayas (2011)	Applications of Thermal Imaging in Agriculture and Food Industry—A Review	Infrared thermal imaging is a non-invasive, non-contact, and non-destructive technique with wide applications in various fields such as agriculture and food industry. The technique can assist in predicting water stress in crops, planning irrigation scheduling, disease and pathogen detection in plants, predicting fruit yield, evaluating the maturing of fruits, bruise detection in fruits and vegetables, detection of foreign bodies in food material, and temperature distribution during cooking. The review emphasizes the potential use of thermal imaging in various agricultural practices due to its advantages.
Gonzalez *et al.*, (2013)	Using high resolution UAV thermal imagery to assess the variability in the water status of five fruit tree species within a commercial orchard	The paper presents a viable method for precision irrigation management in commercial orchards by assessing water stress using remote sensing-derived indicators. The approach allows for the identification of water-stressed areas and variability within irrigation units. The Crop Water Stress Index (CWSI) was calculated and threshold values were defined for precision irrigation management based on crop developmental stages and economic considerations. This method provides an effective tool for growers to manage irrigation and optimize water use in orchards.
Masseroni *et al.,* (2017)	Assessing the Reliability of Thermal and Optical Imaging Techniques for Detecting Crop Water Status under Different Nitrogen Levels	The study confirms that imaging indices derived from thermal and optical techniques can be used as reliable operational tools to detect crop water status, regardless of the presence of nitrogen stress, making them potential tools for efficient irrigation management and detection of drought stress in different soil nitrogen conditions.
Kullberg *et al.*, (2017)	Evaluation of thermal remote sensing indices to estimate crop evapotranspiration coefficients	This study found that remote sensing methods, specifically the thermal indices DANS and DACT, were effective in estimating crop water stress and evapotranspiration in a deficit irrigation experiment for corn. These less data-intensive methods were found to have low RMSE in ET calculations, highlighting their suitability for estimating crop water stress. The study also provided insights into the appropriate remote sensing methods based on data availability and irrigation levels, along with an estimation of associated ET errors.

Bian *et al.*, (2019)	Simplified evaluation of cotton water stress using high resolution unmanned aerial vehicle thermal imagery	The study aimed to simplify the calculation of the crop water stress index (CWSI) and improve its diagnostic accuracy for cotton under different irrigation treatments using thermal and multispectral images. A simplified CWSI (CWSIsi) was developed and found to have higher correlation with stomatal conductance, transpiration rate, and soil volumetric water content compared to other methods. CWSIsi only requires parameters from a canopy temperature histogram and has potential for precision irrigation management.
Pereira *et al.*, (2020)	Prediction of crop coefficients from fraction of ground cover and height.	Study reported that crop water stress coefficient Ks can be calculated based on the temperature-based crop water stress index (CWSI) extracted from UAV-based infrared thermal imagery.
Krishna *et al.*, (2021)	Application of thermal imaging and hyperspectral remotesensing for crop water deficit stress monitoring	This study identified drought-tolerant and drought-sensitive rice genotypes using thermal and visible imaging techniques, along with measurements of relative water content and canopy reflectance spectra. The Crop Water Stress Index (CWSI) was used to quantify water deficit stress, and 10 most optimal wavebands related to water deficit stress were identified from hyperspectral data. The study provides valuable input for the development of drought-tolerant rice genotypes in the future.
G. Shao *et al.*, (2023)	Prediction of maize crop coefficient from UAV multi-sensor remote sensing using machine learning methods	The study found that the multispectral and thermal-based VIs, along with texture information from the near-infrared band, made significant contributions to the Kc-RFR model, particularly under different irrigation treatments. Additionally, the maize Kc-RFR model accurately estimated cumulative evapotranspiration ($R2 = 0.89$, RMSE = 15.0 mm/stage) during different growth stages and daily soil water content ($R2 = 0.85$, RMSE = 0.0089 m^3/m^3) in the root zone.
H. M. Jalajamony *et al.*, (2023)	Drone Aided Thermal Mapping for Selective Irrigation of Localized Dry Spots	A smart irrigation system is presented, utilizing a quadcopter drone equipped with a Thermal Infrared (TIR) camera and GPS module. The drone captures georeferenced thermal images to identify localized dry spots in an agricultural field. The images, along with flight data, are processed by an onboard edge intelligence module. Smart sprinklers in the field receive the coordinates of dry spots wirelessly and irrigate them selectively. A terrestrial edge unit utilizes a pre-trained machine learning (ML) model to generate an irrigation pattern by adjusting the head rotation angle (θ) and water flow control valve rotation angle ($\emptyset$) of the smart sprinkler.

Conclusions

The application of thermal imaging is gaining popularity in agriculture and food industry in recent years. The major advantages of thermal imaging are non-contact, non-invasive, and rapid technique which could be used for online applications. The thermal cameras are easy to handle and highly accurate temperature measurements are possible. With the thermal imaging, it is possible to obtain temperature mapping of any particular region of interest with fast response times which is not possible with thermocouples or other temperature sensors which can only measure spot data. Repeatability of temperature measurements is high in thermal imaging. Also, thermal imaging does not require an illumination source unlike other imaging systems. Previous models of thermal camera's required cryogenically cooled sensors to obtain temperature resolution of 0.1 °C whereas recent day cameras can operate at room temperature making these cameras user friendly and promoting an increase in the use of thermal imaging in various fields.

The use of thermal imaging for irrigation and water management in agriculture is becoming increasingly popular due to its numerous advantages. Thermal imaging allows for non-invasive and non-contact measurement of temperature distribution, which can be used to predict water stress in crops and plan irrigation scheduling more accurately. This technology can also be used for disease and pathogen detection in plants and evaluating fruit maturation, among other applications. One approach to using thermal imaging for water management is through precision agriculture, which involves the use of agronomic concepts and innovative technology to control the geographical and temporal variance related to every aspect of agricultural output. Remote sensing technologies, including thermal imaging, can be used to monitor crop water status and attributes over vast distances, making data collection more efficient. Thermal imaging can be used to calculate evapotranspiration, which is the process by which water is transferred from land to the atmosphere through plant transpiration and soil evaporation. By accurately measuring evapotranspiration rates, farmers can more effectively plan irrigation schedules and conserve water resources. Infrared thermography is another technique used in thermal imaging for water management, which allows for the detection of temperature differences in crops and soil. By identifying areas of high and low temperature, farmers can identify areas of the field that require more or less water and adjust their irrigation accordingly. Overall, thermal imaging is a valuable tool for irrigation and water management in agriculture, allowing for more efficient use of water resources and improved crop yields. With advancements in technology, including the development of user-friendly thermal cameras, the use of thermal imaging in agriculture is likely to become more widespread in the future.

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