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THERMOGRAPHY

Thermography or thermal imaging is the technique of detecting spatial and time variations of radiated heat energy and transforming them to a visible display. The equipment, called the sensor, consists of an (ir) camera connected to a television and video tape recorder. The heart of the ir camera (1) is an array of innfrnared detectors sensitive from visible to at least 5 μm and preferably to 14 μm wavelength (see Photodetectors). The detector array and a set of optics provide for two-dimensional spatial resolution of the thermal scene. The high speed response of the sensor results in "real time" television displays. Since thermal radiation is a function of emissivity and temperature a calibrated thermographic sensor can remotely measure the surface temperature of objects. When the camera is coupled to a spectrometer or narrow band filters the sensor is capable of spectral discrimination. Thus thermography can become both spatial radiometry and spectral imaging. The major trades-off in sensor design are typically among spatial resolution, spectral resolution, field of view, frame time and scene-temperature sensitivity.

The development of thermography began in the 1950s using either uncooled but low sensitivity bolometers or InSb photodiodes cooled to 77 K. These sensors had single detector elements, two axes scanning, large scanning mirrors, approximately 0.2 K sensitivity and a frame time exceeding 2 minutes. Adaptation to medical diagnosis was difficult because the patient was not allowed to move during the long frame time. During the 1960s linear arrays of mercury-doped germanium detectors (240 elements cooled to 35 K) were used for higher sensitivity and frame times of less than 0.1 seconds. With smaller optics, one axis scanning and a television-like display these machines were the first thermal imaging cameras. The military versions were called "forward looking infrared" or flir because heretofore military infrared with a single detector was primarily aerial reconnaissance with the airplane's motion providing one dimension of the scan. The linear array eliminated the need to move the entire airborne sensor to get a picture. During the 1970s linear detector arrays made from HgCdTe provided good sensitivity with only 77 K cooling and led to the military "Common Module" concept for lower cost, smaller size and television-like display.

From the early 1980s to present, infrared sensitive two dimensional arrays were mated to integrated circuits for signal processing and sensitivity to better than 0.03 K (see Photodetectors). These focal plane arrays of some 500 by 500 elements eliminate the need for scanning and provide good spatial resolution. Some versions have no special cooling requirements. The development trend is to increase the number of pixels to improve resolution, increase the field of view and keep the size and cost of the optics within acceptable bounds.

With reduced sensor cost the range of applications now includes thermal vision (2, 3) industrial processing, industrial security, police work (3), maritime safety, airline safety and vision enhancement for night driving and flying and weather satellites. For these applications, the thermal sensor typically uses a broad spectral band to achieve highest sensitivity.

A schematic of a thermographic sensor for thermal imaging is illustrated in Figure 1. The infrared lens is often coated silicon, germanium, or an infrared glass. The ir window may also be an interference filter made of materials similar to the lens. The detector array is an integral part of the silicon integrated circuit readout chip and contains circuits which buffer (impedance match), and switch to sequentially output the detector signals. Signal processing on the focal plane is limited to buffering, switching (multiplexing), and amplification.

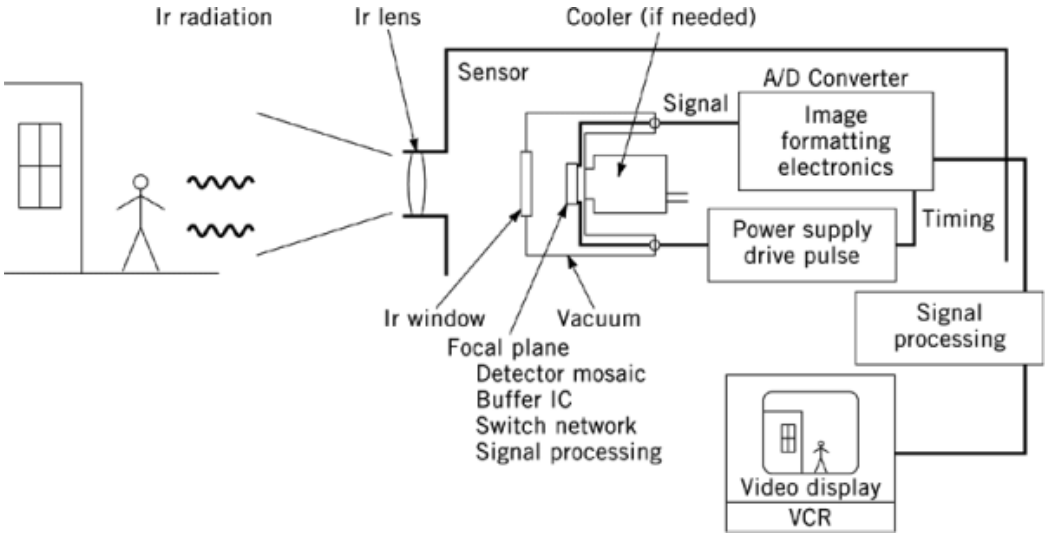

Fig. 1. Schematic for thermographic imaging. The ambient thermal radiation is imaged on the focal plane which converts the infrared to an electrical signal for display on a video monitor. Sensors with uncooled focal planes are now the size of a minicam and cost 5 to 10 times as much.

Typically, the focal plane signal is an analog of the photon intensity variations. The analog signals are converted to a digital format (A/D conversion) for signal processing which may consist of gain and offset corrections (for uniformity), contrast enhancement, resolution vs sensitivity tradeoff, frame addition, freeze frame (snap-shot or frame-grabbing), dithering for reduction of aliased signals, data compression for transmission, false color renditioning, and many other processing techniques. The digital signal level is typically near one volt and as such is not readily corrupted by electromagnetic interference. Although it is desirable to put the A/D converter on the focal plane for maximum noise immunity the power needed to convert at high data rates would overheat the focal plane.

In situations where sufficient thermal radiation is available the spectral band can be narrowed (by filters or spectrometer) with only a proportional reduction in sensitivity. When the spectral band is narrowed to a particular absorption band of a given chemical substance the spatial distribution and temporal variation of that substance may be measured as was done in the visible by astronomers (scanning slit spectrographs) for many years. Infrared focal plane array technology is making possible spectrographic imaging in the infrared portion of the electromagnetic spectrum which is rich in molecular absorption lines. This will have a major impact on industrial processing where control of the chemistry is essential for cost reduction and safety. The potential applications are detection and source location of toxic gases, monitoring chemical manufacturing processes on a real-time basis, remote temperature profile sensing, automobile exhaust gas monitoring and measuring the location and degree of chemical leaks in production or storage. Spectral thermography will help detect and control toxic atmospheric gases such as CO, N_xO, SO_x, NH_4 and ozone. A thermographic sensor with an integral gas sampling tube is a spot sensor and that with a remote heat source or retro-mirrors performs remote sensing.

1. Principles of Thermography

A brief review of the figures of merit (1) for thermal imaging (4) and gas detection is given to show the various trades-off required to image the thermal environment and detect atmospheric contamination.

1.1. Noise Equivalent Power

The total system electronic noise V_T may be combined with the responsivity, R_V to give the noise equivalent power equation:

$$NEP = \frac{V_T}{R_V} \qquad (1)$$

The NEP may be written in terms of the detector element active area, A_p, the number of detector pixels elements connected for additive output n_p, the electronic noise bandwidth B and the detector element detectivity, D^*. Typically $n_p = 1$, but may be increased for improved sensitivity with an attendant loss in resolution.

$$NEP = \frac{1}{D^*}\sqrt{\frac{BA_p}{n_p}} \qquad (2)$$

The typical D^* for a cooled infrared detector is ca 5E10 cm $Hz^{1/2}$/W and is ca 1E9 cm $Hz^{1/2}$/W for an uncooled detector.

1.2. Thermographic Sensitivity

The noise equivalent temperature difference (sensitivity to scene temperature variations in degrees C) may be expressed in terms of the NEP:

$$NE\Delta T = \frac{\pi}{\Omega A_p n_p \epsilon_0}\left[\int_{\lambda 1}^{\lambda 2}\frac{dJ_s}{dT}d\lambda\right]^{-1}(NEP) \qquad (3)$$

where ϵ_0 = the optical efficiency of the sensor and is typically 85%
A_p = the detector element (pixel) active area, typically 1.5 E-5 cm^2
Ω = the collection solid angle of the optical system ($= \pi \sin^2(\tan^{-1}1/2f_n)$, typically 0.15 str
f_n = optical f number, typically 2.2 or less. For fast optics $f_n = 1.0$
J_s = spectral power density in watts/cm^2cmK emitted by an element of the scene.

The integral of the temperature gradient of the spectral power density from wavelength $\lambda 1$ to $\lambda 2$, is readily calculable using the Planck radiation law (5). Constant emissivity is assumed for equation 3.

Thermographic sensitivity for representative sensors may be calculated with equation 3. The results are summarized in Table 1 for both cooled and uncooled focal planes and for scanned and staring type sensors. Scanning sensors use a larger area detector to achieve higher sensitivity and virtual overlap of the detector geometry to suppress aliasing. The optical speed is slower ($f_n = 2$ vs $f_n = 1$) to lower the cost of optics. The D^* values are typical and refer to the cooled platinum silicide, InSb, AlGaAs superlattice or HgCdTe focal planes and the uncooled pyroelectric barium–strontium–titanate or semiconductor bolometer focal planes (1, 2, 6, 7).

In all cases, the imaging is conducted in real-time with a near standard television read-out display. This results in a 40,000 Hz bandwidth for scanning an a 100 Hz bandwidth for staring. It is possible to do frame addition and effectively reduce the bandwidth to achieve more sensitivity. The display can be repeated at the normal 60 Hz rate to avoid the appearance of flicker. Satellite infrared weather imaging thermography has a

Table 1. Thermographic Sensitivity For Scanned and Staring Sensors[a]

	Cooled focal plane				Uncooled focal plane			
Figure of merit ⟶ Sensor type ↓	D^* cm $Hz^{1/2}/W$	NEPpW	$NE\Delta T$3–5 μmmK	$NE\Delta T$8–12 μmmK	D^* cm $Hz^{1/2}/W$	NEPpW	$NE\Delta T$3–5 μmmK	$NE\Delta T$8–12 μmmK
scanned linear array A = 2.2E − 5 cm^2 B = 40 KHz f_n = 2.0	5E10	19	750	80	2E9	470	4700	500
staring area array A = 1.5E − 5 cm^2 B = 100 Hz f_n = 1.0	1E10	100	250	25	1E9	40	560	60

[a] $\epsilon_0 = 0.85$.

low bandwidth, resulting in a distinctive stepping motion to cloud patterns as displayed during a TV weather report. Advanced staring sensors will greatly improve weather imagery within the next decade yielding better sensitivity, resolution, and continuous movement of cloud patterns.

Thermographic imagery is considered useful when the minimum detectable temperature ($NE\Delta T$) is less than 200 mK (8). Thus the uncooled focal plane is not used in the scanning mode. The cooled area focal plane can achieve less than 5 mK but this sensitivity can not be taken advantage of because of sensor instability and limited dynamic range. Stability can be improved by periodically imaging a surface of uniform infrared irradiance, as a "reference" and electronically computing for each pixel a factor for gain correction and a difference value for offset correction. For the scanned sensor these corrections are programmed to occur at the end of each scan. For the staring sensor a low rate chopper blade is a useful, if awkward, device to achieve gain and offset correction. When the drift is slow enough, an operator briefly caps the optics or closes a shutter every hour or so to perform the correction function. The gain and offset corrections can be computed and implemented in less than 20 ms. Without correction, the random drift in the output of each detector element degrades the displayed image.

The thermographic sensor is used as a remote sensing radiometer when a reference target is imaged. It is usually necessary to correct for emissivity and atmospheric transmission to determine surface temperature with a reasonable degree of accuracy.

The dynamic range (1) is limited by the focal plane electronics which is an array of integrated circuits. The small pixels force the designer of the IC chip to use aggressive design rules to leave enough room for reasonable charge storage. Even so, the small capacitors result in a dynamic range of less than 60 dB. If for example the sensitivity is only 5 mK the dynamic range becomes 5 K and objects greater than 5 K different in temperature appear black or white on the display. The dynamic range problem is further complicated by variations in emissivity of the radiating surfaces. Since manufactured materials have a wide range in emissivity, boundaries of structured objects are usually clearly defined in thermal imagery. The user selects between higher gain (displayed sensitivity) and higher contrast (displayed dynamic range). However when the emissivity is uniform (eg, bodies of water, rural scenes) high sensitivity is desired and good stability is critical.

The resolution quality of thermal imaging is the product of the MTF or modulation transfer functions (1) for each component in the sensor system. The ideal MTF is that produced by the detector to detector spacing. Optical aberrations, photon scattering at the focal plane, shared signal charge in the detector material, electromagnetic interference and display blur combine to degrade the sensor MTF. A good sensor will have an MTF of 80% of the optimum value at a spatial frequency given by the reciprocal of twice the detector spacing (Nyquist frequency). The detector array MTF is given by the sinc function of the spatial frequency. For a detector spacing or pitch of 50 μm the optimum MTF at a spatial frequency of 10 line pairs/mm is 64%.

An achievable MTF of 50% at Nyquist frequency is quite good. The minimum resolvable temperature given by equation 3 can be achieved only at low spatial frequency. Temperature resolution degrades as the image size of objects approaches detector size. Thus an imaging figure of merit, minimum resolvable temperature (MRT) is defined as the resolvable temperature difference on a display observed by a person when the bar pattern frequency matches the detector pitch, ie, at the Nyquist frequency. The MRT is typically 50% more than the NEΔT.

2. Thermographic Spectroscopy

The broad-band spectral capability of most thermographic sensors is generating a lot of interest for developing a low cost imaging spectrometer. The focal plane itself is sensitive from visible well into the infrared. The cooled HgCdTe array responds to 12 μm wavelength and the uncooled pyroelectric and bolometer arrays can efficiently detect from the uv to 50 μm (see Photodetectors). The spectral transmission of the window material of the detector package must be specified and the imaging optics must be designed for the specific application. Spectral discrimination is achieved by plane-wave interference, diffraction gratings, spectral wedge filters or an array of filters. Spectral dispersion is aligned parallel to a linear array so that each element is exposed to a different part of the spectrum. The linear array takes the place of the film or plate. The area arrays add the other spatial dimension and can be used for enhanced sensitivity by signal addition. When the entire array detects the same portion of the spectrum the display shows the spatial features in that spectral band. In certain cases the entire array output can be summed to achieve high sensitivity and fast response.

Although thermal imaging can be achieved by observing the irradiation of the ambient environment, spectral imaging is a different matter. Bodies, including liquids and gases emit radiation according to their temperature and emissivity and therefore act as emitting gray bodies. In addition to gray body emission substances have specific spectral emissions depending on excitation energy somehow transferred to the substance. Excitations are typically generated by electric spark, uv radiation, or localized heating. Detection in these cases is by spectral emissions. When there is no external excitation spectral discrimination by a remote spectrometer is difficult relying on second-order effects. In general, detection of small amounts of a specific material such as a toxic gas will depend on a powerful excitation source or absorption of excess ir radiation. If only internal radiation (by the material's own temperature) is available the material will be spectrally gray and will not be detected. However, an external ir radiation source as shown in Figure 2 such as a heated body can provide enough excess radiation for spectral absorption by the material and therefore spectral discrimination and identification.

Spectral discrimination (9) and specific gas detection can be modeled if one assumes the gas absorbs photons of a specific wavelength exponentially with distance into the gas (Beer's law). When the absorption distance is x (cm), the incident ir power density at the detector in the spectral band pass is J (W/cm^2) and the power density incident on the gas is J_o, the gas concentration, C (ppm) is given by:

$$C = \frac{G_o}{x} \ln\left(\frac{J_o}{J}\right) \qquad (4)$$

G_o (ppm-cm) is the normalized absorption length for a specific gas at a specific wavelength centered in specific bandwidth. Both J_o and J are referred to the collection optics. It is a measure of atomic or molecular absorption. The energy absorbed by the gas molecules is dissipated by molecular collisions and photon radiation. Even if the molecules emit the exact same wavelength, very little of the emission is in the direction of the thermographic sensor and selective absorption will be observed. The G_o value for each gas can be calculated using high resolution spectral absorption data bases by integrating the absorption of the spectral lines in the preselected bandwidth. The data for a specific gas is searched for a convenient absorption (not corrupted by other gases

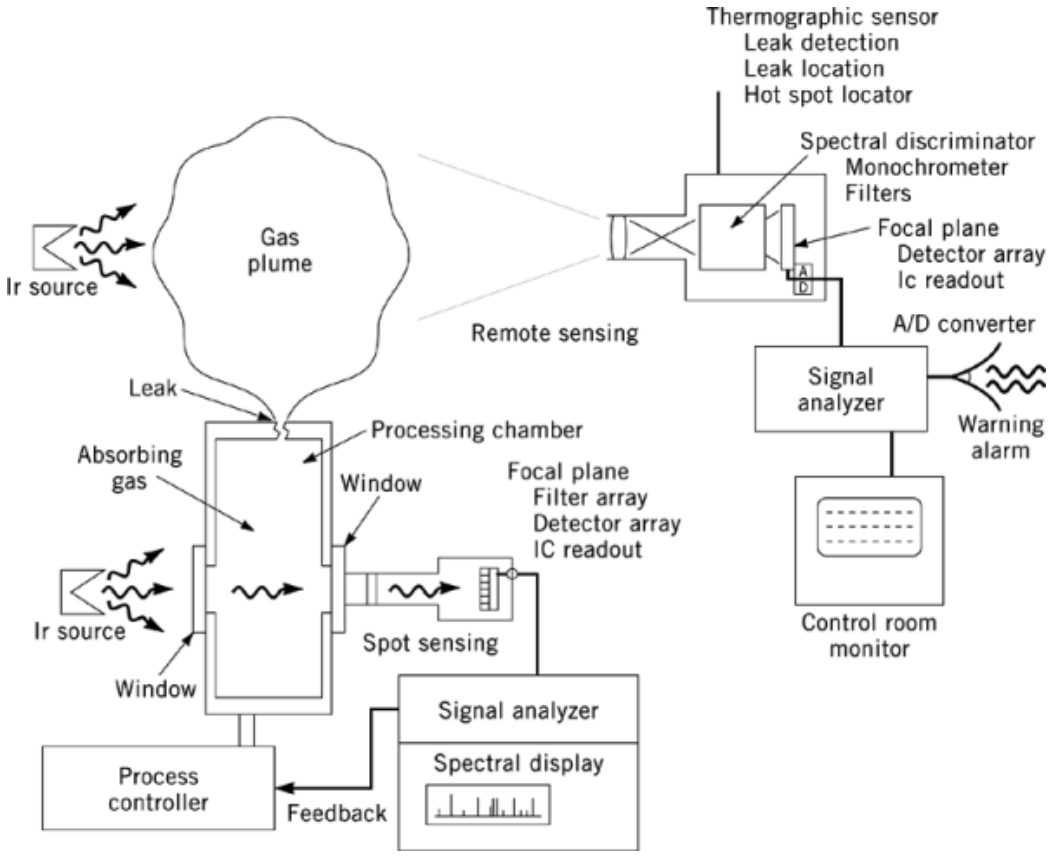

Fig. 2. Thermography combined with precise spectral discrimination provides for spatial spectroscopy for remote spectral sensing as well as "spot sensing" for process control and safety.

that may be present) band and G_o is calculated for a bandwidth consistent with spectrometer capability. For example Figure 3 shows attenuation of infrared for carbon monoxide for a 0.2-μm bandwidth centered on 4.65 μm. Since the slope is nearly constant in the range where the absorption is less than 1%, G_o is given by the slope of the curve. It is clear that the thermographic spectrometer must have high sensitivity to detect small amounts of CO in a reasonable path length of less than 1 meter.

The detection of a specific gas (10) is accomplished by comparing the signal of the detector that is constrained to the preselected spectral band pass with a reference detector having all conditions the same except that its preselected spectral band is not affected by the presence of the gas to be detected. Possible interference by other gases must be taken into account. It may be necessary to have multiple channels or spectral discrimination over an extended spectral region to make identification highly probable. Except for covert surveillance most detection scenarios are highly controlled and identification is not too difficult.

The sensitivity equation can be developed by differentiating equation 4 with respect to J. Since the signal is proportional to J and detection is defined as to when the measured signal to noise ratio equals 3, the gas

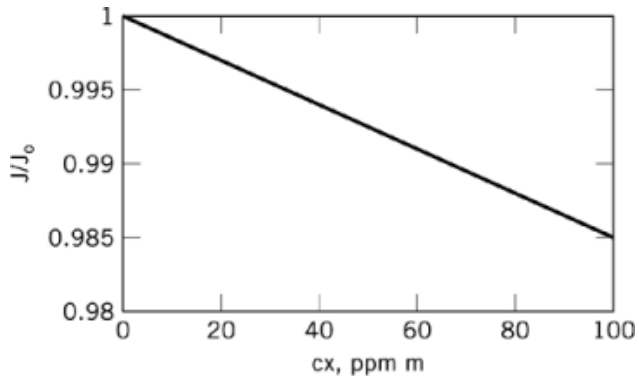

Fig. 3. Attenuation of infrared as a function of normalized concentration caused by CO absorption in the 4.6 μm band. G_o=6.6E3 ppm m, spectral bandwidth=0.2 μm.

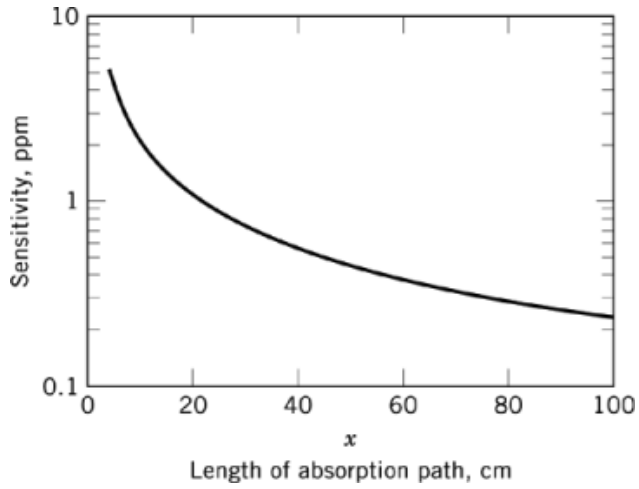

Fig. 4. Sensitivity for the detection of CO using spectral thermography as a function of absorbing path length. Detector NEP=30 pW, J=1.0 mW/cm^2, A=1.5E−5 cm^2, samples=60, number of detectors=600, G_o=6.6E5 ppm−cm; center wavelength=4.65 μm; spectral bandwidth=0.2 μm.

detection sensitivity (ppm) in terms of the NEP for gas detection becomes:

$$\Delta C = \frac{3G_o NEP \exp\left(\dfrac{xC}{G_o}\right)}{J_o A_p \left(n_s n_p\right)^{1/2} x} \qquad (5)$$

This expression includes the use of detector arrays of n_p detectors with additive signals and sample addition of n_s samples to improve sensitivity. Typical sensor parameters are $J_o = 1$ mW/cm^2, $NEP = 30$ pW, $A_p = 1.5\mathrm{E}-5$ cm^2, $n_s = 60$, $n_p = 1$ for imaging and ca 600 for nonimaging gas detection.

For the case of CO detection at 4.65 μm wavelength, where $G_o = 6.6$ E5ppm − cm, the sensitivity as a function of x and C is shown in Figure 4. The number of signal samples n_s can be taken at a 60 Hz rate giving in this case a measuring time of 1 second. For an absorption tube length of only 50 cm the sensitivity of detection

Fig. 5. The Night Sight commercial thermograph made for all-weather operation uses the uncooled pyroelectric focal plane.(Courtesy of Texas Instruments Inc.)

is 0.4 ppm. The specified margin of 3 in the signal to noise ratio rather than 1 improves the probability of identification from 50% to 98%.

An imaging thermographic sensor may be modified for spectral imaging by using a monochrometer or putting a narrow band filter over the sensor aperture (11). The filter may have a constant wavelength or tapered wavelength in the form of a wedge or wheel. A schematic of this arrangement is shown in Figure 2 for the applications of industrial process control and safety. When high spectral resolution (hyperspectral) is required an interferometer spectrometer is utilized in conjunction with the thermographic sensor. At the high dispersion necessary for accurate substance identification remote sensing is very difficult because the signal level is very low. A very narrow spectral bandwidth results in a high value of G_o for gas detection. This can be alleviated somewhat by sensing two or more portions of the spectrum where absorption is expected (multispectral) and performing signal analysis for identification. The presence of several chemicals in any typical scene complicates the entire process.

3. Applications

3.1. Thermal Imaging

Thermography as a night vision tool in the nonmilitary sector is being used by law enforcement (3) agencies to detect the movement of suspects in the complete dark. In fact contraband discarded by suspects in flight

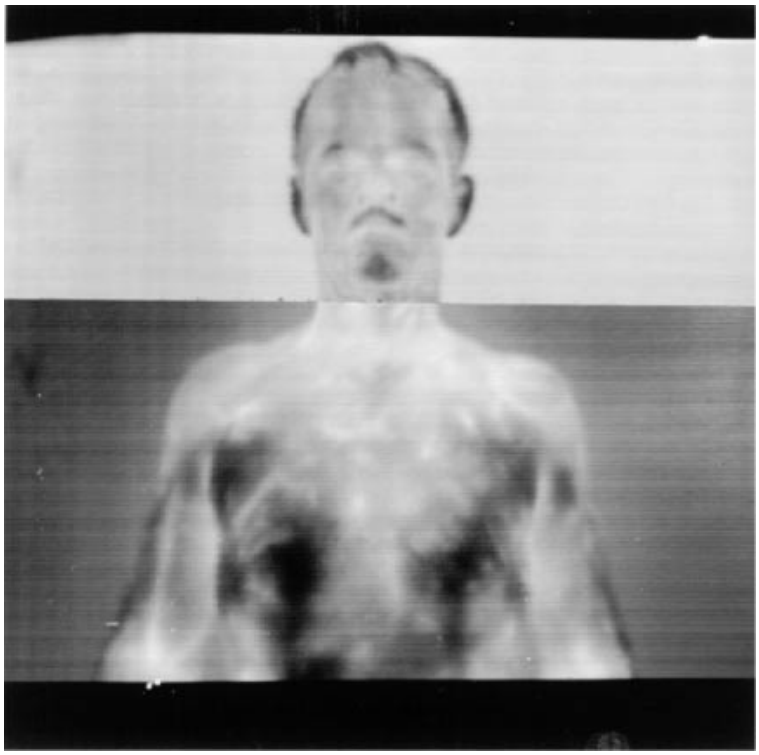

Fig. 6. Thermograph of a person in the 3 to 5 μm spectral band. Spatial resolution is 1 mm and temperature sensitivity is 0.1°C.

have been detected and recovered using their latent heat signature acquired by body contact. A multipurpose commercial thermographic sensor is shown in Figure 5. Sensors are finding use by rescue services looking for survivors floating in the water at night. Since the average adult body even at rest has the energy consumption of a 100 W light bulb and emits 30% of its radiation in the 8 to 12 μm spectral band, the lightly clothed human is a bright thermographic source. All mammals are easy to detect in relatively clear weather making it easier to count livestock at night than in daylight.

Thermal imaging is under development as nighttime vision enhancement for drivers of trucks and automobiles. When perfected the driver will have a display projected on the windshield (heads-up display) showing the forward view as seen by the infrared camera. Distant vision will be similar to daylight viewing. Humans and animals approaching the roadway will be readily seen and there will be no glare from street light or even oncoming headlights. Thermal vision in rain and fog will be better than unaided, but infrared absorption and scattering by water droplets will still greatly reduce penetration. Automobile companies project this option to be available by 2001 and will cost 5%of the average car price. Although thermal imaging is common in military aircraft, commercial airlines have been slow to introduce it because of the high cost of the airborne version. It is being used by a few airlines to help with collision avoidance and landing in light fog.

Efforts have been made to evaluate human trauma caused by disease and injury using thermal imaging. Investigations continue by medical schools to make thermography an early screening tool for the detection of kidney disease and breast cancer (12). A cancer in its early stages grows quickly creating a small amount of excess heat which appears as a bright spot on a thermograph display. Since only one breast is likely to be affected at the early stage, the radiologist looks for thermal pattern asymmetry in comparison of one breast to

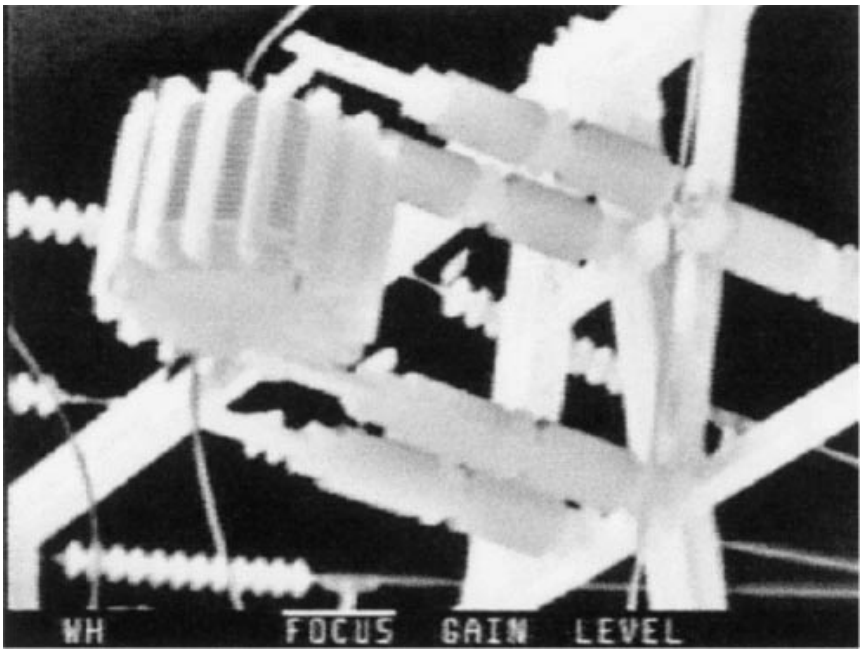

Fig. 7. Thermographic image of a power distribution station and transformer. Spatial resolution is 0.3 m-radians and temperature sensitivity is 0.08 C.(Courtesy of Texas Instruments Inc.)

the other. However complications caused by blood vessels near the skin and weak response to deep lesions, have led to unacceptably high false-positive and false-negative detection as determined by the medical community. A medical thermograph is shown in Figure 6.

Industrial use of thermal imaging typically is the detection of thermal anomalies (13, 14) such as leaking pipes and valves, overheating boilers, transformers and power lines, and friction generated heat in bearings. A thermal image of a transformer station is shown in Figure 7. These are simple heat detection applications but the imaging process quickly locates the problem in the three-dimensional industrial environment. The ir camera is scanned like a TV camera and the output signal is digitized for evaluation by a programmed computer than compares the output of each frame with a calibrated reference frame. An alarm declares when a thermal anomaly is detected. Defects in materials (15) and circuit boards (16) can be detected by the associated discontinuities in thermal conduction.

3.2. Chemical Gas Detection

Spectral identification of gases in industrial processing and atmospheric contamination is becoming an important tool for process control and monitoring of air quality. The present optical method uses the ftir (Fourier transform infrared) interference spectrometer having high resolution (<1 cm^{-1}) capability and excellent sensitivity (few ppb) with the use of cooled MCT (mercury–cadmium–telluride) (2) detectors. The spectral data is massive and requires normalization to remove the effects of interfering gases. The ftir equipment is expensive ($>$100K\$) and difficult to move around. Low cost ($<$5K\$), small size (<10 kg), and low power spectral thermography is under development. However, its lower spectral discrimination (>20 cm^{-1}) is an issue and will limit the use of the spectral thermograph to situations where the gases to be detected are known but

their concentrations must be monitored. This will result in the use of well-defined spectral filtering and signal processing.

Spectral monitoring for chemical process control (17) has been demonstrated for semiconductor integrated circuit manufacture (18, 19) and detection of contamination of processing gases and liquids (20). Open path or remote ir sensing (see Fig. 2) is used to monitor workplace gas and vapor exposures, emissions from hazardous waste sites and to track emissions along fence lines (21). Aerosol analysis by infrared spectroscopy are used to set mass detection limits and spectral quality (22). The removal of NO_x has been monitored by analysis of the by-products of the process using ir spectroscopy (23). Ir spectroscopy will be an important process control technique when the system cost is significantly reduced (24). Air quality monitoring increases in importance and U.S. Government agencies are beginning to create Guidance Documents (25, 26) for the development and utilization of spectral thermographs.

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