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From IR thermal images to heat source assessments

Part 1

Measurements of temperature fields

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What are the necessary investments?

Part 1
1 - Thermal sciences and heat diffusion .................. 9 slides
2 - Thermal sensors .................................. 3 slides
3 - Quantitative Infrared thermography .................. 3 slides

Part 2
4 - Theoretical framework (CM + TIP) .................... 11 slides
5 - Image processing and heat source assessment ...... 11 slides
6 - Illustrative examples .................................. 6 slides

Part 3
7 - Tutorial session
Notion of temperature

**temperature** $T$:

– intensive physical quantity objectively characterizing the subjective sensation of “coldness” or “hotness” in contact of a body

– several definitions:
  
  “macroscopic”: following the 2nd principle of Thermodynamics (see IHS-1)
  
  $\forall$ non-negative scalar such as: $s \geq \delta Q/T$

  “thermo-statistics”: increasing function of the kinetic energy of the system

...
Heat equation

\[ \rho C T - k \ \text{grad} \ (T) = w \downarrow c h \uparrow \cdot \]

\text{hyp.:} \text{ conduction follows Fourier’s law}

\[ q = -k \ \text{grad} \ (T) \]

\text{regularizing effect of heat diffusion} \ \text{of heat diffusion} \ \text{inverse estimation} \text{ of the heat sources from the temperature: very instable!}

cf. IHS–PS1 and the (old) following example ...
Example of heat diffusion

1990, 20 years ago !!
Agema 880 camera,
digitized video signal
2 Hz
IBM 80286
Dos 4.1, HD 60 Mo
(NETD : 200 mK)

temperatures maps :
1 « hot spot »
$q = 3.5 \, ^\circ C$

heat sources map :
2 wires heated via Joule effect
power : $3. \times 10^{-2} \, W$

screen capture, Turbo Pascal programming
Example of heat diffusion

- steel plate: 4 spots:
  - active before \( t_0 \), then deactivated

- temperature variations can be observed (somewhere) …
  … while no heat sources are active!

- no temperature variations can be observed …
  … while heat sources are active (somewhere else)!
Measurement of temperatures

**measurement chain:**

```
sensor ➔ transmission/conversion ➔ recorder
```

**common types of sensors:**

- thermo-mechanic effect: dilatation of a gas/liquid/solid
- thermo-electric effect: thermocouples
- radiation: pyrometers, bolometers, (cf. IR cameras)
- electric resistance: thermistances
- …
thermocouples are made of two different metals \( M_A \) and \( M_B \), connected by two junctions:
- a reference “cold” junction \( R \)
- a measuring “hot” junction \( M \)

\[ \text{voltage difference (} V \text{) generation through the thermo-electric Thomson effect} \]
Characteristics


– most common thermocouples:

  type K: NiCr (Chromel) / NiAl (Alumel).

  operating temperature \( T_{\text{ext}} \) [90K, 1000K]

  accuracy: 1.5K (Class 1), 2.5K (for Class 2)

– necessity to protect the thermocouples:

  electrical insulation/thermal protection

    - PTFE: \( T_{\text{ext}} \) [200K, 520K]

    - silk glass: \( T_{\text{ext}} < 720K, \ldots \)
Advantages:
- low cost (a few € to a few hundred €).
- good accuracy: 1.5K (Class 1), 2.5K (Class 2)
- good response time (depending on the thermocouple):
  time constant $t_{63\%}$ [0.05 s, 5s], even 0.007s (0.25mm)
- wide range of temperature (depending on the type)

Drawbacks:
- contact measurement
- punctual measurement fields?

... collections of sensors!
any body at a temperature $> 0$ K emits a thermal radiation

- the infrared radiation occupies only one part of the thermal radiation spectrum (IR-visible-UV : cooler warmer)

- the spectral band covered by the infra-red thermography is narrower: [2$\mu$m, 15 $\mu$m]
**Principles of IR radiometry**

**Motives:** surface temperature measurements
(… for heat sources identification, see IHS–1)

radiating target

I.R. radiation

atmosphere

IR detector
(single, linear, matrix sensor)

Medium: pyrometer, IR focal plane array camera

detector: produces an electrical signal (V) related to the radiated power (W)
exitance: overall flux emitted by the target per unit surface (W.m⁻²)
… for a given bandwidth

\[ R = \int_{\Delta \lambda} \frac{\partial R(\lambda, T)}{\partial \lambda} d\lambda \]

spectral exitance varies with \( T \)!
A simple common situation ...

- **target = « black body »**: able to absorb every incident radiation, \( \text{j} \), \( \text{j} \), \( \text{j} \), (i.e. no reflexion, no transmission: see slide 14).

- **atmosphere = small distance, dry air** (transparent to IR radiations)
  - perfect transmission
  (i.e. every radiation emitted by the target is received on the detector)
Radiation laws

for a black body …

- Planck’s law

\[
\frac{\partial R_{cn}(\lambda, T)}{\partial \lambda} = \frac{2\pi h c^2 \lambda^{-5}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}
\]

- Stefan-Boltzmann’s law

\[
R_{cn} = \sigma_s T^4
\]

\(\sigma_s\) : Stephan’s constant

\[
\sigma_s = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67 \times 10^{-8} \text{ W.m}^{-2}.\text{K}^{-4}
\]

\(R\) : exitance, W.m\(^{-2}\)
\(h\) : Planck, 6.66.10\(^{34}\) J.s
\(k\) : Bolzmann, 1.38.10\(^{23}\) J.K\(^{-1}\)
\(c\) : light celerity, 3.10\(^{8}\) m.s\(^{-1}\)
\(T\) : temperature, K
Remarks on Planck’s law

- the emission spectrum of a black body is continuous
- if $T<2300K$, the totality of emitted energy is in the infrared spectrum
- at fixed $l$, the exitance increases if $T$ increases
- when $T$ increases the maximum of energy moves to the weak wavelength (cf. Wien’s law)
  
  this displacement explains the change of color during the heating of a body.

white yellow orange red

---

displacement of max$(R)$ when $T$ increases
Target and environment

\[ A(\lambda) + R(\lambda) + T(\lambda) = 1 \]

- Energy conservation:
- « Thermal » equilibrium:

\[ A(\lambda) = \varepsilon(\lambda) \]

\[ \text{emissivity} \]

\( A, R \) and \( T \) depend on \( \lambda \), but also on \( j, T, \) surface roughness, …
Classification of several bodies

opaque body: \( \mathcal{T}(l) = 0 \)

black body: \( e(l) = 1, \ R(l) = 0, \ \mathcal{T}(l) = 0 \)

grey body: \( e(l) = cte, \ R(l) = cte \)

selective body

reflective body: \( R(l) \) large, \( e(l) \neq 0 \)

(Reflection and absorption are surface phenomena (occur within a limited, less than 1 \( \mu m \), depth under the surface)

N.B.:  
– no other surface can emit more energy than a blackbody, for given (\( T, l \))  
– the emission of a blackbody is isotropic

\[
\frac{\partial R}{\partial \lambda}(\lambda, \varphi, T) = \varepsilon(\lambda, \varphi) \frac{\partial R_{cn}}{\partial \lambda}(\lambda, T)
\]

\[
R_{\Delta \lambda}(T, \varphi) = \int_{\Delta \lambda} \varepsilon(\lambda, \varphi) \frac{\partial R_{cn}}{\partial \lambda}(\lambda, T) d\lambda
\]
Radiations’ incidence angle

dielectric sphere
emissivity

up to \( j = 45-50 \) degrees, lambertian bodies …

small risks: flat samples

+ grey body with a large emissivity (paint, …)

+ small temperature variations

\[
R_{\Delta \lambda} (T) \approx \varepsilon R_{cn\Delta \lambda} (T)
\]

water emissivity for \( l=10 \mu m \)

\( j \) : observation angle

\( e \) : emissivity
Atmospheric transmittance (I)

\[ T_{\text{at}} : \text{atmospheric transmittance for the standard atmosphere (thickness of 30 m)} \]

(source: Pajani D. ADD Ed.)

- **forbidden wavelength bands** (in \( \mu m \)):
  - [2.5,2.8] absorption of radiation by \( \text{CO}_2 \) and \( \text{H}_2\text{O} \)
  - [4.2,4.4] absorption of radiation by \( \text{CO}_2 \)
  - [5.5,7.3] absorption of radiation by \( \text{H}_2\text{O} \)

- **two common bands** used for infrared detectors:
  - SW: Short Wave [3 \( \mu m \), 5\( \mu m \)]
  - LW: Long Wave [8\( \mu m \), 12\( \mu m \)]
Atmospheric transmittance for the standard atmosphere (30 ppm of CO$_2$ and 50% of humidity)
(source: Pajani D. ADD Ed.)
Measurement by IR radiometry

• advantages:
  - no contact
  - response time ($\mu$s)
  - temperature fields (lines, arrays) at each recorded time
  - good accuracy: $2K$ or $2\%$
  - good spatial resolution (10 $\mu$m)

• drawbacks:
  - cost: from 5k€ to 100k€ …
  - calibration

• many products with many technologies:
  - thermo-detectors: bolometers, …
  - photo-detectors: semi-conductors (In-Sb, …)

• difference between imagery and measure
4 – Infrared Thermography

IR camera description

- image: 320 x 240 pixels
- coding: 14 bits
- frame rate: 250 im/s
- spatial resolution: ± 100 µm/pix.
- NETD: 20 mK at room temp.

NETD: (noise equivalent temperature difference)

\[ \text{NETD} (T_0) = \frac{\text{std}(S)}{\left( \frac{\partial S}{\partial T} \right)_{T_0}} \]

\( (*) \) DL: digital level
IR camera calibration (I) : NUC

manufacturer procedure

- 2 uniform thermal scenes ($F_1$ and $F_2$)
  - white paper sheet ($F_1$) + hand ($F_2$) ...
- DF [X] 50% of the sensors’ range (linear part)
- NUC and BPR operations

**principle of NUC:**

find the gains ($a_{ij}$) and the offset ($b_{ij}$) of each pixel in order to bring the linear part of the responses on the same curve :

$$\tilde{DL} = \alpha_{ij} DL + \beta_{ij}$$

- determination of **one set** of calibration parameters ($a_{ij}$) :

$$T = \sum_{k=0}^{\text{DF}} \alpha_k DL$$
IR camera calibration (II) : NUC

limits of the NUC

- hypothesis of the linear response of the sensor
- non intrinsic definition of \((a_{ij})\) and \((b_{ij})\)
IR camera calibration (III) : BPR

principle of BPR :
(i) detection of « dead » or « abnormal » pixels
(ii) possible replacement of the « defective » pixels

T (°C)

(i) search algorithm (3 criteria) :
– in « gain » :
  (i,j) : \(|\alpha_{ij} - 1| > a\)
– in « offset » :
  (i,j) : \(|\beta_{ij} | > b_2 \ \Uparrow \text{ dyn}\)
– in « noise » :
  (i,j) : \(\text{rms}(T_{ij}) > T_{ij} + c_{\text{std}}(T_{ij})\)

pixels whose response is « very » different from the others

☒ defective pixels
IR camera calibration (IV) : BPR

(ii) different replacement algorithms

drawbacks of the BPR :

– introduction of correlations between neighboring pixels

– errors in the estimation of gradients

– « clusters »
**IR camera calibration (V)**

**laboratory procedure:**
- pixel by pixel calibration

extended plane **black body**:
- \( e(I) \geq 0.98 \)
- \( T(x,y) = T_0 \) (±0.02°C uniformity
  0.008°C precision)

« **dead** » pixels
« **abnormal** » pixels
« **saturated** » pixels
IR camera calibration (VI)

Calibration relation:

\[ T_{ij} = \sum_{k=0}^{d_k} a_{ijk} DL_{ij,k} \]

- (d_k+1) \( n_i n_j \) coefficients
- \( 1,600,000 \) for a \((320\times240)\) image

« defective » pixels determination:

\[(i,j) : \exists k, |T_{ij,k} - T_{BB,k}| > \varepsilon_{dead}\]

- 539 « bad » pixels \( 0.07\% \)
- homogeneous distribution
- a few « clusters »
IR camera calibration (VII)

- precision of the black body
- non-uniformity < 0.02°C

limits of the « laboratory » procedure:
- requires 1 extended black body (30 k€)
- thermal stability of the camera in its environment (4-5 h)
- 1 calibration per shooting condition (integration time, image size, lens, focus, …)
Scales in Infrared Thermography

« microstructure », « mechanisms »

IR camera: 3-5 µm, ...
spatial resolution: ... 15 µm – 0.1 mm ...

Ms: macro

[ L. Bodelot, LML ]
[ M. Poncelet, LMT]
[R. Fillit, ENSM-SE]
Temperature fields for IHS

– « dense » temperature fields on the boundaries
  multiple punctual sensors (thermocouples, optical fibres pyrometers, …)
  IR cameras

– high temporal resolution:
  ultra-fast imaging devices (1 MHz frame rate, scanning devices)

– emissivity determination:
  multi-spectral thermography, …

– multiple physics:
  simultaneous knowledge of other state variables (strain, phase proportion, …)

– IR tomography?
  identification of heat sources: see IHS–1