Part 1
Introductory examples

Thermal imagery, what does it look like?

- Incoming cold air
- Fuses
- Moisture in flat roofs
- Floor heating
Introductory examples

- Inner structure of walls
- Bad contact
- Layers of air
- Storage tanks
- Another bad contact

Introductory examples

- Mechanics
- Electronics
- Electric power transmission

Introductory examples

- Transformer
- Inflammation
- Water leak
- District heating

Part 2
Infrared and other "light"

What does the camera see, and why?

From where cometh the light?

From where comes the radiation?

- Emitted
- Transmitted
- Reflected
Components of the radiation

- Incoming radiation
- Reflected radiation
- Absorbed radiation
- Transmitted radiation
- Studied object

So why does it shine?

Emitted (thermal) radiation

Emission according to Planck's Law:

\[ L_\nu(T, \lambda) = \frac{2\pi^5 \kappa^2 \cdot 10^4}{\lambda^5 \exp\left(\frac{\kappa \lambda}{\theta}\right) - 1} \]

Emitted radiation

\[ L_\nu(T, \lambda) = \frac{\epsilon(\lambda)}{L_\nu(T, \lambda)} \]

Spectral signature

\[ L_\nu(T, \lambda) = \epsilon(\lambda) \cdot L_\nu(T, \lambda) \]
What does the camera see?

Atmosphere transmission
Atmosphere temperature
Radiation from atmosphere
Reflected radiation
Radiation from environment
Opaque object
Emitted energy
Object emissivity
Object temperature

Some fundamental units

- Emissivity $\varepsilon$
- Absorptivity $\alpha = \varepsilon$
- Transmittance $\tau$
- Reflectance $r$
- Radiance $L \ [W \ m^{-2} \ sr^{-1}]$
- Irradiance $E \ [W \ m^{-2}]$
- $\tau + \varepsilon + r = 1$
- For many materials, $r$ or $\tau$ are close to zero.

Angle dependence - BRDF

Domains and wavelengths

Reflective vs emissive, visual vs infrared, ...

Domains

- Light is originally emitted and then commonly reflected.
- Light sources emit light. Per definition.
- In the reflective domain, light behaves as we are used to.
  - Dominated by reflected light.
  - Many materials have high and varying reflectance (ie, colour).
- The emissive domain is dominated by emitted light.
Atmospheric transmission

Transmission

Wavelength [µm]

[Graph showing transmission over different wavelengths]

Infrared, and other, "light"

- UV: Ultra violet
- VIS: Visual
- NIR: Near infrared
- V-NIR: VIS+NIR
- SWIR: Short wave IR
- MWIR: Midwave IR
- LWIR: Longwave IR
- FIR: Far infrared
- TIR: Thermal IR

- Almost visual, you just can’t see it. Your cellphone can.
- Mostly emitted light.
- Mostly reflected light.
- Often the same as LWIR.
- Yeah, this one too. Can include MWIR as well.

Example:

- Reflected radiation
- Emitted radiation
- Reflected and emitted

Example: Reflected radiation
- Visible image (0.3-0.7 micrometer)
- Longwave image (8-12 micrometer)

Example: Emitted radiation

- A sensor integrates the incoming energy over a certain bandwidth.
- The radiation appearing at the sensor is (typically) the sum of:
  1. The emitted object radiation transmitted through the atmosphere
  2. The emitted atmosphere radiation
  3. The reflected radiation transmitted through the atmosphere
- This does not equal the temperature of the object!
And remember, the radiation is...

Part 3
Thermal cameras
Cooled vs uncooled – Performance measures – Image formation

IR cameras

Temperature measuring cameras

IR cameras

Cooled vs uncooled cameras

Sensitivity: 20 mK – 150 mK.
Precision: ± 1 K to ± 2 K / ± 1% to ± 2 %
Frame rate up to:
  • Hundreds / thousands fps (cooled)
  • 62 fps (uncooled)
Resolution: 60 x 60 to 1920 x 1280
Cooled vs uncooled cameras

Titanium 520M, integration time = 170µs

Uncooled camera 320 x240 pixels

Cooled vs uncooled cameras

Cooled detectors

- Previous lecture
- Semiconductors whose bandgap energy is less than the photon energy we want to detect.
  - 0.25 eV for 3-5 µm
  - 0.1 eV for 8-13 µm
  - 1.1 eV for silicon detectors (visual cameras etc.)
- Incoming photons give a change in resistance, voltage or current (depending on detector).
- Requires cooling!
  - Stirling engine cryometer
  - Liquid nitrogen

Cooled

Common cooled detector materials

- MCT – Mercury Cadmium Telluride (HgCdTe)
  - SWIR, MWIR, LWIR: Broad spectral range
- InSb – Indium Antimonide
  - SWIR, MWIR
- GaAs – Gallium Arsenide
  - QWIP – Quantum Well IR Photodetector
  - Shot noise, but almost no thermal noise
  - MWIR, LWIR

Uncooled

Thermal detectors

- Pyro-electric detectors
- Microbolometer

The common detector in handheld and industrial IR cameras.

Internal radiation

- Much of the radiation hitting the sensor is emitted by the camera.
  - 90% is a realistic value.
- One or more internal thermometers.
- On-board processing.

Uncooled

3 thermometers in this one!
Pros
• No cooling
• Robust
• Low weight
• Small
• Inexpensive
• Quiet

Cons
→ Angular resolution
→ Temperature resolution
→ Slow

• Glass transparent in VNIR. Inexpensive optics.
• Germanium (sometimes with diamond coating) transparent in IR. Expensive optics.

Performance measures (1)
• Temperature resolution = the smallest temperature difference that can be measured
  – NETD (Noise Equivalent Temperature Difference)
    \[ \text{NETD} = \frac{\sigma_N}{\Delta T} [\text{mK}] \]
  – MRTD (Minimum Resolvable Temperature Difference): Minimum temperature difference between a "4-bar" and the background for enabling an operator to count the bars. Typical value: 0.3 K.

Performance measures (2)
• NEP (Noise Equivalent Power): The incoming radiation \( S \) giving a signal-to-noise-ratio equal to one (\( S/N = 1 \)).
• Normalised detectivity \( D^* \): Performance measure independent of detector size \( A_d \) and bandwidth \( \Delta f \).
  \[ D^* = \frac{\sqrt{A_d \Delta f}}{\text{NEP}} [\text{cm} \sqrt{\text{Hz/W}}] \]

Image formation
Scanning vs. staring
Detector to image (1)

- One pixel (detector) or a line of pixels scan the image mecanically/optically using moving mirror(s).

Detector to image (2)

- Two dimensional “staring” array of pixels generating the image directly.

FPA development

Generalised Focal Plane Array development

- Dense array
- Sparse array
- TDI array
- Sprite array
- Small 2-D array
- Large 2-D array

Limitations

- Blooming – Noise – Uniformity – MTF

Sensor limitations

- Blooming: Leakage between pixels.
- Noise: Background, detector, electronics.
- MTF: Modular Transfer Function.
- Uniformity (next slide).

Uniformity (example)

- Two acquisitions, \( \Delta t = 0.04 \) s, surface with flat temperature \( \sim 22.5 \) °C.
- Measurement in 4.5-5 µm (MWIR).
- Operability [%] – Percentage useful (= non-defect) detector elements in an FPA.
- NUC: Non-uniformity correction.
Sensor development

1990

2006

2012

Summary

- Thermal cameras are cooled or uncooled
  - Cooled: Noisy, cumbersome, expensive, fast, sensitive.
- Most cameras you will see are uncooled bolometer cameras operating in LWIR.
- Optics for VNIR: Glass.
  Optics for thermal: Germanium (expensive).
- Sensor development is fast.

Multispectral sensors

- Sensors for multiple wavelengths.
- Each pixel gives a spectral signature.

Multispectral cameras

What, how, and why?

Spectral images

- Grayscale image – one band
- Color image – three bands
- Multispectral image – several bands
- Hyperspectral image – many bands

Hyperspectral image processing

- Why?
  - Each pixel gives information about the material!
  - See the difference between "tank pixels" and "tree pixels"!
- Hyperspectral information is not that easy to "watch"
  - Each pixel is a multidimensional vector.
Five ways of making a multi/hyperspectral sensor

Mosaic – Multilayer – Filter wheel – Scanning – Interferometer

**Principle 1 - Mosaic**

- The common digital camera
- Small filter on each sensor element
- The colours are not aligned!
- OK, Klas already told you in a previous lecture, right? So let’s move on.

**Principle 2 – Multilayer**

- Broad band sensor.
- Rotating filter wheel with N filters between the sensor and the optics.
- Each N:th image from band k.
- In a static world, the pixels are registered (aligned).

**Principle 3 – Filter wheel**

- 2 bands in SWIR
  - Much reflected radiation
- 2 bands in MWIR
  - Much emitted radiation

**MultimIR: 4-band SWIR/MWIR**

**Sensor example - MultimIR**
Principle 4 – Scanning

Push-broom

Principle 5 – Interferometer

Hyperspectral: Ground-to-ground recon

Summary

- Use multiple wavebands to see better!
- Recognize materials in one pixel!
- Five ways of making a multi/hyperspectral camera.
- Applications: Mostly remote sensing (military, environment)
Part 5
Application examples

Military applications

Application example

Night Vision Devices

High night sky radiance!

“Image enhancers”, not thermal IR!

Mine detection

08:14 08:22 16:47

IRST – Infrared Search and Track

LWIR

Missile Approach Warning

• Detects IR from rocket engine ans/or missile hull
• MWIR and/or LWIR
• Advanced signal processing
• Detection distance ~3-10 km
• Scanning systems are available commercially, staring under development.
UAV reconnaissance

Night vision for driving

Night vision for driving

Target detection

Non-destructive testing (NDT)

Non-destructive testing

Application example

Real-time (video rate) detection of pedestrians in thermal-infrared video.

Robust detection of military ground vehicles in thermal infrared data.
No, you can’t see inside solid objects with a thermal camera, but you might observe the effects of the inside.
Cows!

Application example

Operator view

Automatic milking

Example images
Surveillance & tracking

Application example

An image-based tracker

Tracking of objects

- Note that objects are not always warmer than the background.

Pirates (ok, this is a fake pirate)

Computer vision problems

- Extreme scale variations
- Low contrast (sometimes)
- Wakes
- Occlusion (wakes, waves, ...)

To be solved...

District heating pipes

Application example

District Heating Pipes
District Heating Pipes

Fire detection in waste & biofuel

"The Ultimate Handbook..."

- Read Ch. 1-3.
- Books donated by Termisk Systemteknik AB.
Master's thesis projects:
- Image analysis
- Thermography
- Software development

Contact Jörgen Ahlberg, jorgen@termisk.se