Infrared Imaging for Investigations of Plants and Plant Products

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Content

• Introduction:
  Background & state of the art

• Material and methods:
  Basic principles and cameras

• Results and discussion:
  Laboratory experiments,
  Field experiments

• Conclusions
Historical background

• First night vision systems used in World War II

• Sensitive IR-sensors (MCT, DTGS, micro-bolometer arrays) as secret military development, then in science (FT-IR), astrophysics (IR-cameras) and satellites (remote sensing)

• Routine applications of IR-imaging start with availability of powerful PCs and sensor arrays (security systems, building insulation, control of engines, electrical wiring and circuits, medicine etc.)

• Since 1990 IR-imaging in different plant studies
Background

• Literature: NIR reflection may depend on variety, state, and composition of plants


• West J.S. et al.: The potential of optical canopy measurement for targeted control of field crop diseases (2003)
Background

- **Literature:** Infrared temperature measurements of fruits, leaves, single plants, and crop canopies (transpiration, dry stress etc.)

- Tanner C. B.: *Plant temperatures* (1963)

- Danno A. et al.: Quality evaluation of **agricultural products** by infrared imaging method (1978)

- Beverly D. et al.: Thermography as a non-destructive method to detect invisible **quality damage in fruits and vegetables** (1987)

- Inoue Y.: Remote detection of **physiological depression in crop plants** with infrared thermal imagery (1990)

Background & state of the art

• Thermography at ATB (since eight years):
• Transpiration of fruits

Sound apple:

Cut apple:

Apple with notch:

Local temperature decrease by transpiration at defect skin
Background & state of the art

• Thermography at ATB:
• Transpiration of fruits
Background & state of the art

- Thermography at ATB:
  - Classification of mechanically damaged surface of carrots

left ... level 2 – high intensity cleaning,
middle ... level 1– lower intensity cleaning,
right ... two unwashed references
Background & state of the art

• Thermography at ATB:
  • Temperature distribution over lettuce in a chilled food display cabinet
Background & state of the art

• Frozen chicken temperatures in freezer unit

http://www.flirthermography.com/success/ir_image/1010/application_id/1000/
Background & state of the art

• Thermography at ATB:
• Temperature distribution at potato storage boxes

Photo and IR-image of potato boxes (4000 kg) shortly after harvest
Background & state of the art

- Thermography at ATB:
  - Thermal imaging camera with dust protection
Background & state of the art

• **Thermography at ATB:**
  - Temperature of potatoes at top of storage boxes

(after harvest, beginning of storage period)
Current project

- Does **imaging at different wavebands** (NIR and MIR) improve the diagnostics of plants?

- Can a change in transpiration rate be made visible by **images** taken in NIR spectral ranges with and without **water bands**?

- Is it possible to **distinguish infested plants** from less infested plants in field measurements?
Temperature of biological objects

- Metabolic heat generation

- Exchange of heat and water with ambient air (radiation, convection, condensation, and transpiration).
Temperature and image

Image: measured distribution of radiation flux density

\[ \Phi_I = C_{\text{constant}} \varepsilon_I T_I^4 \]

Temperature: ratio of \textit{radiation flux density} and emissivity

\[ T_i = C_{\text{measure}} \left( \frac{\Phi_i}{\varepsilon_i} \right)^{0.25} \]

Camera sensor

Calibration
Materials and Methods
• Materials and Methods

**Thermal Imaging camera**

**Static scenes:**
Stirling engine cooled IR scanning camera
Varioscan™ 3021-ST (Jenoptik Technologie GmbH) with
**MCT-sensor** (*Mercury Cadmium Telluride*),
8-12 μm wavelength with

temperature **resolution of about 0.03 K** at 300 K,

**one image per second**, 360h x 240v pixels
• Materials and Methods

Thermal Imaging cameras

FPA-camera (Focal Plane Array)
ThermaCAM® 545 (FLIR Systems GmbH),
ThermaCAM® SC 500 (FLIR Systems GmbH),
with micro-bolometer array, non-cooled,
7.5-13 µm wavelength with

temperature resolution of 0.1 /0.07 K at 300 K,

50 images per second, 320h x 240v pixels
Materials and Methods

**NIR Imaging camera**

FPA-camera (*Focal Plane Array*)

ALPHA NIR™ (Indigo Systems Corporation, now merged with FLIR systems),

**InGaAs-sensor** (*Indium Gallium Arsenic*),

0.9-1.7 \( \mu m \) wavelength with sensitivity of \( 10^{10} \) photons cm\(^{-2} \) s\(^{-1} \) \( (2 \times 10^{-5} \) W m\(^{-2} \)

30 images per second, 320h x 256v pixels
Laboratory measurements
VIS and NIR reflection spectra of healthy wheat plants and of plants, infected by stripe rust.

Each given spectrum is the mean of 20 individual spectra. Arrows indicate characteristic wavelengths (chlorophyll and H$_2$O).
NIR Transmission – Water bands

Humidity 50 %
Temperature 23°C
Path 3 m
Range: 0.9 – 1.7 μm
Calculated by HITRAN92

[Graph showing transmission bands at 1000 nm, 1075 nm, 1175 nm, and 1420 nm with NIR Filter highlighted]
Thermal image of wheat plants (*Triticum aestivum*, variety “Kanzler”)

Air temperature 22.5°C, relative humidity 47%

Left plant is infected by powdery mildew and right plant is healthy.
Wheat plants infested by powdery mildew and of healthy wheat plants (right pot)
Evaluation of greyscale images

Histograms for two greyscale images are shown, with the following statistics:

**Image 1: 1075nm_auto.bmp**
- **Mittelwert:** 138.94
- **Std-Abweichung:** 78.55
- **Zentralwert:** 143
- **Pixel:** 79632

**Image 2: 1420nm_auto.bmp**
- **Mittelwert:** 119.25
- **Std-Abweichung:** 72.05
- **Zentralwert:** 117
- **Pixel:** 79632
Evaluation of greyscale images

<table>
<thead>
<tr>
<th>Greyscale pseudocolour</th>
<th>Binary image threshold 100</th>
<th>Binary image threshold 128</th>
<th>Binary image threshold 175</th>
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</thead>
<tbody>
<tr>
<td>![Image](1075 nm)</td>
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<td>![Image](1420 nm)</td>
<td>![Image](1420 nm)</td>
<td>![Image](1420 nm)</td>
<td>![Image](1420 nm)</td>
</tr>
</tbody>
</table>
Evaluation of greyscale images

Quotient and difference
pseudocolour

1075 nm - 1420 nm

Quotient and difference
Binary image threshold 128

1075 nm - 1420 nm

1075 nm / 1420 nm

1075 nm / 1420 nm
Evaluation of greyscale images

Difference 1075 nm - 1420 nm in pseudocolour (Examples for pseudocolour)
Field experiments
Tractor with mounted thermal IR and NIR cameras in the experimental field
Scheme of stripe arrangement and measuring path in 2003

(1 – 10 Notation for the following temperature diagram)

- 3 p.m. summertime
- 2 p.m. summertime
- 4 p.m. summertime

Sun: irradiation 11th of June
Thermal images and photos of different areas of wheat fields (above: left side untreated and right side sprayed; below: sprayed). The dominating effect is scattered heating (shadow effect) of wheat plants.
Winter wheat crops at the experimental field with non-sprayed (spot 6, upper images) and sprayed (spot 4, lower images) stripes.

Measurement on 11/06/2003,
air temperature $T = 30.5 \, ^{\circ}C$ and humidity $RH=42.5\%$.
The mean temperature of spot 4 is 2.0 K higher than the mean of spot 6.
Temperature difference between wheat crop and ambient air

Measuring conditions: Measurement on June 11, 2003, 1.20 - 4.00 p.m.;
Variability between measuring spots: few clouds
(sunshine between ca. 50% and 100%),
air temperature 26.2°C - 32.5°C, relative humidity 42.4% - 66.2%,
air speed 1 m s⁻¹ - 9 m s⁻¹, average crop height at measuring spots 42 cm - 93 cm
Temperature difference between wheat crop and ambient air

Measuring conditions: Measurement on July 10, 2003, 10.10 - 11.30 a.m.;
Variability between measuring spots: cloudy,
(sunshine between ca. 0 % and 25 %),
air temperature 17.2°C – 19.9°C,
relative humidity 53.8% - 66.5%, air speed 3 m s⁻¹ - 9 m s⁻¹
**Temperature of air and crop**

Measuring conditions: Measurement on June 11, 2003, 1.20 - 4.00 p.m.;
Variability between measuring spots: few clouds
(sunshine between ca. 50% and 100%),
air temperature 26.2°C - 32.5°C, relative humidity 42.4% - 66.2%,
air speed 1 m s⁻¹ - 9 m s⁻¹, average crop height at measuring spots 42 cm - 93 cm

<table>
<thead>
<tr>
<th>Measuring plots</th>
<th>Mean value 1-10</th>
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<tbody>
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- **Green**: Air within canopy
- **Blue**: Air above canopy
- **Orange**: Sprayed crop
- **Yellow**: Non-sprayed crop
Temperature of air and crop

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![Graph showing temperature variations across different plots and conditions.](image)
Conclusions

(shortcomings)

• Dependence on state of ambient air (definite airflow, constant relative humidity, constant temperature, influence of shape and surface to volume ratio on transpiration, ...)

• Dependence on emissivity, on type, and on state of plant material (emissivity & water status, shape of fruits & cosine law, ....)

• Reflection of ambient heat sources (as emissivity is < 1)

• Heat capacity (temperature drift of material or ambient air)

• Cost intensive (and relatively sophisticated) technique
Conclusions
(examples for fast and remote sensing)

• Mechanical damage of fruits and vegetables can be detected.

• Qualitative classification of varieties and stage of ripeness.

• Evaluation of freshness and microbial infestation, if transpiration is involved.
• Air conditioning for food displays and storage houses.

• Fungi infections, which cause variations of surface temperature, may be recognised by infrared cameras under laboratory conditions.

• In the field, natural temperature variations of several Kelvin within the crop canopy prevent the recognition of infected plants by commercial thermal vision systems as stand-alone solutions.

• Near infrared cameras fitted with band-pass filters show different intensity distributions of the reflected radiation. The evaluation of the spectral intensity relations improves the differentiation chances.