Appendix U

Development towards 3D thermography

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Abstract

The presentation reports on an activity aimed at solving the biggest issue of existing IR camera thermography, i.e. the temperature measurement of objects with significant 3D surface variability (wrinkles and folds). Such variations can alter the interpretation of images where the surfaces have significant directional emissivity variations and hot sources are brought in the field of view of the test surfaces. The latter is especially critical when measuring cold objects.

The activity covered the development of a method using IR cameras for 3D geometrical mapping of the test specimen and IR flux measurement. Correction of measured apparent temperature is based on a ray tracing approach. The method developed was validated by test.
Non-contact temperature measurement for thermal (vacuum) testing

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- Introduction
- Background
- Concept
- Development and validation
- Testing at ESTEC
- Conclusions
Introduction

All space-craft need a validated thermal model – tested in a TVC

Contact sensor (limitations)
- single point; spatially limited
- slow response time (vs camera)
- thermally disruptive (adds to thermal leakage)
- requires all sensors to be perfectly matched (and calibrated) when used in multiples
- visualisation not automatic

Non-contact sensor (advantages)
- visualisation available live - detect areas “missed” by contact sensors
- rapid response time (vs. contact sensors)
- non-contact i.e. no thermal disruption, no contamination, or potential for physical damage
- can read true surface temperatures (except if not corrected for ambient/material)

Objective: from captured apparent temperature thermal images recover true surface temperature

Background – Thermal imaging challenges

- Emissivity: varies with temperature, wavelength, surface angle (material structure)
- TVAC: wide temperature range (including sub ambient)
- Background radiation: external (environment & 'hotspots’) AND local radiant sources can be reflected from the surface of interest
- Robust thermal imaging temperature measurement traceability (temperature calibration)
- Robust thermal / dimensional spatial registration (geometrical calibration)
Development towards 3D thermography

Development – Geometrical & Thermal measurement (Hardware)

- Image point measurement
- Image orientation
- Building the network
- Bundle adjustment
- Network scaling

- Calibration to ITS-90 (ISO-17025)
- Uncertainty (GUM)
- Stability / uniformity
- SSE (size of source effect)

- Emissivity measurement rig (angular)
- Determinations for full temperature range
- Same spectral responsivity (same detector / filter combination)
Development – Software (undistorted & ray tracing)

Thermal photogrammetry: Images, calibration corrections etc..

Virtual scene generation: material properties, ray tracing etc..

WP3 – Design concept overview and test object Design

Given temperature image

Ray tracer engine (including Plank formula)

Rendered image

Modify initial temperature value

Difference small?

True temperature image
Validation – simulated and laboratory

Simulated wedge scenario temperature validation

By using the calibrated BRDF lookup table
By using the built-in pbrt pure lambertian material.

Laboratory wedge scenario temperature validation

Raw "apparent" temperature
Contact thermocouple
NPL - Commercial
Rendered "true" temperature

1/3 scale TEDY

Validation – ESTEC

LWIR camera

10 [labels]

NPL - Commercial
Development towards 3D thermography

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8b. WP5 - Pre-test at NPL and ESA pre test and full test at ESTEC – data collection

- Software validation trials at ESTEC
  - A pre-test was done to check operation of the TEDY and cameras and to trial process some data – this was successful producing similar results to the NPL test.
  - Then - ESTEC TEDY (full test) was done with project team collecting data and pre-evaluation results.
  - TEDY shown in ambient conditions and with 25kw “sun”

8c. WP5 - Pre-test at NPL and ESA pre test and full test at ESTEC – data collection

- Example test data collected – thermocouple data and example IR image from one MW camera
- 16 data sets in all collected with 2 MW and 1 LW – temperatures of heated zones from 20-70°C
9b. WP6 – Overview of Test data analysis, performance assessment, conclusions, recommendations and forward outlook

- Effect of reflections and external hot spots reproduced in the ray traced simulations of the IR temperature field.
- Ray-traced/rendered corrected temperature of all regions agrees to thermocouple almost within uncertainties at $k=2$ (95% confidence)

<table>
<thead>
<tr>
<th>Material</th>
<th>Internal function</th>
<th>Apparent Temperature</th>
<th>Thermocouple Temperature</th>
<th>True Temperature</th>
<th>Difference Temperature</th>
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<tbody>
<tr>
<td>Plaster</td>
<td>0.8 (matte)</td>
<td>300</td>
<td>301</td>
<td>N</td>
<td>N</td>
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<tr>
<td>MCL 107</td>
<td>0.2 (matte)</td>
<td>299</td>
<td>302</td>
<td>3</td>
<td></td>
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<tr>
<td>CP108</td>
<td>0.9 (matte)</td>
<td>305</td>
<td>304</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B1 (0.3, matte)</td>
<td>305</td>
<td>307</td>
<td>302</td>
<td>3</td>
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<tr>
<td>A1 (0.1, mirror)</td>
<td>305</td>
<td>297</td>
<td>300</td>
<td>+5</td>
<td></td>
</tr>
<tr>
<td>B2 (0.1, mirror)</td>
<td>302</td>
<td>292</td>
<td>300</td>
<td>+5</td>
<td></td>
</tr>
<tr>
<td>A2 (0.3, matte)</td>
<td>298</td>
<td>295</td>
<td>305</td>
<td>+10</td>
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<tr>
<td>Roof (0.1, mirror)</td>
<td>298</td>
<td>297</td>
<td>302</td>
<td>+3</td>
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<td>Cylindrical (0.1, mirror)</td>
<td>320</td>
<td>320</td>
<td>336</td>
<td>+10</td>
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<tr>
<td>Black body (0.99)</td>
<td>327</td>
<td>327</td>
<td>328</td>
<td>0</td>
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</table>

Validation – ESTEC: 50 °C (no illumination)
Validation – Uncertainty model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Source of Uncertainty</th>
<th>Value ±</th>
<th>Type</th>
<th>Divisor</th>
<th>Conversion</th>
<th>UI</th>
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<tr>
<td>U1</td>
<td>Camera calibration</td>
<td>1.00</td>
<td>B (normal)</td>
<td>1</td>
<td>1</td>
<td>±0.0</td>
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<tr>
<td>U2</td>
<td>Emissivity of material</td>
<td>0.05</td>
<td>B (normal)</td>
<td>1.73205</td>
<td>0.008888</td>
<td>±0.0</td>
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<tr>
<td>U3</td>
<td>Image non-uniformity</td>
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<td>B (rectangular)</td>
<td>1</td>
<td>±0.0</td>
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<td>U4</td>
<td>Distance effect</td>
<td>0.06</td>
<td>B (rectangular)</td>
<td>1.73205</td>
<td>0.008888</td>
<td>±0.0</td>
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<tr>
<td>U5</td>
<td>Digitalisation of signal</td>
<td>0.01</td>
<td>B (rectangular)</td>
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<td>Camera location</td>
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<td>U11</td>
<td>Software processing</td>
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<td>U12</td>
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<td>A (normal)</td>
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<td>1</td>
<td>±0.6</td>
</tr>
</tbody>
</table>

k = 1 U combined 2.3
k = 2 U combined 4.6

9f. WP6 – main conclusions

- The 3-D thermography system can detect most surfaces and reconstruct the surface angles successfully where there is a thermal contrast / texture in the image, or where external patterning is “achieved” on mirror surfaces – to better than 1mm at 3m standoff.

- The ray tracing process for correcting temperatures compares well to thermocouple data within the combined standard uncertainty of the system based on a GUM assessment / estimate.

- The system can correct apparent T(IR) temperatures for internal reflections within the structure and external hot sources (where the hot source is correctly modelled or imported into pbrt).

- The system has illustrated how correcting T(IR) temperatures can improve on poorly located thermocouples or where heating is dynamic.

- Uncertainties are on average +/-5°C at 68% confidence with the largest sources of uncertainty being the image non-uniformity and the hemispherical emissivity measurement.

- Uncertainties can be reduced by full traceable calibration of the instruments.
Conclusions

- A non-contact temperature measurement solution (hardware + software) is fully operational for testing (in ambient scenario)
- Validation tests proved the uncertainty of the true temperature for the mean case to be within the anticipated range, but can be improved as we see the largest sources of uncertainty can be readily reduced
- The method gives confidence in situations where thermocouples are erroneous (placement / malfunction / transient heating)
- A robust metrological approach (calibration, traceability, uncertainty mapping and standardised procedure) ensuring confidence in the geometrical and thermal outputs

Applications:

- In general where:
  - Non-contact thermometry is beneficial or necessary
  - Higher thermal nodes (measurement points) are of benefit / required
  - Additional measurement (e.g. geometric / dynamic) information is required
  - Thermocouples are missed or read wrong due to their location or local transient heating

Future development:

- In situ thermal and geometrical calibration of sensors
- Use of higher resolution IR cameras
- Combining the visible and IR images
- Improving the true temperature estimation
- Speed-up of the computation
Questions