

Motivation & Background

Active infrared thermography (IRT) is a key tool in non-destructive testing (NDT), providing real-time visual representations of thermal patterns caused by subsurface defects such as cracks, delaminations, and voids. Defect detectability is frequently constrained by measurement noise, spatial non-uniformities, and the intrinsically diffusive nature of heat transfer. To mitigate these limitations, a range of post-processing approaches has been proposed to enhance defect detectability.

Challenges with current post-processing approaches:

- **No consensus** on the best post-processing technique for a given material or defect type. Practitioners rely on trial and error and experience guidelines.
- Most techniques produce a **sequence of images** that must be manually reviewed, making the process time-consuming and error-prone.
- **Optimal frame varies** per defect: shallow defects peak early, while deeper defects require later frames.
- Environmental factors (emissivity variation, non-uniform heating) further complicate interpretation.

Post-processing methods reveal complementary information. No single method captures all defects optimally.

Post-Processing Methods Reviewed

Thermographic Signal Reconstruction (TSR)

Fits a polynomial to the temperature-time profile of each pixel. Enables analytical derivative computation, significantly enhancing defect contrast, especially using the **2nd derivative**. Optimal frame depends on defect depth.

Principal Component Thermography (PCT)

Applies SVD to decompose the thermal sequence into Empirical Orthogonal Functions (EOFs). Improves SNR and highlights subtle thermal anomalies. In some applications (e.g. cultural heritage), relevant features may reside in higher-order components.

Pulse Phase Thermography (PPT)

Applies FFT to each pixel's temperature-time history, extracting phase images. Phase is less sensitive to non-uniform heating and emissivity variations.

Partial Least Squares Thermography (PLST)

Decomposes temperature histories into latent variables via PLS regression, discarding irrelevant information and reducing effects of non-uniform heating.

Key Insight

No single post-processing technique captures all defects in a single frame. **Combining multiple sequences** from different methods into a unified representation can improve defect detectability and simplify operator analysis.

Proposed Approach

The method fuses multiple post-processed thermal sequences using a **Multi-Scale Signal-to-Noise Ratio (MS-CNR)** metric. The workflow:

1. Apply TSR, PCT, PPT, and PLST to the raw infrared sequence.
2. **Concatenate** the resulting sequences into a single combined 3D tensor.
3. Apply the MS-CNR metric at each pixel and frame across multiple spatial scales.
4. Generate four **condensed images** summarising the entire sequence.

MS-CNR Metric

The MS-CNR operator applies the Laplacian of Gaussian (LoG) at multiple scales, normalised by local noise:

$$\text{MS-CNR}(I) = \max_{(x,y,\sigma_x,\sigma_y)} \frac{|\sigma_x \sigma_y \nabla^2 n_{\sigma_x, \sigma_y} * I(x, y)|}{\sigma_N}$$

where σ_N is estimated via a windowed median of local standard deviations, ensuring scale-sensitive, robust noise compensation across sequences with different intensity ranges.

Condensed Images

- **Maxigram**: Maximum MS-CNR value across all frames and scales for each pixel – highlights regions of highest contrast.

$$Mg = \max_i \text{MS-CNR}(I_i)$$

- **Sigram**: Scale σ at which the maximum MS-CNR is achieved – encodes the spatial size of the detected feature.

$$\text{Sig} = \sigma_i \text{ where } \text{MS-CNR}(I_i) = Mg$$

These representations are **complementary**: The maxigram captures the maximum contrast per pixel while the sigmagram encodes the spatial scale (sigma) at which this maximum occurs. The maxigram captures the most informative representation of the defect, while the sigmagram provides insights into the spatial characteristics of the thermal response, which is related to defect size.

Experimental Validation

A carbon fiber composite specimen with challenging subsurface defects is used for evaluation. Internal defects were introduced using two materials:

- **PTFE sheets** – simulate delaminations (ply separation)
- **Metal shavings** – represent accidental manufacturing inclusions

The 12 defects vary in size and depth, ranging from a 12×12 mm defect at 0.63 mm depth to a 5×5 mm defect at 2.08 mm depth.

Inspection is performed in **reflection mode**. The specimen is heated for 10 s over a 20 s acquisition at 50 fps. The raw sequence is post-processed with **TSR**, **PCT** (EOF components), **PPT** (phase images) and **PLST**.

Results

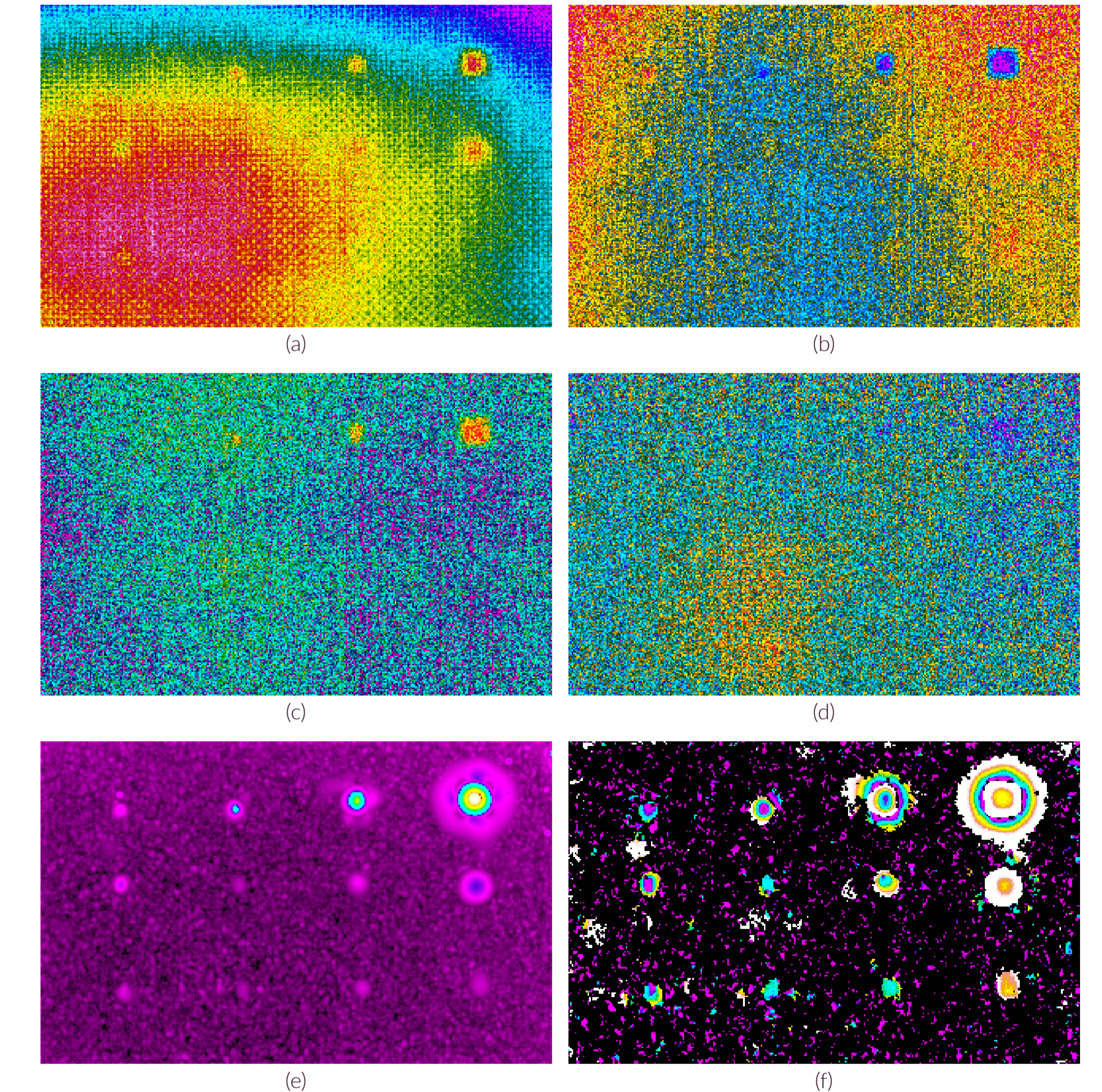


Figure 1. Results of the inspection for the carbon fiber composite specimen. (a): First derivative at time 1.6 seconds. (b): Second derivative at time 1.6 seconds. (c): EOF 4. (d): Lowest frequency of the PPT. (e): Maxigram, (f): Sigmagram.

The **Maxigram** and **Sigmagram** enable identification of *all* defects in the specimen in a single image, with clear contrast and a uniform background.

The proposed method clearly outperforms other fusion methods such as wavelets both qualitatively and quantitatively across all experiments.

Conclusions

- A novel **multi-sequence fusion framework** for active IRT NDT is proposed, based on the MS-CNR metric.
- The method condenses multiple post-processed sequences into **interpretable images** (Maxigram, Sigmagram), simplifying operator analysis.
- **Superior SNR** compared to individual post-processing techniques and wavelet-based fusion.
- **Method-agnostic**: compatible with TSR, PCT, PPT, PLST, or any future technique.
- Reduces reliance on manual frame selection and expert knowledge, improving inspection **efficiency and reliability**.