A Diagnostic Approach for Ancient Book via Solar Loading Thermography Method

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Abstract

This work applies 3D super-resolution to outdoor thermographic data of cultural heritage objects using a 3D Enhanced Video Denoising and Resolution (3D-EDVR) model pre-trained on the 3D Image Super-Resolution Dataset (3D-SR) dataset and fine-tuned on custom simulation data. Enhanced thermal sequences undergo Fast Fourier Transform (FFT), and Fast Iterative Filtering (FIF) to improve defect visibility. Results show a substantial increase in Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index Measure (SSIM) compared to original data, enabling clearer detection of fabricated defects under natural light conditions.

1. Introduction

Thermographic inspection is a valuable non-invasive technique for monitoring the condition of precious artefacts [1,2,3]. When applied outdoors under natural lighting, however, thermal images often suffer from noise, low resolution, and temperature fluctuations, which can obscure not visible defects. Enhancing the resolution of the three-dimensional thermal sequences is therefore essential for accurate alterations detection and conservation planning.

In this study, the authors build upon the stabilization methods introduced by Huang et al. (2022) by applying a 3D super-resolution approach using 3D-EDVR [4]. The model is first pre-trained on the publicly available 3D-SR and then fine-tuned on a custom simulation dataset that closely replicates outdoor thermography conditions [5]. By combining 3D-EDVR with post-processing techniques FFT, and FIF [6,7,8,9]. This research aim to produce high-quality thermal sequences in which defects become more pronounced and easier to analyse [10,11,12].

The remainder of this paper outlines the methodology suggested by the authors, evaluates the results under standard metrics (PSNR, SSIM), and compares the enhanced sequences to the original data, demonstrating clear improvements in defect visibility.

2. Related Work

Thermographic enhancement for cultural heritage has historically relied on classical signal-processing techniques such as Principal Component Analysis (PCA) and FFT to suppress noise and highlight thermal patterns. More recently, deep learning approaches have achieved notable success in medical and industrial imaging for super-resolution tasks. The 3D-EDVR framework extends video super-resolution to volumetric data by learning spatiotemporal correlations through deformable convolutions and residual modules. Transfer learning from large, publicly available 3D datasets (e.g., 3D-SR) to domain-specific tasks has proven effective when annotated data are scarce. The present work integrates these advances by fine-tuning 3D-EDVR on thermographic simulation data and applying post-processing to maximize defect detectability.

3. Methodology

The authors employ a two-stage training strategy. First, the 3D-EDVR network is pre-trained on the3D-SR, learning a mapping $F_\theta : LR_{3D} \rightarrow HR_{3D}$ with parameters θ .During this stage, the loss function l_1 combines and perceptual terms:

$$\mathrm{L_{pre}} = \lambda_1 \left\| \mathrm{F}_\theta(\mathrm{LR}) - \mathrm{HR} \right\| + \lambda_2 (1 - \mathrm{SSIM}(\mathrm{F}_\theta(\mathrm{LR}), \mathrm{HR}), \tag{1}$$

where $\mathrm{SSIM}(\cdot,\cdot)$ is the structural similarity index and λ_1, λ_2 balance pixel accuracy and perceptual quality.

Second, the researchers fine-tune on a custom simulation dataset derived from Liu et al.'s study, which replicates outdoor thermal conditions via synthetic temperature fluctuations and solar loading profiles. Fine-tuning uses the same loss $\mathrm{L_{fine}}$ with reduced learning rate, enabling the network to adapt to thermal noise characteristics and dynamic illumination.

After super-resolution, enhanced volumes $\hat{T}(x,y,t)$ undergo post-processing. PCA projects the volumetric data onto its top k components, retaining the principal thermal patterns. FFT transforms each frame $T(x,y)$ to the frequency domain, filtering out components above cutoff f_c. Finally, FIF filtering h_{FIF} smooths residual artifacts:

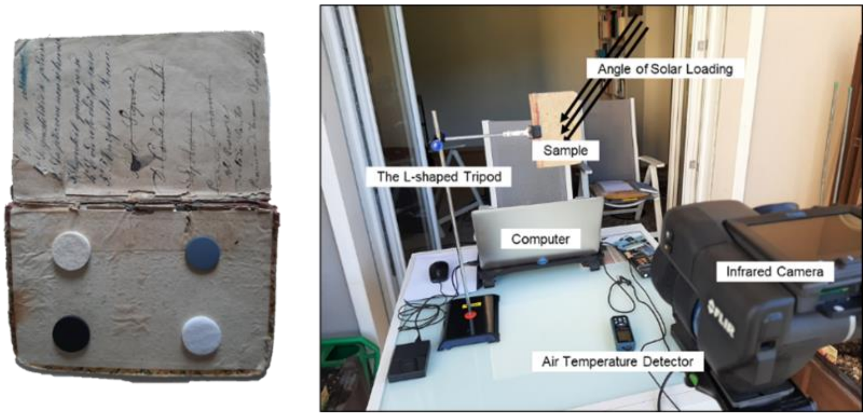
$$\hat{T}_{\mathrm{filtered}} = h_{\mathrm{FIF}}(\mathrm{F}_{\theta}(\mathrm{LR})). \quad (2)$$

4. Experimental Setup

Thermographic sequences were captured from ancient book under natural sunlight, using a FLIR 1020 infrared camera (1024 × 768 resolution, spectral range 7.5–14 μm, sensitivity <20 mK at 30°C). The camera was positioned less than 1 meter from the sample, between the sun and the object, with automatic focus engaged during the data collection. Fig.1 (a) shows the ancient book with the four dowels present on the rear side of the front cover, while Fig. 1 (b) displays the experimental setup. Thermal images were collected on May 5, 2024, when the defects were visible. The thermal imaging was recorded at a sampling frequency of 0.01 Hz (one frame every 1 minute and 40 seconds), synchronized with solar radiation flux measurements taken by a pyranometer.

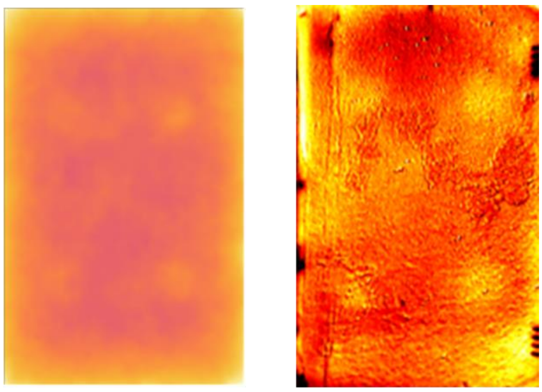
The custom simulation dataset consisted of 200 volumetric sequences (voxel size 128 × 128 × 64), generated through physics-based rendering of heat diffusion under varying solar angles and ambient temperatures (15°C and 30°C). The simulation was carried out using COMSOL Multiphysics, which allows for the modeling of heat transfer. Fig. 2 (a) shows one frame from the simulation results, which were generated by solving the heat diffusion equations under different solar exposure conditions. Fig. 2 (b) presents one frame from the experimental results. This simulated data was used to enhance the real-world thermal sequences, providing a comprehensive dataset for model training.

The training process lasted for 50 epochs, with pre-training on 3D-SR for 30 epochs followed by 20 epochs of fine-tuning. The Adam optimizer (β_1 = 0.9, β_2 = 0.999) was employed, with an initial learning rate of 1×10^{-4} during pre-training and 1×10^{-5} during fine-tuning. The learning rate decayed by a factor of 0.5 every 10 epochs to improve convergence



(a) (b)

Fig. 1. *(a)Internal condition with artificial round defects; (b) experimental setup of solar loading thermography.*



(a) (b)

Fig. 2. *(a) Simulation results of the sample of solar loading thermography. (b) Experimental results from solar loading thermography experiment.*

5. Results and Discussion

Applying 3D-EDVR to the natural-lighting thermograms yields a mean PSNR increase of ΔPSNR = +3.2dB and SSIM improvement of ΔSSIM = +0.08 over the baseline. The enhanced volumes exhibit sharper defect boundaries and reduced noise, allowing for better visibility of defects. Figure 3 shows the comparison between the raw data of a particular frame (left) and the image of that frame after super-resolution processing (right). Before super-resolution, defects are not clearly visible, but after applying 3D-EDVR, four distinct defects become clearly identifiable. These defects appear as contiguous hot regions in $\widehat{T}_{\text{filtered}}(x, y, t)$, which were previously indistinct in the raw data. This demonstrates that 3D-EDVR with tailored post-processing significantly enhances defect visibility under outdoor conditions.

In addition to the super-resolution process, Figure 4 presents the results of applying FFT and FIF to the enhanced thermal sequences. The image on the left (FFT) demonstrates how high-frequency noise is attenuated, allowing the thermal features associated with the defects to become more pronounced. The FFT process helps in smoothing the image by removing unwanted high-frequency components, which would otherwise obscure the finer details. The image on the right (FIF) further refines the result by suppressing the ringing artifacts that are often introduced during upsampling. This FIF contributes to producing smoother temperature gradients, ensuring that the enhanced thermal sequences display clear, well-defined defect features. These results confirm that combining 3D-EDVR with these post-processing techniques significantly improves the quality and visibility of defects in the thermograms.

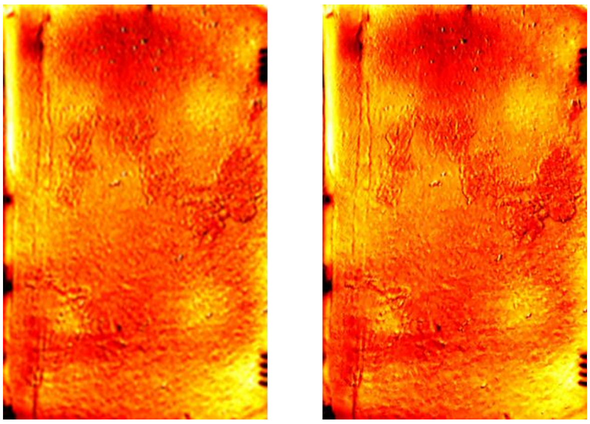


Fig. 3. *On the left: the raw data of a particular frame; on the right: the image of the same frame after super-resolution processing.*

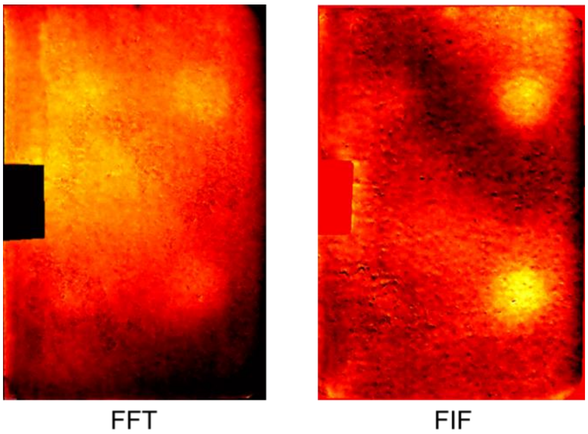


Fig. 4. *FFT (on the lef) and FIF (on the right) results for data after super-resolution processing.*

6. Conclusions

This study demonstrates the effectiveness of applying 3D super-resolution using the 3D-EDVR model—pre-trained on the 3D-SR dataset and fine-tuned with thermographic simulations—on enhancing the visibility of anomalies in thermographic sequences of cultural heritage objects exposed to outdoor conditions. By improving the resolution of thermal sequences, the method enhances the detection of issues like surface deterioration, and other thermal inconsistencies in the objects' structure. Additionally, post-processing techniques such as FFT and FIF further highlight thermal irregularities, ensuring that defects are clearly visible and easily analysed for conservation purposes. Future work will focus on integrating multispectral imaging to provide a more comprehensive view of these objects' conditions, as well as enabling real-time inference with edge-deployed infrared cameras to facilitate more efficient monitoring and preservation efforts in dynamic environments.

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