3D infrared-terahertz fusion non-destructive inspection for cultural heritage and composite materials

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Abstract

Defects inside cultural heritage objects and composite structures have the potential to cause extensive damage. There is a need to develop 3D non-destructive imaging techniques to determine and visualize the positions of defects. The aim of this research is to develop a new non-destructive imaging technique using infrared-terahertz fusion approach. Recently, time-domain terahertz and infrared tomography proved the capability of providing 3D imaging. To combine the advantages of the two non-destructive imaging techniques, a feature-based fusion algorithm is designed in order to fuse the images generated by the systems. The fusion images shows the slices through the thickness, i.e. from the surface to a known depth of the specimens themselves. Finally, a 3D visualized model is reconstructed by combining these through-depth slices.

1. Introduction

Non-destructive testing (NDT) is a significant methodology both for composite material maintenance and cultural heritage conservation. Infrared thermography (IRT) is a well-known NDT technique and it has the advantages of fast inspection rate, absence of contact, excellent spatial resolution and acquisition rate [1]. The heat transfer process through materials, that is at the base of IRT, determines its sensitivity for the detection of both surface and sub-surface defects. Terahertz time-domain spectroscopy (THz-TDS) is a non-invasive, high-resolution imaging technique which can discriminate between materials effectively. However, complex material composition and geometry suppress the signal-to-noise ratio (SNR) of imaging on the internal defects using single imaging modality.

To tackle this problem and provide high contrast imaging results, a non-invasive imaging technique is proposed in this work for NDT of both cultural heritage objects and natural fibre composites. The proposed technique combines the surface information provided by IRT and internal structure retrieved with THz-TDS using an unsupervised deep residual fusion network. Experiments show that the fusion results provide additional material information than single modality. In addition, 3D imaging has been achieved using the fusion results of natural fibre composites.

2. Materials and Methods

2.1. Specimens

An ancient marquetry composed by three layers was inspected herein. The support is made of fir wood, the animal glue is in the middle, and the ornamental layer is present at the top of the sample itself; the upper layer was fabricated with a variety of materials including (but not limited to) pearl (white tesserae), and bovine horn. The perimeter was built using boxwood. Seven flaws (i.e., missing and broken tesserae) are present in this sample [2].

Also, a natural fibre composite, mainly constituted by kenaf, was inspected by the proposed approach. In particular, the composite was realized with a hybrid method using both kenaf and glass fibres. A sandwich structure was realized at the end of the fabrication process. The core was realized with continuous kenaf/glass hybrid fibre yarns whereas the skins were made of chopped strand matrix with a surface veil. The composite was later impacted in order to provoke a damage partially visible to the naked eye.

2.2. Infrared-terahertz fusion

As an extension of the FE-S-F framework [3], the fusion process was designed based on features from different modalities. First of all, raw data from active thermography and terahertz imaging systems is processed using feature extraction methods to gather features from a temporal, frequency, and statistical aspects. Meanwhile, the SNR of each feature was calculated through the pixels sampled from defect regions and defect-free regions. Then, depending on the criterion of highest SNR, feature selection was carried out to choose the best feature image for the fusion step. Finally, the features from two imaging systems were processed with cropping, rotating and scaling operators to maintain geometrical alignment, and then merged in an unsupervised deep residual network; in this way, a fusion image including defect information from surface to interior of the sample was realized.

3. Results and discussion

Fig 1(a) illustrates the fusion results of marquetry sample. The fusion technique successfully detected all the defects with high contrast, such as the missing tesserae A, B, C, E and the defects F, G (detachments). It is worth mentioning that, the deep detachment G cannot be seen in the active thermography results. This part was integrated by fusing the feature image provided by terahertz imaging. On the other hand, the defects due to biological attack was detected in the final result. Active thermography provided useful surface information such as the shapes of the tesserae and small scratches (see region 2 and 3, for reference). Terahertz imaging gathered internal defects and material distribution information. The fusion technique (extended from FE-S-F framework) extracted features containing high contrast defect information; these features were integrated into the final fusion image, showing defect information at different depths.

The 3D reconstruction results of the kenaf fibre composite are shown in Fig. 1(b). The cross-section imaging was cut at the position of 71.5 mm and 88.5 mm from the upper edge of the sample. Interestingly, the position of 71.5 mm from the upper edge is exactly the location of the impact-induced damage. Therefore, the morphology of the impact can be observed on this cross-section imaging. The horizontal-section imaging presents the kenaf fibre yarns layer. As an internal layer in such a 3D structure with a not usual fibre content, the kenaf yarn layer having plant fibre information was chosen for the detailed comparison with the computed tomography (CT) slice. Foa r sake of clarity, the kenaf yarns present on the cropped horizontal-section of the 3D fusion imaging and, the cropped CT slice, are matched with a red arrow. A total of 26 kenaf yarns can be mapped into the X-ray CT inspection result one-by-one. This illustrates that the proposed 3D fusion imaging technique generates high-quality images on the internal structures. The fusion of the information from complementary depths of different imaging systems paves the way for conducting high contrast and high-resolution imaging on hybrid laminates.

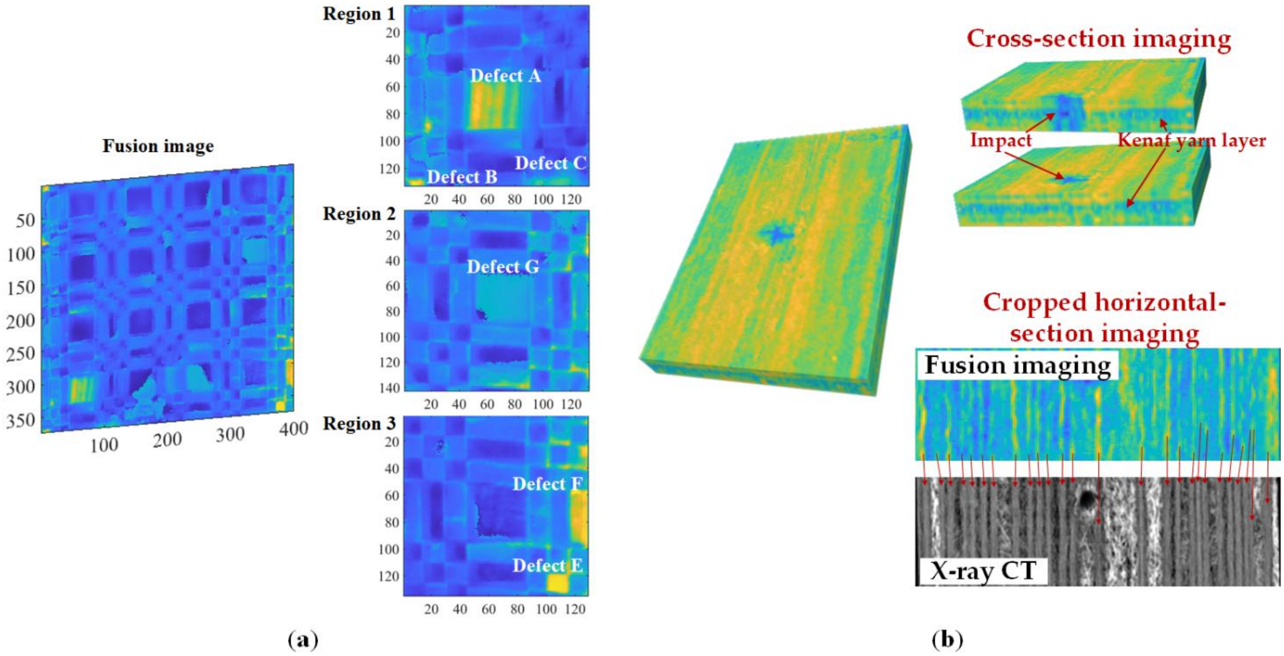

Fig. 1. *Fusion results on a cultural heritage object and a composite sample. (a) Marquetry sample, and (b) composite sample.*

4. Conclusions

In this study, a non-invasive imaging technique is proposed for the non-destructive inspection of cultural heritage objects and natural fiber composites. The proposed technique combines the surface information using IRT and the internal ones obtained via THz-TDS; a feature-based fusion algorithm is here developed for the first time. Results on an ancient marquetry combines the defect information from two modalities by enhancing the contrast of imaging at the same time. Results on a natural fibre composite using 3D imaging offers a better way to understand the characteristics of the composite itself. Comparison between 3D fusion imaging results and X-ray CT inspection proves that the proposed fusion imaging technique has interesting performance on imaging of different layers in such complex structures.

REFERENCES

[1] H. Zhang et al., “Non-destructive investigation of paintings on canvas by continuous wave terahertz imaging and flash thermography,” J. Nondestruct. Eval., vol. 36, no. 2, p. 34, 2017.
[2] C.-M. Wen, S. Sfarra, G. Gargiulo, and Y. Yao, “Thermographic data analysis for defect detection by imposing spatial connectivity and sparsity constraints in principal component thermography,” IEEE Trans. Ind. Informatics, vol. 17, no. 6, pp. 3901–3909, 2020.
[3] J. Hu et al., “Multi-Excitation Infrared Fusion for Impact Evaluation of Aluminium-BFRP/GFRP Hybrid Composites,” Sensors, vol. 21, no. 17, p. 5961, 2021.