



# Infrared, Terahertz and Air-Coupled Ultrasonic Non-invasive Inspection for Artworks: A Comparative Study on an Old Hand-Bound Book of the XIXth Century

Qinqian Lei<sup>1,2</sup>, Hai Zhang<sup>2(✉)</sup>, Stefano Sfarra<sup>3</sup>, Ahmad Osman<sup>4,5</sup>,  
Clemente Ibarra-Castanedo<sup>2</sup>, and Xavier P. V. Maldague<sup>2</sup>

<sup>1</sup> School of Automation, Beijing Institute of Technology, Beijing 100081, China

<sup>2</sup> Computer Vision and Systems Laboratory (CVSL), Department of Electrical and Computer Engineering, Laval University, Quebec City G1V06, Canada  
hai.zhang.1@ulaval.ca

<sup>3</sup> Department of Industrial and Information Engineering and Economics, University of L'Aquila, 67100 L'Aquila, Italy

<sup>4</sup> Department of Inspection of Components and Assemblies, Fraunhofer IZFP, 66123 Saarbruecken, Germany

<sup>5</sup> University of Applied Sciences (Htw Saar), 66117 Saarbruecken, Germany

**Abstract.** This work presents a comparative study for the inspection of an old book, which was bound in the XIXth century. Infrared thermography (IRT), terahertz time-domain spectroscopy (THz-TDS) and air-coupled ultrasonic C-scan (ACU) were used to retrieve the damages and defects in the book cover. Image processing techniques including Fast Fourier Transform (FFT), peak-to-peak and time-delay analysis in time domain were applied in order to highlight the shapes of subsurface features. X-ray radiography was used to anticipate the inspection results. Overall, this work appears useful to investigate the feasibility of different non-invasive inspection (NII) techniques applied to ancient books.

**Keywords:** NDT · Hand-bound book · Infrared · Terahertz · Ultrasound

## 1 Introduction

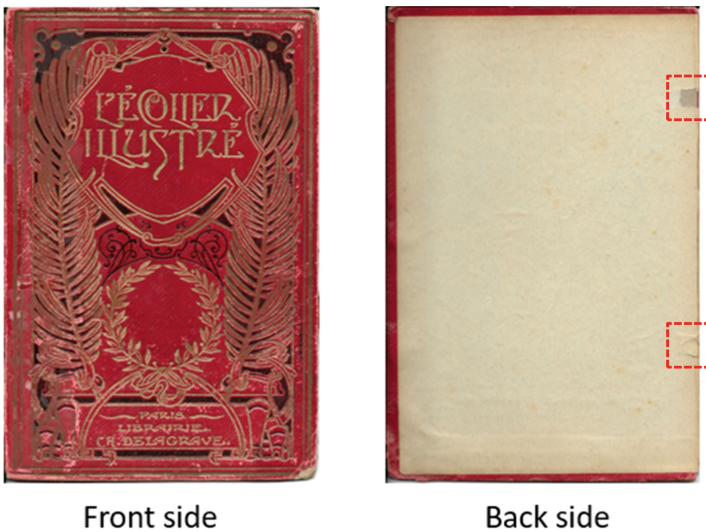
The use of non-invasive inspection (NII) techniques has magnificently been described in the recent literature [1]. Among the various applications that are possible with NII, its use into the cultural heritage (CH) field has attracted increasing attention, including architectural heritage [2], old paintings [3], books [4], and so on. In fact, the detection of subsurface defects such as splitting, cracks, tunnels caused by woodworms, foreign materials due to ancient restorations is a concern of any restorer [5]. Although an array of analytical techniques is useful in the cultural heritage field, the prevention is the best course of action with brittle materials. Thus, the use of NII techniques (that do not require collection of material) is of paramount importance [2].

In this work, the authors studied the advantages of various NII techniques for detecting the conservation status of an ancient book. Since ancient books may be damaged, defected and/or built with different materials, what is visible to the naked eye sometime doesn't exactly line up with the hidden reality. This explains why the use of NII techniques exploring different wavelengths (i.e., different depths in the sample under testing – SUT) is highly desirable [6].

In this paper, infrared thermography (IRT), terahertz time-domain spectroscopy (THz-TDS) and air-coupled ultrasonic C-scan (ACU) were used to retrieve damages in the book cover. Interestingly, additional defects were also detected because the SUT was handmade. Image processing techniques including Fast Fourier Transform (FFT), peak-to-peak and time-delay analysis in time domain were applied to the raw images to highlight the shapes of subsurface features. Finally, a comparative study of these techniques was conducted to summarize pros and cons.

## 2 Sample Under Test (SUT)

The SUT is an ancient book. It seems a children's book, published in Paris, France. The translated title (from French to English) shown on the book cover (Fig. 1) means «The little illustrated student». It belonged to Prof. Maldague's grandparents; the book was preserved in his parents' house. The purpose of the study is the detection of possible damages and defects, as well as the evaluation of sub-surface features by trying to understand the execution phase of the time. (The width of the book is 18 cm its height is 27 cm and its depth is 3 mm.)



**Fig. 1.** Photographs of the hand-bound book.

### 3 Methodology

In the following, the most important methods (Sects. “3.1 Infrared Thermography (IRT)”, “3.2 Terahertz Time-domain Spectroscopy (THz-TDS)” and “3.3 Air-Coupled Ultrasound (ACU)”) and techniques (“Fast Fourier Transformation”) used in this work are explained for the sake of clarity of the reader.

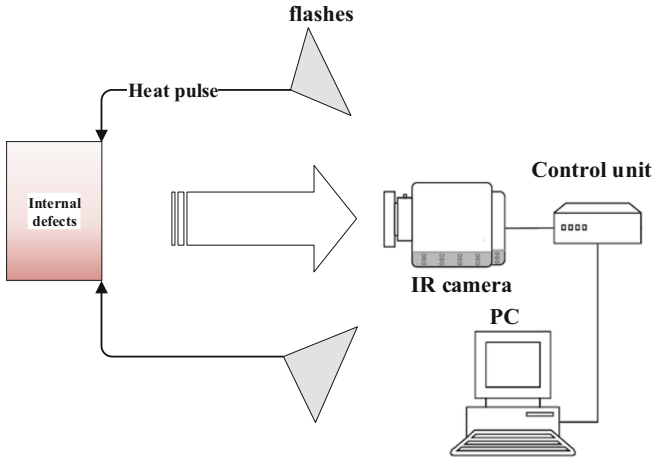
The Discrete Fourier Transform (DFT) plays an important role in our case because it links the time domain to the frequency domain of the discrete signals, that is the most common one in physics compared to continuous signals. The Fast Fourier Transform (FFT) enhances the Discrete Fourier Transform (DFT) by making the transformation more practical and effective [7]. Here, FFT is used as a tool to analyze the IRT, THz and ACU images by obtaining the frequency spectrum of the detected signals.

The use of the FFT on thermographic data was first proposed by Maldague and Marinetti in 1996 [9], known as pulse phase thermography (PPT). PPT is able to retrieve defects by analyzing phase and amplitude data from a PT acquisition. Phase data is commonly analyzed owing to their tolerance both to nonuniform heating and environmental reflections [8]. More information regarding PPT can be found in [9]. THz-TDS measures the electric field and, therefore, provides information both on amplitude and phase of the THz wave through the use of FFT in frequency domain. Frequency information may be obtained from ACU images by using FFT, too.

#### 3.1 Infrared Thermography (IRT)

Infrared thermography, one of the NII techniques has received increasing attention in the last few decades. Reasons for this include improved sensibility, higher resolution of thermal cameras and, also, advanced data processing technology. Several active thermography techniques have been proposed and, in this work, the pulsed thermography (PT) is used. In PT, the specimen surface is subjected to a heat pulse generated from a high-power heat source. Through a short pulse, the sample can be heated uniformly. As time goes, the surface cools down uniformly for a sample without any defects, while some subsurface discontinuities such as e.g., porosities, may change the diffusion through the material by producing abnormal temperature patterns at the surface. The latter may be detected by an IR camera [10].

Figure 2 displays the experimental setup for pulsed thermography.

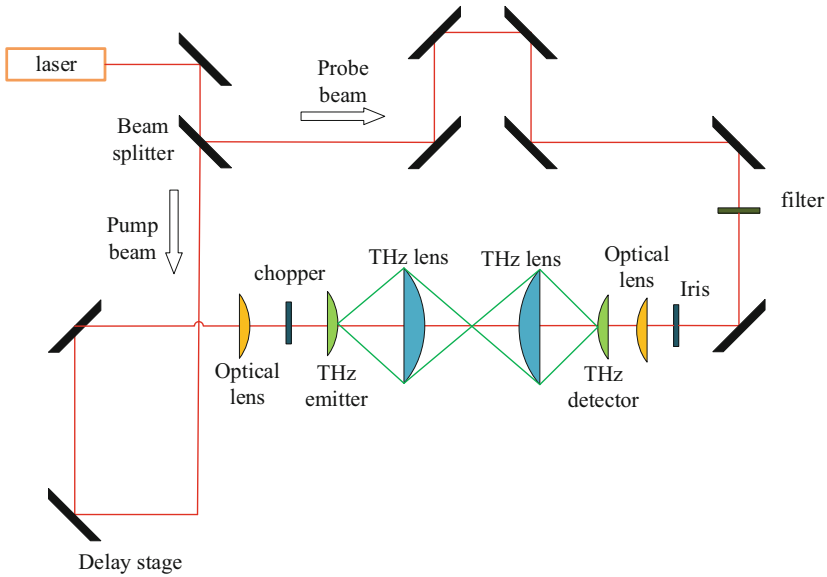


**Fig. 2.** Experimental set-up for PT

### 3.2 Terahertz Time-Domain Spectroscopy (THz-TDS)

The terahertz (THz) region of the electromagnetic spectrum lies in the gap between microwaves and infrared. THz has a series of ideal and unique properties, including the good transparency of many materials such as, e.g., cardboard. Also, a lot of materials can be identified in the terahertz range due to its distinctive characters exhibited [11]. However, the challenges it faced date back to the 1960s and the early 1970s were related to both a lack of reliable source and a sensitive detector [12]. The significant development came with the coherent terahertz generation and detection, known as THz-TDS. Its wide band measurement and the immunity to the background noise have attracted many researchers in a broad range of fields [13]. One more important thing is the two possible modes for THz images generation, i.e., the through-transmission and the pulse-echo modality. Because the inspected book cover was flat and not so thick, the through-transmission modality was considered the best candidate to detect possible subsurface defects [14].

Figure 3 shows the experimental set-up of the employed THz-TDS system. The pump wavelength was centered at 1550 nm, while the repetition rate was set at 100 MHz. The system had a 15 GHz frequency resolution. As already mentioned, the experiments were performed in transmission mode. The specimen was positioned in the focus of the optical system, between the THz emitter and the receiver [15].

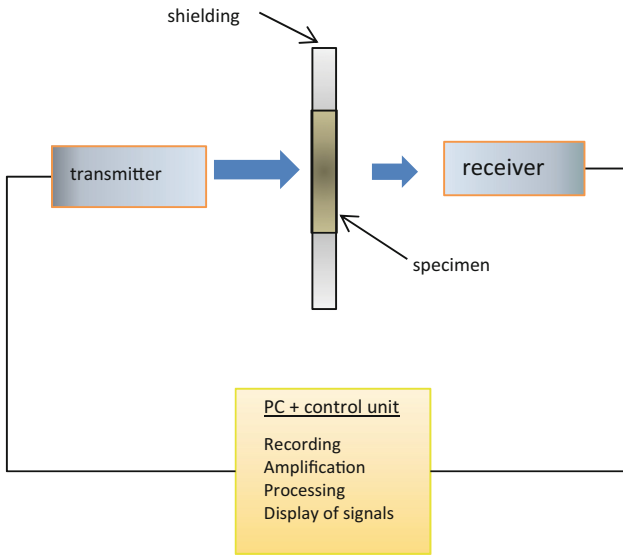


**Fig. 3.** Experimental set-up for terahertz time-domain spectroscopy.

### 3.3 Air-Coupled Ultrasound (ACU)

Classical ultrasonic C-scans are processed in water tank to obtain good coupling between the transducers and the tested samples, indicating contact and also a risk of water penetration in the specimen. A recent technique free the specimen from the link with water thanks to the use of new air-coupled transducers. This is an important achievement in NII, which even makes possible the performing of tests on non-waterproof materials [16].

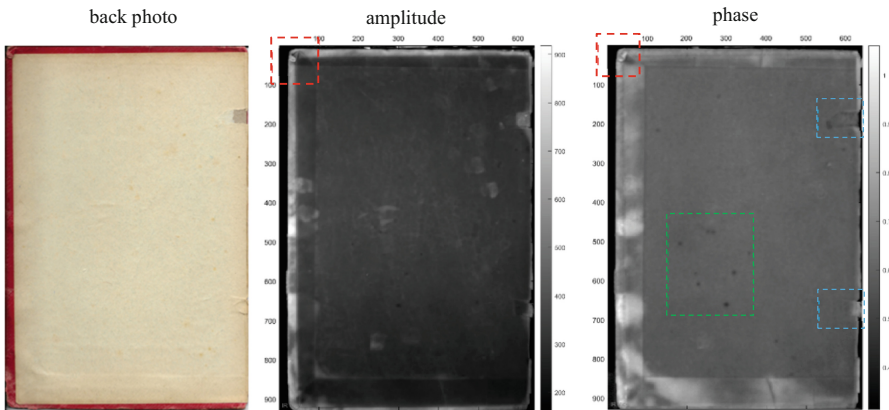
The experimental set-up used for the air-coupled ultrasound (ACU) tests is shown in Fig. 4. Bearing in mind the size of the inspected object, also in this case the authors worked in transmission mode.



**Fig. 4.** Experimental set-up for ACU.

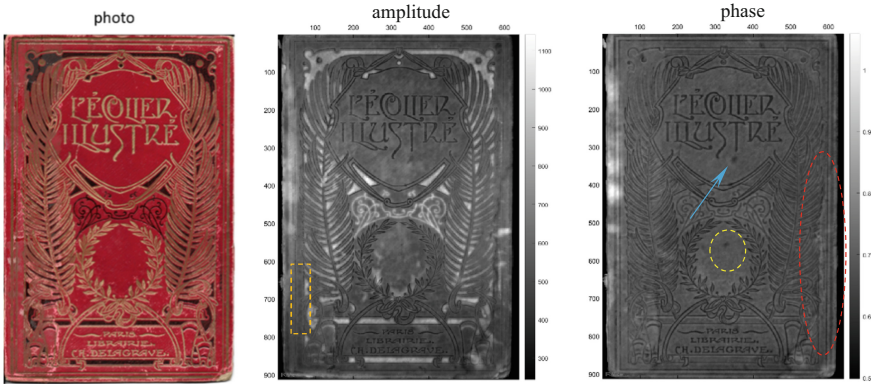
## 4 Result Analysis

The rear side book images is shown in Fig. 5. Reinforcement areas partially detectable in Fig. 1 (rear side – see the red dotted squares for reference) become clear in the phase result (Fig. 5). Additionally, the black dots (see the green dotted square on the right side of Fig. 5) can be related to tunnels caused by woodworms and not visible in the photograph. The worn area on the upper left-hand corner (see the red dotted square on the right side of Fig. 5) is more evident both in the amplitude and phase result.



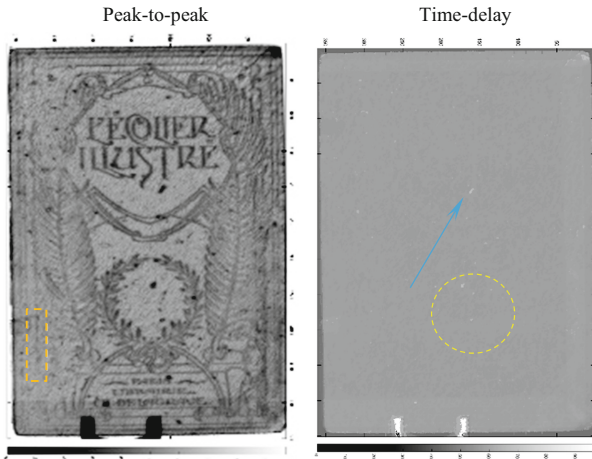
**Fig. 5.** IRT: Rear side of the book cover (on the left), amplitude (at the center) and phase result (on the right) at 0.1 Hz.

Figure 6 represents the result of the front side of the book cover acquired in frequency domain (0.1 Hz). Since foreign materials, such as, e.g., ashes or stains may limit the wavelength penetration, lower frequencies having higher anti-disturbance ability is analyzed; in such a case, signals may explore the book cover more deeply.



**Fig. 6.** IRT: front side photograph (on the left), amplitude (at the center) and phase (on the right) result at 0.1 Hz.

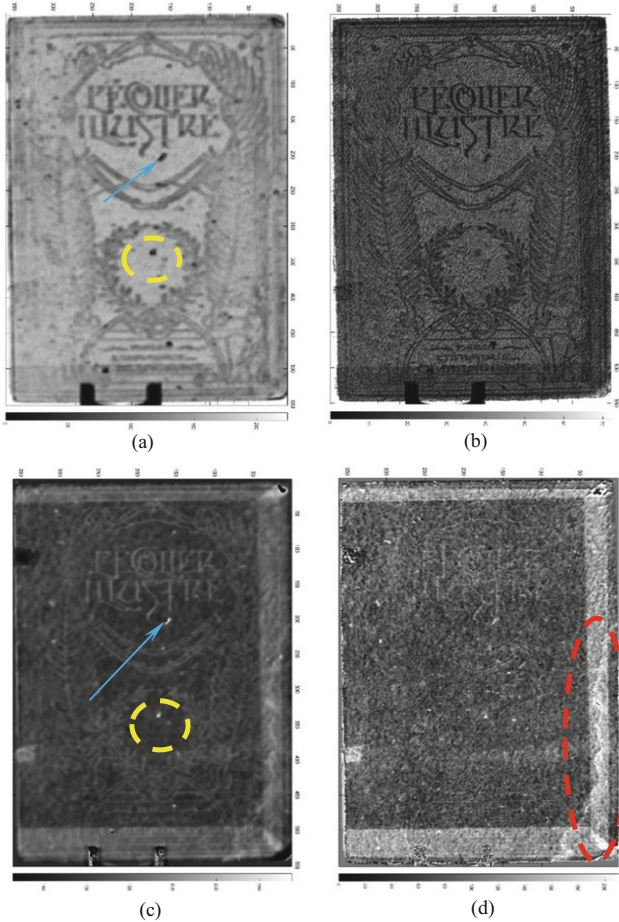
In Fig. 6, a series of black dots in the amplitude result (see the orange dotted rectangle) are evident. They can also be seen in Fig. 7; presumably, they are related to a variation of the heat conduction caused by defects due to woodworms.



**Fig. 7.** THz-TDS: peak-to-peak (on the left) and time-delay (on the right) result.

Also, an irregular pattern (see the red dotted oval on the right side of Fig. 6) in the phase image resembles to a crack. As part of it, the whiter curved line (i.e., a part of the

crack) may acts as starting point for a possible water ingress. Seeing the phase result of THz (Fig. 8(d)), this defect is also detectable (see the red dotted oval for reference) at the same position. Since this defect become evident only at higher frequencies, it should be located near the front side of the book cover.



**Fig. 8.** THz-TDS frequency domain: amplitude results at (a) 0.28 THz and (b) 0.80 THz, and phase results at (c) 0.28 THz and (d) 0.79 THz

Moreover, there are two black dots in the phase result of Fig. 6; the first one located below the letter “T” (pointed out by a blue arrow), and the second one inside the laurel wreath (see the yellow dotted circle). The latter cannot be seen to the naked eye in the photograph of the front side of the book cover. They should probably foreign materials added accidentally during the manufacturing of the book.

However, these two signals also appear in Fig. 7 and Fig. 8. Figure 7 shows the THz-TDS inspection results. The time-domain peak-to-peak imaging reflects the absorption



characteristic of the sample for whole THz radiation. Therefore, dark points in the peak-to-peak imaging can surely be linked to different absorption coefficients with respect to the surrounding area [17]. In the time-delay imaging, correlating the thickness and refractive index information of the sample, the dark points matching with the whiter areas. This indicates a different thickness due to the longer time delay.

In the amplitude image of THz technique (Fig. 8), the dark points appear more evident at lower frequencies, meaning that they are located deeper. Figure 8(c) and 8(d) show the phase information at 0.28 THz and 0.79 THz, respectively. The meaning is based on the refractive index at the corresponding frequency, by providing thickness information [17]. The two signals discussed above can be detected more clearly in Fig. 8(c) which has higher resolution.

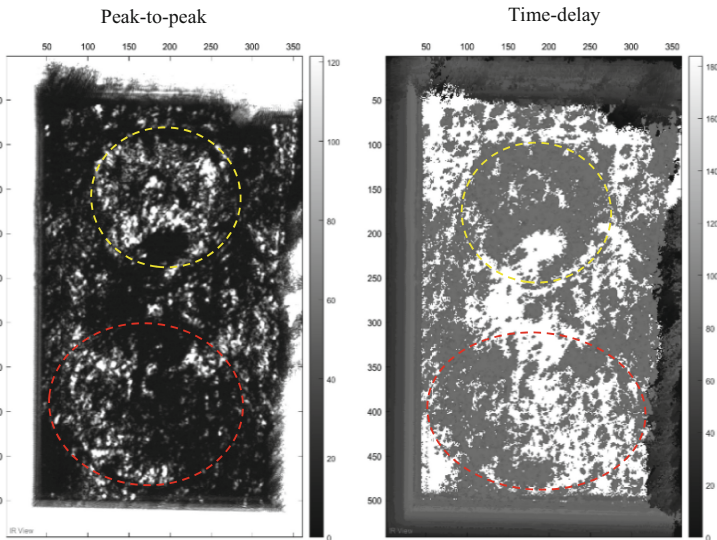
In addition, in the time delay imaging (Fig. 7), the pattern on the book is obscure. This is caused by the limited depth resolution, which can be calculated as below:

$$\Delta L = c \times \Delta t \quad (1)$$

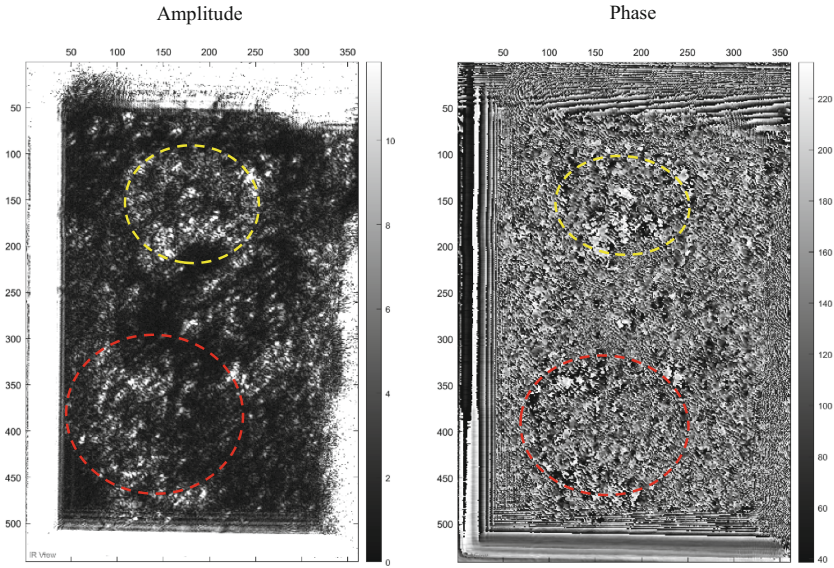
where  $\Delta L$  is depth resolution,  $c$  is ultrasonic transmission speed,  $\Delta t$  is minimum time step.

Paper is considered as a random assembly of individual particles, namely fibers and pigments [18], thus it is hard to measure the propagation of light in paper. However, by estimation, the depth resolution is larger than the thickness of the pattern on the book cover.

The ACU results are shown in Fig. 9 and Fig. 10. time-delay can be used to determine the density of the materials, as below:



**Fig. 9.** ACU: peak-to-peak (on the left) and time-delay (on the right) results.



**Fig. 10.** ACU: amplitude (on the left) and phase (on the right) results.

$$\rho = Z/v \quad (2)$$

where  $\rho$  is material density,  $Z$  is acoustic impedance,  $v$  is sound velocity in the material.

Because ultrasonic transmission varies in different materials, so the scattered black points can indicate the existence of different materials. Therefore, it can be concluded that the title of the book (marked in yellow) is made of different materials from other parts of the book cover, which has better ultrasonic transmission. So is the laurel wreath in the darker region. Actually, the darker regions can also be caused by the increase of the material density, but refer to the peak-to-peak result, the brighter regions indicate higher absorption coefficients which is linked to different materials.

Figure 10 shows the ACU frequency domain results. The identical areas Fig. 9 are also detectable in Fig. 10, which are marked in yellow and red. However, the spatial and temporal resolutions are limited if compared to the THz-TDS results.

## 5 Conclusions

In this work, IRT and THz techniques provided more information than ACU. Both IRT and THz techniques were able to retrieve information concerning materials composing the book cover and its thickness. IRT shown the material thermal properties from a qualitative point-of-view. It should be noticed that THz technique can be used to analyze absorption coefficients related to materials as well as refractive indexes linked to thickness. Moreover, while IRT shown interesting details at high resolution (thanks to

the thermal camera used), THz results displayed much information concerning the identification of defects. ACU in the TT mode is effective to identify the different materials and defects, but the spatial and temporal resolutions are limited.

FFT were used in all three methods by providing both amplitude and phase patterns. It is particularly efficient when combined with peak-to-peak and time-delay imaging obtained via THz and ACU technique by processing the data in time domain.

**Acknowledgements.** This research was supported by the Natural Sciences and Engineering Research Council (NSERC) Canada through the Discovery Grant program, Create-oN DuTy! Program, and the Mitacs Globalink Program.

This research was supported by the Canadian Foundation for Innovation (CFI) and the Canada Research Chair in Multipolar Infrared Vision (MiViM).

This research was also supported by the AutomatiQ-Group of the htw saar.

The authors would like to thank Thomas Waschgies and Andrea Mross from Fraunhofer IZFP for their assistance in generating the ACU-data.

## References

1. Shull, P.J.: *Nondestructive Evaluation – Theory, Techniques, and Applications*. CRC Press, USA (2002)
2. Moropoulou, A., et al.: Non-destructive techniques as a tool for the protection of built cultural heritage. *Constr. Build. Mater.* **48**, 1222–1239 (2013)
3. Abraham, E., et al.: Non-invasive investigation of art paintings by terahertz imaging. *Appl. Phys. A* **100**(3), 585–590 (2010)
4. Mercuri, F., et al.: Infrared thermography applied to the study of cultural heritage. *Int. J. Thermophys.* **36**(5–6), 1189–1194 (2014)
5. Sfarra, S., et al.: Discovering the defects in paintings using non-destructive testing (NDT) techniques and passing through measurements of deformation. *J. Nondestruct. Eval.* **33**, 358–383 (2014)
6. Tortora, M., et al.: Non-destructive and micro-invasive testing techniques for characterizing materials, structures and restoration problems in mural paintings. *Appl. Surf. Sci.* **387**, 971–985 (2016)
7. Nussbaumer H.J.: The fast fourier transform. In: *Fast Fourier Transform and Convolution Algorithms*. Springer Series in Information Sciences, vol. 2. Springer, Heidelberg (1982). [https://doi.org/10.1007/978-3-642-81897-4\\_4](https://doi.org/10.1007/978-3-642-81897-4_4)
8. Duan Y., et al.: Quantitative evaluation of optical lock-in and pulsed thermography for aluminum foam material - ScienceDirect. *Infrared Phys. Technol.* **60**(5), 275–280 (2013)
9. Maldague, X., Marinetti, S.: Pulse phase infrared thermography. *J. Appl. Phys.* **79**, 2694 (1996). <https://doi.org/10.1063/1.362662>
10. Ibarra-Castaneda, C., Maldague, X.P.V.: Infrared thermography. In: Czichos, H. (ed.) *Handbook of Technical Diagnostics*. Springer, Heidelberg (2013). [https://doi.org/10.1007/978-3-642-25850-3\\_10](https://doi.org/10.1007/978-3-642-25850-3_10)
11. Chan, W., Deibel, J., Mittleman, D.: Imaging with terahertz radiation. *Rep. Prog. Phys.* **70**(8), 1325–1379 (2007)
12. Gebbie, H.A., Stone, N., Findlay, F.D.: A stimulated emission source at 0.34 millimetre wave-length. *Nature* **202**(4933), 685–685 (1964)

13. Nishizawa, S., et al.: Terahertz time-domain spectroscopy (THz-TDS) approach to the quality control on pharmaceutical products. In: International Conference on Infrared Millimeter & Terahertz Waves, IEEE (2010)
14. Yuan, M., et al.: Numerical study on surface roughness measurement based on nonlinear ultrasonics in through-transmission and pulse-echo modes. *Materials* **14**(17), 4855 (2021). <https://doi.org/10.3390/ma14174855>
15. Zhang, H., et al.: An infrared-induced terahertz imaging modality for foreign object detection in a lightweight honeycomb composite structure. *IEEE Trans. Ind. Inf.* **14**(12), 5629–5636 (2018)
16. Imielinska, K., et al.: Air-coupled ultrasonic c-scan technique in impact response testing of carbon fibre and hybrid: glass, carbon and Kevlar/epoxy composites. *J Mater Process Technol* **157**, 513–522 (2004)
17. Zhang, Z., et al.: Terahertz time-domain spectroscopy for explosive imaging. *Optik – Int. J. Light. Electron. Opt.* **118**(7), 325–329 (2007)
18. Farnood, R.: Review: optical properties of paper: theory and practice. In: I'Anson, S.J. (ed.) *Advances in Pulp and Paper Research*, Oxford 2009, Transactions of the XIVth Fundamental Research Symposium Oxford, 2009, pp. 273–352, FRC, Manchester (2018). <https://doi.org/10.15376/frc.2009.1.273>