JPhys Photonics

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To cite this article: Claudia Daffara and Dario Ambrosini 2024 *J. Phys. Photonics* **6** 045006

IOP Publishing J. Phys. Photonics 6 (2024) 045006 https://doi.org/10.1088/2515-7647/ad6abc

Journal of Physics: Photonics

OPEN ACCESS

RECEIVED
2 January 2024

REVISED
5 July 2024

ACCEPTED FOR PUBLICATION
1 August 2024

PUBLISHED
14 August 2024



PAPER

# Smartphone-based diagnostics with coherent and infrared imaging for cultural heritage

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**Keywords:** smartphone, optical imaging, speckle methods, cultural heritage, NDT, mobile diagnostics, infrared, low-cost instrumentation

## Abstract

Nondestructive optical techniques are crucial in heritage science for monitoring the condition of artworks in full field. Various imaging methods based on infrared and interferometry techniques have been proposed, but they often require specialized training and expensive equipment. This paper explores the emerging field of smartphone science and its potential to revolutionize artwork diagnostics, especially for cultural institutions with limited budgets. The smartphone science approach is divided into using the device 'as is' or enhancing it with add-on sensors. After a concise overview of smartphone sensing in different fields, the paper demonstrates smartphone-based optical diagnostics on traditional wooden painting models, employing coherent techniques like laser speckle imaging and moiré fringe technique, and infrared techniques like reflectography and thermography. The comparison of obtained results with established instrumentation in the field clearly shows that smartphone-based diagnostics have the potential to greatly contribute to cultural heritage preservation and conservation, transforming the field's accessibility and cost-effectiveness.

## 1. Motivation and research aims

Non-destructive optical techniques play a crucial role in heritage diagnostics. Monitoring the artwork's condition in full field can reveal its history and the factors contributing to its degradation. Various imaging methods based on infrared and interferometry techniques have been proposed [1–3], enabling the inspection of surface and subsurface features. However, they typically require specialized, expensive, and bulky equipment, thus limiting the dissemination in the restoration community.

The recent trend of the so-called smartphone science [4, 5] is likely to be more than just a fad. Indeed, smartphones have the potential to revolutionize science, as they have done in everyday life. The main question is whether smartphones can be employed for authentic scientific purposes in a specific field. As discussed later, there are numerous examples in the literature of smartphone-based devices that can be used for viscosity measurement, schlieren imaging, particle image velocimetry, and biosensing, among others, while smartphone-based diagnostics of the cultural heritage artifact is still a novel paradigm.

This paper aims to explore whether the smartphone sensing approach could be helpful in artwork diagnostics. Cultural institutions often struggle with tight budgets: if feasible, smartphone-based diagnostics can significantly alter this scenario. Following a concise overview of smartphone applications in different fields, the paper demonstrates a series of smartphone-based optical diagnostics performed on wooden painting models within a validation scenario that includes benchmarking with established instrumentation and procedures used in the cultural heritage field.

The study focuses on coherent source-based methods such as laser speckle imaging and the moiré fringe technique, and on infrared methods such as reflectography and thermography. Such techniques are exemplary of optical imaging used in the field, they include surface and subsurface inspection and allow us to investigate the capability of smartphones in infrared and laser sensing, i.e. beyond the native use of the VIS photographic camera.

## 2. Overview of smartphone applications

### 2.1. The smartphone as a measurement system

Equipped with many sensors and dedicated software applications, smartphones are used in various applications in an easy and immersive way. A simple interrogation of the Scopus database using the search term 'smartphone' in the title returns about 29 782 documents, while the results obtained with the search term 'smartphone-based' returns 3876 items (data accessed June 2024). This simple way of querying the database shows the growing research interest in the topic. The increasing role of the smartphone science approach and the potentially high impact in many areas are confirmed by the increasing reviews about smartphone-based spectrometers [6], biosensors [7], applications for geoscience [8], agriculture [9], food diagnostics [10], as well as about smartphone-based bioanalytical, health monitoring and diagnosis applications [11–15].

Table 1 reports and compares some references on smartphone-based sensing and applications. The smartphone science approach can be roughly divided into two categories [6, 16]: on the one hand, the device is used 'as is', i.e. only the built-in sensing is involved; on the other hand, the device is 'enhanced' using suitable add-ons based on external sensors, such as the thermal camera module utilized in this work and described later.

### 2.2. Smartphones in the diagnostics of artworks

From the literature survey, the call for further work emerges, especially on smartphone use in nondestructive optical techniques for artwork decay diagnostics, with coherent and infrared methods.

So far, the role of smartphones in cultural heritage has mainly been related to applications such as serious games [48] and smart fruition [49], often through augmented reality [50]. Only a relatively small number of articles deal with the diagnostic analysis of the artifact, with the smartphone as a measuring system [18, 21, 26, 46]. Early work by Schirripa Spagnolo *et al* [46] proposed smartphone-based imaging for stone lithography authentication, while in Daffara *et al* [26] the authors started investigating smartphone use for painting diagnostics. Recent literature on smartphone-based artwork inspection mainly concerns the use of the VIS camera for 3D reconstruction with multiple capture methods, such as Reflectance Transformation Imaging [51] and videogrammetry [52], for color analysis in pigments discrimination [21] and archaeometric screening [53].

Smartphone diagnostics of cultural heritage should be considered as auxiliary tools that can be used when needed by people with different backgrounds. Smartphone metrology in crowdsourcing projects has been proposed for color characterization [54]. Situations in which smartphone features could represent an advantageous option are, for instance, limited budget and/or the need to conduct multiple surveys; *in situ* measurements and/or measurements in challenging access conditions; integration with IoT, cloud, or satellite data; measurements carried out by multiple operators at the same time. Smartphone-based diagnostics can enhance non-destructive monitoring procedures in at least three ways: the smartphone can act as a multi-modal acquisition device, providing an integrated portable system that is easier to handle, allowing the collection of data during various phases of restoration; the restorers are encouraged to utilize scientific tools more often during their decision-making process, producing more data and resulting in a more informed restoration; eventually, the comparison between previously recorded data and the current situation is easily performed by smartphone.

Smartphone diagnostics that takes advantage of built-in sensors can be easily adopted by the cultural heritage community. Several apps are available to handle sensors and record the measurement data, e.g. Physics Toolbox [55] and FizziQ [56]. Furthermore, peripherals can be connected to extend the sensing capabilities of the smartphone. A list of techniques and the related sensor modules is given in table 2.

## 3. Materials and methods

We describe the setup for smartphone-based diagnostic techniques in cultural heritage with coherent and infrared imaging with a focus on surface and subsurface painting inspection. Among the coherent methods, laser speckle pattern imaging and moiré fringe techniques are considered. Among the non-coherent methods, near infrared (NIR) reflectography and IR thermography are considered. Additionally, we briefly recall their role in artwork analysis on which we designed the validation scenarios.

**Table 1.** A short and not exhaustive literature review about smartphone-based sensing and applications.

| Authors | Year | Application | Note |
|---|---|---|---|
| Wu *et al* [17] | 2023 | LASCA | |
| Daffara *et al* [18] | 2023 | artworks | |
| Lee *et al* [19] | 2023 | fundus camera | |
| Wang *et al* [11] | 2023 | health | review |
| Kim *et al* [20] | 2022 | digital holography | |
| Sáez-Hernández *et al* [21] | 2022 | artworks | |
| Costantino *et al* [22] | 2022 | LiDAR urban scenario | |
| Chan *et al* [23] | 2022 | LiDAR fluid testing | |
| Luetzemburg *et al* [24] | 2021 | LiDAR geoscience | |
| Wang *et al* [25] | 2021 | LIBS lithology | |
| Straczkiewicz *et al* [12] | 2021 | health | review |
| Hunt *et al* [13] | 2021 | medicine | review |
| Majunder and Deen [14] | 2019 | health | review |
| Daffara *et al* [26] | 2019 | artworks | |
| Mu *et al* [27] | 2019 | spectrometry | |
| Zeng *et al* [28] | 2019 | spectrometry | |
| Yu *et al* [29] | 2019 | stereo-DIC | |
| Settles [30] | 2018 | schlieren | |
| Vidvans and Vasu [31] | 2018 | reverse engineering | |
| Kanchi *et al* [15] | 2018 | health | review |
| McGonigle *et al* [6] | 2018 | spectrometry | review |
| Lewis and Franco [32] | 2018 | medicine | |
| Jarujamrus *et al* [33] | 2018 | environmental analysis | |
| Stanger *et al* [34] | 2018 | thermal imaging | |
| Kim *et al* [35] | 2018 | microfluidics | |
| Lee *et al* [8] | 2018 | geosciences | review |
| Liu *et al* [36] | 2018 | fringe projection | |
| Rateni *et al* [10] | 2017 | food diagnostics | review |
| Feeldbush *et al* [37] | 2017 | engineering | |
| Edwards *et al* [38] | 2017 | medicine | |
| Scire *et al* [39] | 2017 | digital holography | |
| Roda *et al* [7] | 2016 | biosensors | review |
| Zhao *et al* [40] | 2016 | structural health monitoring | |
| Wilkes *et al* [41] | 2016 | UV imaging | |
| Russo *et al* [42] | 2015 | medicine | |
| Hossain *et al* [43] | 2015 | laser beam profiler | |
| Razdan and Bateman [44] | 2015 | machine vision | |
| Pongnumkul *et al* [9] | 2015 | agriculture | review |
| Butel *et al* [45] | 2015 | deflectometry | |
| Schirripa Spagnolo *et al* [46] | 2014 | artworks authentication | |
| Daponte *et al* [47] | 2013 | metrology | review |

**Table 2.** Examples of smartphone analysis using built-in sensors and add-on modules.

| Analysis | Built-in system | Add-on module |
|---|---|---|
| Air quality | Cat VOC and humidity sensors | Atmotube Pro [57] |
| Ambient light level | light sensor | SS04U [58] |
| Colorimetry | camera [59] | Nix Sensors [60] |
| Fluorescence imaging | | UV Module Eigen Imaging [61] |
| IR Thermography | Lepton LWIR camera [62] | FLIR One, SeeK Thermal |
| Macro-photography | | ShiftCam macro lens [63] |
| NIR imaging | NIR enabled devices by Eigen Imaging [61] | NIR Module Eigen Imaging [61] |
| Reprography | | ScanTent [64] |
| Spectrometry NIR | [65] | Sagitto [66] |
| Spectrometry Raman | Smartphone-based Raman [67] | |
| Spectrometry VIS | | GoSpectro [68] |

### 3.1. Smartphone as a sensor for coherent diagnostics: laser speckle imaging

When coherent light interacts with a medium characterized by a random distribution of scattering centers on the scale of a wavelength, a multi-interference effect occurs, and the resulting random optical field (speckle

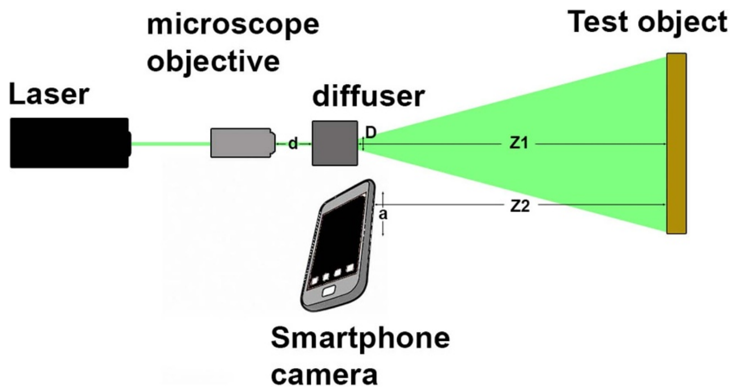



**Figure 1.** Experimental scheme. Setup parameters: laser spot size $D$ focused on the diffuser, diffuser-object $z1$, and camera-object $z2$ distances. The lens aperture $a$ is fixed or variable according to smartphone models.

field) produces a peculiar intensity pattern at the observation plane. In general, speckle metrology [69] techniques extract information from the speckle pattern as it interacts with the target object.

Speckle correlation imaging [70] is a basic technique that can be applied to the analysis of artworks such as panel paintings [71], mosaics [72], and frescoes [73]. In its most straightforward configuration, laser speckle patterns are acquired before and after an induced deformation, then image correlation is performed on pairs of images to extract regions of decorrelation (i.e. local displacement) that are induced by structural defects.

In this paper, smartphone-based laser speckle correlation imaging is demonstrated using the built-in camera of the smartphone and the speckle-projection setup of [74] in figure 1. Namely, a speckle pattern is generated from a laser through a glass diffuser, projected on the artwork surface, and captured before and after a thermal stimulus is applied. As shown [74], the speckle pattern acquired with the camera is controlled through the optical chain parameters; the size of the single speckle (i.e. the resolution sensitivity) is optimized for the smartphone by adjusting the distance parameters diffuser-object ($z1$) and object-camera ($z2$). Specifically, the size of the projected speckle cell at the object plane is $\sim\lambda z1/D$, with $D$ the laser spot on the diffuser and $\lambda$ the laser wavelength; this is imaged by the camera at distance $z2$ to optimize the field of view and the sampling resolution.

The laser speckle pattern acquired by a smartphone with different setups is shown in figure 2, proving the smartphone camera capability in coherent laser-based imaging. We report some tests with the models iPhone 8 (12 Mpx camera; lens: $f/1.8$ aperture; sensor: 1/3 inch, 1.22 $\mu$m pixel pitch) and Samsung S6 (16 Mpx camera; lens: $f/1.9$ aperture; sensor: 1/2.6 inch, 1.12 $\mu$m pixel pitch) and different laser sources. The setup used in the smartphone speckle diagnostics on the polychrome painting (Results section) is with the Samsung S6 model and the pigtailed laser diode (638.5 nm, 5 mW).

A simple speckle correlation algorithm [74] takes as input the intensity patterns $I_{\text{ref}}(x,y)$ and $I_{\text{mod}}(x,y)$ acquired before and after the thermal stimulus and returns a correlation map, pointing out anomalous in-plane displacements. Specifically, it computes the local correlation coefficient of the speckle intensity

$$\rho_c(x,y) = \frac{\langle [I_{\text{ref}}(x,y) - I_{\text{mod}}(x,y)]^2 \rangle}{\langle I^2(x,y) \rangle}, \tag{1}$$

where the average is taken spatially over an area containing many speckles.

### 3.2. Smartphone as a sensor for coherent diagnostics: moiré method

The moiré method is a well-known tool in non-destructive testing [75, 76]. It relies on the superposition of two sets of lines or gratings, generating a moiré pattern that can reveal anomalous surface deformations caused by underlying defects in response to an environmental or thermal stimulus. For example, the moiré method is suitable for detecting surface cracks or delaminations on various materials such as painted wood, metals, and composites. The moiré effect has frequently served as a diagnostic and/or measurement tool in scientific literature [77].

In this paper, we demonstrate smartphone moiré diagnostics using the built-in camera of the smartphone and an external laser-based fringe generator. The schematic diagram of the proposed diagnostic method follows [78] and is shown in figure 3. The fringe pattern is generated by an interference phenomenon using a diffractive optical element (DOE) illuminated by coherent light; parallel Young's fringes are formed on a plane at a distance $R$ from the DOE. The distinctive feature of this illumination unit

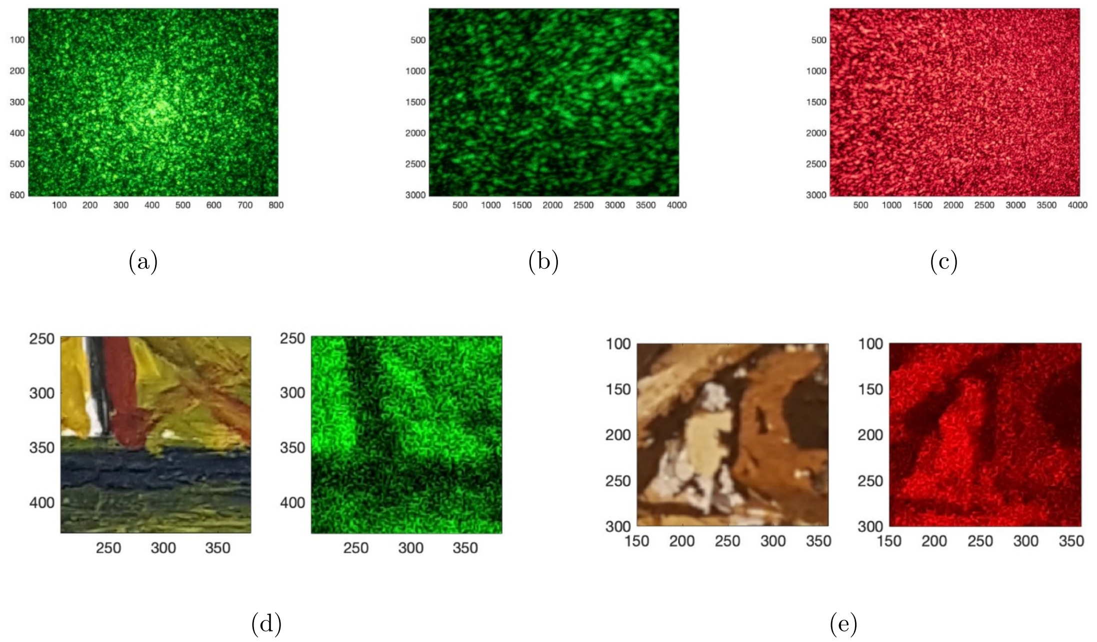


**Figure 2.** Acquisition with a smartphone of a speckle pattern generated by a diffuser (spot $D \sim 1$ mm) with different setups. Pattern projected on optical screen (iPhone 8, $f/1.8$): (a) $z1 = z2 = 60$ cm. (b) $z2 = 0.1 \times z1$, $z1 = 60$ cm, (DPSS laser 532 nm). (c) $z2 = 0.5 \times z1$, $z1 = 120$ cm (He-Ne laser 632.8 nm). Pattern projected on polychrome painting (Samsung S6, $f/1.9$): (d) Laser diode 532 nm, 5mW. (e) Laser diode pigtailed to single-mode fiber 632.8 nm, 5mW.

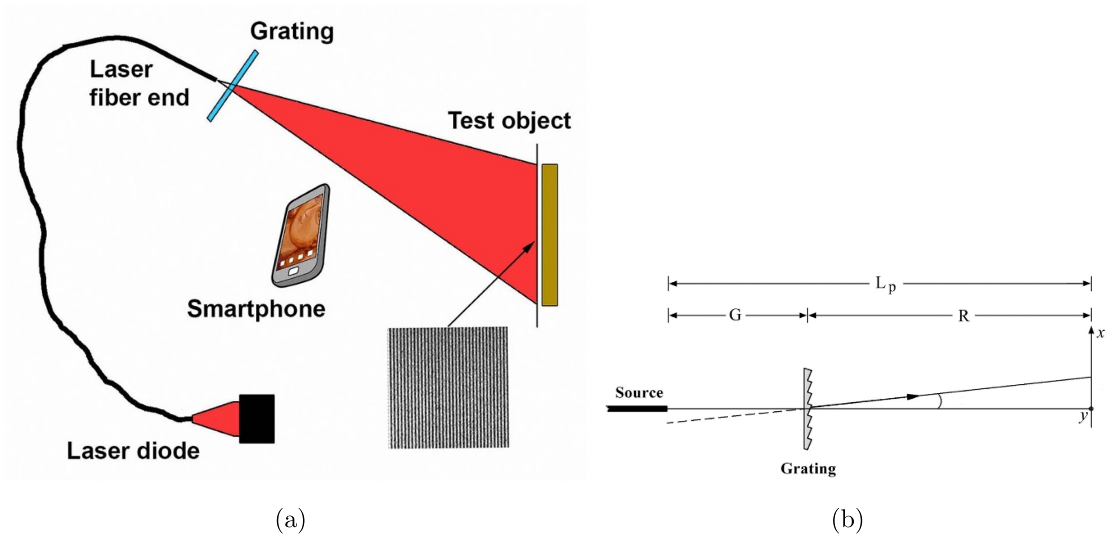



**Figure 3.** (b) Experimental scheme. The inset shows the fringes projected on the test object. (a) Fringe generator principle.

is the capability to change the projected fringe pattern frequency by changing the distance $G$ between the light source and the phase grating itself [78], thus allowing the realization of variable resolution devices. The coherent light source is a laser diode (638.5 nm, 5mW) pigtailed to a single-mode fiber; the DOE is a blazed phase grating made from index-matching epoxy.

The sinusoidal fringe pattern acquired by a smartphone with different DOE setups is shown in figure 4, proving the smartphone camera capability in coherent, laser fringe imaging. We report some tests with the Samsung models S6 (16 Mpx camera; lens: $f/1.9$ aperture; sensor: 1/2.6 inch, 1.12 $\mu$m pixel pitch) and S22 (50 Mpx camera; lens: $f/1.8$ aperture; sensor: 1/1.56 inch, 1 $\mu$m pixel pitch). The setup used in the smartphone moiré diagnostics on the polychrome painting (Results section) is with the S22 model.

The simplest method to obtain a contour map of deformation in moiré metrology is to superpose the undistorted grating with the distorted one. This can be achieved with a simple differentiation and is known as the infinite fringe moiré [79]. In this case, the eye is capable of detecting low-density gradients but

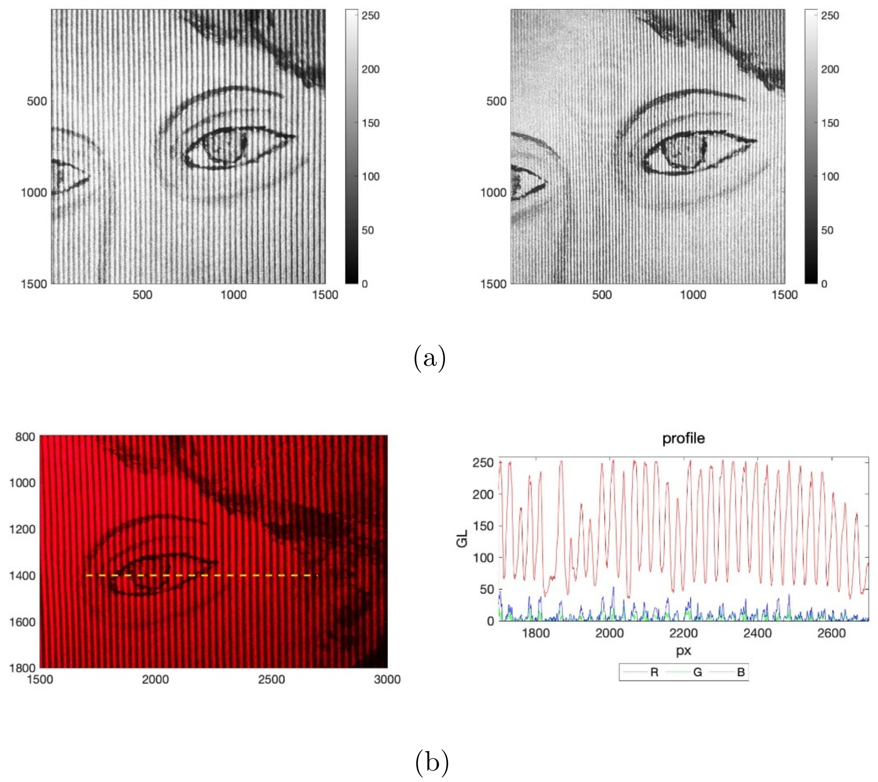



**Figure 4.** Acquisition with a smartphone of a fringe pattern generated by a DOE and projected onto a polychrome painting with different source-DOE distance *G*. (a) Samsung S6; Red channel, same cropped ROI. (b) Samsung S22; RGB image and intensity profile. Laser diode pigtailed to single-mode fiber 638.5 nm, 5 mW.

overlooks the high-density ones. A better performance is given by the so-called finite fringe moiré method, suitable for the smartphone setup [18] and detailed below.

A contour map of deformation $f(x,y)$ is obtained by combining distorted and undistorted gratings. Given the reference vertical pattern $x = mp$ of pitch $p$, the deformed pattern is then $x + f(x,y) = np$, from which the deformation is extracted by subtraction, leading to $f(x,y) = lp$ with $l = n - p$ (dense infinite fringes). In the finite fringe processing method [79], the reference and the deformed patterns are rotated respectively of $\theta/2$ and $-\theta/2$ and then combined. This leads to the finite fringes moiré pattern, in which the pitch and the distortion function are magnified by a factor of $\theta$:

$$y - \frac{f(x,y)}{\theta} = l\left(\frac{p}{\theta}\right). \tag{2}$$

In our setup, single (non-overlapping) grid patterns are recorded, so the moiré pattern must be generated digitally: the single laser fringe pattern is recorded and combined with a rotated copy, which is a simple and fast data processing. In the case of works of art that have a heterogeneous surface (e.g. polychrome, decorated), we must generate the moiré pattern by combining the laser fringe pattern acquired on the artwork with a reference laser fringe pattern acquired on a white plane.

### 3.3. Smartphone as a sensor for IR diagnostics: NIR reflectography

NIR reflectography is a significant diagnostic tool in heritage conservation. With respect to the visible range, NIR wavelengths from 0.7 $\mu$m to 2.5 $\mu$m experience low scattering through layers of ancient paintings, which makes it possible to capture high-resolution sub-surface images. The NIR reflectogram provides information about several interesting features for conservators [80]: the layering of pigments, overpainting, as well as underdrawings, which are typically traced using an absorbing medium (e.g. carbon-based) on a highly reflective background (e.g. chalk-based).

An analysis of the technologies for NIR reflectography of ancient paintings is given in [81]. Currently, cameras equipped with InGaAs-sensors ranging from 0.9 $\mu$m to 1.7 $\mu$m or Si-sensors ranging from 0.7 $\mu$m to 1 $\mu$m are used for NIR reflectography of artworks. Customized cameras equipped with InSb-sensors and scanner-based devices equipped with multiple sensors for acquiring the full NIR range (i.e. up to 2.5 $\mu$m) are also utilized [80, 82].

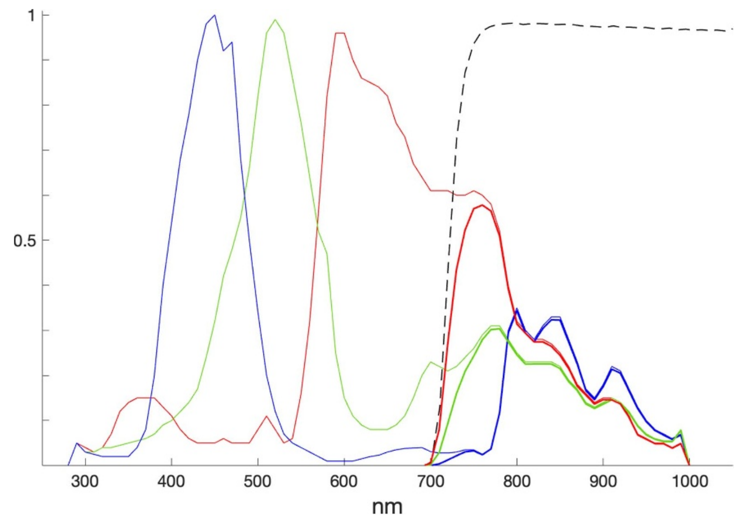



**Figure 5.** Full spectral response (normalized) of a CMOS sensor (red, green, blue curves are the RGB channels), transmittance of Hoya R72 filter (dash curve), and response of the CMOS coupled to the filter (bold curves).

The NIR sensitivity of the CMOS smartphone sensor extends inherently up to $\sim$1 $\mu$m. The full sensitivity of the sensor with the cut-off IR filter removed has been characterized in [83]. Smartphone camera systems are detailed in [84].

In this paper, smartphone NIR reflectography is demonstrated using the smartphone's built-in camera and a typical setup consisting of an IR source and an IR filter coupled to the optics. The smartphone is a Samsung S22 (lens: $f/1.8$ aperture; sensor: 1/1.56 inch, 1 $\mu$m pixel pitch). The source is a standard tungsten halogen lamp (500 W), typically adopted in NIR reflectography. The long-pass Hoya R72 filter with cut-on at 720 nm is chosen for acquiring the wide NIR range with the CMOS (from 0.7 $\mu$m to 1 $\mu$m) as it is among the standard adopted in IR photography of works of art. Figure 5 depicts an analysis of the spectral response of the system, which is obtained from the CMOS nominal response and the transmission curve of the IR filter, measured with a UV–VIS–NIR spectrometer. The filter has a flat transmittance, higher than 95%, from 720 nm, which enables us to test the NIR capability of the smartphone camera.

The reflectogram is obtained from the raw image by gray level transformation and by radiometric calibration with a reference target in the scene. The reflectance map $R_{ij}$, defined as the ratio of the incident and reflected radiant flux, is obtained pointwise from the image $I_{ij}$ as a measurement relative to a Spectralon standard of known reflectance value, as follows

$$R_{ij} = R_{\mathrm{REF}} \frac{I_{ij}}{I_{\mathrm{REF}}} \quad (3)$$

where $R_{\mathrm{REF}}$ is the certified reflectance (averaged in the system's response), and $I_{\mathrm{REF}}$ is its measurement (averaged image).

Regarding camera performance in the NIR, figure 6 shows the acquisition of the 1951 USAF chart with the reflectographic setup. Element 6 of group 1 is well resolved in the NIR range, giving a resolution of 3.56 lp mm$^{-1}$ at the object plane. In the VIS range a resolution down to 5.04 lp mm$^{-1}$ (element 3, group 2) is obtained. As the diameter of the Airy diffraction disk of the ideal image is proportional to the wavelength [84], imaging in the NIR exhibits greater diffraction disks, consequently the lower performance was expected.

### 3.4. Smartphone as a sensor for thermal diagnostics: IR thermography

IR thermography is a widely used and well-established diagnostic technique, also in the field of cultural heritage [85, 86]. Active thermography is based on sending a thermal stimulus to the object and acquiring a sequence of thermograms; the analysis of the surface temperature field allows for detecting the presence of 'defects' in the bulk. Thermography provides information about several features of interest to conservators: hidden structures like detachments in the pictorial layer, subsurface cracks, and discontinuities in the materials like restoration fillings can be identified from temperature maps [3].

In the last decades, thermal cameras shifted from expensive and bulky instruments with relatively low thermal resolution and sensitivity to more usable and better-performing cameras. Nowadays, thermal

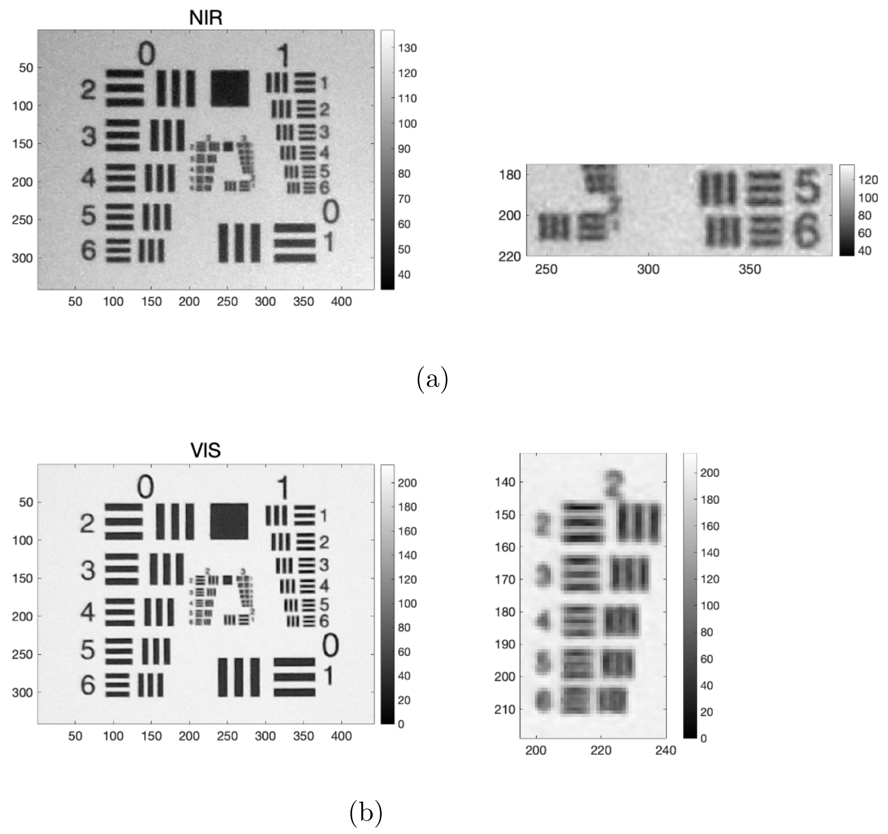



**Figure 6.** Acquisition of the 1951 USAF test pattern Groups 0–3. (a) NIR filter. Zoom on element 6 - group 1 (resolved) and element 1 - group 2. (b) VIS. Zoom on element 3 - group 2 (resolved). Working distance 15 cm, 12 Mpx camera (cropped detail).

cameras in the long-wave IR (LWIR) range have also entered the consumer market as low-cost cameras (e.g. FLIR C2, SEEK Shoot) and smartphone accessories (e.g. FLIR One, SEEK Compact) [87].

In this paper, smartphone IR thermography is demonstrated using a smartphone with the add-on sensor FLIR One mounting the micro thermal camera core Lepton [88]. The thermal sensor has sensitivity in the LWIR range from 8 $\mu$m to 14 $\mu$m with a nominal thermal sensibility of 100 mK and an array of $80 \times 60$ elements of 12 $\mu$m pixel size. Data are stored as radiometric images for processing. The system is equipped with a VIS camera aligned with the thermal one. Acquiring a dual VIS-thermal dataset is a powerful option in heritage diagnostics. The superimposed images are handled with the smartphone FLIR App for a fast inspection of the results. Thermography can provide qualitative as well as quantitative data.

### 3.5. Validation scenarios with painting models

The feasibility of smartphone diagnostics is demonstrated by measurements on three panel painting models realized on poplar wood, coated, according to ancient recipes of the 15th century, with the usual priming layers of canvas, gesso, and glue.

It is worth noting that some models have been used in different experiments and shared with different research groups, thus providing further benchmarking to the present work from literature, e.g. [89, 90].

#### *3.5.1. Model with underpainting and underdrawing for testing NIR reflectography*

Sample #1 was specifically created to test NIR reflectography of subsurface features. An underdrawing was traced in charcoal (which absorbs NIR) on the preparatory ground (which reflects NIR), then covered by layers painted with tempera colors (which are partially transparent to NIR). The subsurface features are detected by contrast imaging thanks to the variegate reflectance of the painting matter. The model is suitable for testing the full capability of NIR reflectography to image the drawing beneath the pictorial layer as well as the overpainting, thus allowing us to compare the smartphone reflectography with conventional and advanced setups.

Figure 7 depicts the construction phases of the multilayered painting model (size 20.5 cm$\times$36 cm$\times$1.5 cm).

**Figure 7.** Painting model #1 with subsurface features. The successive stages in the realization of underdrawing and overpainting are depicted.

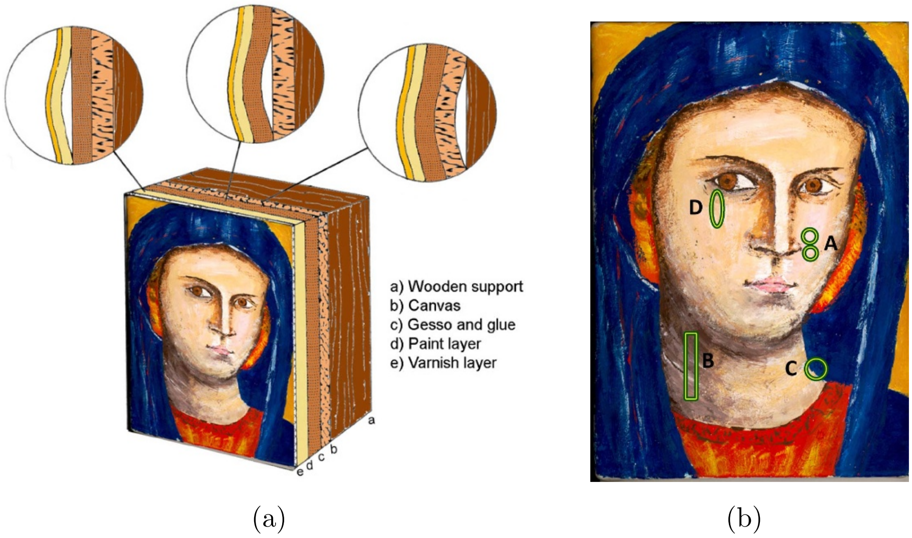



**Figure 8.** Painting model #2 with artificially detached regions. (a) Traditional panel painting structure. Insets show examples of layer separation (detachments) that can occur at any depth. (b) Location of the artificial defects.

*3.5.2. Models with structural defects for testing IR thermography and coherent techniques*

Sample #2 and Sample #3 are characterized by artificially detached regions obtained by inserting thin Mylar sheets at different depths and cracks. They are designed for testing nondestructive techniques for structural evaluation, namely IR thermography, laser speckle imaging, and the moiré method. The defective features are detected with an active scheme, i.e. by monitoring the response after sending a thermal stimulus. The matter discontinuities cause a different heat diffusion and are detected by thermal and displacement signatures.

Figure 8 depicts the painting model #2 (size 15 cm× 21.5 cm×1.8 cm) with the typical sandwich structure of a painting on wood [91] and the location of the artificial detachments. Details about the defects (size and depth) are given in table 3, following [89, 90].

Figure 9 depicts the painting model #3 (size 21 cm×32 cm×1.8 cm). It must be remarked that here, the defects were not positioned '*a priori*' but were induced by artificial aging; the position of the main cracks is shown in the holographic interferogram.

## 4. Smartphone-based artwork diagnostics: demonstration results

### 4.1. Laser speckle imaging

Smartphone laser speckle imaging is demonstrated on the panel painting model #2 with artificial detachments (depicted in figure 8) and the pigtailed laser diode (638.5 nm, 5 mW) as a coherent source. Deformation was induced by moderately warm airflow.

**Table 3.** Defect estimated dimensions and depths (painting model in figure 8(b)).

| Defect | Dimensions [89] | Depth [89] | Depth [90] |
|---|---|---|---|
| A | ø 5 mm | 0.3 mm–0.8 mm | 0.3 mm–0.7 mm |
| B | 28 mm×4 mm | 0.8 mm–0.9 mm | 0.5 mm–1.1 mm |
| C | ø 8 mm | >1.4 mm | 0.7 mm–1.6 mm |
| D | 14 mm×3 mm | >2 mm | |

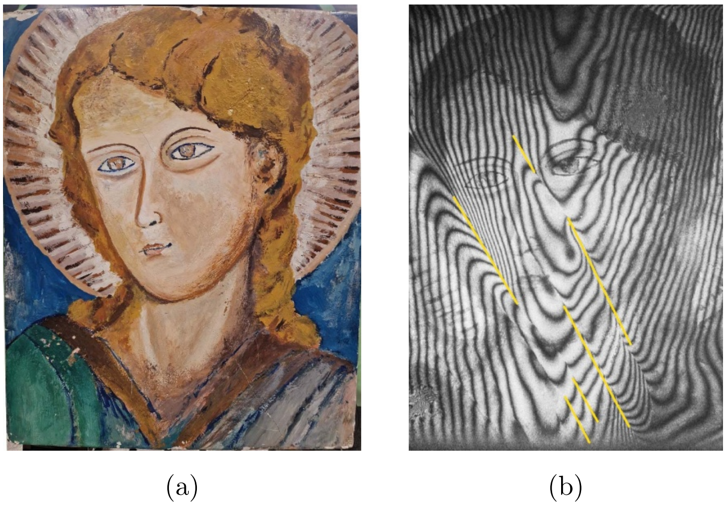



**Figure 9.** Painting model #3 with structural defects after artificial aging. (a) Picture (b) Holographic interferometry enhancing the induced painting cracks (yellow lines).

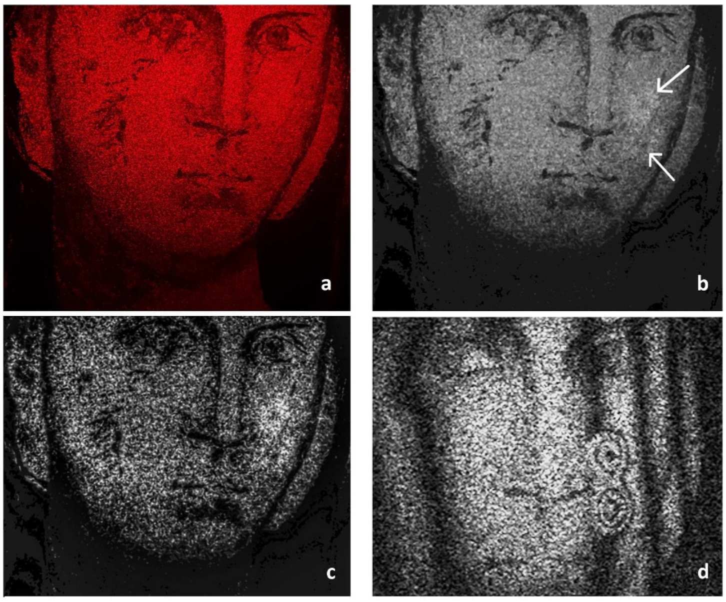



**Figure 10.** Smartphone laser speckle imaging on a wooden painting. (a) Speckle pattern acquired before the deformation, showing speckle smartphone sensitivity. (b) Result of speckle pattern correlation, showing defects detection capability. (c) Result after contrast enhancement. (d) ESPI on the same model.

Figure 10 shows the results obtained with the smartphone model Samsung S6. In figure 10(a), it is shown that the smartphone resolves the laser speckle pattern on the polychrome painting; the versatile setup allowed for tailoring the speckle cell size. The speckle correlation algorithm in equation (1) was applied to compute the local correlation map $\rho(x,y)$ to detect the anomalous in-plane displacements locally. This was obtained through a discrete convolution with a small matrix (kernel), which performs an average in the neighborhoods of image points [74]. In figures 10(b) and (c), bright areas represent the regions of high decorrelation induced by the displacement field, while dark areas indicate where the pattern was almost

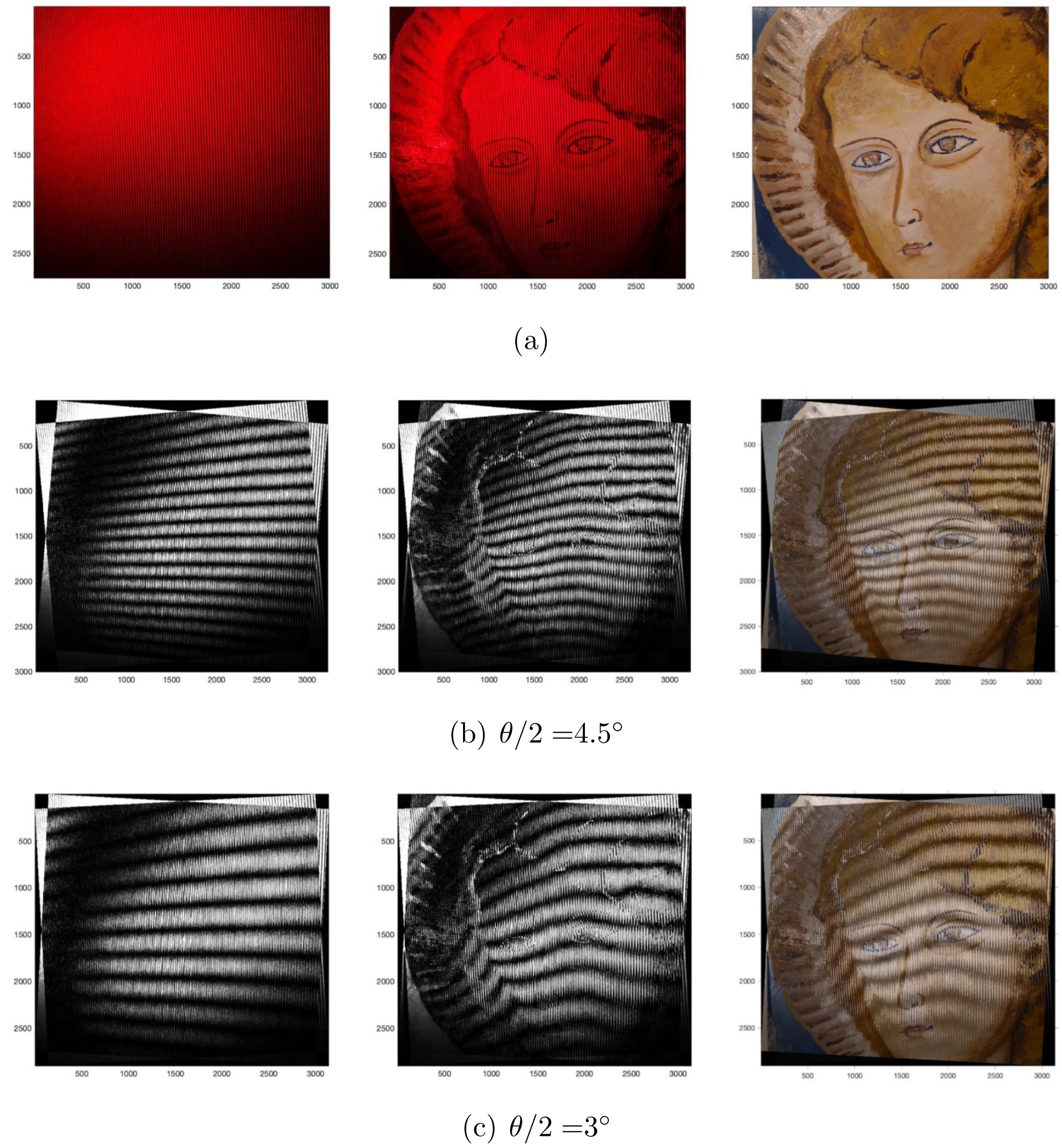


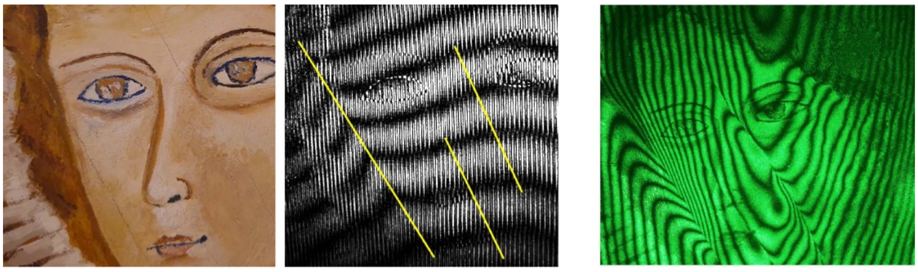

**Figure 11.** Smartphone moiré diagnostics on a wooden painting for testing cracks detection capability. (a) Smartphone dataset: sinusoidal fringes (reference plane and sample) and VIS. (b) and (c) Moiré pattern by finite fringe method: (left) reference; (center) distorted by the sample; (right) VIS-moiré alpha fusion for defects location.

unperturbed. It is shown that the smartphone-based technique can detect some structural defects. The same investigation performed with more established instrumentation can be found in the literature [90, 92]. Figure 10(d) shows a benchmarking from literature [71] with the same model investigated by electronic speckle pattern interferometry (ESPI).

### 4.2. Moiré method

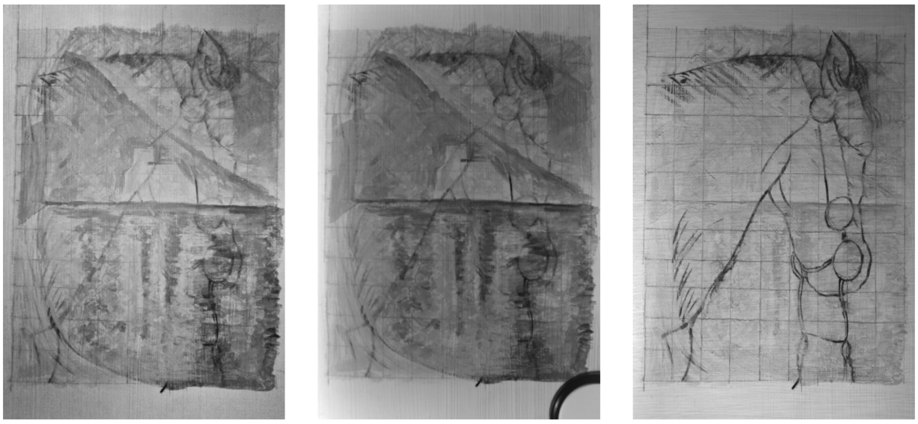
The effectiveness of the proposed approach for smartphone-based Moiré diagnostics is demonstrated on the panel painting model#3 with crack defects induced by artificial aging (depicted in figure 9). The smartphone's built-in camera captures images of the pattern when the object is in non-deformed and in loaded condition. The test object was mildly heated using warm air.

Results are given in figure 11 with the smartphone model Samsung S22. Figure 11(a) shows the smartphone dataset, including the sinusoidal fringes on the reference plane and on the polychrome painting, and the VIS image. It is shown that the fringe pattern is resolved effectively by the smartphone, thanks to the versatile setup that allowed us to optimize the fringe step. Figures 11(b) and (c) show the result of the moiré processing with the finite fringe method with a different rotation angle. Where the moiré fringes deviate from a regular pattern, it can be assumed that there is a defect. The fusion of VIS and moiré pattern images allows the precise location of the defects.



(a) (b)

**Figure 12.** Defects mapping. (a) VIS and moiré pattern ($\theta/2 = 3°$); main cracks identified by yellow lines. (b) Holographic interferometry on the same model.



(a) (b) (c)

**Figure 13.** IR reflectography on a wooden painting for testing smartphone detection capability of underdrawing. (a) IR reflectogram by smartphone (Samsung S22) and Hoya R72. (b) IR reflectogram by CCD camera (Sony DSC F828, nightshot) and same Hoya filter. (c) IR reflectography performed with professional camera Apollo, InGaAs sensor with sensitivity 0.9 $\mu$m to 1.7 $\mu$m.

Figure 12 depicts for clarity a detail with defects mapping and the benchmarking with holographic interferometry realized by the authors in previous investigations following the setup in [93]. As expected, holographic interferometry offers superior image quality and sensitivity: many cracks are located by abrupt changes in the fringes. In contrast, the moiré result exhibits significantly lower quality, albeit capable of identifying the main cracks. The lower performance of the smartphone moiré method is partially offset by its simplicity, affordability, and on-site applicability.

### 4.3. NIR reflectography

Smartphone IR reflectography is demonstrated on painting model #1 with subsurface features (depicted in figure 8) using the built-in camera CMOS sensor coupled to the typical adopted setup: the IR filter Hoya R72 to acquire the NIR band and a tungsten halogen lamp as IR source.

Figure 13 shows the results obtained with the smartphone model Samsung S22. It is shown that smartphone-based IR reflectography is effective in detecting hidden features underneath the painting surface: the underdrawing, not visible to the naked eye, is clearly disclosed in the IR image. For validation, the smartphone reflectogram is compared to the reflectogram acquired with the CCD camera Sony DSC F828 using the same Hoya filter. This camera is not a recent model; anyway, it has been adopted as a standard for many years, and it is still being used by conservators and restorers. The reason is the native 'nightshot' option that allows shooting without the IR blocking filter from the sensor. For further insights, we also report the results obtained with the professional scanning camera Apollo (by Opus Instrument, Atik Cameras) equipped with InGaAs sensor (0.9 $\mu$m–1.7 $\mu$m).

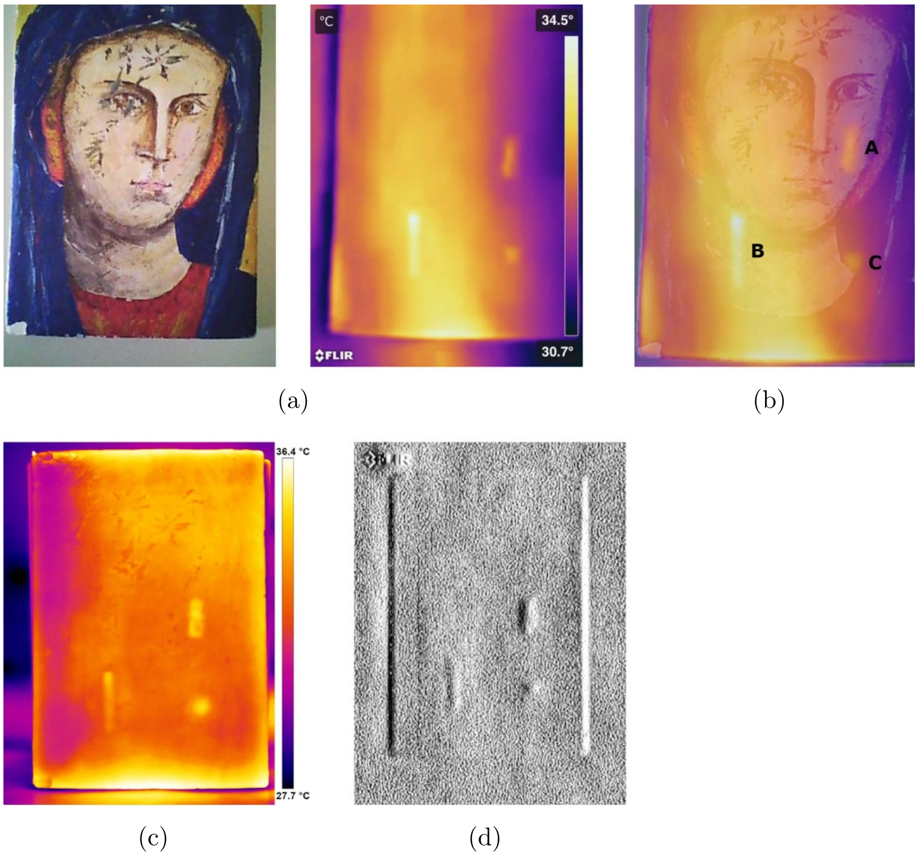



**Figure 14.** Smartphone IR thermography on a wooden painting for testing detachments detection capability. (a) VIS-thermal Dual dataset with smartphone (add-on sensor FLIR One) and FLIR App. (b) VIS-thermal alpha fusion with location of the detected defects. (c) Comparison with professional LWIR thermal camera FLIR T1020. Sensor array: 80 × 60 for smartphone accessory and 1024 × 768 for thermal camera. (d) Example of L2 vertical Haar wavelet transform with Image Processor App, image result has been further elaborated in Snapseed [94] by applying HDR filtering and adjusting contrast.

### 4.4. IR thermography

Smartphone IR thermography is demonstrated on the wooden painting model #2 with artificial detachments (depicted in figure 8) using the add-on sensor FLIR One. The heat stimulus was provided by moderately warm airflow at about 50 °C applied to the object for about 20 s.

Figure 14 shows the results obtained with the smartphone and the benchmarking with the professional LWIR camera FLIR T1020. It is shown that the smartphone-based technique can detect structural defects effectively. Defects A, B, and C are clearly identified with a good contrast. Defect D is not detected, probably due to its depth in the panel; this is in accordance with previous studies using more established instrumentation and quantitative thermal processing techniques [89, 90].

Specific smartphone thermal camera models have features that superimpose in real time the VIS image's profile on the thermal image. This makes the process of detecting thermal anomalies and defects easier; however, mismatch alignments may occur due to parallax error, especially for close-up acquisition, which must be adjusted in post-processing. In general, thermal images generated with smartphones can be analyzed offline on a PC with dedicated processing. However, our focus here is on exploring how much can be accomplished with the entire procedure being performed on smartphones. The Image Processor App, for instance, can perform several image processing with the smartphone, including wavelet transforms, which can be applied to thermograms to enhance defect localization. An outstanding example is given in figure 14(d).

## 5. Discussion: performance, potential, limitations, and further steps

### 5.1. Smartphone coherent imaging: laser speckle imaging and moiré method

The smartphone device was shown to effectively capture the laser-projected speckle pattern, with the small aperture lens allowing a speckle cell size suitable for *in situ* analysis. It is interesting to discuss the optimization of the optical setup through a tuneable speckle size, obtained following the theoretical analysis of performance based on statistical optics given in [74]. The ratio of the sizes of the projected speckle pattern (generated by the diffuser) and the direct speckle pattern (inherent to the surface roughness) is given by $r \approx \frac{z}{z'}\frac{a}{D}$, with $z/z'$ the ratio of the diffuser-object and camera-object distances, and $a/D$ the ratio of the lens aperture and the diffuser laser spot. In the case of the smartphone's small aperture lens (a few millimeters), the acquisition of the speckle projected pattern is optimized at a camera working distance shorter than the laser source distance. A compact system with the source and the camera in a unique block ($z/z' = 1$) would not have been a versatile setup.

In conclusion, despite the feasibility of a cost-effective system and the use of a smartphone, it should be remarked that speckle-based techniques require strong skills in optics. Due to its high sensitivity, the technique is worthy of further investigation, with efforts being made to prepare an easily accessible measurement protocol for objects as complex as works of art.

The smartphone device was also shown effective in artwork moiré diagnostics for cracks detection, using a DOE with a fiber optic laser diode. The coherent source has the advantage of projecting sinusoidal fringes onto the object; coupled with a DOE, multiresolution is obtained because fringe frequency can be easily changed. A disadvantage is given by speckle noise; the use of white light projectors can be investigated in future works. It is worth saying a few words about the choice of the laser source. In our case, it is a low-power laser, 5 mW, which, when expanded, does not induce significant heating on the surface of the artwork. Furthermore, as the laser diode is pigtailed to a fiber, the light source is easy to position, and the safety problems caused by a free laser beam are avoided.

The proposed simplified approach cannot rival the sophisticated processing algorithms described in the literature, yet our results are promising. Smartphone-based moiré is capable of providing the diagnostic information at a fraction of the cost and processing, therefore, we believe that it is worthy of further investigation.

### 5.2. Smartphone IR reflectography

The primary feature of smartphone IR reflectography is the limited spectral range (up to $\sim$1 $\mu$m), which permits imaging of subsurface traits beneath pictorial layers only for a restricted range of pigments with partial optical transparency in that range [81]. On the other hand, a positive aspect of the CMOS limited spectral range is that the lower penetrating capability may allow the contrast detection of pictorial layers not imaged in the more extended InGaAs range. This observation is evident by comparing the IR reflectography results (figure 13) with the painting model structure (figure 7). As can be seen, the InGaAs camera detects the underdrawing very well, but the more penetrating IR range can not probe the painted layers that are instead detected using the smartphone CMOS sensor.

Regarding the setup, it could be interesting the further implementation of a compact filtering system, using a set of ø 0.5 inch narrow band filters that are available in commerce at low cost, in order to realize smartphone-based multispectral imaging.

### 5.3. Smartphone thermography

The add-on FLIR thermography system mounts a Lepton core, which has great potential in acquiring real-time thermograms for qualitative mapping of defects in low-conductive materials, such as wooden painting. The slow acquisition rate $\sim$10 Hz is not suitable for thermography applied to metals, while the small array sensor limits the investigation to medium-sized artifacts. On the other side, the compactness of the device allows to easily implement scanning procedures for the acquisition of large areas. A peculiar advantage of the employed add-on sensor is the registration of the thermogram with the visible image, allowed by the dual camera of the module, which enables mosaicking. The capability of acquiring and visualizing in real-time the superimposition of VIS-thermal images is very powerful for the inspection of artworks on field. Moreover, a precise location of the defects is necessary for their restoration.

Regarding the setup, better results are expected with the increase in resolution, which at present already reaches 160 × 120 pixel (FLIR One Edge Pro) and 320 × 240 pixel (Seek CompactPRO).

To conclude, being easy-to-access and low-cost with respect to traditional instrumentation, we believe that the smartphone add-on thermography system could be a very interesting tool for diagnostics of artworks, i.e. for enlarging the portfolio of portable instruments in use of the museum operators during restoration.

### 5.4. Smartphone devices and sensors

The evolution of smartphones is tumultuous. This means that new models are continuously being offered to the market. This fluidity of the imaging technology could represent a difficulty from the point of view of smartphone-based diagnostics. Indeed, different models may have different imaging technology [84] and interact with ad-hoc sensors in different ways. What we have found is that when the smartphone camera is used as a sensor in the visible, there are no significant differences in the results obtained by different smartphones, apart from the performance of the camera itself, of course. This changes when infrared reflectography is considered. Although the design of the camera may be different in different smartphones, it is generally optimised to work in the visible. Because the sensor chip is sensitive in the NIR, down to wavelengths of about 1 micron, smartphone cameras usually include an infrared filter to limit the sensor's response. Thus, different smartphones have different NIR responses depending on how much these wavelengths are filtered out. Generally speaking, it may well be the case that older devices will prove to be better suited to perform certain diagnostics than new ones. In conclusion, it is not possible to provide a list of devices suitable for the different diagnostic techniques, because it would quickly become outdated. What we would like to observe is the importance of the possibility of using smartphones in diagnostics with interesting results, even when compared with much more expensive and difficult-to-use instrumentation. As the demand for such applications increases, the market itself will move towards proposing dedicated devices and sensors, as is already partially happening (see table 2).

## 6. Conclusion

Smartphone diagnostics is an expanding area of scientific research. Novel sensors based on smartphones are continuously being proposed, especially in fields like medicine and chemistry. Currently, the cultural heritage field does not seem to show an interest in the potential applications of such sensors. Typical applications in this field involve improving user experience, for instance, through augmented reality. This article aims to discuss the potential for a smartphone-based approach in cultural heritage diagnostics, following a concise analysis of this new and revolutionary trend.

Smartphones can be considered an auxiliary tool in the diagnosis of cultural heritage, which may prove to be very useful in specific conditions. Smartphone diagnostics offer the distinctive advantage of being ubiquitous and relatively low cost. Consequently, it has the potential to be used by people of different backgrounds.

Various image-based diagnostic techniques have been demonstrated on wooden painting models, such as IR reflectography, thermography, and portable coherent methods that are based on a laser diode, namely speckle imaging and the moiré method.

A comparison of the obtained results with established techniques demonstrates that smartphone-based diagnostics have the potential to contribute to the preservation and conservation of cultural heritage. Being portable and user-friendly, it is well-suited for routine inspections and assessments by art conservators, historians, and collectors.

## Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

## Acknowledgments

Special thanks are due to Dumitru Scutelnic of the University of Verona and to Giovanni Pasqualoni of the University of L'Aquila for their technical assistance in the Laboratory.

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