Smartphone diagnostics for Cultural Heritage

Claudia Daffara[a, c], Giacomo Marchioro[a], and Dario Ambrosini[b, c]

[a]Dept. of Computer Science, University of Verona, Str. le Grazie 15, 37134, Verona, Italy
[b, c]DIIIE, University of L'Aquila, P.le Pontieri 1, 67100, L'Aquila, Italy
[c]CNR-ISASI Institute of Applied Science & Intelligent Systems, via Campi Flegrei 34, Pozzuoli (NA), Italy

ABSTRACT

In recent years, smartphones have developed tumultuously; in fact, they have increasingly taken on the role of portable and compact personal computers equipped with a range of sensors and applications capable of monitoring, for example, physical activity, heartbeat and sleep. Their ability to manage and transmit data makes them a very interesting tool even in the scientific field, where the concept of "lab in a phone" is gaining ground. In this work, after briefly summarizing these new approaches, we will consider the application of smartphones to the diagnostics of Cultural Heritage.

Keywords: Artworks diagnostics, smartphone, NDT, low cost instrumentation

1. INTRODUCTION

The recent trend of the so-called smartphone science[1] will likely be more than just a fashion topic. As a matter of fact, smartphones could drive in science the same revolution they brought in everyday life. Currently, the role of smartphones in citizen science and big data can hardly be overestimated, but the main question now is: can smartphones be used for real science? As detailed later, we have now plenty of examples in literature of smartphone-based devices to measure viscosity, to perform schlieren imaging, particle image velocimetry or to realize bio-sensors, to name a few.

Smartphone science approach can be roughly divided in two categories:[2, 3]

1) the device is used "as is"; this means that only the usual recording, connecting and processing capabilities of the smartphone are involved;

2) the device is "enhanced" by means of suitable add-ons: a commercial example is the FLIR™ One series of thermal cameras for smartphones.

The aim of this paper is to discuss if such an approach could also be interesting and useful in artworks diagnostics. Cultural institutions, apart from the large and famous ones, are often struggling with tight budgets. Smartphone-based diagnostics, if feasible, has the potential to change deeply this scenario. After a very brief review of smartphone applications in different fields, this paper demonstrates a number of different diagnostics on wooden painting models, realized with the traditional materials and techniques. Reflectography, thermography and an optical methods based on coherent sources will be considered and realized. Experimental results will be compared with the ones obtained from more established instrumentations.

2. THE SMARTPHONE AS A MEASUREMENT SYSTEM

The technological development of smartphones can be summarized as in figure 1.

A simple interrogation of the SCOPUS database using the search term "smartphone" returns about 12626 papers, while the results obtained with the search term "smartphone-based" are shown in figure 2 (data accessed June 2019). This very simple way of searching a major scientific database is, however, able to show the relative uptake in attention.

Send correspondence to
Claudia Daffara: E-mail: claudia.daffara@univr.it, Telephone: +39 045 8027942

Optics for Arts, Architecture, and Archaeology VII, edited by Haida Liang, Roger Groves, Piotr Targowski, Proc. of SPIE Vol. 11058, 110581K

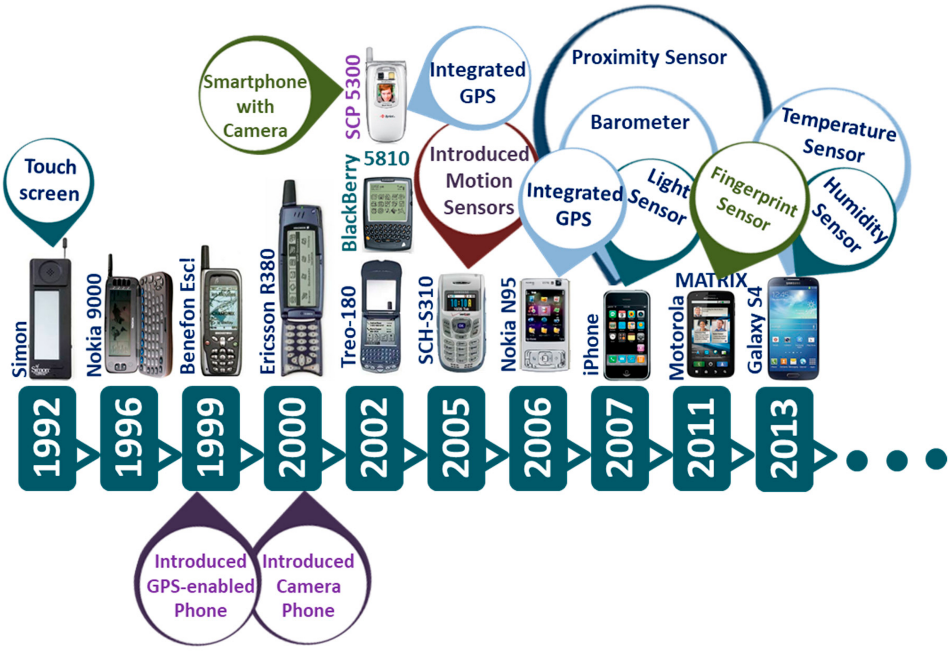

Figure 1: The technological evolution of smartphones as summarized by Majunder and Deen[4] (reproduced under the terms and conditions of the CC BY license http://creativecommons.org/licenses/by/4.0/).

The increasing role of this approach and the potentially high impact in many areas are confirmed by the recent rewiews about smartphones spectrometers,[2] smartphone-based bioanalytical, health monitoring and diagnosis applications.[4,5] Table 1 reports and compares some references.

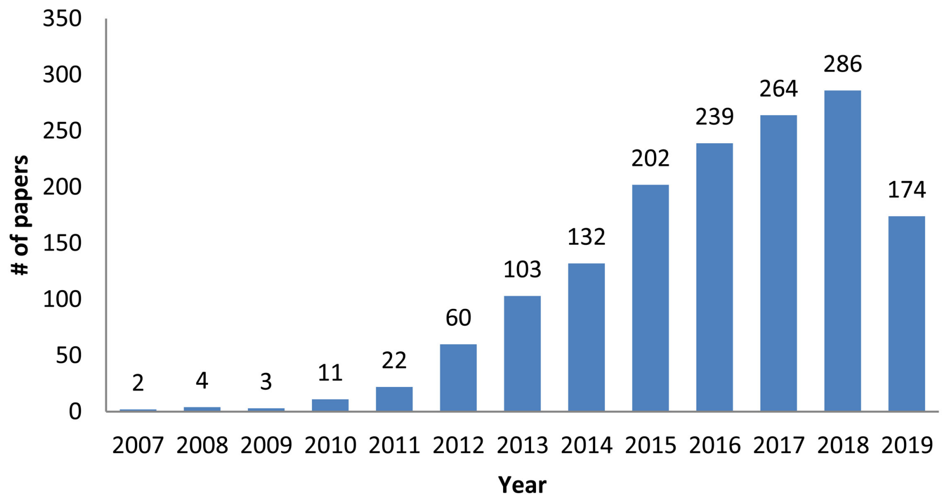

Figure 2: Number of published papers reported in SCOPUS, with the word "smartphone-based" in the title: an escalation in interest is evident. Data for 2019 not complete (June).

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

Authors	Year	Application	Notes
Majunder et al.[4]	2019	health	review
Mu et al.[6]	2019	spectrometry	
Yu et al.[7]	2019	spectrometry	
Zeng et al.[8]	2019	stereo-DIC	
Asinelli et al.[9]	2018	microclimate museums	
Settles[10]	2018	schlieren	
Vidvans et al.[11]	2018	reverse engineering	
Kanchi et al.[5]	2018	health	review
McGonigle et al.[2]	2018	spectrometry	review
Lewis et al.[12]	2018	medicine	
Jarujamrus et al.[13]	2018	environmental analysis	
Stanger et al.[14]	2018	thermal imaging	
Kim et al.[15]	2018	microfluidic	
Lee et al.[16]	2018	geosciences	review
Rateni et al.[17]	2017	food diagnostics	review
Feeldbush et al.[18]	2017	engineering	
Edwards et al.[19]	2017	medicine	
Scire et al.[20]	2017	digital holography	
Roda et al.[21]	2016	biosensors	review
Zhao et al.[22]	2016	structural health monitoring	
Wilkes et al.[23]	2016	UV imaging	
Russo et al.[24]	2015	medicine	
Hossain et al.[25]	2015	laser beam profiler	
Razdan et al.[26]	2015	machine vision	
Pongnumkul et al.[27]	2015	agriculture	review
Butel et al.[28]	2015	deflectometry	
Schirripa Spagnolo et al.[29]	2014	artworks authentication	
Daponte et al.[30]	2013	metrology	review
Ozdalga etal.[31]	2012	medicine	review
Tseng et al.[32]	2010	microscopy	

3. SMARTPHONES IN THE DIAGNOSTICS OF ARTWORKS

Up to now, the role of smartphones in Cultural Heritage has been mainly linked to applications such as game-based learning[33] and improved fruition,[34,35] often through augmented reality.

Smartphones in the diagnostics of Cultural Heritage should be considered as auxiliary tools that can be used when needed by people with different backgrounds; the following are some conditions in which smartphone features could represent a "win-win" option:

- restricted budget and/or need to carry out numerous surveys
- in situ measurements
- measurements under difficult access conditions
- measurements carried out simultaneously by several operators.

We might consider different scenarios where smartphone diagnostics can be applied in an efficient and deontologically correct way. When restoring an artwork, restorers and curators can not dispose of analysis when needed during the restoration. This is particularly likely for on-site analysis, when, for instance, conservators perform restorations on scaffolding or in situations where special efforts are needed to place the instrumentation for acquiring the data. It is common during the restoration, to use small UV lights for inspection, checking the adhesion of the support by knocking on mural paintings, or placing raking lights for enhancing the visibility of some features of the surface under treatment. Smartphone diagnostics can optimize these procedures in at least three ways. The smartphone can be turned into a multimodal acquisition device providing an integrated portable system easier to handle and to carry. Thus, allowing to collect data also in these phases of the restoration. This means for instance that the restorer, in its continual decision-making process, might be encouraged to take advantage of the scientific tools more often, resulting in a more reasoned restoration. Furthermore, the inspection can and should be followed by a recording and logging of the data. Introducing the smartphone as an active instrument, the inspections of the restorers that do not produce any data, can become part of the data collection campaign and be valuable to the interpretation of other data or as a reference for conservation report. This way the restorer or the conservation scientist benefits from the opportunity to confront the data in real-time with the original. Furthermore, the smartphone is designed to communicate, therefore data can be shared and discussed easily with curators and supervisors and stored in a server for reference. Following this perspective it might be easier to imagine a second scenario where the smartphone can be used as a tool for monitoring the conservation status of artworks or reporting any damage or threat to its conservation. Just to mention an example towards this direction, the Italian Carabinieri Command for the Protection of Cultural Heritage, branch responsible for combatting art crimes, has introduced the "iTPC" App for citizen partecipation in the identification and reporting of stolen artworks.[36] Eventually, different augmented reality frameworks are available that might be used for facilitating the restorer during the conservation.

4. SMARTPHONE SENSORS

In this paper, following the approach described in the Introduction, sensors are divided in the following two main categories:

- built-in smartphone sensors, integrated in the body of the smartphone
- add-on sensors: external unit connected to the smartphone

Smartphone diagnostics that takes advantage of built-in sensors can be easily adopted by the community conserving the Cultural Heritage. On the other hand, the capabilities of the smartphone can be extended connecting other hardware as peripherals. In this case, the smartphone is used as a controlling unit for the hardware connected to it. However, external units connected to the smartphone have the drawback of requiring investments, which under certain circumstances might discourage their adoption, and additional effort to connect them. Between these two categories, it is possible to employ some built-in sensors together with some minor external hardware components. The best choice would be a diagnostics using built-in sensors, as they are ready to use as the need occurs. Nonetheless, opting for non-consumer sensors to be built-in instead of designing them as peripherals means creating products confined to a little niche and this might affect the cost and performance of the device.

Besides these two alternatives, one can consider the modular smartphone approach. A modular smartphone is a smartphone where the hardware is divided into different blocks that can be assembled by the user, allowing the configuration of smartphones tailored for a specific need. Should this alternative be extensively adopted by the market, it will lead to greater benefits in terms of portability, cost and integration, than connecting external units. In fact, many different projects attempting to create such devices did not reach the production stage (e.g. Googles Project Ara, phone block). All considered, making use of such everyday devices like smartphones in the framework of the conservation of cultural heritage seems to be a promising path to take.

5. DEVELOPING TAILORED SMARTPHONE APPLICATIONS FOR CULTURAL HERITAGE DIAGNOSTICS

We subdivided the process of implementing a tailored smartphone diagnostic tool in two main phases: the design or adaption of the hardware and the development of the software (App).

Table 2: Examples of devices and studies using built-in sensor and add-on modules.

Analysis	Built-in sensor example	Add-on module example
Photography	Any e.g. Huawei P30 Pro	Sony ILCE–QX1
Macro-photography		Olloclip
Reprography		ScanTent[37]
NIR imaging	iPhone 6s NIR Enabled EigenImaging	NIR Module EigenImaging
Fluorescence imaging		UV Module EigenImaging
Thermal camera	Cat S60 and S61	FLIR One
VIS spectrometry		GoSpectro
NIR spectrometry	Changhong H2[38,39]	Sagitto
Raman spectrometry	Smart-phone Raman[6]	
Colorimetry		Nix Color Sensor
Relative humidity	Samsung Galaxy S4	TALESEA[40]
Temperature	Samsung Galaxy S4	TALESEA[40]
Pressure	Xiaomi Mi 6X	Smart Home Weather Station (Netatmo)
Vibrations	Any with accelerometer	Digiducer
Ambient light	Any with ambient light sensor	LumoPower 2
VOC	Cat S61	Atmo Tube

5.1 Designing of the hardware

For implementing most of the diagnostic techniques used in Cultural Heritage is often necessary to dispose of components that are not available on the consumer's smartphone. There are very few possibilities for creating smart-phone with custom built-in sensors left to the researchers or inventors outside the smartphone manufacturing industry. The concept of phone blocks has been recently revised in Kiteboad smartphone project,[41] a platform for prototyping smartphone with the possibility of integrating different sensors. In fact at the moment there is a lack on tools for prototyping smartphones tailored to specific needs. Most of the smartphone scientific applications take advantage of the high performance of the latest smartphone coupled with external hardware, add-ons. The hardware integration in many cases relies on supports or adapters for joining the hardware with the smartphone. These often include smartphones cases or clips used for aligning the add-ons to the built-in hardware (e.g. cameras or LEDs).

5.2 Software development

When external units are connected to a smartphone, customized software is needed. The first step is establishing communication between the external hardware and the smartphone. Different protocols might be used depending on the operating system and type of connection, in case of an USB connection on Android devices[42] Android Open Accessory (AOA) protocol is used. Blue Tooth connection may be established using Simple Serial Protocol (SSP). The development of the App it's a crucial phase on the deployment of the smartphone application. Most of the built-in sensors can be accessed using proper API. Regarding the camera sensor, the latest Android smartphones allow acquiring RAW data using Camera 2 API.[43] This feature was implemented since Android 5.0 Lollipop, allowing to record raw data in .DNG format. Not all smartphones support this feature and if is not by default, the user might have to install a custom ROM to be able to use Apps with the possibility to save RAW data (e.g. OpenCamera.[44] iPhone allows shooting in RAW .DNG format since iOS 10[45] an app must be installed to shoot in RAW (e.g. VSCO Camera). For allowing users with a lower understanding of software development to implement their own App, MIT created a web platform called MIT App inventor[46] that allows building easily Apps that interacts with the external world by means of sensors.

5.3 Artificial Intelligence and Mobile Cloud Computing

Besides portability, another appealing feature of the smartphones compared to computers is the high connectivity. Smartphones can connect with the internet not only through Wi-Fi and LAN connections, but also using cellular network technologies. This feature permits to take advantage of the cloud technologies for expanding the capabilities of the smartphone-based diagnostics. Mobile Cloud Computing (MCC) is not only used for increasing the processing power, but also for connecting and sharing information through large databases and using Artificial Intelligence (AI) for improving the outcome of the computation. Most of the smartphone spectrometers rely on MCC for attribution of the spectra.[6] However, MCC and AI algorithms might not be always transparent and the processing carried out by the application might distort the result.

6. EXAMPLES OF SMARTPHONE IMAGE-BASED DIAGNOSTICS

In the Cultural Heritage field image-based diagnostics plays an important role. Here, the feasibility of smartphone imaging is demonstrated through measurements on two panel painting models. The models are realized on poplar wood coated, according to the ancient recipes, with the usual priming layers of canvas, gesso and glue. The first specimen was specifically realized for testing IR imaging: a horse head, drawn in black coal, was covered by tempera colors. The second one has artificially detached regions, obtained by inserting thin Mylar sheets at different depths, and is suitable for testing nondestructive techniques for structural evaluation as thermography and speckle imaging.

6.1 Smartphone IR Reflectography

Smartphone IR reflectography is demonstrated on a wooden painting model using the built-in camera sensor coupled to the IR filter Hoya R72. This filter is among the standard adopted in IR photography of artworks. For the aim of this paper, a 52mm filter was just placed over the lens of the smartphone and used as IR window; of course, optimized small optics is commercially available and can be properly adapted. The figure 3 reports the transmission curve of the IR filter measured with a UV-VIS-NIR spectrometer. As shown, it opens at 720 nm with a flat transmittance, allowing us to test the near-IR capability of the smartphone camera sensor. The source was a normal tungsten halogen lamp, typically adopted in IR reflectography.

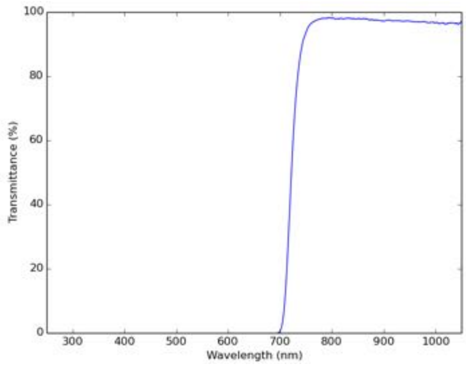

Figure 3: Transmittance of the Hoya R72 filter (UV-VIS-NIR spectrometer Ocean Optics).

The results obtained with a smartphone model Xiaomi Mi 8 are reported in figure 4. The raw photography, i.e. without post-processing, shows the near-IR sensitivity of the smartphone camera sensor. Then, it is shown that smartphone-based IR reflectography is effective to detect hidden features underneath the painting surface: the underdrawing, not visible to the naked eye, is clearly disclosed in the IR image. Here, the IR image was just cropped, converted to grey level, and cut in the histogram using the reflectance standard (Spectralon). 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.

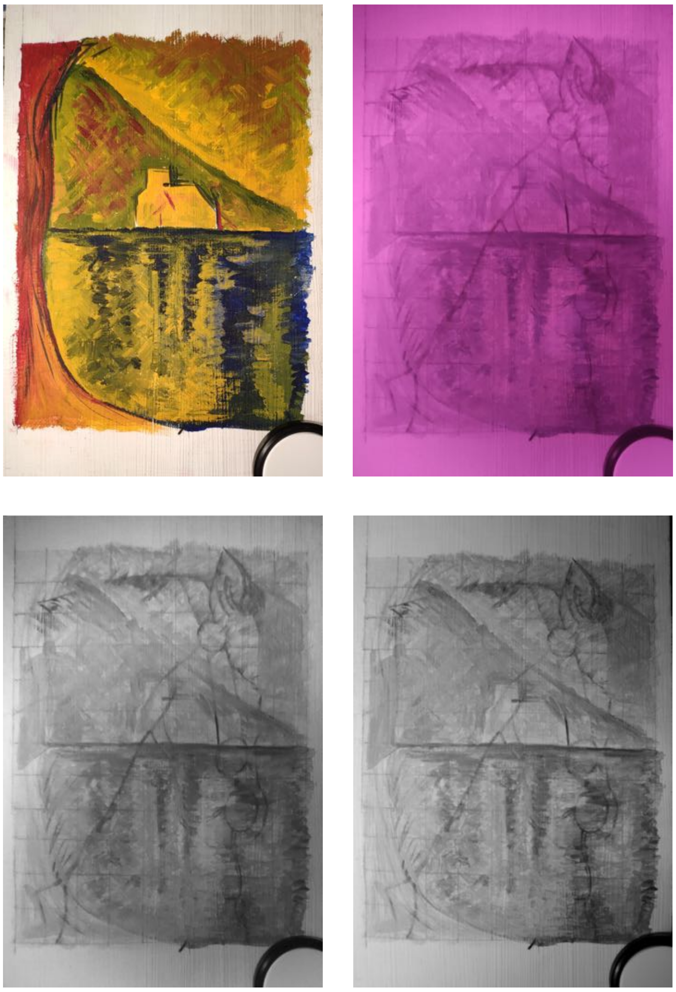

Figure 4: Smartphone IR reflectography on a wooden painting (smartphone model Xiaomi Mi 8). Top: photography (left); smartphone IR shot (right) with Hoya filter - no processing. Bottom: comparison of IR reflectography with smartphone (left) and with CCD camera (model Sony DSC F828, nightshot) and same Hoya filter (right), showing sub-features detection capability - IR images in grey levels (8 bit) with histogram optimized. Pixel array: 3024×4032 for smartphone and 2448×3264 for CCD camera.

6.2 Smartphone IR Thermography

Smartphone IR thermography is demonstrated on a wooden painting model using the add-on sensor FLIR One. The system has sensitivity in the Long-Wave IR range from 8 µm to 14 µm with a nominal thermal sensibility of 100 mK, and an array of 80×60 elements of 12 µm pixel size. Data are stored as radiometric images for processing. The range of emissivity is limited to preset values.

The figure 5 shows the results obtained with smartphone thermography and the benchmarking with the thermography performed with the Long-Wave IR professional camera FLIR S65 HS. The heat stimulus was provided by moderately warm air flow. It is shown that the smartphone-based technique is able to detect the structural defects effectively.

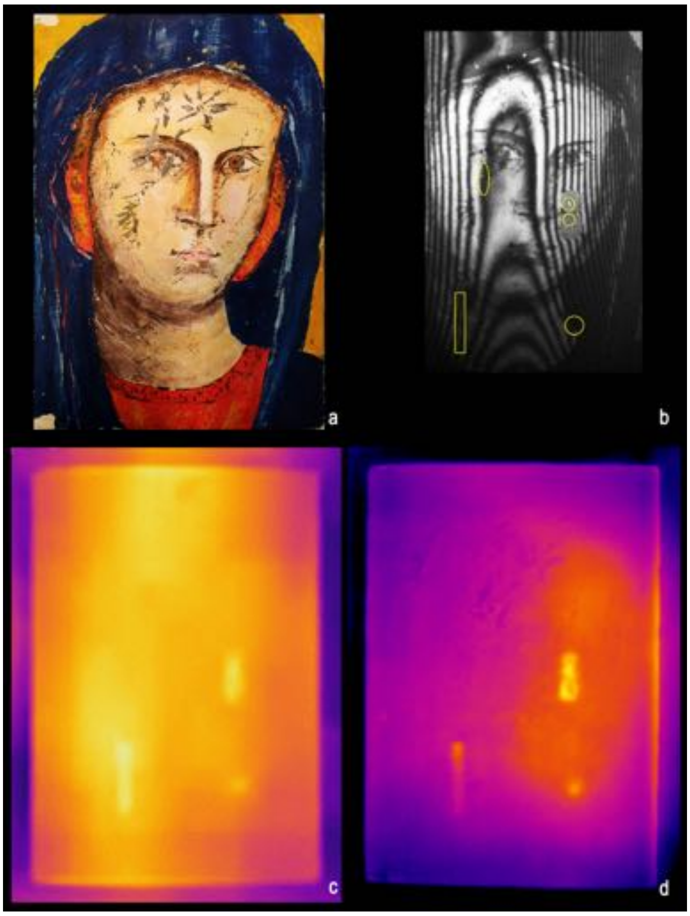

Figure 5: Smartphone IR thermography on a wooden painting (smartphone add-on sensor FLIR One). Top: photography (left); holographic interferometry (right), showing the location of the hidden defects. Bottom: comparison of IR thermography with the add-on smartphone sensor (left) and with a scientific Long-Wave IR thermal camera (model FLIR S65 HS), showing defects detection capability. Thermal sensor array: 80×60 for smartphone accessory and 320×240 for thermal camera.

6.3 Smartphone Speckle Decorrelation

Speckle decorrelation is a basic technique in speckle metrology that can be applied to analysis of panel paintings.[47] In its simplest configuration, it basically requires a laser source and a camera: two images are recorded and stored, before and after the induced deformation. Performing a digital subtraction, if the images are perfectly correlated they will cancel when subtracted, otherwise regions of decorrelation (often induced by structural defects) may appear.

The figure 6 shows the results obtained with smartphone speckle decorrelation (smartphone model Samsung S6). As a source a laser diode (wavelength 638.5 nm and output power 5 mW) was used. Deformation was induced by moderately warm air flow. It is shown that the smartphone-based technique is able to detect some structural defects. The same investigation performed with more established instrumentation can be found in literature.[48]

Figure 6: Smartphone speckle decorrelation on a wooden painting (smartphone model Samsung S6, pixel array 5312 × 2988). Speckle pattern acquired before the deformation (left), showing speckle smartphone sensitivity; result of speckle pattern decorrelation (right), showing defects detection capability (see also figure 5-b.)

7. CONCLUSION

Smartphone diagnostics is a rapidly expanding field in scientific research. New smartphone-based sensors are continuously being proposed, especially in areas such as medicine and chemistry. Such an interest does not seem to be present at the moment in the Cultural Heritage field, where the typical applications concern the improvement of the fruition, for example thanks to augmented reality. In this preliminary paper, after a brief analysis of this new and potentially revolutionary trend, the application of a smartphone-based approach to Cultural Heritage diagnostics was discussed.

Smartphones in the diagnosis of Cultural Heritage should be considered as auxiliary tools; the following are some conditions in which smartphones' features could represent a very interesting option:

- restricted budget and/or need to carry out numerous surveys
- in situ measurements
- measurements under difficult access conditions
- measurements carried out simultaneously by several operators.

Smartphone diagnostics has also the distinctive features of being ubiquitous and relatively low cost and, therefore, has the potential of being used by people with different backgrounds. Finally, some image-based diagnostic techniques have been demonstrated on wooden painting models.

ACKNOWLEDGMENTS

We are grateful to Dumitru Scutelnic of University of Verona for his help with the IR imaging measurements and to Giovanni Pasqualoni of University of L'Aquila for his help with the thermographic measurements.

REFERENCES

[1] Cartwright, J., "Technology: Smartphone science," *Nature* **531**, 669–671 (2016).

[2] McGonigle, A., Wilkes, T., Pering, T., Willmott, J., Cook, J., Mims, F., and Parisi, A., "Smartphone spectrometers," *Sensors* **18**(1), 223 (2018).

[3] Saini, S. S., Sridhar, A., and Ahluwalia, K., "Smartphone optical sensors," *Optics and Photonics News* **30**(2), 34–41 (2019).

[4] Majumder, S. and Deen, M. J., "Smartphone sensors for health monitoring and diagnosis," *Sensors* **19**(9), 2164 (2019).

[5] Kanchi, S., Sabela, M. I., Mdluli, P. S., Bisetty, K., et al., "Smartphone based bioanalytical and diagnosis applications: A review," *Biosensors and Bioelectronics* **102**, 136–149 (2018).

[6] Mu, T., Li, S., Feng, H., Zhang, C., Wang, B., Ma, X., Guo, J., Huang, B., and Zhu, L., "High-sensitive smartphone-based raman system based on cloud network architecture," *IEEE Journal of Selected Topics in Quantum Electronics* **25**(1), 1–6 (2018).

[7] Yu, L., Tao, R., and Lubineau, G., "Accurate 3d shape, displacement and deformation measurement using a smartphone," *Sensors* **19**(3), 719 (2019).

[8] Zeng, F., Mou, T., Zhang, C., Huang, X., Wang, B., Ma, X., and Guo, J., "Paper-based sers analysis with smartphones as raman spectral analyzers," *Analyst* **144**(1), 137–142 (2019).

[9] Asinelli, M. G., Serra, M. S., Marimòn, J. M., and Espaulella, J. S., "The smarts_museum_v1: An open hardware device for remote monitoring of cultural heritage indoor environments," *HardwareX* **4**, e00028 (2018).

[10] Settles, G. S., "Smartphone schlieren and shadowgraph imaging," *Optics and Lasers in Engineering* **104**, 9–21 (2018). Optical Tools for Metrology, Imaging and Diagnostics.

[11] Vidvans, A. and Basu, S., "Smartphone based scalable reverse engineering by digital image correlation," *Optics and Lasers in Engineering* **102**, 126–135 (2018).

[12] Lewis, W. and Franco, W., "Smartphone imaging of subcutaneous veins," *Lasers in surgery and medicine* **50**(10), 1034–1039 (2018).

[13] Jarujamrus, P., Meelapsom, R., Pencharee, S., Obma, A., Amatatongchai, M., Ditcharoen, N., Chairam, S., and Tamuang, S., "Use of a smartphone as a colorimetric analyzer in paper-based devices for sensitive and selective determination of mercury in water samples," *Analytical Sciences* **34**(1), 75–81 (2018).

[14] Stanger, L., Wilkes, T., Boone, N., McGonigle, A., and Willmott, J., "Thermal imaging metrology with a smartphone sensor," *Sensors* **18**(7), 2169 (2018).

[15] Kim, S., Kim, K. C., and Yeom, E., "Microfluidic method for measuring viscosity using images from smartphone," *Optics and Lasers in Engineering* **104**, 237–243 (2018). Optical Tools for Metrology, Imaging and Diagnostics.

[16] Lee, S., Suh, J., and Choi, Y., "Review of smartphone applications for geoscience: current status, limitations, and future perspectives," *Earth Science Informatics* **11**(4), 463–486 (2018).

[17] Rateni, G., Dario, P., and Cavallo, F., "Smartphone-based food diagnostic technologies: A review," *Sensors* **17**(6), 1453 (2017).

[18] Feldbusch, A., Sadegh-Azar, H., and Agne, P., "Vibration analysis using mobile devices (smartphones or tablets)," *Procedia engineering* **199**, 2790–2795 (2017).

[19] Edwards, P., Zhang, C., Zhang, B., Hong, X., Nagarajan, V. K., Yu, B., and Liu, Z., "Smartphone based optical spectrometer for diffusive reflectance spectroscopic measurement of hemoglobin," *Scientific reports* **7**(1), 12224 (2017).

[20] Scire, J. J., Furniss, J., Mauro, J., and O'Sullivan, K., "Digital holography with a cell-phone camera module," in [*2017 IEEE Sensors Applications Symposium (SAS)*], 1–6, IEEE (2017).

[21] Roda, A., Michelini, E., Zangheri, M., Di Fusco, M., Calabria, D., and Simoni, P., "Smartphone-based biosensors: A critical review and perspectives," *TrAC Trends in Analytical Chemistry* **79**, 317–325 (2016).

[22] Zhao, X., Liu, H., Yu, Y., Zhu, Q., Hu, W., Li, M., and Ou, J., "Displacement monitoring technique using a smartphone based on the laser projection-sensing method," *Sensors and Actuators A: Physical* **246**, 35–47 (2016).

[23] Wilkes, T., McGonigle, A., Pering, T., Taggart, A., White, B., Bryant, R., and Willmott, J., "Ultraviolet imaging with low cost smartphone sensors: Development and application of a raspberry pi-based uv camera," *Sensors* **16**(10), 1649 (2016).

[24] Russo, A., Morescalchi, F., Costagliola, C., Delcassi, L., and Semeraro, F., "Comparison of smartphone ophthalmoscopy with slit-lamp biomicroscopy for grading diabetic retinopathy," *American journal of ophthalmology* **159**(2), 360–364 (2015).

[25] Hossain, M. A., Canning, J., Cook, K., and Jamalipour, A., "Smartphone laser beam spatial profiler," *Optics letters* **40**(22), 5156–5159 (2015).

[26] Razdan, V. and Bateman, R., "Investigation into the use of smartphone as a machine vision device for engineering metrology and flaw detection, with focus on drilling," in [*Automated Visual Inspection and Machine Vision*], **9530**, 95300C, International Society for Optics and Photonics (2015).

[27] Pongnumkul, S., Chaovalit, P., and Surasvadi, N., "Applications of smartphone-based sensors in agriculture: a systematic review of research," *Journal of Sensors* **2015** (2015).

[28] Butel, G. P., Smith, G. A., and Burge, J. H., "Deflectometry using portable devices," *Optical Engineering* **54**(2), 025111 (2015).

[29] Spagnolo, G., Cozzella, L., and Papalillo, D., "Smartphone sensors for stone lithography authentication," *Sensors* **14**(5), 8217–8234 (2014).

[30] Daponte, P., De Vito, L., Picariello, F., and Riccio, M., "State of the art and future developments of measurement applications on smartphones," *Measurement* **46**(9), 3291–3307 (2013).

[31] Ozdalga, E., Ozdalga, A., and Ahuja, N., "The smartphone in medicine: a review of current and potential use among physicians and students," *Journal of medical Internet research* **14**(5), e128 (2012).

[32] Tseng, D., Mudanyali, O., Oztoprak, C., Isikman, S. O., Sencan, I., Yaglidere, O., and Ozcan, A., "Lensfree microscopy on a cellphone," *Lab on a Chip* **10**(14), 1787–1792 (2010).

[33] Mortara, M., Catalano, C. E., Bellotti, F., Fiucci, G., Houry-Panchetti, M., and Petridis, P., "Learning cultural heritage by serious games," *Journal of Cultural Heritage* **15**(3), 318–325 (2014).

[34] Garau, C. and Ilardi, E., "The non-places meet the places: virtual tours on smartphones for the enhancement of cultural heritage," *Journal of Urban Technology* **21**(1), 79–91 (2014).

[35] Garau, C., "From territory to smartphone: Smart fruition of cultural heritage for dynamic tourism development," *Planning Practice and Research* **29**(3), 238–255 (2014).

[36] Rush, L. and Benedettini Millington, L., [*The Carabinieri Command for the Protection of Cultural Property: Saving the World's Heritage*], The Boydell Press, Woodbridge (2015).

[37] Kleber, F., Diem, M., Hollaus, F., and Fiel, S., "Mass digitization of archival documents using mobile phones," in [*Proceedings of the 4th International Workshop on Historical Document Imaging and Processing*], 65–70, ACM (2017).

[38] "Changhong and scio nir sensor revolutionize mobile phones." https://www.consumerphysics.com/business/blog/changhong-h2-worlds-first-molecular-identification-sensing-smartphone-miniaturized-integrated-material-sensor-unveiled-ces-2/. (Accessed on 06/22/2019).

[39] Reinig, P., Grüger, H., Knobbe, J., Pügner, T., and Meyer, S., "Bringing nir spectrometers into mobile phones," in [*MOEMS and Miniaturized Systems XVII*], **10545**, 105450F, International Society for Optics and Photonics (2018).

[40] Fujinami, K., "Smartphone-based environmental sensing using device location as metadata.," *International Journal on Smart Sensing & Intelligent Systems* **9**(4) (2016).

[41] "https://www.kiteboard.io/blog." https://www.kiteboard.io/blog. (Accessed on 06/23/2019).

[42] "Custom accessories — android open source project." https://source.android.com/devices/accessories/custom. (Accessed on 06/22/2019).

[43] "android.hardware.camera2 — android developers." https://developer.android.com/reference/android/hardware/camera2/package-summary. (Accessed on 06/22/2019).

[44] "Open camera - apps on google play." https://play.google.com/store/apps/details?id=net.sourceforge.opencamera&hl=en. (Accessed on 06/22/2019).

[45] "Capturing photos in raw format — apple developer documentation." https://developer.apple.com/documentation/avfoundation/cameras_and_media_capture/capturing_still_and_live_photos/capturing_photos_in_raw_format#overview. (Accessed on 06/22/2019).

[46] Pokress, S. C. and Veiga, J. J. D., "Mit app inventor: Enabling personal mobile computing," *arXiv preprint arXiv:1310.2830* (2013).

[47] Spagnolo, G. S., Ambrosini, D., and Paoletti, D., "Image decorrelation for in situ diagnostics of wooden artifacts," *Applied optics* **36**(32), 8358–8362 (1997).

[48] Spagnolo, G. S., Ambrosini, D., and Paoletti, D., "Comparative study on the efficiency of some optical methods for artwork diagnostics," in [*Laser Techniques and Systems in Art Conservation*], **4402**, 227–235, International Society for Optics and Photonics (2001).