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Using a commercially available LIDAR scanner for IR reflectography in cultural heritage research

IR reflectography is being applied in art conservation and art history research especially for non-invasive uncovering of sublayers and underdrawings in the works of art. Often, however, outside large research teams, the technology required for investigations using IR radiation beyond the silicon detection range (above 1100 nm) is not always available. This paper shows how to access these techniques with a commercially available LIDAR for 3D scanning often used for exploration of cultural heritage, especially in architecture. Presented workflow promotes a non-traditional usage of the LIDAR. In this case, the IR reflectogram is obtained at the wavelength of 1550 nm. The working principle of this method is demonstrated in a case study of Bečov nad Teplou (Czech Republic) chapel walls.

1. INTRODUCTION

The usage of IR radiation has a long tradition in the art historian's research [1]. The need to observe the underlying layers of paintings is of paramount importance both for the knowledge of the content of the painting (where the degradation processes no longer allow its accurate reading), and to fully understand the technical construction of the painting. IR radiation offers a greater possibility of obtaining important information on the construction of a secco painting. IR radiation wavelength is long enough to pass through the front layers of the paintings. Thus, it opens the possibility to study the sub-layers or under-drawings [2]. IR reflectance spectra are also invaluable in pigment identification [3]. Thanks to this knowledge it is also possible to plan the restoration and subsequently carry out the restoration in the best possible way. Standard cameras are commonly being modified today to extend their detection range to near IR [4]. However, they can only reach the detection limit of silicon chips at approx. 1100 nm [5]. Reaching longer wavelengths requires germanium or InGaAS-based chips that are substantially more expensive, with lower resolution and more noise [6]. To increase resolution, it is possible to combine individual photos (panoramic image), but seams between photos may appear [4]. One can use panoramic photography, but it requires specialized additional equipment on top of an already expensive germanium-based camera [7].

The diffusion of technical equipment allowing complete IR reflectography surveys to be carried out is still limited today. Their scarce diffusion also depends on the economic factor. In 2006, the Osiris camera (Opus Instruments, developed in collaboration with the National Gallery of London) was presented [8]. In 2018, Ceccarelli et *al.* presented a prototype of an IR-ITR scanner [9]. In both cases, certainly commendable, these instruments were developed with the aim to carry IR reflectographic investigation. This paper proposes the use of a laser scanner instrument already existing in the field of archaeometry investigation. The possibility of integrating laser scanners into the historical-artistic research field has recently been the subject of a study by a group at the Sapienza University in Rome [10]. In this case, it was the research carried out with a prototype laser scanner that is not commercially available and thus accessible to other groups. It is the progress made in recent years to commercial LIDARs that give the possibility to extend their primary use also to this type of investigation. More specifically, until several years ago most manufacturers of LIDAR devices used a wavelength of 905 nm which is detectable by silicon-based chips and hence attainable by DSLR (Digital Single-Lens Reflex) cameras with removed IR filters [11]. More recently, LIDARs operating at 1550 nm became available to customers. This wavelength is beyond the detection range of silicon-based chips and requires either a specialized camera or, as we promote in this paper, can be detected by a LIDAR.

In this paper, we promote the idea to use a commercially available LIDAR scanner for IR reflectography at 1550 nm. Our idea is cost-effective considering that LIDAR is already often used in the exploration of cultural heritage, especially architectural heritage [12, 13, 14]. We describe our established workflow and present a case study. Our technique is deployable in the field conditions and does not require any external source of illumination or light shielding. This technique is also non-destructive and quasi non-invasive. For all demonstrations in this paper, we have used a 3D scanner Faro Focus 150 (for its relevant properties see *tab. 1*).

Tab. 1 Manufacturer supplied relevant parameters for Faro Focus 150

Parameter	**Value**
Angular accuracy	19 arcsec for vertical/ horizontal angles
Distance accuracy	±1 mm
Minimum distance	0.6 m
Maximum distance	150 m
Scanning wavelength	1550 nm
Field of view (vertical/horizontal)	300°/360°
Laser spot diameter at the output	2.12 mm

2. METHODS

The measured object is prepared by removing any glass cover, if present and possible. In this way, direct reflection of the beam can be avoided and undesired absorption of IR in the cover material can also be eliminated. The overview of material reflection geometries is depicted in *fig. 1*. Note that in the case of the fully absorbing or fully specular reflecting object, the scanning is not possible. Only objects with measurable diffuse reflections can be observed. The scanner is placed on the mount, the optimal distance takes into account the size of the object and a reasonable angle of view (approximately 30 degrees, the minimal scanning distance of the LIDAR has to be observed as well). Non-glossy objects (objects where specular reflection can be neglected, e.g. walls) are scanned in the perpendicular configuration for maximum resolution and minimum perspective distortion (see *fig. 2a*). In the case of glossy objects, a minimum scanning angle clear of specular reflection needs to be established before the measurement procedure (see *fig. 2b*). This highly depends on the surface structure of the object. A preview scan is carried out, allowing to select the required horizontal and vertical angles of view to encompass the entire object (see *fig. 3*). With these parameters, a full-resolution scan is taken, and the data is transferred to a computer with a scanner-compatible program, in this case, Scene by Faro [15]. Here the IR scan is exported as an image in a standardized format, typically a lossless compressed TIFF file. In the case of large data files, we recommend to export the point cloud from the Scene to CloudCompare (open source program) and export the image from there. Further processing now takes place in an image manipulation software. Due to the scanning geometry, the exported image manifests strong barrel aberration, usually even asymmetric (astigmatic). We use the open-source tool Image Magick [16] to correct this aberration. The corresponding command code is given for illustration:

```
convert in.tiff -virtual-pixel Gray + distort Cylinder2Plane <amount> out.tiff,
```

where *<amount>* denotes the value needed to counteract the barrel aberration. As a result, we obtain an orthographic image of the scanned object. If a non-perpendicular configuration has been used because of the glossy surface of the scanned object, perspective correction is performed in Image Magick as well, using a command in the form of:

```
convert in.tiff-matte-virtual-pixel transparent-distort Perspective <cords corner> out.tiff,
```

<cords corner> are coordinates of selected shape to be transformed into a rectangle. The full resolution scan can be repeated, and processed images averaged for additional noise suppression for example using this command code:

```
convert in1.tiff in2.tiff in3.tiff ... inN.tiff -average out.tiff.
```

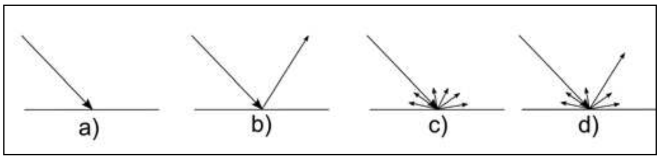

Fig. 1 Scheme of light reflection from different kind of surfaces a) non-reflective (absorbing) b) full specular reflection (mirror) c) diffuse reflection only (non-glossy) d) diffuse-specular reflection (glossy)

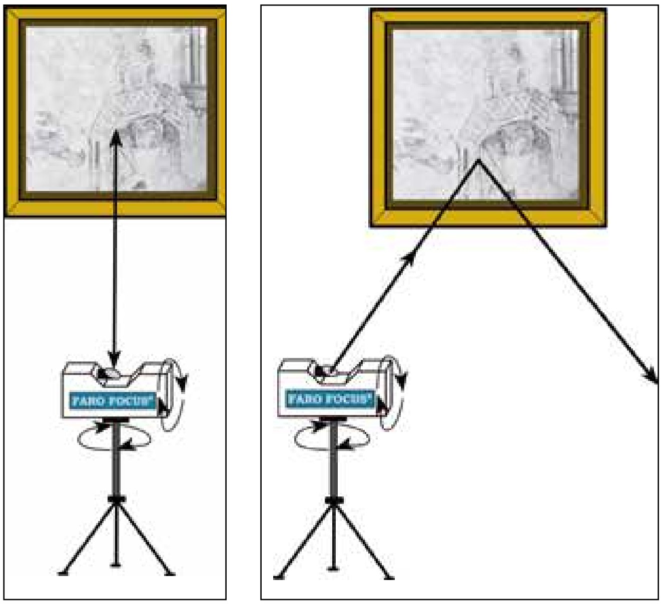

Fig. 2 Scaning layout for perpendicular mode (left) for non-glossy object and non-perpendicular mode (right) to reduce glare in case of glossy object

Fig. 3 Preview mode, allowing to choose the horizontal and vertical angle of view for subsequent full-resolution scans

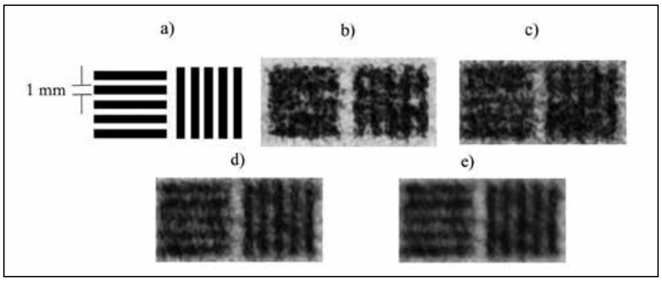

Fig. 4 Comparison between a) original testing target, b) single scan, c) 4 consecutive scans internally averaged by the scanner, d) 3 scans averaged in post-processing, e) 9 scans averaged in post-processing

3. TESTING ON LABORATORY TARGET

In this section, we discuss the results of the above-described workflow on a testing target. This target consists of a system of periodic patterns of lines with a different spatial period ranging from 6.7 mm to 0.2 mm (frequencies 0.15 mm^{-1} to 5 mm^{-1}). The segment of the target corresponding to the highest resolvable spatial frequency of 0.5 mm^{-1} is depicted in *fig. 4a*. Target was positioned 1 m from the scanner and perpendicular configuration was used. In the first step, we have taken one scan only and processed the image according to the described workflow (see *fig. 4b*). Not being satisfied with this result, we resorted to multiple scan averaging. Faro Focus 150 allows for internal averaging by measuring each point multiple times. We have, however, discovered that this procedure does not increase contrast at all (see *fig. 4c*). We have therefore decided to average images obtained by single scans after they have been fully processed. *Figs. 4d* and *4e* show the results of averaging 3 and 9 scans respectively. The best result has been achieved by averaging 9 scans. This way we are able to distinguish a 2 mm wide line-gap pattern from the distance of 1 m yielding achieved an angular resolution of 7’. This result is also consistent with the output beam diameter of 2.12 mm considering some improvement in resolution might be gained by averaging.

4. TESTING IN FIELD CONDITIONS: Bečov nad Teplou chapel walls

The study of painting on the walls of the chapel located in the donjon of the Bečov nad Teplou castle [17] was proposed by the Arteca project partner, National Heritage Institute of Czech Republic [18], the manager of the monumental complex of the castle. The complex has its foundations in the fourteenth century [19]. Its oldest part, Donjon, incorporates the chapel dedicated to the Visitation of the Virgin Mary, added in this building in the mid-fourteenth century. The rare pictorial decoration of the chapel was created using a secco technique. Its importance is linked to the high iconographic value of the cycles represented here (History of the Virgin, The legend of the Ten thousand martyrs, the Holy Face, and others) [20]. However, an equally important value derives from the fact that the walls are not covered by a single pictorial layer, but represent a kind of palimpsest, with stratification of the pictorial films not yet well defined. The paintings also represent an important object of study thanks to the lack of major restoration works. This absence enables obtaining of rare information on pictorial techniques and materials in use in the central European area in the fourteenth century. The tracing of stylistic paths, but above all the movement of materials, is the subject of another study currently under preparation. This research also uses the so-called Arteca workflows - a complex battery of non-invasive and micro-invasive investigations - the multimodal method. In addition to producing an extension of the historical and artistic knowledge of painting in the chapel, the aim is to develop a series of knowledge intended to improve the restoration process. At this National monument, a model procedure of an in-depth study aiming at a future restoration has already been started [21]. The Arteca team was also invited to continue the investigation. The research that is the subject of this study was carried in two study sessions (September 2018, March 2019). The use of LIDAR has proved to be a valuable tool for capturing the pigments that providing return signal (more precisely, it is actually the contrast in the returned laser signal between parts of the scanned object that allows for imaging) to the emitted laser light at a wavelength of 1550 nm and thus allowing the better reading of the lower pictorial layers. Acquaintance with these hidden layers allows bringing back more complex images than the mere analysis of the top painting layers now destroyed by the centuries of the degradation process.

An example of the results obtained with this technique is visible in the image of the Virgin Mary with the Child (a very archaic form for the mid-XIV century) in the scene of the Three Kings. Degradation of the upper layers of the painting has made evident in many parts the preparatory layer with the tracing of the shapes and volumes. But for example, on the roof of the architecture, which makes up the throne of the Virgin, the roof tiles are not visible, which instead are clearly evident in the 1550 nm laser scanner (see *fig. 5*). In this particular case, the scanner was positioned about 3 m from the target and the presented segment is about 1.5 m× 2.5 m big. It should, however, be emphasized that the scanner can capture much wider fields (almost the entire sphere) of view as shown in fig. 3. That would prove difficult with typical cameras. The in-situ scanning time ranges from half an hour to three hours depending on the scanned area and the number of averaged scans. About three additional hours of processing time is needed to prepare presentable IR reflectograms. This, of course, depends strongly on the computational power available.

Note that a detailed analysis of the acquired reflectograms goes beyond the scope of this paper.

5. CONCLUSIONS

We have presented a workflow for IR reflectography at 1550 nm using a commercially available LIDAR scanner. Considering that LIDAR is a common instrument in cultural heritage research, promoting its unconditional application represents a significant economy as specialized germanium-based cameras are rather costly. Moreover, LIDAR is particularly suitable when taking reflectograms of large surfaces (e.g. walls). Because of its mode

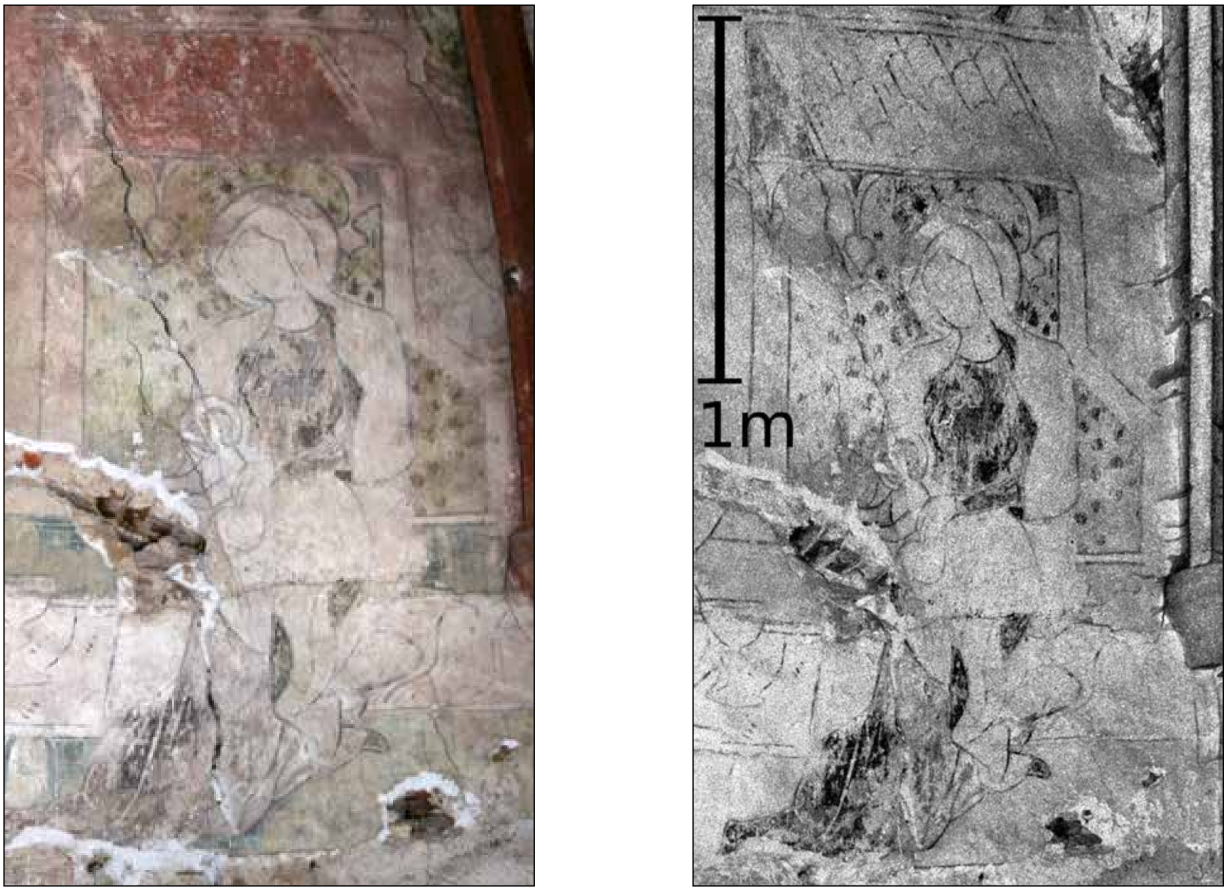

Fig. 5 The segment of wall paintings displaying the Virgin Mary with the Child in the scene of the Three Kings, visible photo (left), processed IR image taken by LIDAR (right)

of operation, the user can obtain high-resolution images without resorting to lengthy image stitching. We have established that LIDAR is capable of delivering images with a resolution of 7’ in full solid angle except for a small solid angle directly below the device. Our workflow is designed to cope with a glossy object as well. The only apparent drawback is the capability of LIDAR to register reflectance at a single wavelength. To showcase our method, we have presented a case study on a chapel of Bečov castle. The IR image allows us to visualize layers of the painting that are undistinguishable in photographs. Presented findings support the above mentioned benefits of our technique and invite its future usage on other cultural artifacts.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Contributions

KL proposed the method, JŠ and AČ performed further investigations, JM provided art-historian content. All authors contributed to the writing of this paper.

Competing interests

The authors have no competing interests.

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