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Contributions of Photometry to the 3D-digitization of Heritage

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ABSTRACT

The nature of archaeological research implies documenting and recording the remains or structures uncovered in the most precise and objective way possible. Archaeologists use digital tools precisely because they meet the challenges of their discipline. The creation of digital twins thus actively contributes to the study, protection and dissemination of archaeological heritage. From the study of a territory to the analysis of a trace left by a tool, archaeology reasons at different scales and combines analyses and multi-scalar approaches. This represents a challenge in itself. The development of an open-source photometric stereo suite makes it possible to respond in part to this work by taking into account the great diversity of archaeological remains while producing models that combine volume accuracy and color reliability.

KEYWORDS

3D-scanning, photogrammetry, photometry, heritage, archaeology.

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1 INTRODUCTION

1.1 Need for Digitization

Archaeological remains are by nature three-dimensional objects. Whether it is the Chauvet-Pont-d'Arc cave with its Paleolithic cave art, the Neolithic statue-menhir known as the "dame de Saint-Sernin" preserved at the Fenaille Museum in Rodez, or a zodiacal tablet from the Gallo-Roman period preserved at the National Archaeology Museum, the archaeologist wishes to apprehend a

volume in order to integrate his observations. All these elements of the archaeological heritage impose problems related to their conservation and study. 3D tools being one of the predominant supports to answer them, it becomes necessary to proceed to their digitization.

The first need is related to the conservation and perpetuation of the remains. The Chauvet-Pont-d'Arc cave is a karstic environment in constant evolution from a geological, hydrological and microbial point of view, to the extent that certain Paleolithic remains can be affected by it [2]. Moreover, the climatic change in progress imposes a follow-up of the environment and of the surface state of the walls in time. It is also a very particular place in which traffic is limited to specific areas, so it is necessary to set up protocols for recording remote areas that are inaccessible to researchers from authorized areas. Concerning the statue-menhirs that are outside and exposed to climatic or human hazards, the analysis of the 3D data will be taken into account in the decision to choose the appropriate protection (do nothing, build a shelter or put them in storage). As for the ancient ivory tablet, the acquisition of the volume will accompany the restoration on the filling of the missing parts and the creation of support.

The second need integrates the objectives of understanding and analysis of the artifact. Archaeologists wish to describe the technical gestures and approach the symbolic choices made. 3D provides spatial measurement information that produces analysis supports with a precision and resolution adapted to the scale of the work [13]. However, this information is raw and requires an interpretation to give it meaning. For the three objects presented in our study, the answer lies in the details and fine engravings. For the statue-menhirs or the zodiacal tablet, the reading of the tracings and their relative chronology describes the process of creation of the work but also the life of the object after its first use. In the context of the Chauvet-Pont-d'Arc cave, the analysis of the antero-posteriority of the engravings merges with the different phases of creation of the paintings or of the animal activity [10]. This means that it is necessary to be able to easily separate the relief from the color during the study.

The third need is directly linked to the transmission of heritage, and the production of 3D data is a formidable resource for mediation and promotion. In an image-based society, digital technology is an important vector for involving citizens and giving them access to a heritage that is sometimes fragile and inaccessible. 3D offers experiences in line with the evolution of its uses. The methods of

use are multiple, from the generation of renderings facilitating the reading of vestiges to immersive virtual reality (VR), via holographic projection or 3D printing. The anticipation of this need is crucial in order to adapt the acquisition carried out for conservation or archaeological research.

1.2 History of Survey Techniques

Since the 19th century, and in order to compensate for the lack of 3D tools, researchers have used modes of representation that simulate the third dimension on 2D supports (photography with a grazing light, drawing with perspective, point drawing, planimetric projection) or techniques of survey with contact (tracing, molding, direct measurement) [20]. The development and democratization of topographic, computer and digital tools have made it possible, since the end of the 20th century, to propose non-invasive survey protocols.

The 3D analysis capacity of archaeologists has thus followed the technological development. In the history of the study of caves [19], the starting point is a precise topographic acquisition allowing the georeferencing of the remains and the cartographic projection. Surveying instruments such as the tacheometer measure a point in XYZ at the same time describing the ground surface and sections of the cave. Scanning by a laser beam of lasergrammetry (TLS) has considerably increased the number of points acquired. This technology has been used since the 2000s for the survey of caves. It allows to obtain a volume of millimetric precision, the information of the color being provided by photographs constituting a photo-realistic texture. The use of photographs for the generation of 3D by photogrammetry enters the chain of operations from the 2010s [6].

The increase in the resolution of the sensors makes it possible to consider the multi-scalar digitization of heritage, from the global acquisition of volumes to the detail of fine engravings. However, 3D acquisition tools require a high level of skills and computer resources for their management and handling. Very often, this task is assigned to external providers with expensive equipment and proprietary software licenses. The current functioning of project-based research, with interdisciplinary teams, allows for the integration of this skill within the team, like the scientific team of the Chauvet-Pont-d'Arc cave. As this approach is not possible for all projects, the use of a simple acquisition protocol and light calculations are then to be envisaged.

2 3D ACQUISITION FOR ARCHEOLOGY

The 3D acquisition of an object is carried out either in a volumetric way (capture of internal information) or in a surface way (surface information). The fragility of archaeological remains means that contact sensors are not taken into account and that the focus is on non-invasive and surface acquisitions. Digitization tools are adapted to certain types of heritage. In this non-exhaustive state of the art, we will focus on the adaptation of these methods for the reading of fine details of millimetric or sub-millimetric order.

2.1 Lasergrammetry

Terrestrial Laser Scanning (TLS) or LiDAR (Light Detection And Ranging) allows a 360° acquisition of the environment around the

sensor. It calculates distances by launching infrared beams, either by measuring the time of flight or by phase shift. Each station captures several hundred thousand measurement points per second. This generates a spherical depth map from the center of the sensor. Each point has polar coordinates and a distance that will allow the creation of points in Cartesian coordinates. Each point has a measure of return signal strength. The TLS takes a series of photographs to generate an RGB view that will either colorize the point cloud or create a photorealistic texture on the mesh.

The main advantage is the acquisition accuracy, of the order of 1 mm to 4 mm at a distance of 10 m, depending on the model. However, the scanner is limited by the size of its incident beam which defines its accuracy. This dimension forces it to be able to detect, at best, only millimetric details. Because of its operation, it is adapted to architecture and indoor spaces. The laser beam operates in complete darkness, which makes it an asset for cave mapping. In order to acquire the most complete volume possible and with a spatial resolution of 3D points, the operator must multiply the stations and therefore the points of view. This increases the uncertainties of registration between stations, resulting in a thickening of the point cloud. The equipment, which costs several tens of thousands of euros, is expensive. Recent models, equipped with a tablet, allow a quick and simplified implementation. We do not mention the SLAM (Simultaneous Localization And Mapping) laser technologies which have a centimetric precision not adapted to our case studies.

2.2 Photogrammetry

Photogrammetry is the combination of two 3D-reconstruction techniques: Structure-from-motion (SfM) and Multi-view Stereo (MVS).

The acquisition of volume is obtained from photographs by multiplying the points of view. The implementation is simple since it relies on the overlap and displacement between the shots. Its cost is theoretically low since a digital camera is sufficient. The camera can be used on a vector (drone, pole) to reach remote areas and thus adapt to different types of volume. Photogrammetry is adapted to scale changes and multi-scalar digitization, from general volume to details. In order to make the changeover to metric or for its georeferencing, it is necessary to integrate rules or topographic coordinates.

The SfM needs contrasting data for a good aerotriangulation result of the cameras. The same is true for the densification of the SfM, which allows a geometric reconstruction of volumes by generating depth maps. This constraint makes it difficult to digitize poorly textured surfaces. During the shooting, it is necessary to have a controlled and constant light for the creation of a photo-realistic texture without shadows and with the most accurate colorimetry possible. The quality of the model produced depends, on the one hand, on the precision of the marks and, on the other hand, on the overlap of the shots on the rest of the object.

The research of the reading of fine engravings depends on the quality of the photographic material (size and resolution of the sensor, quality of the lens). The increase in the number of pixels to be taken into account in the calculation will require a substantial computer equipment with sometimes long calculation times for the generation of the geometry.

2.3 Handheld 3D scanners

Pulsed light scanners (white, blue LED, with infrared) generate depth maps by triangulation, with the advantage of obtaining the metric directly. The announced spatial resolution is around 100 microns, with an accuracy of a few tens of microns depending on the model. Everything depends on the calibration of the sensor and the quality of the measurement defined by the manufacturer. The assembly of the different depth maps is done by geometry and with or without color. This mode of operation can make it faulty on objects without asperity and non-textured.

Its simplicity of implementation and learning makes it very functional for most small objects for obtaining sub-millimeter details. However, it is no longer suitable for objects larger than a few square meters. The color sensors are of low resolution, which results in textures closer to a mesh colorization than to a photorealistic texture. Its high cost, from a few thousand to a few tens of thousands of euros, associated with the purchase of the computer for the calculations, limits its wider use in archaeology.

2.4 Combining these Techniques

In order to improve the quality of the results obtained by each of these three techniques, they can be combined.

Lasergrammetry and photogrammetry can be combined if they work in the same reference frame. This can be the case, either after alignment by SFM, or by using common benchmarks, or finally by georeferencing. The depth maps are then cross-referenced in the MVS step.

Lasergrammetry or handheld scanner can be combined with photogrammetry after alignment of the acquisitions. The volumes are generated by the scanner, then the texture uses the data from photogrammetry.

2.5 Reflectance Transformation Imaging

Reflectance Transformation Imaging (RTI) has been developed since the 2000s for epigraphic purposes [5, 23]. Its field of use has subsequently expanded considerably [8, 15]. This method is based on the principle that the grey level at a pixel is maximum when the normal to the surface at that pixel is directed towards the lighting (see Section 3 for more details). Using several images, taken from the same point of view but under varying lighting, a normal map can be deduced by detecting the maximal value at this pixel through the set of images. This method does not produce accurate normal maps. Rather, it seeks to produce an improved surface simulation to facilitate study since the object can then be relighted. This method is particularly suitable for flat objects and comes close to the use of grazing lights for reading engravings.

In order to avoid lighting calibration, which would require the presence of a sphere in each image, it is possible to use a previously calibrated dome. However, this solution has the disadvantage of limiting the size of the object studied to that of the dome. While RTI is a fast and resource-efficient method, it has two major drawbacks. On the one hand, it does not produce volume, thus considerably reducing the study of the reconstructed object. On the other hand, the fact that it is based on interpolation greatly limits its accuracy.

2.6 Towards Photometric Techniques

The 3D scanning methods presented here aim to provide a volume on which a photorealistic texture is plated. In some cases, fine engravings are visible on the texture, but are not readable on the relief. For certain heritage objects, for example, cave art which mixes engravings and paintings, it is relevant to be able to distinguish the volume from the colour in each pixel. For this, the contributions of photometry seem undeniable [18].

3 PHOTOMETRIC 3D-RECONSTRUCTION

Photometric techniques are based on the analysis of the amount of light received by each photosite of the camera sensor. If it is calibrated, then the gray level (or color level) is proportional to the luminance emitted by the scene, which depends on the relief of the scene, its reflectance and the illumination.

In the simplest case of a Lambertian surface, the gray level at an image point $\mathbf{p} = [u, v]^T$ is written :

$$I(u, v) \propto \rho(u, v) \max\{\mathbf{n}(u, v) \cdot \mathbf{s}(u, v), 0\} \quad (1)$$

where $I(u, v)$ denotes the gray level, $\rho(u, v)$ the albedo, $\mathbf{n}(u, v)$ a normal to the surface with unit norm, and $\mathbf{s}(u, v) \in \mathbb{R}^3$ a vector characterizing the illumination. A simplifying assumption is to neglect the self-shadows, i.e. to accept the values of $I(u, v)$ for which $\mathbf{n}(u, v) \cdot \mathbf{s}(u, v) < 0$. Another assumption is to assume \mathbf{s} to be parallel and uniform, in such a way that it no longer depends on (u, v) . Moreover, the proportionality coefficient of the relation (1) can be integrated with the albedo, which allows us to rewrite (1) :

$$I(u, v) = \rho(u, v) \mathbf{n}(u, v) \cdot \mathbf{s} \quad (2)$$

Even under the very strong assumptions of known albedo $\rho(u, v)$ and known illumination \mathbf{s} , estimating the 3D-shape from (2) is an ill-posed problem, called shape-from-shading [16], since in each pixel, the normal has two unknowns corresponding to its two degrees of freedom, but a single equation.

The principle of photometric stereo (PS) is to overcome this problem by using several images, taken from the same point of view but under m illuminations. Each illumination is characterized by a vector $\mathbf{s}^i \in \mathbb{R}^3$, $i \in \{1, \dots, m\}$. In order to obtain the most accurate 3D-reconstruction possible, we assume that the illuminations are calibrated. Equation (2) must then be replaced by the system:

$$I^i(u, v) = \rho(u, v) \mathbf{n}(u, v) \cdot \mathbf{s}^i, \quad i \in \{1, \dots, m\} \quad (3)$$

By introducing the unknown $\mathbf{m}(u, v) = \rho(u, v) \mathbf{n}(u, v)$ which, unlike $\mathbf{n}(u, v)$, is a vector of \mathbb{R}^3 of any norm, System (3) becomes linear:

$$I^i(u, v) = \mathbf{m}(u, v) \cdot \mathbf{s}^i, \quad i \in \{1, \dots, m\} \quad (4)$$

As soon as it is possible to illuminate the scene with $m \geq 3$ non-coplanar illuminations \mathbf{s}^i , the linear system (4) is of maximal rank. It thus admits a unique solution in the least-square sense, from which the albedo and the 3D-shape are easily deduced:

$$\rho(u, v) = \|\mathbf{m}(u, v)\| \quad \text{and} \quad \mathbf{n}(u, v) = \frac{\mathbf{m}(u, v)}{\|\mathbf{m}(u, v)\|} \quad (5)$$

Many extensions of this technique have been proposed, for example to the case where the illuminations are not calibrated [4], or to take color into account [28]. Under the Lambertian assumption, the

surface reflectance is entirely characterized by the albedo. However, for a large majority of surfaces, the reflectance shows deviations from model (2). Even if the case of non-Lambertian reflectances has been studied [24], we prefer to take advantage of the simplicity of the Lambertian model and consider deviations from it, such as specular reflections, as outliers, using robust estimators [17]. Note also that deep learning approaches have recently appeared [30], which allow to free oneself from the Lambertian constraint [7].

Finally, it is generally difficult to ensure that the illumination is parallel and uniform. More realistic models have been proposed. The methods for solving PS have been generalized [26] to a point light source, which characterizes a LED illumination rather well. Other approaches [14] modelling the illumination by spherical harmonics have been proposed [4, 29], which allows to describe quite faithfully the natural lightings.

The second step of the classical PS resolution is the integration of the estimated normals, which allows to find the depth function z characteristic of the 3D-shape. Note however that some methods allow to estimate directly the depth, as for example [28, 32].

If the projection is orthographic, the normal is easy to express in terms of the depth gradient:

$$\mathbf{n}(u, v) = \frac{1}{\sqrt{1 + p(u, v)^2 + q(u, v)^2}} [-p(u, v), -q(u, v), 1]^T, \quad (6)$$

where:

$$p := \frac{\partial z}{\partial u} \quad \text{and} \quad q := \frac{\partial z}{\partial v}, \quad (7)$$

so that $\nabla z(u, v) = [p(u, v), q(u, v)]^T$. In the perspective case, the change of variable $\tilde{z} = \ln(z)$ reduces the integration problem to a similar case, with slightly modified expressions of p and q . Several methods can be used for normal integration, depending on the application requirements in terms of speed, robustness to noise in the estimated normal field, and preservation of discontinuities [27]. For instance, a standard solution for the recovery of a smooth height map consists in considering the quadratic variational problem:

$$\min_{z: \Omega \rightarrow \mathbb{R}} \int_{\Omega} \|\nabla z(u, v) - [p(u, v), q(u, v)]^T\|^2 du dv, \quad (8)$$

which can be solved, e.g., using Fourier analysis [9], discrete sine or cosine transform [31] or iterative methods [3], depending upon the reconstruction domain Ω and the boundary conditions.

4 RESULTS

4.1 Chauvet-Pont-d'Arc Cave

The Chauvet-Pont-d'Arc cave, classified as a world heritage site by UNESCO, is an exceptional site because of its state of conservation and the quality of the cave paintings dating back nearly 36,000 years [12]. The Paleolithic artists used different techniques on the walls. In a simplified way, the paintings are realized with hematite (red ochre) or with pine charcoal (black) [11]. The engravings are composed of scraping, incision with a tool (flint, branch, etc.) or of digitized tracings. Some ornate panels such as the “Panneau des chevaux” (see Fig. 3) concentrate several of these techniques. The walls have also recorded the passage of animals, for example the claws of bears. The work of the parietalists is based on the analysis of the elements in order to determine the chronology of human and

non-human actions. PS brings the advantage of dissociating color from volume.



Figure 1: “Panneau des Mammouths raclés” (Chauvet-Pont-d'Arc cave, Ardèche, France). The white sphere allows to estimate the illumination.

The “Panneau des Mammouths raclés” (see Fig. 1) represents three specimens over nearly 5 meters long. It is entirely realized by digitized tracings that erase the thin brown clay deposit and reveal the white of the limestone wall. This interlacing of large semicircular gestures is difficult to capture in 3D because of the general low relief of the wall and the general whiteness of the panel. Photogrammetry is in default, where PS is perfectly operative on this type of support. Lasergrammetry, also functional, does not offer the possibility to study the mixture between clay and limestone. The succession of the traces can be distinguished on the relief.

The emblematic “Panneau des chevaux” in the Hillaire room is a compilation of different techniques with a known chronology. At the level of the horses’ heads, the wall was scraped to make a white surface. Then, the charcoal tracings are made with a charcoal and the heads are filled in with subtle blurring. In order to emphasize and clarify the outline, multiple incisions are made with a fine tool. These engravings of a few tenths of a millimeter are imperceptible by lasergrammetry. Photogrammetry makes them visible on the photo-realistic texture, but hardly legible on the geometry. PS renders them perfectly in volume and allows to appreciate the bistre of the filling of the horses’ heads (see Fig. 3). The size and the volumes of the large panels will oblige us to multiply these acquisitions if we wish to cover them entirely.

4.2 “Dame de Saint-Sernin” Statue-menhir

The statue-menhirs are figurative representations on all four sides [22]. The front and back of the block concentrate the anatomical motifs (face, arms, legs, etc.) and the attributes (scarification, necklaces, belt, etc.). They are conducive to the use of PS, which provides detailed information on the shaping of non-metallic objects. Considered the best preserved, the “Dame de Saint-Sernin” is the most likely to provide information on the sculptor’s gestures.

The face is important to appreciate the round-bossing of the scarifications, the hollowing of the eyes and the staking of the surface. This fine and regular work can be seen on the series of necklaces, where the traces of shaping are hardly perceptible (see Fig. 4). As for the hands, they show a combination of work in the round and grooving for the creation of the fingers.

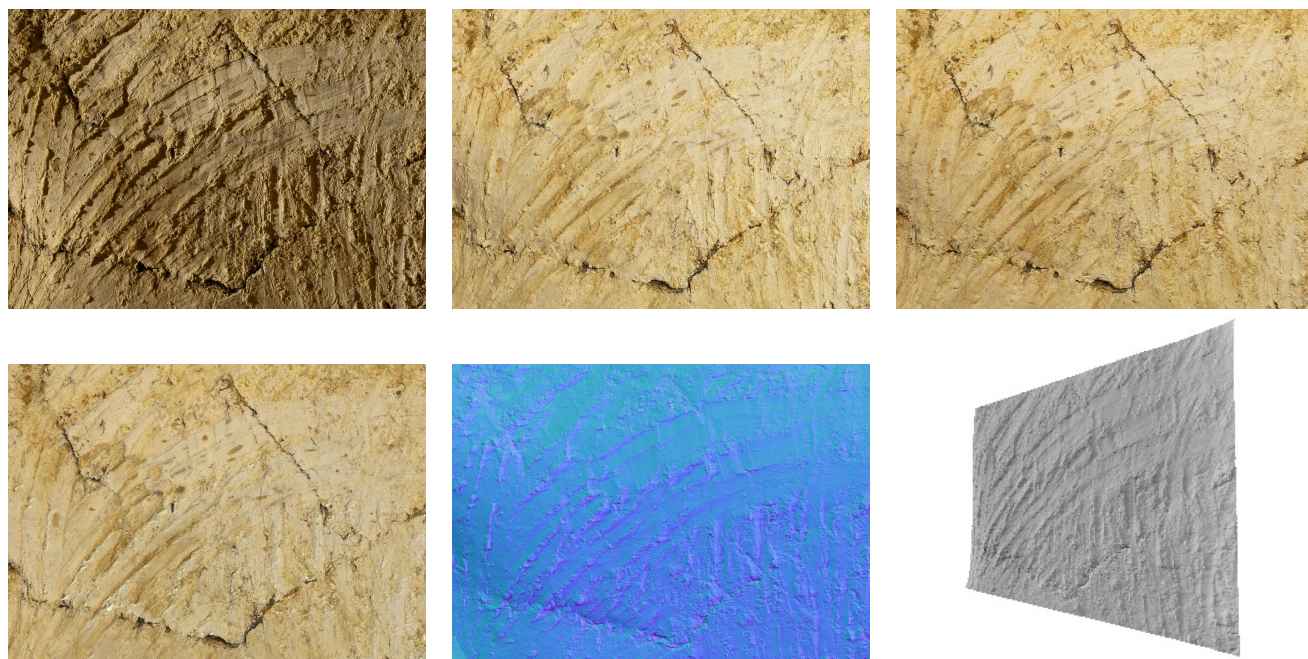


Figure 2: Zoom on the “Panneau des Mammouths raclés” (Chauvet-Pont-d’Arc cave, Ardèche, France). Top row: three images among fifteen. Bottom row, from left to right: estimated albedo; estimated normal map; reconstructed depth in perspective view.

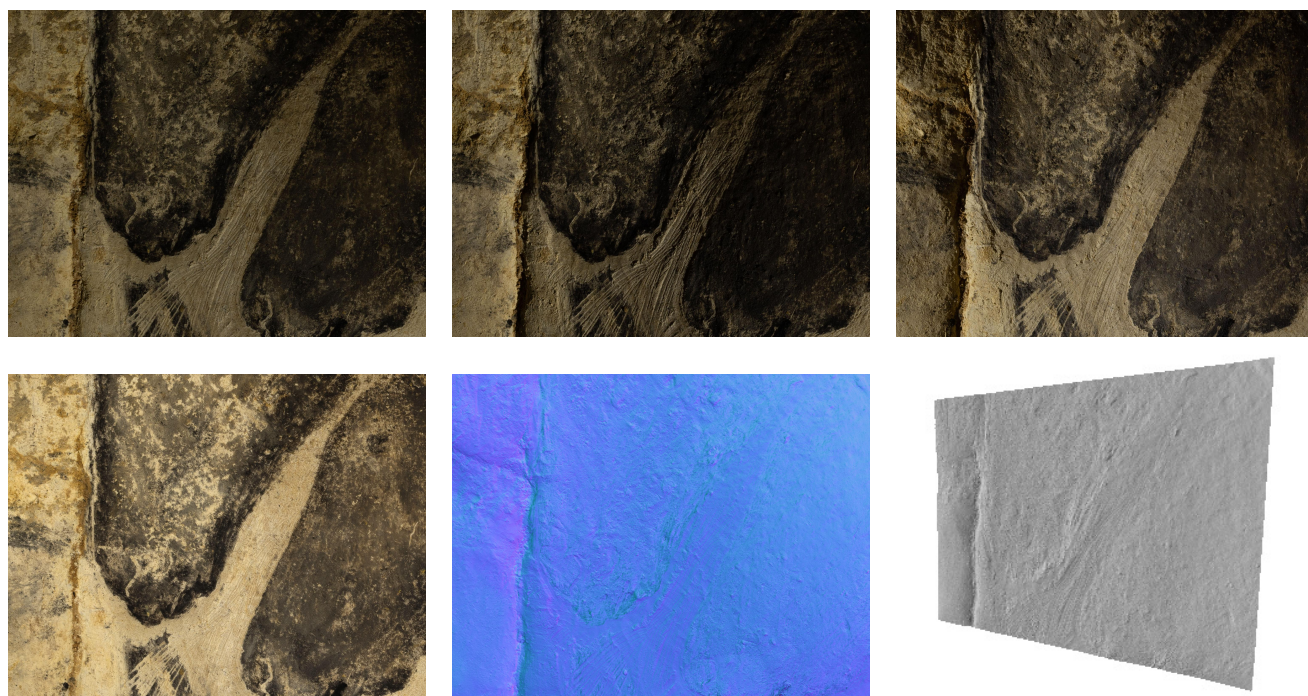


Figure 3: Zoom on the “Panneau des chevaux” (Chauvet-Pont-d’Arc cave, Ardèche, France). Top row: three images among fifteen. Bottom row, from left to right: estimated albedo; estimated normal map; reconstructed depth in perspective view.

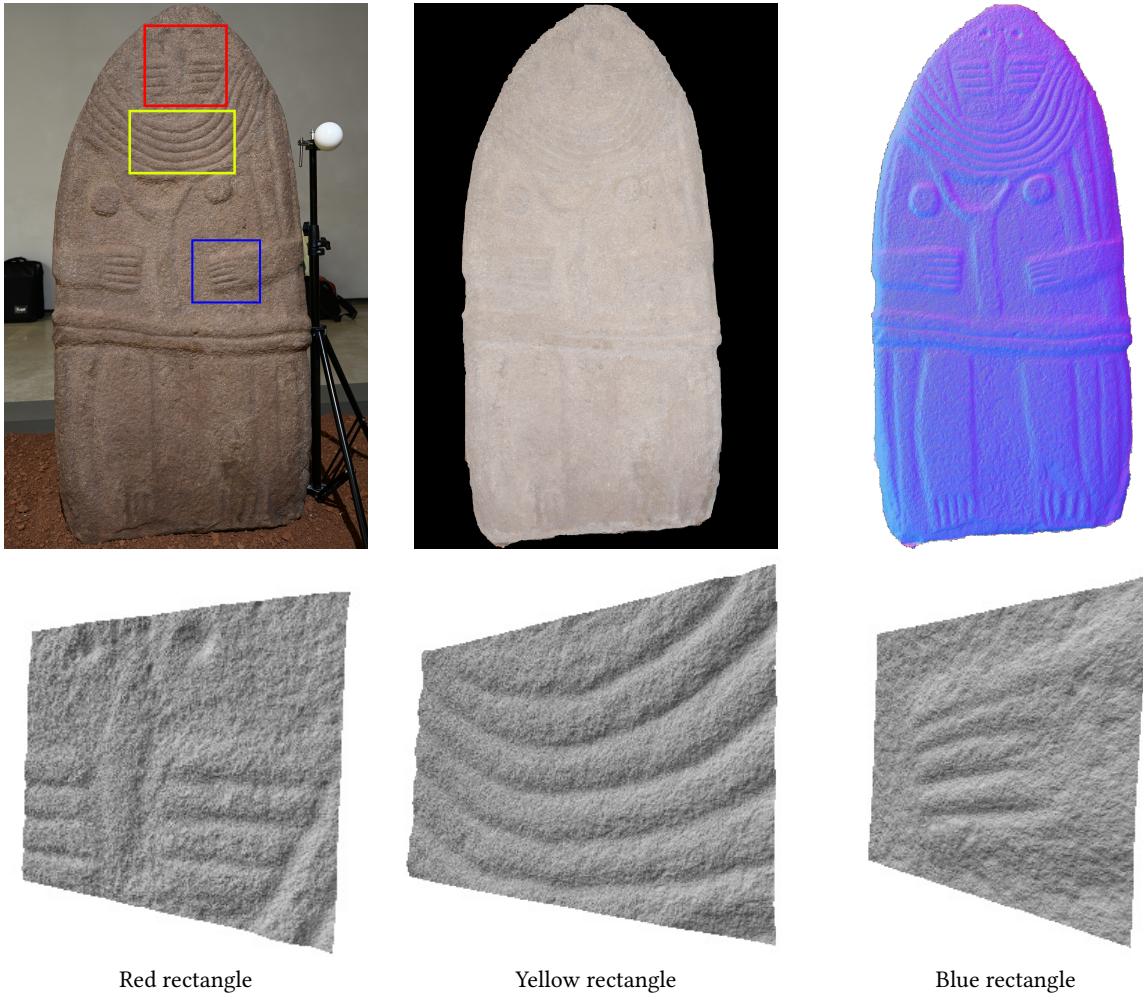


Figure 4: “Dame de Saint-Sernin” statue-menhir (Musée Fenaille, Rodez, France). Top line, from left to right: one image among fifteen; estimated albedo; estimated normals. Bottom line: highlighting of different surface states on the three areas delimited by colored rectangles on the image at the top left.

Of the 157 statue-menhirs recorded to date, not all are equally well preserved. Some were modified during the Neolithic or Proto-history, the ancient representations are tenuous and ambiguity is traditionally removed by the use of low-angled lighting permitted by PS. The most important losses of surface information are due to the burial conditions, as well as to the climatic elements for those that are exposed outdoors again.

The remaining traces become imperceptible to the naked eye in ambient light. The search for sub-millimeter information is crucial for their identification. The pulsed light scanner can capture these details, but is not adapted to the several meters high statue-menhirs located outdoors. Photogrammetry only gives geometric details of the order of a millimeter for the same shooting distance [21].

4.3 Zodiacal Tablet

The zodiacal tablet is a polychrome ivory diptych, with each panel measuring 15 *cm* wide by 20 *cm* high. This divinatory art of Egyptian

origin from the end of the second century A.D. is only 8 *mm* thick. This work of great finesse underwent a significant fragmentation and was finally found at the bottom of a well in the commune of Grand (Vosges, France) [1].

The volume reading of some plots is done at a scale of a few tenths of a millimeter. For this, we acquired photographs with a resolution of the central pixel of about 20 microns. This resolution allows us to access the tool marks inside the star, but also to observe the shifts between the different pieces that are reassembled. Between the characters inside the yellow rectangle, PS highlights the scratches, where photogrammetry only perceives them on the texture.

The fineness of the PS result will allow both to provide a support to the restoration of the tablet but also to a new interpretation of some inscriptions.

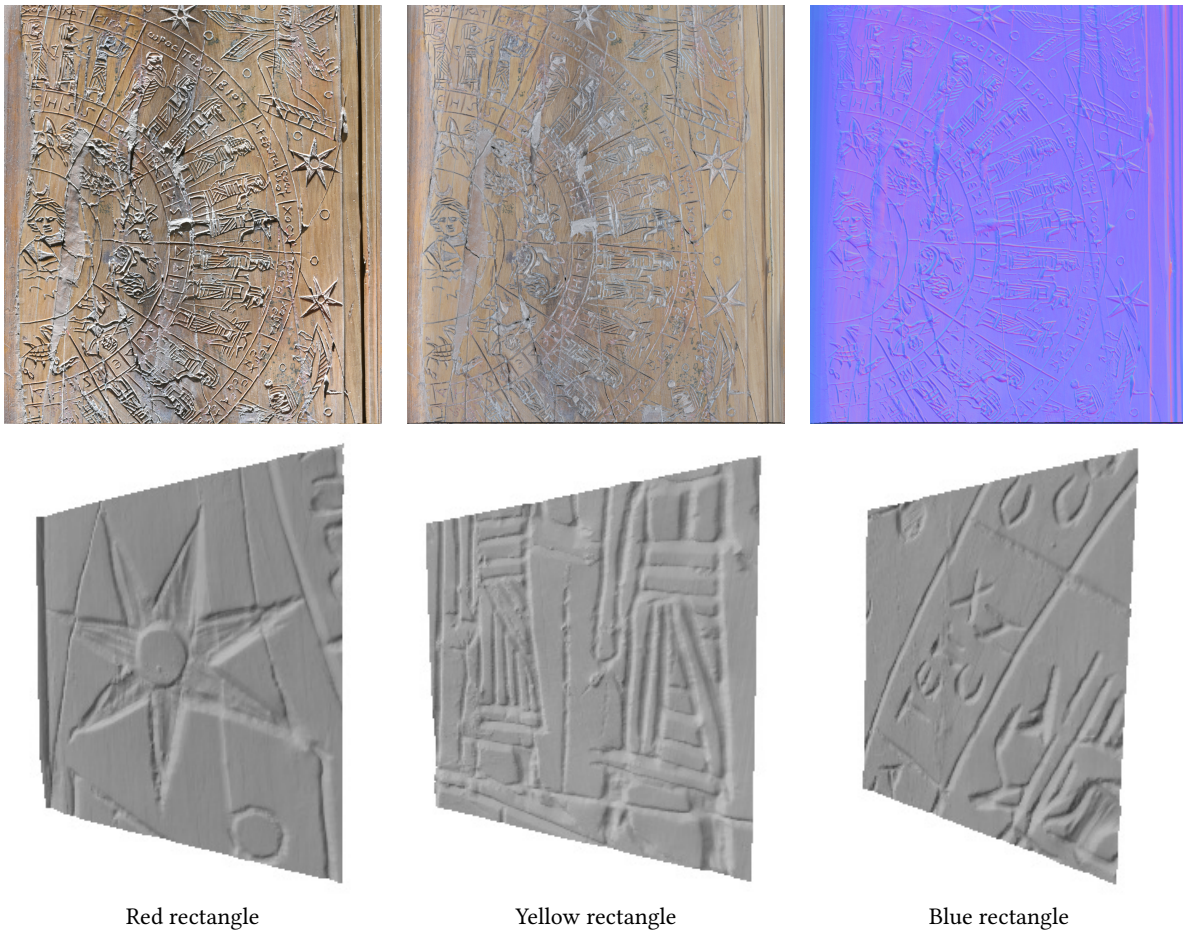


Figure 5: Ivory zodiacal tablet (Musée d'Archéologie Nationale, Saint-Germain-en-Laye, France). Top line, from left to right: one image among fifteen; estimated albedo; estimated normals. Bottom line: details of the relief on three zones with different characteristics (these zones are highlighted by colored rectangles in Fig. 6).

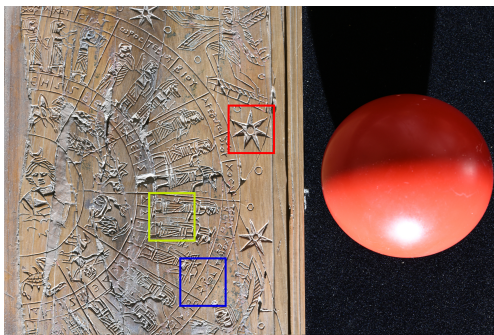


Figure 6: Ivory zodiacal tablet (Musée d'Archéologie Nationale, Saint-Germain-en-Laye, France). The colored rectangles delimit the three zones whose relief is displayed on the bottom line of Fig. 5.



Figure 7: If one of the images has unwanted cast shadows (left), this results in a biased estimate of the albedo (right).

5 CONCLUSION AND PERSPECTIVES

In this work, we have shown that photometric stereo can meet most of the needs of heritage digitization. In particular, this technique can be implemented at a wide range of scales: from several meters for the walls of decorated caves to a few centimeters for objects such as an ivory tablet. PS has two major advantages, compared to the techniques used today “in production”. First, it provides 3D-models whose accuracy is limited only by the pixel size. Second, it allows to estimate the *intrinsic color* of the photographed surface, as opposed to the apparent color, which is not possible with any other 3D-scanning technique.

However, photometry does not allow to answer all the needs of heritage digitization. PS, as it has been described and implemented in this article, suffers indeed from several limitations. In particular, while geometric techniques, which are based on the principle of triangulation, allow to find the global shape of the photographed scene, photometry is better able to restore the details of the relief. For example, while the zodiacal tablet of Fig. 5 is globally flat, the relief reconstructed by PS has a slight deformation at the corners, which reflects a bias in the estimation of low frequencies. To reduce this bias, a first perspective consists in using as a constraint, in the normals integration step, the depth of several 3D-points estimated by SFM.

Undoubtedly, the bias of depth estimation in the low frequencies is due to an imprecise estimation of the illuminations. A second perspective is thus to improve their estimation. The positioning of several spheres in the scene may make the acquisition phase more cumbersome, because each sphere must be positioned as close as possible to the surface to be reconstructed, without its shadow being projected onto it. Indeed, Fig. 7 shows that the presence of a shadow is enough to bias the estimation of the albedo, unless the resolution of the problem in least squares is replaced by a robust resolution method such as that of [17]. Another way to limit this bias is to use a generic lighting model characterized by a few spherical harmonic coefficients [4], rather than a particular physical model as the parallel and uniform one.

By making good use of the redundancy of the information provided by the geometric and photometric approaches, it is also possible to no longer use a sphere at all to estimate the illuminations. Indeed, rather than estimating the illumination from one particular point of the sphere, in this case the brightest point, in which the normal is indeed very easy to compute, it seems possible to deduce from a 3D “coarse” reconstruction of the surface, obtained by photogrammetry, a much more robust estimation of the illumination from normals estimated in all the pixels [25].

A longer-term perspective consists in no longer limiting ourselves to the estimation of “depth maps”, but in producing true 3D-reconstructions. This is necessary, for example, in the case of statues-menhirs, whose front and back faces need to be connected. Moreover, in the case of the walls of decorated caves, where the question of the back face does not arise, the anfractuosités of the wall can result, for certain poses, in depth discontinuities. A multi-view version of PS seems thus essential to overcome such limitations.

Finally, if the RTI technique is more and more used for heritage digitization, another of our perspectives, and not the least, aims at

transforming RTI data into PS data. RTI equipment is more specific than PS equipment, but its use seems simpler. And although the illuminated field is limited, in practice, by the dimensions of the dome, this technique seems adapted to the digitization of small objects such as the zodiacal tablet of Fig. 6, as long as the luminous fluxes of the LEDs can be calibrated beforehand.

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