Journal of Cultural Heritage 30 (2018) 117–123

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Original article

New methodology for the assessment of cleaning treatments. Applications of photogrammetry for restoration

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ARTICLE INFO

Article history:
Received 24 July 2017
Accepted 28 September 2017

Keywords:
Restoration
Photogrammetry
3D model
Cleaning
Assessment

ABSTRACT

The development of new technologies in recent years, together with their cost reduction, have fostered their use in different fields such as Cultural Heritage. Likewise, new software and easy accessibility, either through trial versions or due to open-source software, have endorsed their establishment as essential tools in our everyday life. In this paper, a new methodology based on photogrammetry is proposed for the assessment of cleaning treatments. A set of wall painting fragments was the subject of study. By generating and comparing the photogrammetric model of the fragment before and after the cleaning treatment, this methodology enabled to determine those areas in which the treatment had been more effective – thus removing a higher quantity of dirt – and, on the other hand, those areas in which the treatment had not performed well – and the surface had been left intact. Therefore, photogrammetry offers a low cost, portable and simple solution for objectively assessing the efficacy of a cleaning treatment.

1. Introduction

In the face of a conservation and restoration project, an in-depth analysis of the possible treatments to be implemented during the intervention is essential, with the objective of analysing possible interactions between them and the artwork itself. Therefore, previous research becomes a crucial stage in which the use of new technologies and 3D models is more necessary over the years [1].

There are plenty of examples of cultural heritage being digitalised with very specific aims. Such is the case of the archaeological site of Uppakra, in Sweden [2], where photogrammetric models of the different excavation stages were obtained; the work carried out by A. Gruen and F. Remondino [3], generating a 3D model of the Great Buddha of Bamiyan for its reconstruction; or the restoration of the *Madonna di Pietranico* [4], whose digitalisation aimed at reducing fragments' manipulation.

It is therefore evidenced that new technologies provide a valuable tool in the conservation and restoration of cultural heritage, since they comply with the fundamental requirement of being a non-invasive and non-destructive methodology. Notwithstanding, a big adaptation and innovation effort is required in most cases, due to the fact that these technologies are not specific to this field and hence they need to be adapted to its requirements and need. In this sense, new specific programmes such as MeshLab [5] and Hyper3D [6] have been developed, together with new tools and protocols [7].

In this framework, this paper aims at adapting the well-established technique of photogrammetry to a specific need of restoration, such as the assessment of treatments, and within them, cleaning treatments in particular.

2. Research aims

This paper aims at defining a new methodology for the assessment of cleaning treatments, based on the quantity of dirt crust removed. To date, most evaluations of cleaning techniques were based on the final aspect of the pictorial layer (changes in colour or shine, resistance to abrasion) [8] and those which actually focused on determining the removed substance required specific equipment and software which in many cases entailed a high cost [9].

This paper aims at:

- proposing a methodology for objectively assessing the cleaning treatment by means of quantifying the thickness of the removed layer on each point of the painted surface;
- providing a technique which does not entail an extra cost, by making the most of the advantages of new software, such as trial versions and open source, and using a tool which is available in most cases, such as a photographic camera;

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https://doi.org/10.1016/j.culher.2017.09.019
1296-2074/

- outlining a non-invasive methodology, generic enough so that it is not restricted to one piece of artwork in particular but can be repeated in other cases.

3. Material and methods

The proposed methodology, explained in detail below, is based on the digitalisation of the pictorial layer before and after the cleaning treatment by means of photogrammetry and the comparative analysis of both models.

3.1. Material

The sample for this study consisted of small fragments of wall paintings from two archaeological sites. On the one hand, fragments of Roman wall paintings from the 2nd century A.D. were selected, belonging to the *Sala del Mosaico de los Amores* from the archaeological site of *Castulo* (located in Linares, province of Jaén, Spain). On the other hand, fragments of wall coverings from the 14th century, belonging to the *Alcázar de los Reyes Católicos* in Córdoba (Spain), were selected. Their sizes range between 5–8 cm length and 4 cm width, approximately (Fig. 1).

Choosing these samples enabled us to test the proposed methodology in two wall paintings of different characteristics, since they had been executed with different techniques and presented varied alterations. While two surfaces were differentiated in the wall coverings of *Castulo*: a smooth polished one and a brush-stroke coarse one; the wall painting from Córdoba presented a smooth surface in which the incisive preparatory drawing was noticeable. Alternatively, one of the fragments of medieval wall painting showed an accretion of crust which was quite homogeneous and thick; and less thick and more isolated dirt accretions appeared on the other selected fragments, thus demanding more thoroughness and attention to detail when registering the models and in the subsequent comparison.

3.2. Execution of the photogrammetric model

As it has been previously stated, photogrammetry was the chosen technique for the digitalization of wall paintings fragments, due to the fact that it is a low cost, portable, flexible and simple technique which creates high quality models regarding geometry and texture [10].

Photogrammetry is based on partial overlapping of several photographs, shot from different angles, for the 3D reconstruction of the outer and visible surface of the object [11]. The established work process was as follows [12]:

- acquisition of the images by means of a digital photographic camera;
- image alignment with specific software which automatically rotates the images and extracts their equivalent point pairs;
- generation of the dense point cloud, which results in the 3D model;
- creation of the polygonal model and, finally, its texture.

The advantages of this technique are such, that its use as tool in conservation and restoration projects is increasingly widespread [13,14].

3.2.1. Digitalisation of wall paintings fragments

As it has been described, photogrammetry techniques allow the creation of 3D models based on photographs of an object taken from different viewpoints. The photographs shot must cover the whole surface of the object to be digitalized and must overlap so that equivalent point pairs can be obtained. Lighting conditions and the position of the object play a fundamental role when shooting the photographs; specially in this case in which two models are created: one corresponding to the initial state of the fragment, and the other one corresponding to its state after the cleaning has been carried out.

A Nikon D5100 with 18–55 mm lens was used for the shooting sessions. Each fragment was located together with two scales, which served as reference points to facilitate later alignment of both models. Occasionally, the dirt of a fragment is such that the details of the pictorial layer cannot be recognised. Additionally, the surface of the fragment, and therefore also the resulting model, might be modified due to the fact that many equivalent point pairs between the models to be compared disappear, thus complicating subsequent alignment of the models. In order to make it easier, certain external elements were added for the shooting, ensuring that the fragment (before and after the cleaning) was always placed at the exact position towards them; this is the case of the two scales which, apart from enabling the scaling of the model, were fixed elements which remained in a constant position, therefore providing a higher number of equivalent point pairs. Finally, normal lighting conditions of the room were improved with two spotlights located in such a way that they prevented the appearance of accentuated shadows. The photographs were taken using a tripod to rotate the camera around the fragment at two different heights: one of them positioning the lens almost parallel to the surface, and the other one maintaining a 45° angle with respect to the horizontal. The option of turning the camera around the object was preferred instead of using a rotatory table, given the fact that it provides better results, as argued by I. Nikolov and C. Madsen [15].

A wide variety of 3D reconstruction programmes are available nowadays for the creation of a photogrammetric model based on various photographs. Each of them offers different actions to be implemented on the model, and therefore all of them imply advantages and disadvantages. The objective of implementing a low cost methodology was highlighted since the beginning of this paper; this is the reason why the chosen programme fulfils the needs of a work of this nature and, at the same time, is affordable. The program chosen for composing the photogrammetric models, in this case, was *Autodesk Remake* [16]. This programme creates

Fig. 1. Photogrammetric model of the three fragments of wall paintings analysed in this study. Initial state of the fragments. A: Fragment 019, beloging to the archaeological site of Castulo. B: Fragment 01, beloging to the Alcázar de los Reyes Católicos in Córdoba. C: Fragment 10, beloging to the Alcázar de los Reyes Católicos, in Córdoba.

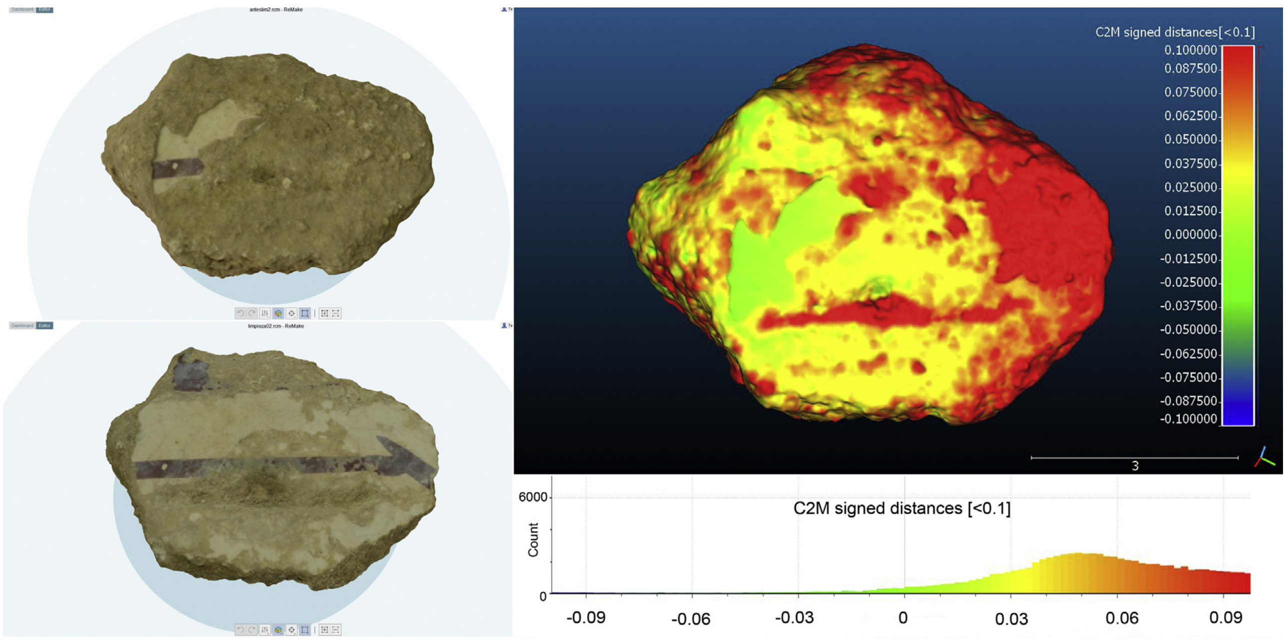

Fig. 2. Assessment of the cleaning treatment on fragment 01. Top left: initial state 3D model of the fragment. Bottom left: 3D model of the fragment after the cleaning. Top right: distance distribution map. Bottom right: histogram of distance percentage distribution.

high quality models in a relatively short time; thanks to its online version, processing time of each model is much shorter if compared with other programmes like *Agisoft Photoscan* [17], for example. Additionally, the trial version allows the user to export models in different formats [15], in contrast with other programmes such as *Reality Capture* [18].

In this case, each model was created using a total of 150 photographs, with a 0.66 mm GSD (ground sampling distance), and an average of 3 hours were needed for creating each model in ultra quality. The size of the meshes varied between 160,000 and 242,000 triangles. Nevertheless, the thicker the mesh is (that is, the higher the number of triangles in the mesh), the higher the reliability of the data obtained and the measurements taken from them. The system was equipped with an Intel® Core™ i7–6500u processor at 2.50 GHz, 16 GB RAM and a Nvidia GeForce 940MX graphic card.

3.3. Comparison of the models

Four photogrammetric models were created (two of each fragment), based on the information collected before and after the cleaning treatment. Fragment 01, belonging to the *Alcázar de los Reyes Católicos* in Córdoba, presented a thick and homogeneous crust of dirt virtually covering the whole pictorial layer. Fragment 10, on the other hand, presented less thick but localized crusts and the incisive preparatory drawing was also visible. The four models were scaled and exported to .obj format in order to compare them using *CloudCompare* [19], an open source editing and processing software of 3D point clouds and triangular meshes.

The photogrammetric models were aligned before and after the treatments, and at least four equivalent point pairs were defined, all of them visible and separated from each other. Once again in this case, the higher the number of equivalent point pairs chosen, the better the alignment of both models will be. These points could not be clustered in one small area; they needed to be well-distributed throughout the model for the alignment to be valid. To this end, points from both the pictorial layer and the support were chosen, as long as there were perfectly recognizable in both models. Additionally, as previously stated, several points of the scales were also selected (making sure at all times during the shooting that the fragment was placed in exactly the same position towards them before and after the cleaning).

Once both meshes were aligned for their comparison, the distances between them were calculated. This procedure was carried out as follows: taking one of the models as reference, the closest distance existing between its triangles and the vertexes of the mesh to be compared was calculated. In this case, the reference model was always that corresponding to the state of the fragment after the cleaning treatment. This comparison resulted in a colour map which ranged from red to blue: being the red zones those vertexes with bigger distances in positive values in relation to the reference model, the green ones those which fully coincided with the reference mesh and, finally, the blue ones those with bigger distances in relation to the reference model, but in negative values.

Fig. 2 shows the assessment of the cleaning treatment carried out on fragment 01. In this case, the comparison of the initial and final state meshes of the fragment was carried out in an interval of [−0.1 cm; +0.1 cm]. According to the colour map distribution, there was a green area in which no crust was removed, since the pictorial layer could be clearly seen. The rest of the fragment presented quite a homogeneous crust of 0.3 or 0.4 mm which was almost entirely removed (yellow colour) and two essentially red areas, corresponding to 1 mm thickness approximately. If observed at first sight from a completely orthogonal position to the pictorial layer, it seemed that both areas corresponded to a dirt accretion whose level stood out from the pictorial layer. Notwithstanding, it was noticed when rotating the 3D model that, even though the thickness of the crust removed was the same, the longer area was located at the same level as the pictorial layer as a whole, therefore corresponding to an incision of the pictorial layer where a considerable amount of accretion had been accumulated (Fig. 3). On the other hand, *Cloud Compare* also offered the possibility of creating a histogram which clearly showed the percentage distribution of the existing distances between both models, for better evaluation of the cleaning. In this case, it showed a quite homogeneous cleaning had been carried out, removing 0.4–0.6 mm thickness crust, while a small percentage of the surface had been left intact.

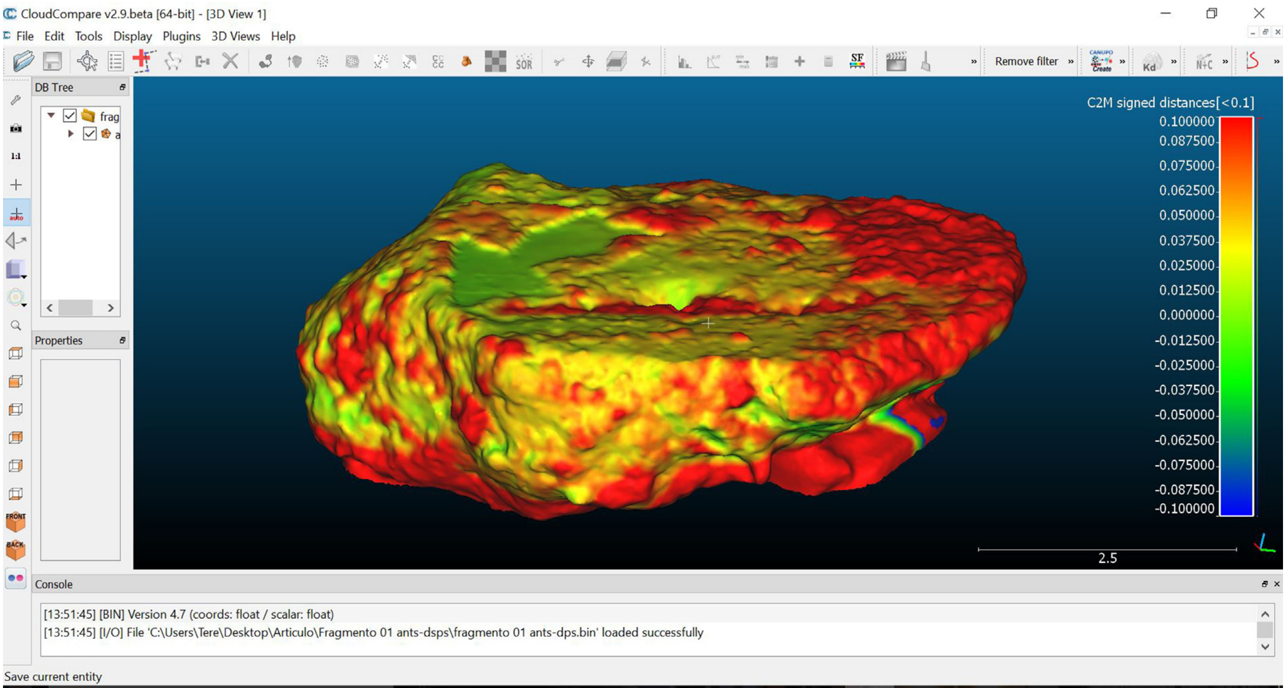

Fig. 3. Fragment 01 3D model with distance distribution map.

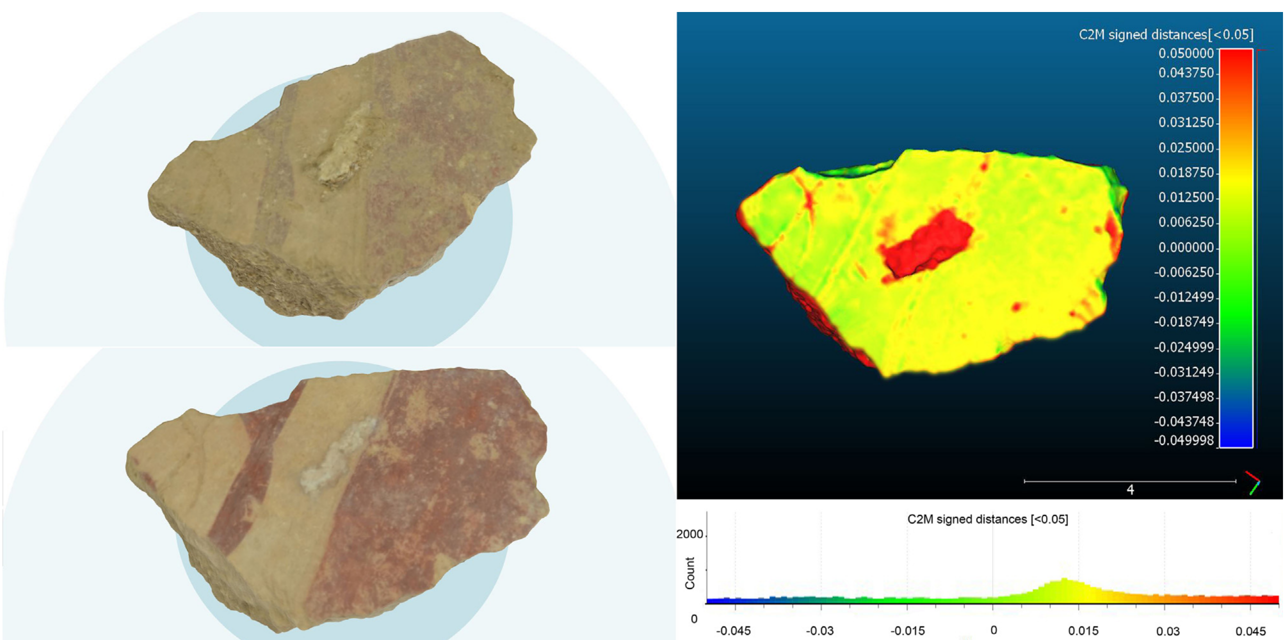

Fig. 4. Assessment of the cleaning treatment on fragment 10. Top left: initial state 3D model of the fragment. Bottom left: 3D model of the fragment after the cleaning. Top right: distance distribution map. Bottom right: Histogram of the distance percentage distribution.

In the case of fragment 10 (Fig. 4), the comparison range was [−0.05 cm; +0.05 cm], since its accretions were very isolated and of minimum thickness in most parts of the pictorial layer. Thanks to this new range, it was possible to distinguish the incisions of the preparatory drawing considering that, as in the previous case, those were the areas with bigger dirt accumulation. Additionally, the histogram showed a distribution of lower values, most of them around 0.1 mm, since it had been a very superficial cleaning to remove the airbone dust which created a layer of minimum thickness.

It should be highlighted that no blue areas appeared in any case in the distance distribution map. This is due to the fact that the reference model was the one generated after the cleaning; accordingly, the differences between this model and the one from the initial state would always provide positive values, because at no time had any substance been added to the pictorial layer. If blue areas had appeared, they would have shown that the models were not perfectly aligned.

4. Experimental data and results

Once the methodology had been roughly outlined, the aim was to improve it. On the one hand, different data collection techniques were investigated, such as the use of a macro lens, in order to evaluate the differences between both methods. On the other hand, it was verified that the technique was repeatable and non-exclusively applicable to one case in particular, so that it could be established as a methodology.

4.1. New conditions

It was necessary to prove that the proposed technique was valid and applicable to diverse cases; and it was with that aim that the cleaning of another fragment of wall painting was carried out. Fragment 019, belonging to *Castulo* archaeological site, was chosen to that purpose, as it had different characteristics: smaller size than the fragment from Córdoba, 2 × 5 cm approximately. Likewise, the finish of the pictorial layer also presented significant changes: there was a smooth polished area in contrast with the coarse one derived from the brush-stroke. The alterations and dirt were very similar to those of fragment 10.

The evaluation of the cleaning treatment followed the same procedure outlined before. The same number of pictures was taken under the same conditions; both photogrammetric models were generated with the same quality and using the same software; and their comparison was established based on identical parameters. The results were quite similar, hence confirming the veracity of the technique. In this case, a minor cleaning had been carried out, mainly focused on small isolated accretions of the pictorial layer which were less of 1 mm thick. Once again, the histogram showed the same results: a very isolated cleaning and a crust of minor thickness (Fig. 5).

At that moment, it was deemed appropriate to verify the differences which could appear between photographs taken with the 18–55 mm lens used up to that point and those taken with a macro lens. In order to do that, the same fragment 019 was digitalised once again before and after its cleaning. The same number of photographs was taken from the same viewpoints as previously stated, so that not a single variable was added with the exception of the macro lens. The same programme was used for generating the photogrammetric models under the same conditions. The comparison of the models was established taking into account three different combinations (Fig. 6): the first one evaluated the cleaning treatment registered with the new lens, by means of measuring the existing distance between the model generated before and after the cleaning; the second one analysed the differences found between the initial state model generated from the macro photographs and those shot using the standard lens; the third one studied the differences found between both models of the already-treated fragments, once again comparing the models based on macro photographs and those taken with the 18–55 mm lens.

In the first case, cleaning assessment based on macro photographs did not substantially differ from that of the first models. The results showed the cleaning had been executed in exceptional and very isolated areas, although it was admitted that the accretions were more clearly shown due to this increase in detail.

When comparing the initial state models of the fragment, a slight mesh separation was noticed in the coarse-finish area of the pictorial layer, corresponding to the area in which the accretions were located. No differences were found when comparing the final state models.

Consequently, it can be stated that the use or lack of macro lens only entails differences when a coarse surface is digitalised. The macro lens captures more details and therefore

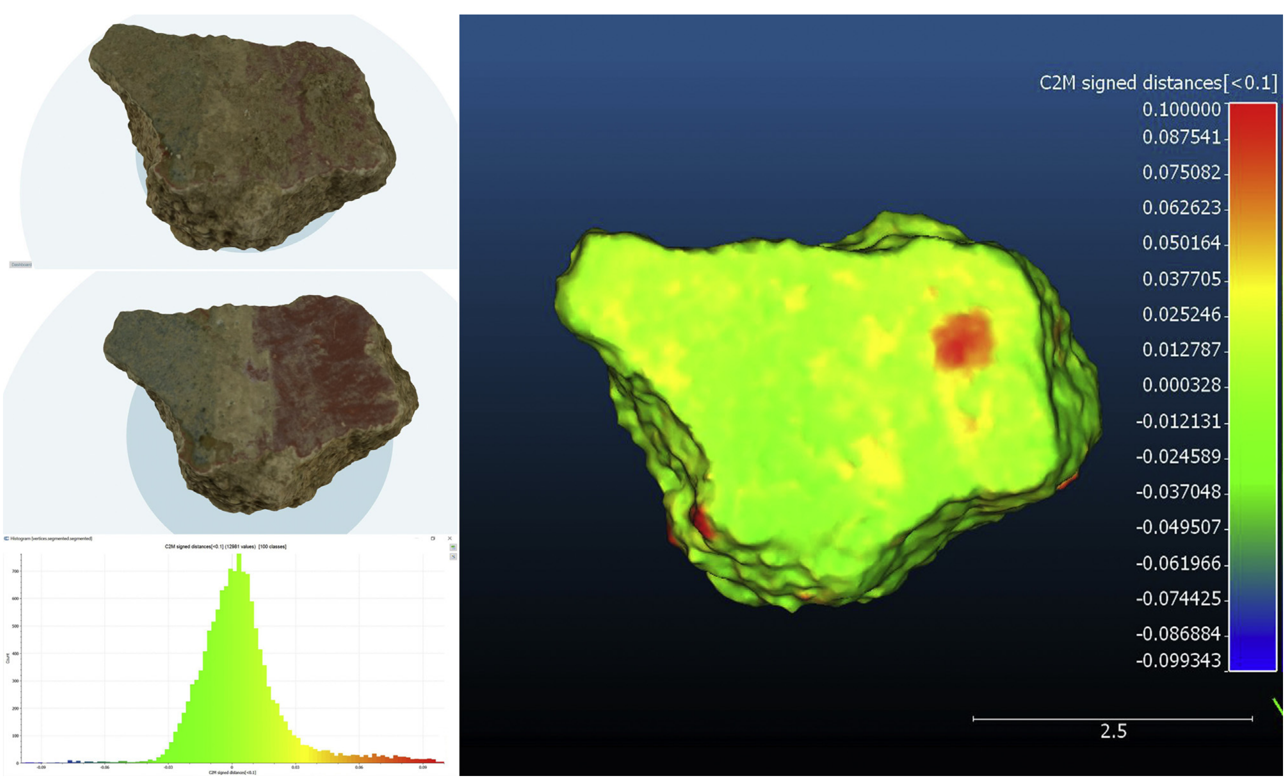

Fig. 5. Assessment of the cleaning treatment on fragment 025. Top left: initial state 3D model of fragment 019. Centre left: 3D model of fragment 019 after the cleaning. Bottom left: Histogram of the distance percentage distribution. Right: distance distribution map.

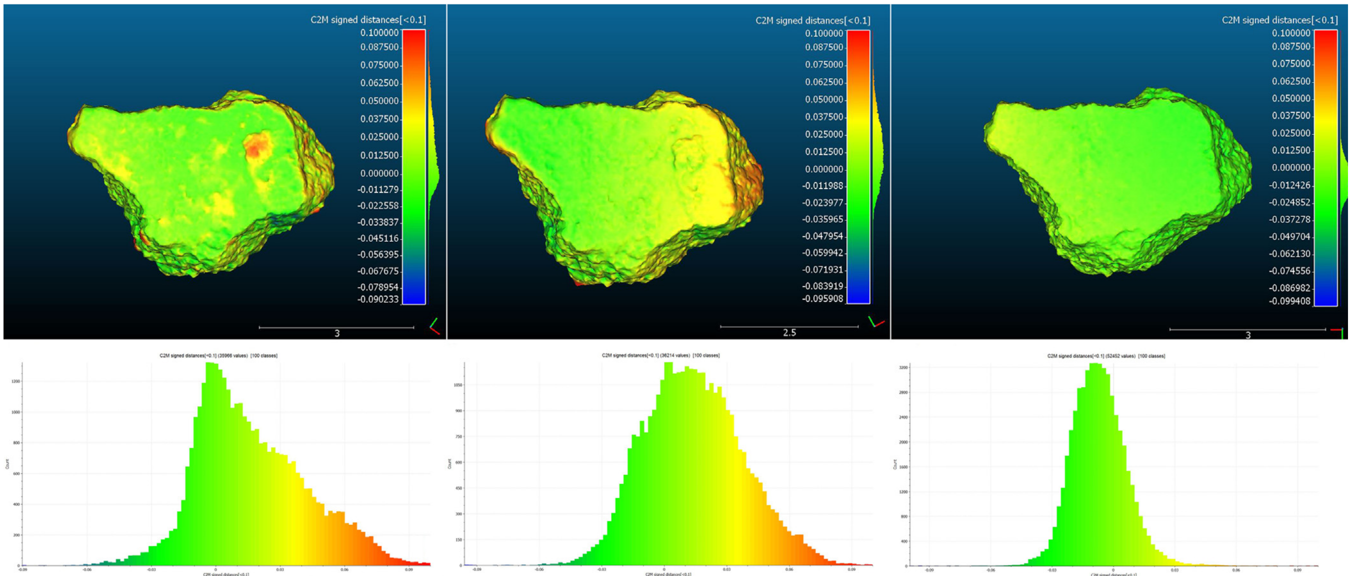

Fig. 6. Left: distance distribution map and histogram of fragment 019 before and after the cleaning, photographs shot with macro lens. Centre: initial state distance distribution map and histogram of fragment 019, models generated from photographs shot with and without macro lens. Right: final state distance distribution map and histogram of fragment 019, models generated from photographs shot with and without macro lens.

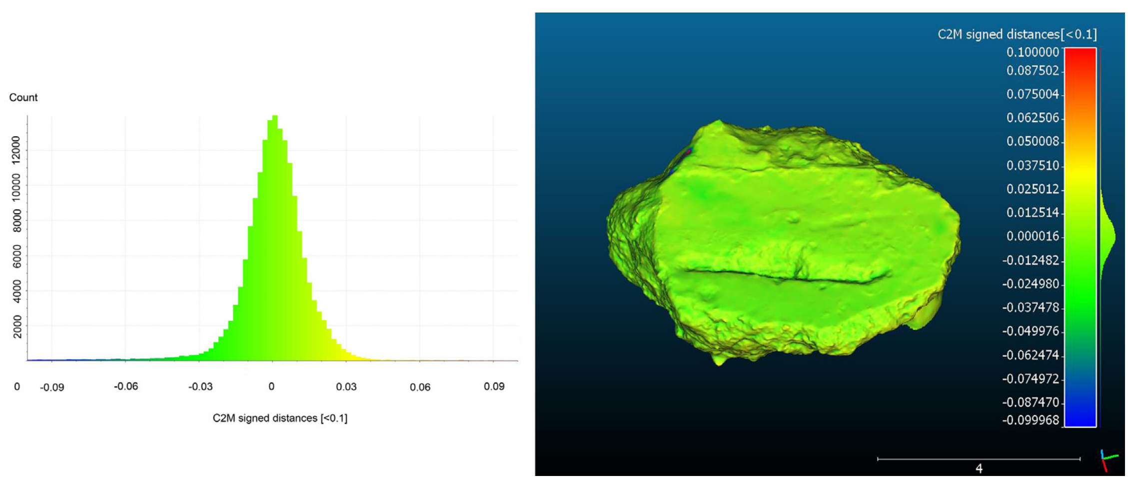

Fig. 7. Distance distribution map and histogram of the two 3D models corresponding to two different datasets of fragment 10 after the cleaning.

the photogrammetric model is generated with higher accuracy; although smooth surfaces are represented with almost the same accuracy in both cases, more heterogeneous coarse surfaces may show more noticeable distances between both meshes.

4.2. Repeatability

One of the main objectives of this work was to propose a methodology for the assessment of cleaning treatments which was applicable to diverse cases and in different moments. The first aspect was proven in the previous section, since it was possible to digitalise and compare the initial and final states of fragments with different characteristics in what respect the finish of their pictorial layer, and even of smaller size. The second aspect gained even more importance in such a technique which aims at creating 3D models of the same object in different moments; this is the reason why it was of crucial importance to verify that the proposed methodology could be repeated showing the same results.

In order to assess the repeatability of this technique, two datasets of the same fragment were collected in different dates. In this case, the final state of fragment 01, after the cleaning, was digitalised.

Once the two sets of photographs had been taken, the steps established in Section 3 were followed: both photogrammetric models were created, scaled and the meshes aligned referencing a minimum of four equivalent point pairs. The comparison was also established within a range of [−0.1 cm; +0.1 cm], as was the case previously. This time, however, the distance distribution map showed an almost identical coincidence between both models (Fig. 7). In this case, the whole surface appeared in green with the exception of some areas in which a yellowish colour appeared. The same occurred with the histogram, whose highest point was 0, therefore confirming that both models fully coincided.

It was hence confirmed that the proposed technique could be repeated in different moments with no changes in results.

5. Conclusions

In this paper, a new methodology for the assessment of cleaning treatments is proposed. The methodology is based on the comparison of photogrammetric models of the pictorial layer before and after the treatment.

New technologies increasingly provide applications for cultural heritage and, among them, photogrammetry has proven to be a simple, portable and low cost tool for restoration works. An objective and quantitative evaluation of the treatment efficacy is achieved by comparing the photogrammetric models before and after the cleaning, as it is possible to analyse whether the cleaning has been homogenous throughout the whole surface or has been limited to isolated areas.

In addition, it is a non-invasive and non-destructive technique which provides high accuracy, since it is possible to evaluate small fragments and recognize variations in dirt crusts of mm thickness. Likewise, it is possible to achieve higher detail of the photographs by using a macro lens as well as by varying the comparison range of the models.

Finally, it has been verified that the technique is applicable to diverse cases and susceptible of being reproduced in different moments, being those two essential requirements for such methodology.

Funding

This work has been funded by the Ministry of Economy and Competitiveness and by the European Regional Development Fund (MINECO/ERDF, EU) within the framework of the Research Project HAR2015-66139-P, as well as by the Excellence Project of the Andalusian Regional Government P12-HUM-1941 and the University Faculty Training programme (in Spanish, *FPU*).

Acknowledgements

The authors would like to thank Marcelo Castro, director of the *Castulo* Archaeological Site and Juan F. Murillo, director of the Archaeology Office of Town Planning Department of the Córdoba City Council, for allowing and facilitating the study of the wall paintings. Likewise, we would like to thank Javier León, creative director of Leonstudio, for his dedication and counselling.

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