Application of a combination of digital image processing and 3D visualization of graffiti in heritage conservation.

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Abstract

In recent years, heritage documentation processes have largely benefited from the application of both 2D imagery analysis and 3D techniques for recording and visualization of assets. In this paper, a combined 2D-3D methodological workflow, especially helpful for the documentation of graffiti on closed and narrow spaces, is presented. It is proposed, firstly, the use of structure from motion software to obtain the 3D model and texture information. Then, the use of decorrelation stretching algorithms is used to obtain enhanced textures. This study found that the performance of the algorithms usually recommended for enhancement of the different colours is sometimes suboptimal. Finally, the integration of 2D and 3D information into Blender, a powerful 3D open-source tool, allows for a detailed exploration of the areas containing graffiti. Additionally, it allows high quality rendition of the resulting model that helps to better understand and record heritage resources. This methodological approach has been applied to the military defense heritage site of Puig-Carassols trench line in Spain.

Keywords: Image enhancement; 3D modeling; Heritage documentation; Decorrelation stretching; Blender

1. Introduction

In the late 1930s all Spanish territory became a huge war laboratory where some of the world military powers were testing new weapons and strategies to prepare for their participation in a major conflict. For this reason, the Spanish Civil War is probably one of the most studied armed conflicts, apart from the Second World War (Pérez-Juez et al., 2004).

The large duration of the Spanish strife, added to the difficulties inherent to the terrain where the main battles took place, caused military strategies to include the use of trench defensive lines. As a result, a large number of military sites of this type can be found at present in Spain. They define a valuable cultural heritage in need of preservation. Unfortunately, most local and regional administrations have shown little interest in conservation actions and, only very recently, after the promulgation by the Spanish Government of the Law of Historical Memory in 2007, some interesting initiatives were promoted. The *Consell Valencià de Cultura* (CVC), a cultural institution belonging to the Government of Valencia, has started one such program aiming to manage, protect and preserve this heritage for the benefit of future generations (Consell Valencià de Cultura, 2004). According to the CVC, the first task to be done is an exhaustive inventory and documentation process that clarifies the location and current state of conservation of the sites. The present paper applies the latest digital information recording techniques to this process of heritage documentation, focusing mainly on the detection and analysis of areas affected by graffiti caused by acts of vandalism.

In recent years, the documentation process has benefited from 2D image analysis techniques and 3D recording and visualization techniques (Stefani et al., 2014). On one hand, the use of 3D content derived from the cultural heritage domain has experienced a dramatic increase (Koutsoudis, 2014). On the other, the application of image enhancement techniques has become standard in any study on heritage conservation (Le Quellec et al., 2015). The combination of both, used only in the very last years, offers excellent advantages over the traditional methods. One example of these advantages can be seen in Domingo et al. (2013), where the integration of 2D image analysis and 3D visualization techniques in rock art documentation produces reduction of subjectivity in interpretation as well as increase in graphic and metric precision and enhancement of the contextual analysis of motif relationships.

In this paper, we present a workflow methodology for the 2D-3D combination that proves to be especially helpful for the case of detection of graffiti in closed and narrow spaces, such as a bunker with a large tunnel within the Puig-Carassols trench line. Under these conditions, a 3D recording system like terrestrial laser scanner (TLS) is not suitable because of the limited space, but especially because this technique is not able to capture the high-resolution textures of graffiti. Instead, we have used Agisoft Photoscan, a well-known Structure From Motion (SFM)-based software tool, which is able to generate 3D models from standard pictures (Verhoeven, 2011). Once the 3D data have been recovered, the original pictures are used to create a blending texture that is processed in ImageJ using its DStretch plugin for decorrelation stretching (DS). Finally, all this information, both the 2D processed texture and the 3D model, is integrated into a 3D visualization tool, such as Blender. This allows for a detailed exploration that permits the location of the affected areas (graffiti, degradation zones, etc.). For a deeper exploration, a specific 3D scene organization is allowed, therefore additional parameters such as cameras, illumination sources and materials can be set up in order to generate suitable renditions that improve the documentation process and, further, may help to analyse which of the DS algorithms is better for delineating the affected areas.

2. Materials and methods

Any conservation project requires 2D-3D data collection, organization and analysis. This section describes the materials and methods used for the acquisition of 3D data by image-based techniques, 2D information by high resolution photography and the combined processing of all this information within a 3D visualization environment to facilitate the 3D analysis in context.

2.1. Site selection

As said in the introduction, the interest in preservation of military vestiges of the Spanish Civil War has increased in recent years. The Valencian Region is one of the most appealing. As capital of the Spanish Republic during almost all war years, Valencia suffered the pressure of some of the last battles. For this reason, the Republican government decided to build several defensive lines for the city and its surroundings, like the Puig-Carassols line, composed by a 26 km-long succession of trenches, bunkers, tunnels, machine gun emplacements that forms an arc-shaped fortification system about 12 km northwest of the city of Valencia.

The construction of the Puig-Carassols line began in the summer of 1938 and lasted until early 1939 and was intended to be the last bulwark to stem a possible direct attack of the national troops to the city of Valencia. Nevertheless, it was never used due to the final republican surrender in 1939. Its location, depicted in Fig. 1, was decided to be a few kilometers off the city in order to control the north, north-west and west routes to Valencia (Durbán, 2009 and 2011).

In this paper, the case of a bunker located at the Paterna sector has been studied.

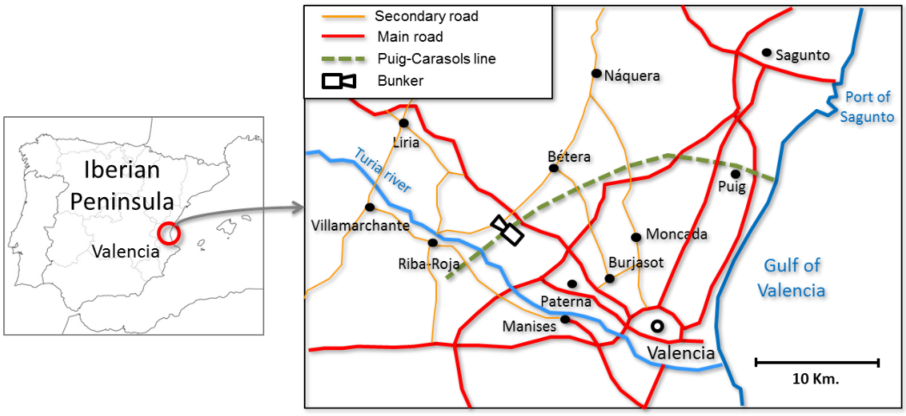

Fig. 1. The Puig-Carassols trench line (adapted from Durbán, 2009), and location of the studied bunker in Paterna.

The main features of this bunker are described next and depicted in Fig. 2:

- It is a large concrete structure consisting of two main parts: an outdoor zig-zagging trench in the south-west and a narrow tunnel with a big entrance in the north-east.
- This structure has a 2 cm armor, 70 to 80 cm of thickness cover, and 60 to 80 cm of thickness walls to withstand 50 kg bombs and heavy artillery. Vestiges of round timber formwork and temporary shoring masonry walls are also found (Frasquet, 2015).
- The tunnel has three machine-gun loopholes pointing to the north-west, and at present it is partially filled with ground and stones.
- Graffiti are the more visible degradation pathologies. They have been caused by acts of vandalism.

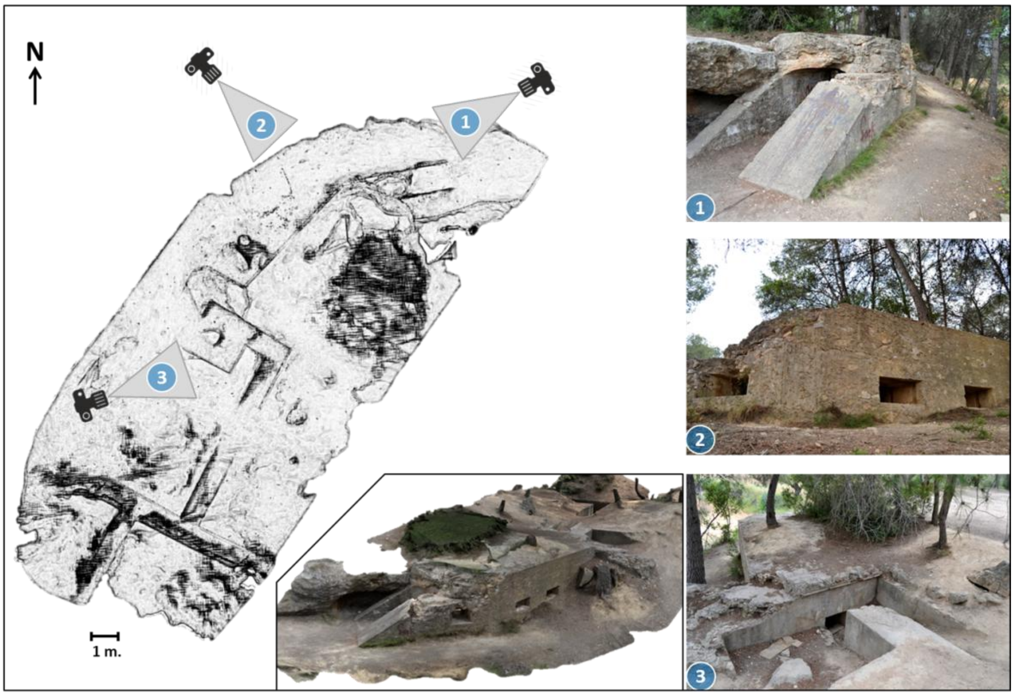

Fig. 2. Outside bunker plot showing different pictures and 3D view. View 1: main entrance; view 2: lateral view with gun-ports; view 3: back structure.

2.2. 3D data collection

Traditionally, surveying techniques methods have been used in a large range of 3D documentation works for heritage applications. In recent years, however, practice has witnessed their increasing replacement by more image-based methods. This is mainly due to the relatively simple and low-cost workflow needed to create a high quality 3D model from photographs. Additionally, clearance requirements, like in the tunnel of the bunker at hand, make it very complicated to use TLS or surveying methods.

2.2.1. 3D photomodeling

Among the existing software that use SFM for 3D reconstruction, we have worked with Agisoft Photoscan. SFM methods use a number of undetermined and unordered photographs of the same object taken from several points of view in order to obtain a 3D point cloud by comparison of homologous information in different photographs (Robertson & Cipolla, 2009). Several authors have evaluated this tool and conclude that Photoscan is a cost-effective accurate method for the recording of archaeological data (Doneus et al., 2011; Remondino et al., 2012, Koutsoudis et al., 2014).

The usual workflow in Photoscan consists of: photographic shot preparation and on-site shooting session, photographic orientation, 3D point cloud generation, 3D mesh reconstruction and texture projection.

- Photographic shots. A DSLR Nikon D3100 camera at 14.2MP with 18-55 mm lens has been used along with a tripod. The presence of narrow sites like the tunnel has required taking special care of illumination and shooting angle in indoor conditions (taking photos as perpendicular as possible to the target, with overlapping percentage over 70% and using diffuse lightning). For the terrestrial photo shooting of the bunker a total number of 495 photos have been taken. Additionally, 49 surveying control points have been measured using a Trimble 5700 geodetic GPS receiver with a Zephyr antenna in order to assess the accuracy of the model (to the level of accuracy provided by the GPS: 5mm + 1 ppm in 1 sigma).

- Photographs orientation. Photoscan allows for manual camera calibration, but in most situations, calibration data are extracted from the EXIF metadata for each photograph. Then, the calibration parameters and the 3D position of each image are known.
- 3D point cloud and mesh generation. Photoscan uses calibration parameters and depth map analysis to determine a set of 3D points. The total number of points has been 23.387.577 (high density mode). Concerning the mesh, a model of 515.143 faces and 260.152 vertices has been obtained.
- Georeferencing. After the georeferencing process using all surveyed control points the XYZ mean square error has resulted in 0.028 m.
- Texture projection onto the mesh. Finally, the software permits taking a selection of suitable images for creating the texture. In this case (a narrow and long corridor) the texture mapping method used has been “adaptive orthophoto” along with the “mosaic” blending parameter. This combination offers good results and better preserves the details of the textures. In the case at hand, a texture of 4096 x 4096 pixels was created.
- 3D model selection. Once all previous processes have been finished, extraction of a partial model was decided. It includes the most interesting areas of the bunker (north-east entrance and tunnel) and contains the majority of the graffiti (Fig. 3).

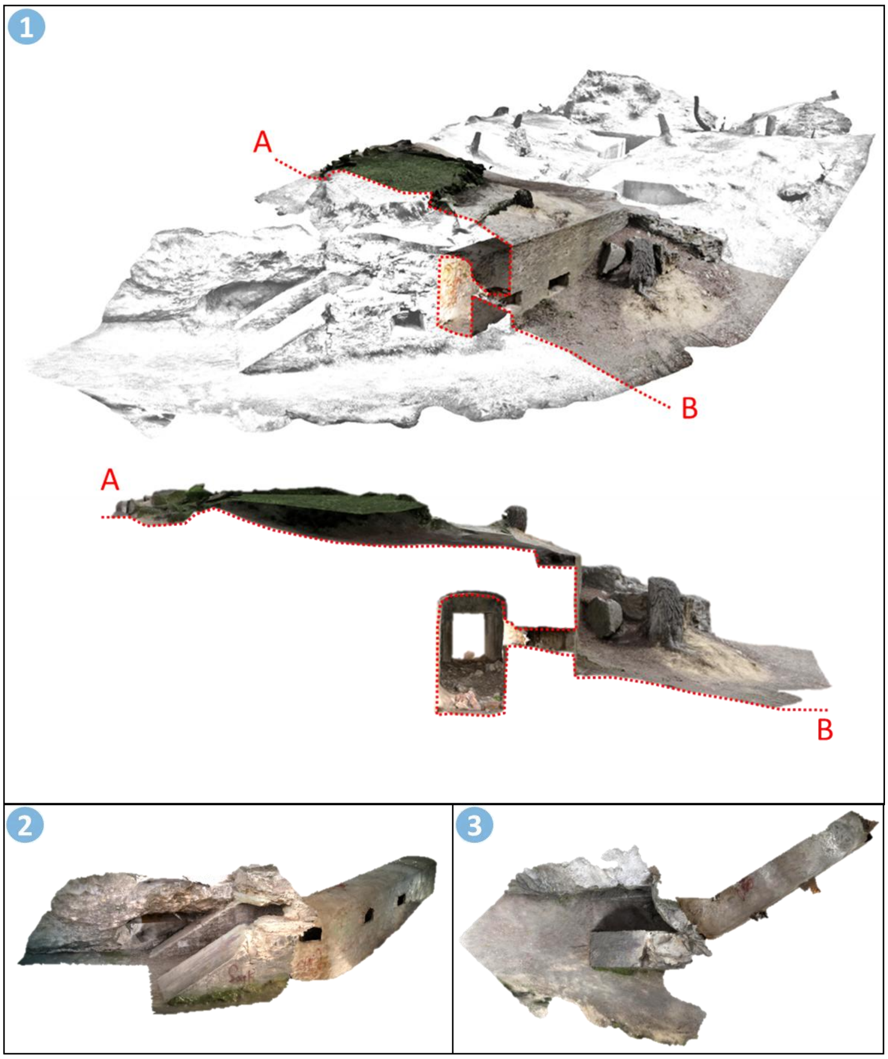

Fig. 3. Different views showing the cross section of tunnel (1) and two views of the studied 3D partial model: isometric view (2) and top view (3).

2.3. Texture processing

3D model generation along with texture projection offers to experts the possibility of studying deeply 2D information in a 3D environment. This approach has some advantages over traditional methods in heritage documentation and conservation: subjectivity reduction, increase of graphic and metric precision, and, specially, the possibility to analyse the relationships among the different features, whether in rock art motifs, graffiti, petroglyphs, erosion or any other kind of pathologies (Domingo et al., 2013).

In heritage conservation applications, image enhancement techniques are often performed over high resolution images focused on specific details. The aim is to enhance the information for a better visual identification or as a preprocessing phase for classification purposes.

We have used enhancement techniques in a preliminary phase of visual exploration in order to identify problematic zones (chiefly graffiti in our case). Therefore, image enhancement has been performed not on each individual photo but on the whole texture attached to the 3D model, enabling us to locate the interesting areas in a 3D context more effectively.

2.3.1. Decorrelation Stretch

Image enhancement is usually executed in post-processing mode by using some of the existing tools; some of them come from the field of photography (Photoshop or Gimp), others from the remote sensing field (ImageJ, Erdas, Envi or Hypercube). Although all of them represent valuable tools for this purpose, they require a relatively high degree of knowledge on image processing and, in most cases, they have a strong dependence on the operator's skills.

Among the different image enhancement algorithms used in heritage documentation, decorrelation stretch (DS) has proved to be extremely powerful to emphasize faint details in photographs (Le Quellec et al., 2015, Rogerio-Candelera, 2015). The DS algorithm was developed by Gillespie et al. (1986) and adapted by Harman (2005) for rock art enhancement. Basically, DS is able to transform a multiband image highly correlated into a new image with no correlation among their bands. This guarantees the maximization of differences among pixels with similar values and allows for a better observation of details.

The DS algorithm has been implemented as an almost fully operator independent plugin (DStretch) in ImageJ software (Harman, 2005), which allows the obtaining of different results through a range of preset parameters that permit the changing of aspects like output colour space, contrast level, etc. Each of these algorithm variants is recommended for a particular pigment colour enhancement (see Table 1), and has been tested in many rock art painting analyses (Collado et al., 2009; Domingo et al., 2013 and 2015; Cerrillo-Cuenca and Sepúlveda, 2015; Le Quellec et al. 2015).

Table 1. Proposed set of algorithms for each type of pigment (source: DStretch plugin information)

Pigment colour	Proposed algorithm
Black	LAB, LBK, LBL,YBK,YBL
Red	CRGB, LRD, LRE, RGB0, YBR, YDT, YRD, YRE
Yellow	LDS, LYE, YDS, YDT, YYE
Green	YBG
Blue	YBK
White	LAB, LWE, YWE
General purpose	LAB, LDS, RGB, YDS, YUV

We processed the original 3D model texture and obtained 23 new textures, some of which are shown in Fig 4. Once obtained, the best way to quickly compare results is importing both the 3D model and the processed textures into a 3D environment.

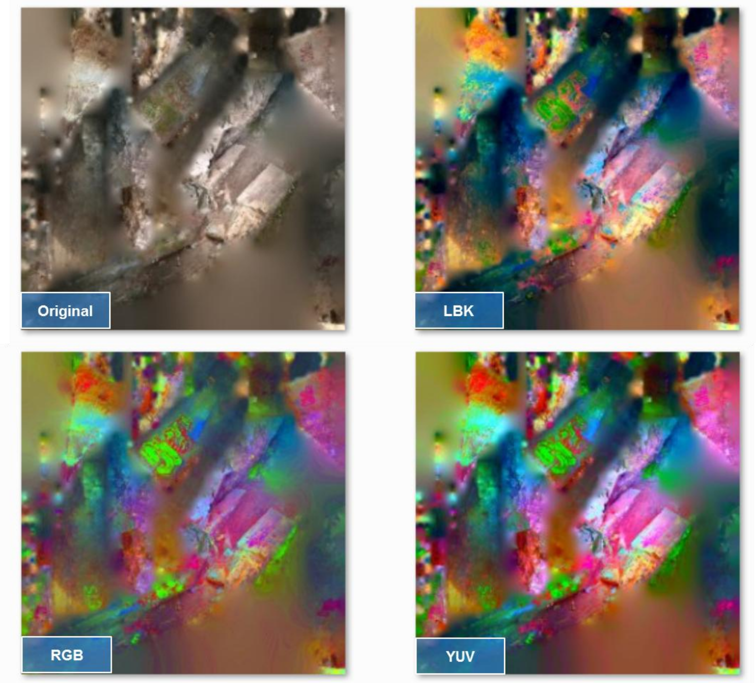

Fig. 4. Some samples of texture processing applying DS algorithms variants.

2.4. Analysis in a 3D environment

Analysis of the enhanced textures within a 3D environment permits the easy identification and study of relationships of the areas of interest. To achieve this, both the 3D model obtained in the photomodeling phase and the enhanced texture have been imported into a 3D software tool. In the present study, we have used Blender, the well-known open source application in the field of 3D design. Blender has a very powerful set of tools for modeling, lighting, animation, rendering and video editing, and has been successfully used in the field of heritage conservation for tasks like virtual reconstruction and anastylosis (Acka, 2012; D'Andrea et al., 2012; Fabregat et al., 2012). We describe in detail the successive steps in what follows.

- Importing the 3D model. The 3D model created in PhotoScan has been exported using the Collada export format (Arnaud and Barnes, 2006), which is supported in Blender and allows for the attachment of textures and animations.

- Material settings. 3D models are called "meshes" in Blender. A mesh contains only geometry (set of vertices, edges and faces) but a texture can be attached to it through the definition of a mesh's material that contains all the necessary texture features (type of texture, colour, specularity, etc.). In the present case we used an image texture. Blender presents a visual interface called "node editor" that makes it easy to modify texture mapping and visualization. By using this tool we can easily change the texture file attached to the mesh in order to display each of 23 resulting textures obtained after the decorrelation stretch. Some of them are displayed in Fig. 5.

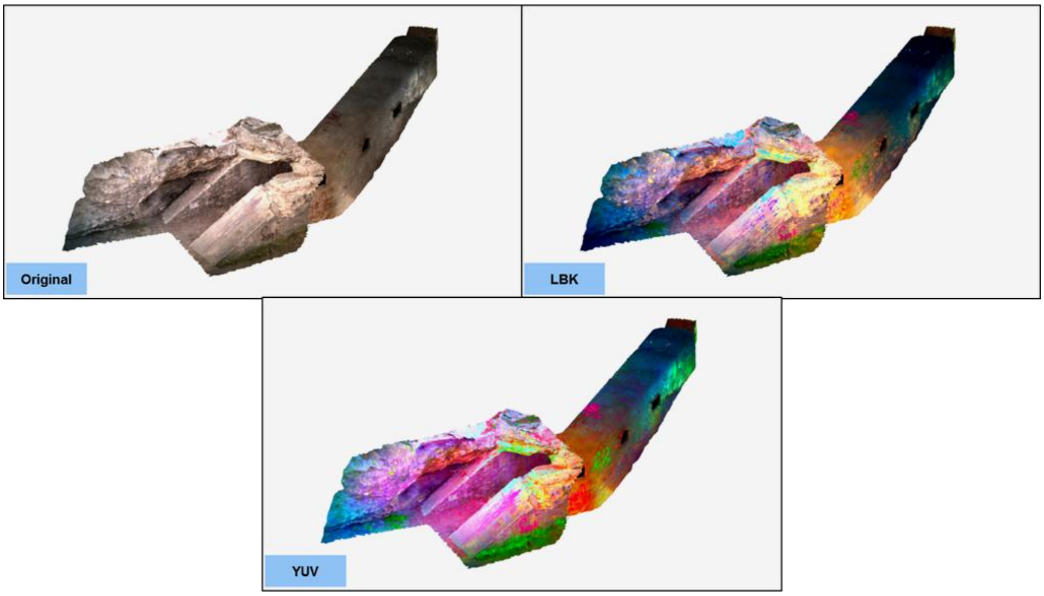

Fig. 5. Application of several DS textures to the 3D model in Blender

- Lighting settings. Blender is able to handle several light sources of different types. In general, global lighting may be enough to visualize a texture correctly, but in some cases, as the bunker at hand, additional lamps may be needed for closed spaces (tunnel) in order to achieve a better visualization. This case may turn out to be problematic inasmuch as several areas of the texture may be lit with different intensities, which is not desirable for an acceptable interpretation. To overcome this problem, division of the original 3D geometry in four submodels was decided in terms of position: upper-left and upper-right models and lower-left and lower-right models. In this way, after switching on only the desired submodel and using a global lighting, we achieve uniform and well-illuminated textures (Fig. 6), which allow for a quick exploration of the bunker in order to examine the areas of interest.

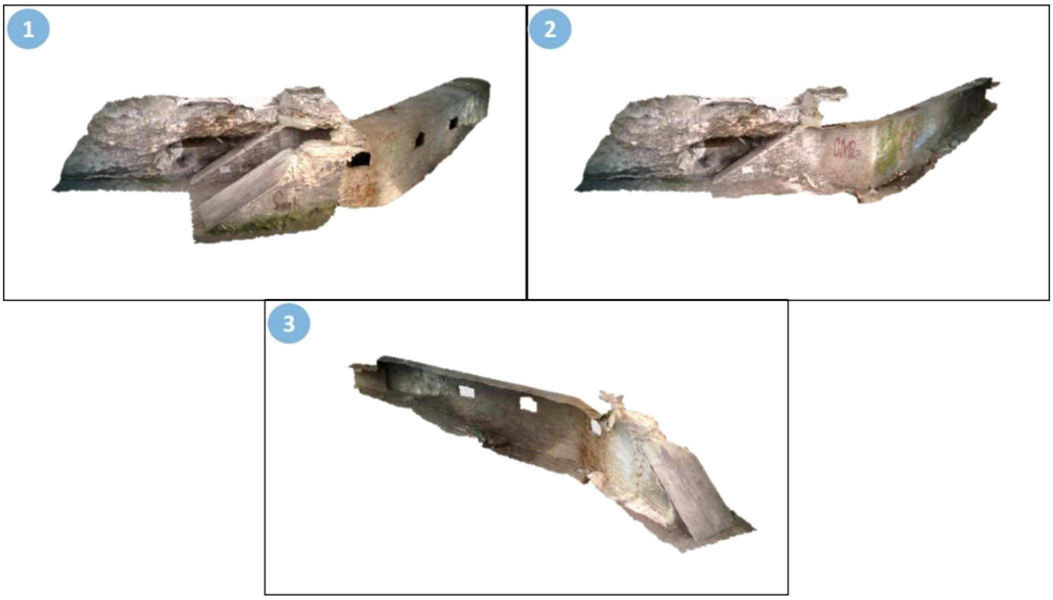

Fig. 6. General view (1) and several partial views after switching on the desired submodels: left (2) and right (3) bunker sides.

- Camera settings. Since the first 3D exploration permits only a shallow visual analysis for determining potential problematic areas, a more detailed study is needed in order to compare the different results of the DS algorithms over the original texture. In this case we have set up seven cameras, adequately located and orientated perpendicularly to the texture plane (Fig. 7). Thus, we obtain high quality renditions of every area for a later analysis.

Fig. 7. Camera settings. Location and view angle are adjusted to cover the seven areas of interest (1 to 7).

- Rendering. In computer graphics, rendering is the process of generating an image from a scene that contains 2D or 3D information (Ignatenko et al., 2004). The scene may also contain additional elements like lighting, textures, shadows or cameras. The process considers all these parameters in rendering the colour of every pixel for the composition of the final, realistic image. In our case, we needed a total of 161 renditions (23 renders for each of the seven areas). Rendering is usually a high cost process that depends on parameters like quality, resolution, shadow casting, etc. We decided to automate this task by making use of the Blender built-in Python API to programming a script that loops through the 23 DS-textures, loads each texture into the mesh material, performs the rendering and saves the final render to an image in the hard disc.

3. Results

We have used so far the visual 3D analysis as a tool to determining potential problematic areas; hence, 23 renditions were obtained for each area. In some cases, the original texture is enough for the expert to appreciate the features (e.g. graffiti in Fig. 7, area 1). In other cases the use of a DS algorithm is needed for enhancement (e.g. Fig. 7, areas 2 and 4). The particular analysis of each of these areas of interest along with the corresponding techniques used is explained next.

3.1. Study of each area of interest

- Area 1. This outside wall of the bunker has only one red colour graffito. After comparative analysis, we find that RGB0, LDS and YRE algorithms offer better results, because they detect not only the graffito borders but also the halo surrounding the main traces. In particular, YRE allows for a better discrimination of "r" letter (Fig. 8).

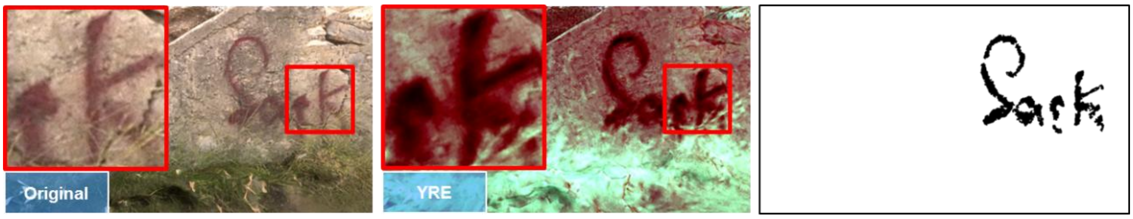

Fig. 8. Area 1: original image, YRE algorithm and result of the tracing process.

- Area 2. Plain surface located on an inclined plane in the bunker entrance. This area has a big cross-shaped red stain with two overlapping graffiti in blue and faint yellow (Fig. 9). Here, the best algorithms for highlighting each of the three paintings have been YRD, LDS and YYE, respectively.

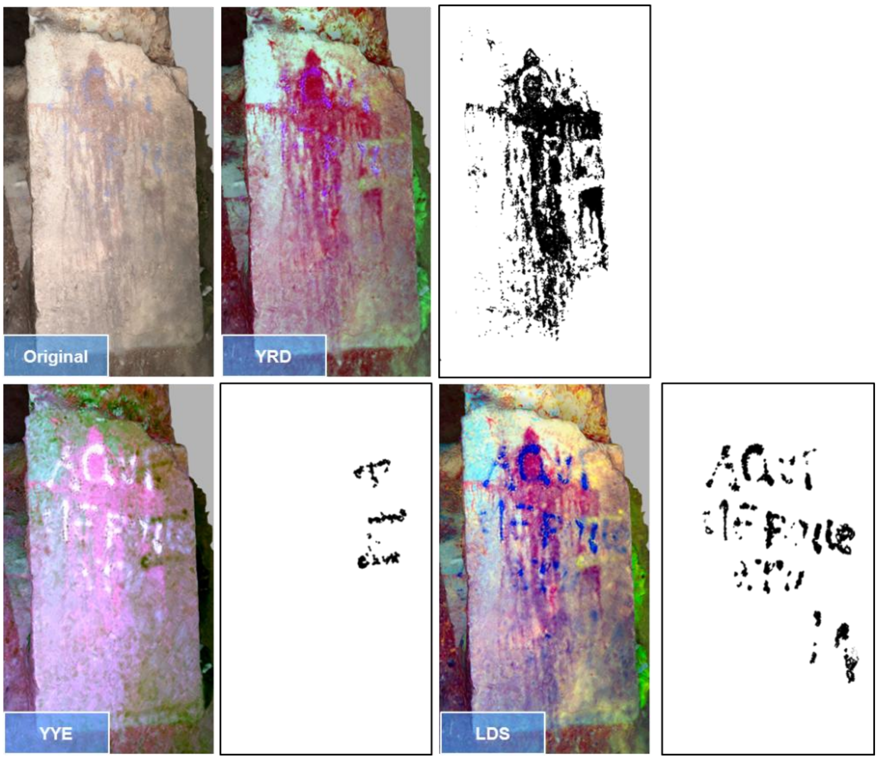

Fig. 9. Area 2: original texture, processed textures and tracings for the different paintings.

- Area 3. Area inside tunnel containing two graffiti. One is the big graffito with red colour borders and filled with green (we only have extracted borders), and the other is a little white signature in the upper-right corner. The best results have been obtained using RGB0 and LWE algorithms respectively (Fig. 10).

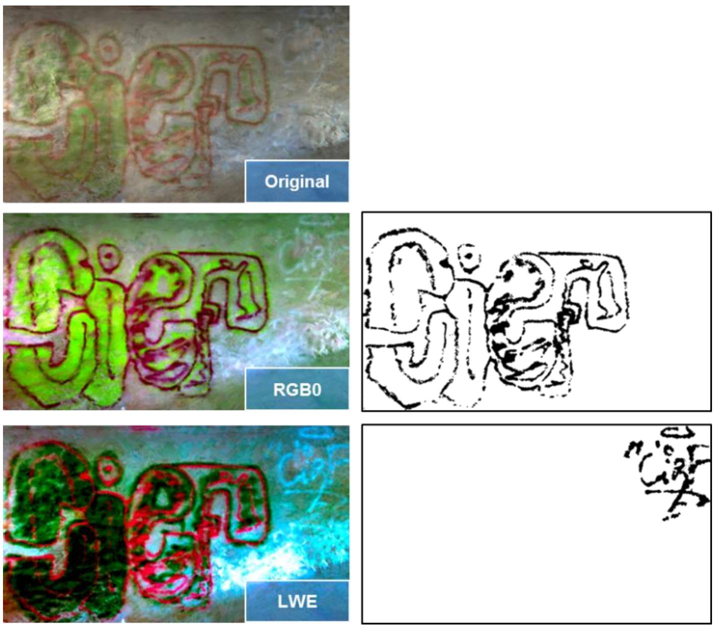

Fig. 10. Area 3: original texture, processed textures and tracings for the two different paintings.

- Area 4. Area inside tunnel with three types of graffiti: a red colour signature, several white drawings and arrows, and some black drawings and letters. In this case, the best results have been obtained by applying LRD, LWE, and LBK respectively (Fig. 11).

Fig. 11. Area 4: original texture, processed textures and tracings for three different paintings.

- Area 5. Red colour signature on an inside wall near the bunker entrance. The best results here are obtained after application of the LBK algorithm (Fig. 12).

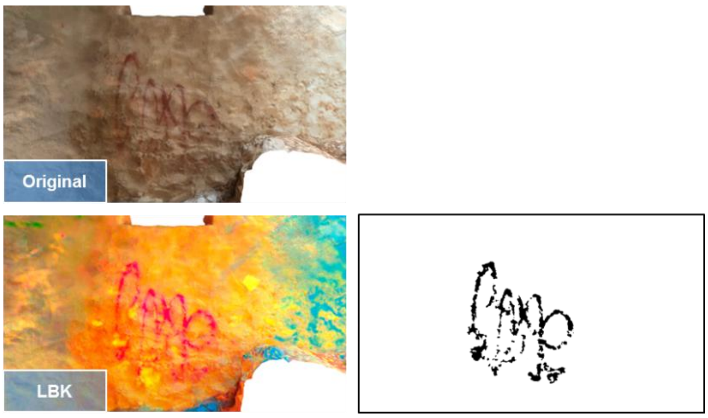

Fig. 12. Area 5: original texture, LBK processed texture and tracing.

- Area 6. Faint signature with green capital letters on an inside tunnel wall. The best results are generated by YWE and YBG algorithms. It can be seen that the last one offers additional information about the starting and ending points of traces (Fig. 13).

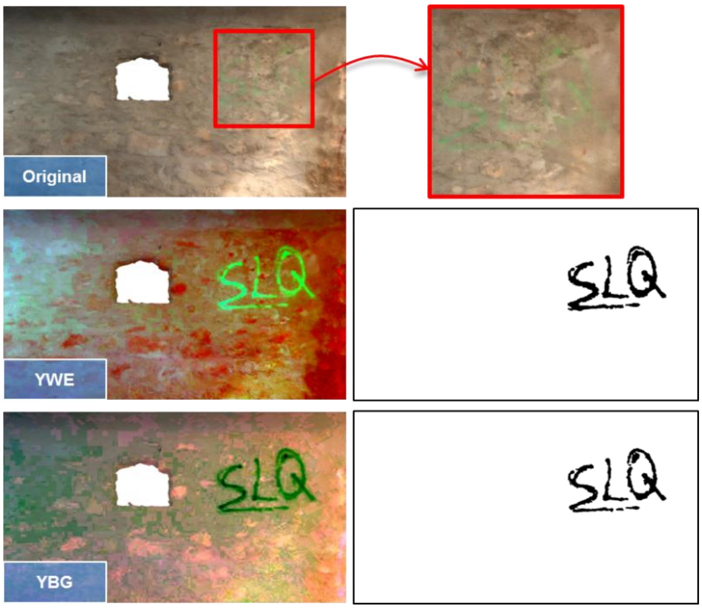

Fig. 13. Area 6: original texture and comparison between YWE and YBG algorithms.

- Area 7. The last area of interest is also located inside the tunnel, this time on its ceiling. Two graffiti, both with very blurred parts, can be found: a red colour signature and a white colour graffito with two capital letters. In this case, the best results are produced by LBL and LAB algorithms (Fig. 14).

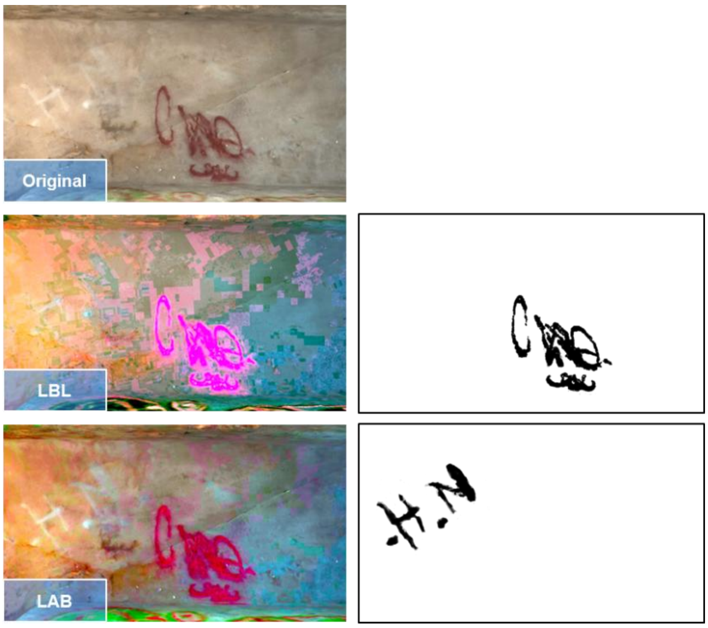

Fig. 14. Area 7: original texture, processed textures and tracings for the two different paintings.

4. Discussion

As previously shown, the combination of 2D image analysis and techniques of 3D visualization offers the possibility of an integral, non-invasive study valuable for heritage documentation tasks. For this purpose, use of Blender has shown its potential for quick area inspection in a 3D context. Besides, the possibility of attaching several textures into the 3D model in real time and control capabilities over all aspects of visualization (illumination, cameras, etc.) offer complementary advantages. Some of the most remarkable examples are the possibility of increasing the lighting intensity in a dark texture and the chance of obtaining a new point of view not captured in the original set of photographs.

Regarding the 2D analysis, DS algorithms have proved to be useful for image enhancement and, particularly, graffiti detection, allowing for a more detailed process of documentation. As experienced, the proposed algorithm in Table 1 works fine in most cases while in others we have found alternative better solutions (see Table 2). This is the case of areas 2, 5 and 7, where the best results were achieved with general purpose algorithms or algorithms recommended for other colours. Obviously, the recommendations were drawn from other authors' experience with the DStretch plugin, so that they are also dependent on the initial image conditions: quality, illumination, etc. (Le Quellec et al., 2015).

Table 2. Level of coincidence between the proposed and the best DS algorithm. The proposed algorithm column represents the set of algorithms suitable for a specific pigment: R, B, Y, W, K and G for all algorithms proposed for red, blue, yellow, white, black and green pigments, respectively.

Area of interest	Proposed algorithm	Used algorithm	Coincidence
1	R	YRE	Yes
2	R, B, Y	YRD, LDS, YYE	Yes, no, yes
3	R, W	RGB0, LWE	Yes, yes
4	R, B, K	LRD, LWE, LBK	Yes, yes, yes
5	R	LBK	No
6	G	YBG	Yes
7	R, W	LBL, LAB	No, yes

5. Conclusion

The application of image enhancement techniques has become common practice in current studies on heritage conservation. In this paper we have proposed the combination of 2D image enhancement techniques and 3D visualization tools in a workflow that has shown its benefits for preliminary studies leading to a better and quicker understanding of the overall current state of conservation.

The texture obtained after 3D modeling allows, once projected onto the mesh, for a thorough degree of analysis and visualization. Further, the possibility of making subdivisions of the 3D model (along with the user's choice of making visible or invisible any of the different parts of the model), combined with the ability to control the position and intensity of the lighting sources, allows for a better exploration of the model, without the need of texture reprocessing.

Regarding the image enhancement techniques, the fact that we work with the whole 3D projected texture instead of independent pictures allows for a global understanding in quick visual analysis. This initial state can be complemented, when necessary, to improve focusing on particular details through the analysis of the original photographs or the addition of new ones taken under better conditions.

We have demonstrated that the use of DStretch algorithms, which produces a set of processed pictures to be projected as textures, is flexibly handled under Blender in real time, allowing for quick visual comparisons. The high quality renders obtained in Blender help to improve considerably the subsequent interpretation tasks. In this regard, we have experienced that the recommended DS algorithm is appropriate for most cases whereas there are some occasions where other methods perform better. All in all, it has to be emphasized that performance of each enhancement technique depends not only on the pigment colour but also on the particular conditions under which the photography was taken.

Appendix. Supplementary data

The referred 3D bunker model is included in the *obj* supplementary file. An interactive representation of the model with the different processed textures can be found at http://personales.upv.es/jpalomav/vallesa/bunker2.html

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