Photometric Stereo for 3D Mapping of Carvings and Relieves

Case Studies on Prehistorical Art in Sardinia

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Abstract

A photogrammetric technique (Photometric Stereo), known since a long time, is here proposed as an agile an cheap tool for 3D recording engravings and relieves.

Different from stereoscopic or monoscopic Photogrammetry, the Photometric Stereo uses a standard camera at a fixed point to take typically four snapshots of the same object under different lighting directions.
Image processing gives three maps: the "Albedo" (that is the color of the surface

without any shading), the x-gradient and the y-gradient. From gradient maps one gets the 3D shape of the original surface, with results comparable with those obtained by the much more expensive and demanding laser scanning machines. The 3D surface, once re-colored with the original Albedo, renders highly natural virtual reconstructions.
The key point is the extreme simplicity of the acquisition procedure and the preservation of the 3D information even under non-ideal conditions.
Examples will be given on decorations of the sadinian "Domus de Janas".

1 Introduction

The most used techniques for archaeological surveys are summarized in **[1].** Among these, the three-dimensional reconstruction of ambiances and artifacts have now pervaded the international practice, but for the special case of engravings and reliefs those techniques don't work so good.

Those findings are often eroded by weather and covered with hundred or thousand years old patinas and them reveal their details only using shave lighting, that has to be adapted in the direction and inclination to reveal every detail on the rock to reconstruct as far as possible the design or text engraved, and the photographic documentations is very difficult.

The archaeologists can't avail himself anymore with the old invasive contact techniques used to support the documentation, then the 3D mapping of the surface and artifacts become utmost important.

This solution reveals many positive points: this allows the reconstructions of the objects on the computer, turning and illuminating them virtually, replicating at home all viewing conditions otherwise possible only on the field; the 3D printing of replicas, possibly enlarged or reduced and the ease of sharing by electronic archives not mediated by the interpretation of the researcher.

However, the solution itself appears prohibitive when it must be recovered using laser scanning for 3D relief. The equipment cost, the operations complexity, the millimetric detail required, the duration of the acquisition phase, discourage to use this methodology in sites with many decorations that must be documented one by one. Last but not least, one big problem could be the color of the surface that contains informations that must be separately registered in the laser scanning by camera (the laser doesn't see itself the colors), including the effects of shadows and shadows that persist even in the reconstruction that uses the original color in the "rendering" to your computer. On the other hand , the outstanding performance of the laser scans in terms of reconstruction and measurement of shapes and volumes appear oversized for objects in which the shape of the surface, flat, convex, irregular, is less important than the stretch on it, engraved or carved .

Other methods based on 3D reconstruction of volumes from images taken from various angles (multi -view) give excellent dimensional perceptions, but they require a very high number of shots with not always possible shooting angles and in any case they keep the limitation of shading in surface color, already cited by laser scanning.

2 Photometric Stereo and engraved and carved decorations

As part of an interdisciplinary project funded by Sardinian Region aimed to documentation of carved and engraved decoration of the Sardinian Domus de Janas, a technique known for decades, but sparsely used, seems to be particularly effective for solving this problem. The technique is called Photometric Stereo and its technical fundamentals are shown in [2]. The principles of Photometric Stereo are based on the assumption that the shading of a surface depends on the direction of the light that illuminates it and on the shape of the surface itself, through a mathematical relationship known , independently of its color.

A single image can give us, under particular assumptions of uniformity of color and knowledge of lighting, an estimate of this form (Shape from Shading , [3]) , but the methodology used for the Domus de Janas is free of these restrictive and often not true in many practical cases assumptions. This problem is solved acquiring four images with a standard camera placed in a fixed position, and moving a light source typically above, below, left and right of the camera, always pointing to the center of the surface framed . Under ideal conditions , the quartet of images allows to obtain separately the height of each image point (pixel) and its original color, point by point, cleansed of every shading (the so-called "albedo"). This is a peculiarity of the Photometric Stereo, often underestimated: the reconstruction of the third dimension is combined to the measurement of pure color of the surface. Any other available 3D technique achieves this result , which is essential for a virtual reconstruction that uses the original color and not an artificial surrogate of it . This, far beyond from purely aesthetic, provides the ability to record and spread the information of the entire specimen in form and color, without artifacts and interpretations.

3 Equipment

The equipment required is unnecessarily composed by highly advanced and expensive cameras and lighting sources: here we wish to emphasize the minimum requirement to achieve fast results and a good documentation of engraved and carved decorations.

In this case, as described in [4], you only need a camera, a tripod, a cable or control for remote shooting (even better if the shot is remote controlled, function now also available in a variety of equipment to medium-low range) and a light source powerful enough to overpower the ambient light which have the emission from a single point. The first requirement says that a continuous source (such as an halogen spotlight) requires to operate in very low ambient light, and certainly not in the open field. In this case, you turn on the light, take the first image, move the light and shooting the second and so on. In bright daylight, however, a commercial flash is able to completely overpower the ambient light (except in direct sunlight, unless we choose flash of high power and cost). This is definitely the easier version of the technique, but it requires that the flash is controlled from the camera that must not shoot and flash with the built-in one, requirement that's met by equipment available at low price category. The second requirement, the point source, is never well verified in practice. The most important thing is that this source (both continuous or flash) is not composed of multiple lights , such as LED sources in some market today.

For example, with reference to the Project Domus de Janas , images 1a and 1b show an anthropomorphic shape engraved in one of the graves of Sos Furrighesos necropolis in Anela. The first image is one of the original quartet and the second a virtual reconstruction, with tilt and lighting arbitrarily chosen, in order to demonstrate the preservation of information. The colors of the reconstructed appear really natural, given that they become from the albedo extracted from experimental images. To follow this assumption, you can estimate that in the first image the illumination comes from right (the drawing is engrave, and not in relief), while in the reconstruction 1b light (virtual) comes from the left . The shading in the reconstruction are only virtual and the original ones disappear. In images 2a, 2b and 2c, is shown the engraving of the map of the village on the floor of the Domus . 2a shows the original image, with all the difficulties of the conventional photographic documentation with the mixing between surface colors and shadings. The image processing 2b is the first sample that corresponds to the x-gradient. The image seems to coincide with a normal shot in shave light, but in reality the operation performed has deleted all the color variations of the surface, leaving only the shadows of the grooves. The image 2c, finally, shows a 3D reconstruction with color removal.

fig.1a

fig. 1b

Finally, referral to the Tomb II ("the Spirals") of the necropolis of Montessu, the Fig.3a shows the original image where once again the decoration is blurred by surface own colors, the image 3b shows the gradient modulus and 3c the 3D reconstruction of the surface, without the albedo in order to enhance the features engraved.

fig.2a

fig .2b

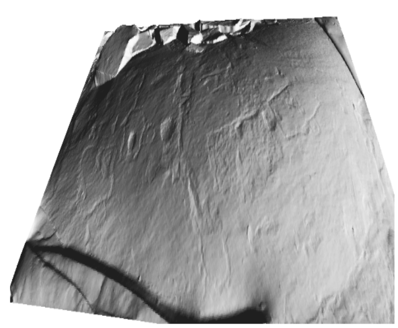

fig. 2c

fig. 3a

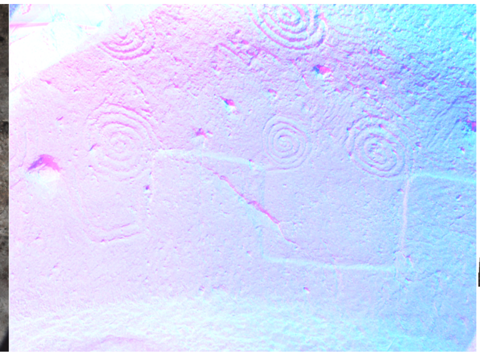

fig. 3b

fig. 3c

4 Mathematical concept

One of the main important information that we lose when we take a photo is the *"depth"*. Most of the 3D techniques require this data to have a 3D representation of surfaces, and this one can be obtain in different ways for each methodology. If we use Photometric Stereo, we are going to achieve to this information, studying the respond of the object to several lights conditions. In other words that means takes several photos in which, for each one, *the camera position it's always the same but the flash light direction it's different*. The minimum number of pictures must be 3 and that come throw a mathematical constraint but in the practise we use to solve over determined problems in which the number of pictures is always major than 3. Furthermore an our standard Data-Set is characterized by 4 pictures taken, respectively, positioning light in the *4 cardinal axes:* North, East, South, West (a typical Data-Set examples is shown in *figure 4.1*). In that case we are able to study the depth finding the *gradients* and immediately after the normal point to point of the object obtaining another important element; the orientation of the surface that we want to reconstruct. Unlikely the only knowledge of the gradients, and so depth, can't be sufficient to obtain a 3D surface. That's because our input data (pictures) are discrete and therefore so are the gradients. That means to merge all discrete points to obtain the final 3D shape solving an integration problem. This procedure can be transformed, using particulars mathematical techniques, in a linear system in which the solution represents our 3D reconstructions.

So summarizing, a standard Algorithm that uses Photometric Stereo as described in [5] can be divided in two main phases:

- Extrapolation of gradients starting from some pictures
- Integration of gradients to obtain final reconstruction

between them, if necessary, we could even find some more *"optimization"* steps; for instance: filtering and image adjustment procedures, with the only finality to increase results.

Does not exist any standard for the implementation of the algorithm that can be written using any language programming. In our case we have used *Matlab*, that contrary to other development environments, it's very simple to use and at the same time it's equipped

fig 4.1

with some useful tools and inside routines that can granter to us better results in terms of exposed time elaborations.

5 Acquisition and elaboration times

The acquisition time of our standard Data Set coincide with the time to take 4 different pictures. When we use the flesh, with remote control, timing can be limited in a few seconds. If we speak about elaboration, we can separate timing considering the first step (elaboration of gradients) and the second step (integration process). In the first step we are going to obtain results in a few seconds, the time of gradient's elaboration is less than one second, but after we require to save results as pictures that must be saved in the hard-disk, according in which we have explain in section 6, and this procedure is done in more less 5-7 seconds. The second step coincide with the integration process and typically it's the critical phase of a standard Photometric Stereo algorithm. In the past this was one of the most tough aspect about our software, that's the why , recently we have focused our attention particularly to this problem looking for new implementative solutions and writing a new software. In fact now we are able to obtain full reconstruction with picture dimension about: 3000x4000 in less than 100 seconds; in the past we took hours. So we have reduced timing with an important scale factor and that's a really important aspect because we are able to obtain immediately results in the field. We are even certain that in the future will be able to create a real-time application without make any distinction from acquisition and elaboration phase. By the way working at 3000x4000 pixels, most of the times, is not necessary, especially in the field. As you can see from the reconstruction that we have shown previously. In all this case we have used pictures in 855x1287 pixels that's a really good compromise for detailed 3D surfaces and timing. Another heavy aspect regards the construction of the export file discussed in the previous section. That's because when we are going to write in the hard-disk we have always to consider the long time that we take in writing and accessing. But even this phase was been optimized obtaining really good results. In the table below we show you a typical example of acquisition plus elaboration time working at 855x1287 pixels.

	Some months ago	**Now**
Acquisition		
3D processing	18 minutes	7seconds
Export file	90 minutes	7 seconds

6 Archiving

From the point of view of storage, we require to memorize the 4 pictures in RAW format. This coincide with the precision of the machine and it's more accurate than compress data like: JPEG or PNG. Typically a Data Set, saved in RAW format, occupies more less 150 Mbytes, that' s a lot of space but in that way we are able to obtain better result. From the first elaboration process, mentioned in section 4, we are able to obtain other 4 pictures: the gradients, the Aledo and finally the normal (fig. 3b). The normal is quite important because can immediately give us an order dimension for reconstruction kindness and in that sense can be used as an estimator of the quality. In the second elaboration step we compute the 3D surface that can be viewed using the Matlab viewer and saved in a *.mat* file. But for the sharing and dissemination, we can't pretend that every scholar has Matlab installed in his PC. For that reason we use to convert our reconstruction in to particular 3D formats, (like: OBJ, PLY), that can be simply visualized using 3D environments like: Meschlab or 3DViewer and others. This format, at the end, are even supported from 3D printers and that's give us, in a second time, the possibility to have a real 3D gypsum plastic.

7 Influence of the inaccuracy in the field

On other important aspect that we have to consider when we compare 3D techniques reconstruction is the robustness. That is because when we work directly in the field we can find so many *not ideal condition* that can compromise our reconstruction. These can be derived from the surrounded environment or acquisition as well. In that sense, one of the most critical aspect, is represented by the fact that during the data acquisition we don't use uniform lights. That, in more cases, leads to 3D *convex* reconstruction but it doesn't involve engravings or other particulars contained in the stones. This phenomenon makes Photometric Stereo unsuitable for all-around 3D reconstruction surfaces but extremely indicated for low-reliefs and engravings. Anyway, our team, nowadays is studying a methodology to delete the convex effect from the surfaces. The idea it's very simple, we look for the distortion form, induced by not ideal lights, using image processing technique and we try to subtract it from the 3D reconstruction. This operation give us the possibility to stretch surfaces as you can see in *figure 7.1* and that partially allows us to an immediately second result. In fact in this paper we have been speaking about 3D reconstruction surfaces but furthermore what we want to obtain is the line or the draw that can be directly extrapolate from the stretched surface (we use to call this procedure *"water felling")*. Obviously if we were able to stretch perfectly the surfaces we could approach very closely to water felling results. We are still working in that sense and we hope for better results in the future.

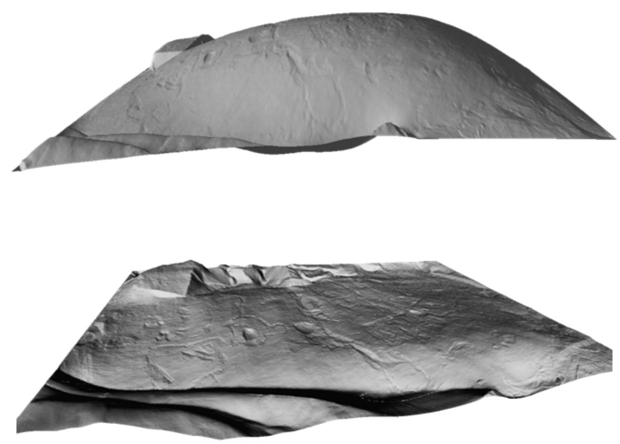

fig. 7.1

Conclusion

This paper report the results regards developments and experimentations of 3D Photometric Stereo technique and software's in archaeological field. Our approach don't want to be an a substitution of others like: laser scanning or Multi View. That's because it's a perfect technique for engraving and rifles but it doesn't work for all-around object. In that sense we are working to build an hybrid application in which both methodologies, Multi View and Photometric Stereo, are used to reconstruct 3D shapes of all around objects. For instance if we want to reconstruct a statue, we are going to repeat the acquisition process several times all around the object. So using Photometric Stereo for each acquisition point we are able to estimate a 3D model that we are going to mesh with the other reconstruction, obtained in other points, using Multi Views techniques. By the way one of the positive aspect is that with Photometric Stereo we are able to obtain surfaces with colour separation that takes realistic reconstruction. If we add even the aspect of cheapness, portability and quick acquisition and elaboration time, we lead us to prefer this technique.

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