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# Recent improvements in photometric stereo for rock art 3D imaging

R. Dessì [a], C. Mannu [a], G. Rodriguez [b,*], G. Tanda [c], M. Vanzi [a]

[a] Department of Electrical and Electronic Engineering, University of Cagliari, Piazza d'Armi 1, 09123 Cagliari, Italy
[b] Department of Mathematics and Computer Science, University of Cagliari, viale Merello 92, 09123 Cagliari, Italy
[c] Department of Archaeological and Historical-Artistic Sciences, University of Cagliari, Piazza Arsenale 1, 09124 Cagliari, Italy

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ABSTRACT

Recent improvements in photometric stereo (PS) are shown to remove the major limitations of this low-cost 3D recording technique. In particular, there are significant improvements in lighting constraints, processing time and presence of deformation in reconstructed surfaces, allowing for fast and accurate restoration of shape and color information. The shooting technique is sufficiently easy to make PS ideal for ancient rock art, which is generally encountered in difficult to access sites, where many of the rock engravings to survey are often placed in a narrow space. This paper focuses on the Sardinia neolithic tombs known as Domus de Janas, as they offer an opportunity to demonstrate the applicability of PS to general rock art.



## 1. Introduction

The role of 3D techniques in rock art documentation is crucial for several reasons. On one hand, the findings are frequently located in difficult to access positions and current protocols exclude any physical contact for creating replicas. On the other hand, the nature of rock art itself calls for 3D reconstruction: the handcrafts are small volume details engraved or sculptured out of wide natural surfaces, often corroded by millenary exposition to weather agents and coated with patinas.

Ordinary photography often requires several shots under different light conditions, in order to reveal all the details of a decorated surface. A contact-less accurate 3D recording is then an ideal solution: virtual reconstruction of the sole shape allows for removal of surface texture and for interactively applying virtual lights, even from directions impossible on site because of existing obstructions.

The difficulty to access many sites and the number of items to be documented, often as large as several thousand in the same site, makes many popular 3D-recording techniques impractical. Laser scanning hardly applies, because it requires a long acquisition time, not to mention the large cost of the instrumentation.

In this paper we go back to a technique as old as photometric stereo (PS) (Woodham, 1980). It is a photographic method that uses a fixed camera and a movable light to acquire a set of images that are proven to embed shape and color (albedo) information of the framed object (Christensen and Shapiro, 1994). The principles are clearly described in the quoted seminal paper, but practical PS never achieved large popularity because of severe limitations. The ideal PS requires some lights oriented along known directions, with uniform intensity and low divergence (Barsky and Petrou, 2003). Any deviation from these constraints results in a poor reconstruction, often affected by distortion, and in an incomplete separation of the shape from the albedo.

A theoretical significant improvement has been achieved in 2006 (Chen and Chen, 2006); see also Basri and Jacobs (2007) which proposes a different approach based on the decomposition of the light intensity, as a function of direction, into linear combinations of spherical harmonics. The target of these new methods is to release the need for accurate location of the light directions, aiming at obtaining this information from the available set of images. This opens the possibility of freehand lighting, removing the requirement for accurate positioning of lamps, one of the most difficult issues in practical PS.

Despite this improvement, other intrinsic limitations typical of PS remain, e.g., the distortion for the steepest parts of the recorded object and the presence of casted shadows, which introduce blind regions in the reconstructed surface. A reduction of the computational complexity is also crucial: a processing time excessively long may lead to the impossibility of processing data during field acquisition, with the result that any shooting mistakes are revealed possibly hours later, when the site has been abandoned.

Another important limitation is the general assumption that the object surface is *Lambertian*; see Eq. (3.1) in Section 3. No real object satisfies exactly this hypothesis, and the presence of a small specular component in the reflectivity of the surface material can distort the direction of the normal vectors. This is a problem

* Corresponding author.
*E-mail addresses:* richidessi@gmail.com (R. Dessì), ca.mannu@gmail.com (C. Mannu), rodriguez@unica.it (G. Rodriguez), gtanda@unica.it (G. Tanda), vanzi@diee.unica.it (M. Vanzi).

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typical in the use of PS, which cannot be easily removed, but during our field experience it did not cause an evident distortion in the reconstructions, at least in rock art documentation; see the images in Section 5. We believe that one of the keys to this self-correction is the redundancy of information used by our algorithm, that is, the fact that we use a larger number of pictures than strictly required for the problem to be mathematically solvable. This issue is discussed in Section 3.

Nevertheless, the features of PS suggest various potential benefits for rock art, e.g., the possibility to document any site in full 3D and color by a simple commercial camera, a tripod, and a hand-positioned flash, even under direct sunlight and in restricted locations (Mannu, 2014). Not less important, the cost of the instrumentation allows for simultaneous operation on different figures by a team of researchers, without technical training.

Moreover, PS can be a highly effective tool in other situations. For instance, the volumetric reconstruction of a complex site could be managed by multi-view methods (Dyer, 2001; Slabaugh et al., 2001), leaving PS for details. Color analysis and enhancement are also important, e.g., for mixed engraved and painted sites. Here PS can provide the unique possibility to operate on the pure albedo, completely removing the shading.

Among the most recent image processing techniques applied in Archaeology, it is important to mention the ones based on polynomial texture mapping coupled to reflectance transformation imaging (PTM/RTI methods) introduced in Malzbender (2001). Some applications to rock art and to other fields of Archaeology are discussed in Duffy (2013), Earl et al. (2010) and Mudge et al. (2006). We also mention a recent study of PS with punctiform light sources, involving the solution of a system of quasi-linear partial differential equations (Mecca et al., 2014).

This paper offers a contribution to the development of effective PS techniques, and illustrates some of its improvements. In particular, computing time is reduced to minutes at full resolution, without compromising the accuracy of the computation, with the intent of making it possible to process field data in near real-time, directly on site. Moreover, the systematic use of redundant data sets by a least squares approach, coupled to a specific post processing procedure (Dessì, 2014), leads to removal or reduction of distortions. Finally, the use of a suitable computational scheme for the final integration process produces an approximation error which decreases proportionally to the square of the physical size of a pixel. Our future intent is to reach complete hands-free lighting operation, with the possibility to perform real-time 3D processing on site. Our main experimental environment consists of the decorations in the *Domus de Janas*, Neolithic tombs typical of Sardinia, Italy.

The paper is organized as follows. Section 2 describes our work from the point of view of the Archaeologist, i.e., the relevance of the tombs, their peculiarities, the challenges posed by their location, and the difficulty in restoring the details of their decorations. Section 3 introduces the mathematical setting, accounting for the computational techniques that led to a substantial improvement in the performance of PS. Practical photographic issues are addressed in Section 4, while results obtained by processing both synthetic and real data sets are illustrated in Section 5. Finally, Section 6 discusses future developments of our research.

## 2. Sardinia Domus de Janas

Domus de Janas are prehistoric tombs, diffused in the whole Mediterranean area, dating back to the Neolithic up to the Bronze age. In Sardinia (Italy) they assume that fascinating name that means “fairy-houses”, because of their similarity to habitations on a smaller scale. They have been studied scientifically since the second half of the last century (Lilliu, 1967).

The past few decades have seen a growing interest on palaeoethnologic studies, focused on 212 Domus characterized by engraved, sculptured and, in few cases, painted decorations.

At the same time, digital 3D imaging technology has gained increasing relevance for Archaeology, leading to various attempt to apply such techniques to the mapping of Sardinia prehistoric tombs. This was the prompt for a critical re-consideration of the previous studies, looking for a wider perspective of the whole set of the available material, with reference to the cultural frames of the mid-western Mediterranean area. In the specific case of Sardinia Domus de Janas, the basic strategy deals with four different scopes:

- The Domus de Janas themselves, in their structural, functional, architectural, environmental, decorative, cult-related aspects, and in the outfit materials possibly found.
- The surrounding anthropic landscape, with the archaeological sources contemporary to the necropolis and, in particular, the inhabited places.
- The reconstruction of the society of the IV–III millennia B.C., with its articulation of lifestyle and economy.
- The sign function of the hypogeal art, with a deeper semeiologic and anthropologic analysis of the meaning of the signs, in order to achieve their decoding and understanding.

Within this framework, we started to develop a 3D methodology with the aim of constructing a tool for the survey of engravings and bas-relieves, that combines a sufficient accuracy in the reconstructions, as well as the capability to deal with high resolution images by real-time computations, to ease of use. The end target is to propose an innovative way for individuating, verifying, and witnessing engraved figurative themes.

This approach has been particularly useful for developing a method of technological characterization specifically designed to catalogue the art motifs found in the necropolis named “Sos Furrighesos” in Anela (Sardinia). Our procedure fulfilled the requirement of considering engravings as cultural data in full, i.e., as elements of a concrete and specific physiognomy, that can be precisely and certainly defined because of their characteristics and peculiar treats (Tanda, 1984, p. 15–21). Such a method sets itself against the exclusively typological characterization, which uses subjective parameters, thus reaching a subjective description and interpretation.

Part of our current on-site activity consists of documenting 52 Domus de Janas. The technological characterization, followed by a typological analysis, is expected to lead to an objective interpretation of the findings, and to a contribution in the reconstruction of the operational chain of engraving arts in the hypogeal sites. In particular, the new studies should help in identifying the engraving tools and clarifying some open questions, such as the preparation of the walls, the allocation of figures in space depending on their relevance and emphasis, the partial reuse of existing figures, and the execution of superimposed schemes.

## 3. The computational procedure

In this section we describe the data processing stage, that is, how to pass from a set of images of an observed object, to its 3D reconstruction.

Let us assume that $q$ digital images are available, each obtained setting the light source in a different direction $\ell_j, j = 1, 2, \ldots, q$. As it is customary, we order the pixels of each image lexicographically, i.