heritage

MDPI

Article

Application of Reflectance Transformation Imaging to Experimental Archaeology Studies

Silvia Florindi [1,†], Anna Revedin [1,†], Biancamaria Aranguren [2,†] and Vincenzo Palleschi [3,*,†]

1 Istituto Italiano di Preistoria e Protostoria, 50121 Firenze, Italy; silvia.florindi@iipp.it (S.F.); annarevedin@iipp.it (A.R.)
2 Soprintendenza Archeologia Belle Arti e Paesaggio di Siena, Grosseto e Arezzo, (retired), 53100 Siena, Italy; arangurenb@yahoo.it
3 Institute of Chemistry of Organometallic Compounds, CNR, 56124 Pisa, Italy
* Correspondence: vincenzo.palleschi@cnr.it; Tel.: +39-050-315-2224
† These authors contributed equally to this work.

Received: 5 October 2020; Accepted: 30 October 2020; Published: 31 October 2020

check for updates

Abstract: In this work, we present a study on experimental archaeology replicas of 170,000-year-old digging sticks excavated in 2012 in the archaeological site of Poggetti Vecchi (Grosseto, Italy). One of the techniques used for documenting and studying the sticks was the reflectance transformation imaging (RTI) technique, which allows the creation of an interactive image by varying the angle of illumination. A reconstruction of the 3D profile of the surface was also made by applying the technique of photometric stereo imaging to the RTI images.

Keywords: experimental archaeology; digging sticks; Middle Paleolithic; Neanderthal; reflectance transformation imaging; photometric stereo imaging

1. Introduction

The recovery of perishable material from Paleolithic contexts is particularly rare in Western Europe because of the easy degradation in the relatively temperate climate that characterizes this region. Therefore, the discovery of several wooden tools, found in the Middle Paleolithic site of Poggetti Vecchi (Grosseto, Italy) [1], has spurred a great interest. In 2012, during the works for the realization of a thermal pool, several archaeological findings came to the light (see Figure 1).

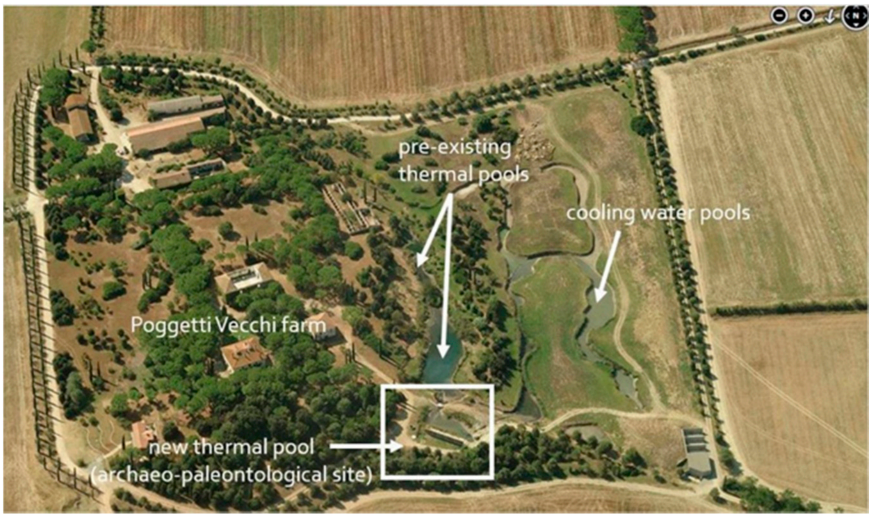


Figure 1. The site of Poggetti Vecchi, Grosseto, Italy.

The prompt intervention of the archaeologists of the Soprintendenza Archeologia Belle Arti e Paesaggio di Siena, Grosseto e Arezzo, led by Gabriella Poggesi and Biancamaria Aranguren, evidenced a complex stratigraphic sequence; in the oldest stratigraphic unit (U 2), the archaeologists found the remains of *Palaeoloxodon antiquus* (an extinct elephant species), as well as several objects in stone, bone and wood [2] (see Figure 2).

Figure 2. The digging sticks (pointed by the red arrows) and the remains of *Palaeoloxodon antiquus.*

In the overlying stratigraphic unit (U 4), geological and organic remains were dated to around 170 ky from present, giving a limit *ante quem* for the chronology of the underlying findings. Among them, more than 50 wooden fragments, of size ranging from 10 cm to 1 m, were recovered. The recovery of such kind of organic material (which, because of its intrinsic perishability, is said to constitute the "missing majority" of the archaeological findings), including several almost intact "digging sticks", was exceptionally important. Manufacts of comparable importance are very rare, including the wooden spears discovered in the archaeological site of Schöningen (Germany), dating about 400 ky from present, and the ones found in the site of Lehringen (Germany, 110–130 ky) and Clacton-on-Sea (England, abt. 350 ky). Part of what is interpreted as a digging stick was found in the site of Aranbaltza (Spain) [3]. This latter manufact shows an evident deformation, due to the conservation processes applied, so that the only way of possibly inferring the original shape of the manufact is from the photographs acquired at the time of the recovery.

The unfortunate fate of the Aranbaltza digging stick fragment evidences the need for developing instruments and methodologies for an accurate documentation of the artefacts which must have the capability of operating quickly in situ, minimizing any contact with the object. In that respect, photogrammetric techniques seem to be the favorite tools for this task [4]. However, it should be noted that the flexibility of conventional photogrammetry techniques, allowing to acquire the 3D model of the object from photographs taken at arbitrary distances and angles with respect to the object, is paid by the need for reconstruction algorithms to infer both the 3D model of the surface and the position and angle of the camera at the moment of the shot. The unavoidable indeterminations resulting from the application of these algorithms might hinder some fine details of the object's surface, which are critical for studies aimed to find tool marks and signs deriving from use.

In that respect, a fixed geometry acquisition, as used in several approaches based on the application of reflectance transformation imaging (RTI) [5], might be preferrable to other more conventional photogrammetric techniques. RTI is a technique widely used for documentation of archaeological and cultural heritage objects [6,7]; contrarily to conventional photogrammetry, the acquisition of the set of images needed for the object's surface reconstruction is acquired keeping the camera fixed and varying the direction of the illumination.

The RTI technique was developed about 20 years ago by Malzbender et al. [8] for the reconstruction of polynomial texture maps (PTM) of a sample's surface. The RTI technique is usually applied following two possible strategies. In both variations of the technique, the position of the camera is maintained fixed, and the angle of illumination is varied, to obtain different photographs that are then elaborated to obtain the surface profile of the object under study. The differences between the two methods rely on the illumination strategy. In one case, the position of the lights is fixed in a definite pre-determined scheme, while in the second—as in standard photogrammetry for the position of the camera—the lighting is varied with some degree of freedom, and the illumination geometry is determined at the time of acquisition (highlights method). This latter approach has been discussed in detail in a recent paper by Antonio Cosentino [9]. Due to its intrinsic simplicity and portability, the RTI technique has been widely used in cultural heritage and archaeology applications. An extensive review on archaeological applications has been recently published by Mytum and Peterson [10].

One of the main disadvantages of the RTI technique is the fact that, by this technique alone, the surface reconstruction is only qualitative, and no metric information can be recovered. However, the set of images acquired for PTM reconstruction by RTI can be further elaborated, using photometric stereo imaging (PSI) algorithms [11,12].

The application of the PTM/RTI technique to organic material has allowed for recovering tiny marks and butchery traces in bone and antler objects [7] and to study wooden statuettes and icons [13,14]. Earl et al. [5] successfully applied RTI to the reconstruction of wooden legal tablets burned in the Mount Vesuvius eruption that destroyed Pompei in 79 A.D. Finally, in a work particularly relevant to the issues studied in this paper, Karsten and Earl [15] demonstrated the possibility of comparing metrically the surface maps of previously waterlogged timber, acquired at different stages of the conservation process. The authors used a fixed illumination scheme, for improving the resolution of the surface reconstruction.

2. Materials and Methods

Due to the intrinsic fragility of the wooden findings from the Poggetti Vecchi site, the feasibility study on the use of RTI for identifying the tool mark and use wear was performed on faithful replicas of the digging sticks obtained from experimental archaeology (see Figure 3). So far, six experimental sessions were performed, using a specific protocol starting from branches of common boxwood (*Buxus sempervirens*), the same timber used for the original findings, using tools compatible with the Paleolithic technology (stone and animal bone tools and firings) [6]. The sticks found in Poggetti Vecchi, in fact, showed evident traces of intentional firing [16], in order to obtain artifacts with a higher level of finishing, with a completely smooth shaft surface, without raised knots and with rounded handles. The experimental working process was carefully documented, to correlate the working signs remaining on the sticks with the procedures and the tools used for the manufacturing [3,16].

Figure 3. One of the experimental archaeology sticks, with the tools used for manufacturing it.

The experimental archaeology work evidenced that the realization of the sticks required physical strength, time and specific skills; the use of fire for removing the bark and refining the sticks implied having control of the fire, which was used not only for providing light and heat, but also exploited as a tool for manufacturing objects.

The digging sticks replicas were analyzed using conventional photogrammetric techniques and reflectance transformation imaging (RTI), as well as digital microscopy.

RTI was recently used for investigation of wooden artifacts by Abdrabou et al. [13] and Munteanu et al. [14], using the highlight method. In our case, as in [15], the reconstruction of fine details of the surface was of paramount importance. Therefore, the first approach was preferred. The lighting was provided by 46 white LEDs, equally spaced at fixed positions on a 3D-printed semi-spherical dome of 20 cm in diameter (see Figure 4). The photographs were taken with a compact Canon camera (14.1 megapixels) synchronized with the lights through a simple electronic circuit. The acquisition of the whole set of photographs takes about one minute.

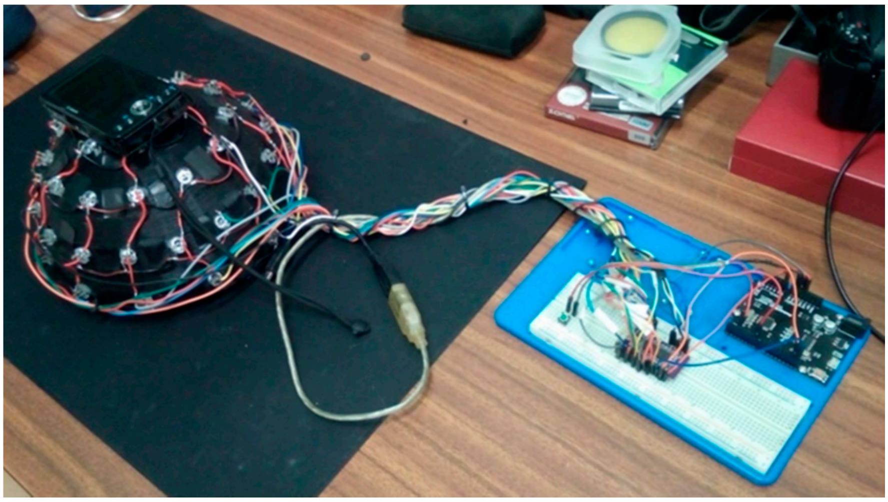


Figure 4. The Reflectance Transformation Imaging (RTI) instrument used in this work.

The RTI interactive images were obtained in a couple of minutes using open source software (RTI Processor). The surface profile was then metrically reconstructed by applying a photometric stereo imaging (PSI) algorithm [11] to the RTI images previously acquired. This method is very powerful, but it involves a complex elaboration of the images which can take several hours, if the original resolution of the images should be maintained. For this reason, it is advisable to use a subset of the original RTI photoset for minimizing the processing time and the numerical errors associated with it. Masking of the object surface against a background is also needed. We wrote a simple Matlab® script, implementing the depth gradient fusion photometric stereo method [17] developed by the VORTEX Team of the IRIT Lab of the University of Toulouse, France [18], to apply these algorithms to the reconstruction of the experimental archaeology replicas of the Poggetti Vecchi digging sticks.

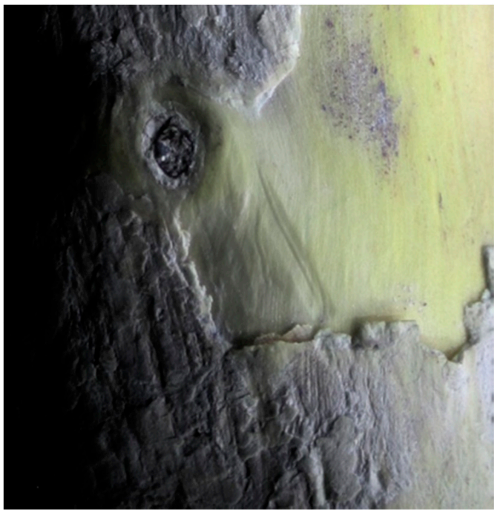
Using a subset of 12 images of the 46 acquired for the RTI reconstruction, the time needed for obtaining the height map of a surface of about 5 cm^2 is around thirty minutes on an average-performance laptop, working at the maximum resolution. Medium-resolution images, useful for a preliminary assessment of the surface profile, can be obtained in less than 5 min.

The results were also compared with the images taken using a digital microscope (DinoLite, 5 Megapixel).

3. Results

In Figure 5, we show the comparison of the digital microscope image and a screenshot of the RTI interactive image, evidencing a tiny scratch on the stick surface. The RTI image covers a length of several cm of the stick; however, the resolution of the image, which is the combination of all 46 images acquired by the instrument, is high enough to allow a magnification comparable to the one of the digital microscope. However, the possibility of interactively varying the illumination angle makes RTI advantageous with respect to digital microscopy, for evidencing details in grazing light that can be hard to detect in the portable microscope image.

(**a**)



(**b**)

Figure 5. (**a**) Digital microscope detail of one of the digging stick replicas; (**b**) screenshot of the RTI interactive image.

The RTI image, although very powerful for documenting at high resolution a relatively large portion of the sample, does not allow for measuring the depth of the surface features, produced by the tool used for manufacturing the stick or by its use. To this purpose, we applied the photometric stereo imaging algorithm to a subset of the RTI images to metrically reconstruct the surface profile.

To this purpose, we first masked the zone of interest in the images (Figure 6).

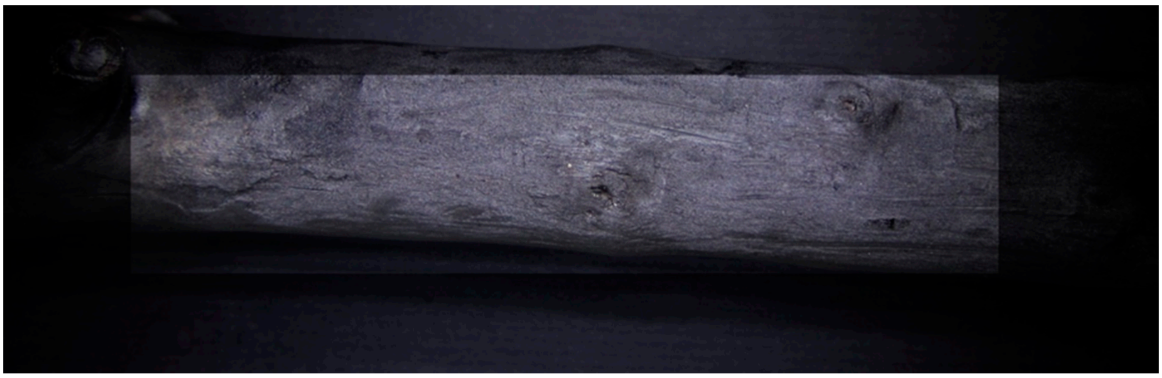


Figure 6. Masking of the region of interest for the application of the Photometric Stereo Imaging (PSI) technique.

Then, the PSI algorithm evaluated the normals of the surface (Figure 7) and, from the integration of the normals, obtained the 3D profile of the surface (Figure 8).

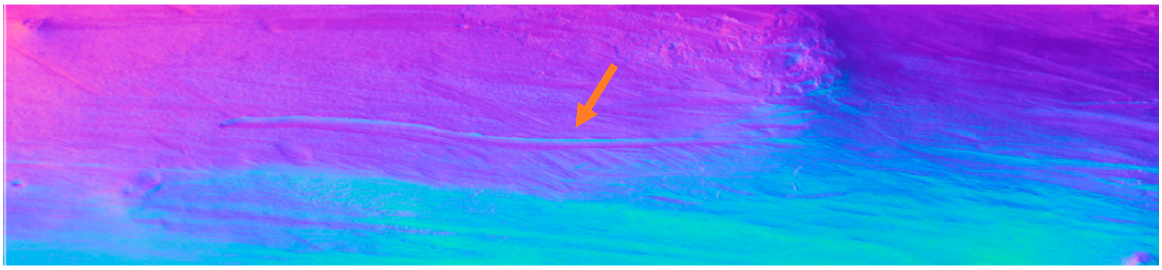


Figure 7. Normals of the surface, obtained from the RTI images. The red arrow identifies the point where the surface scratch depth profile was reconstructed.

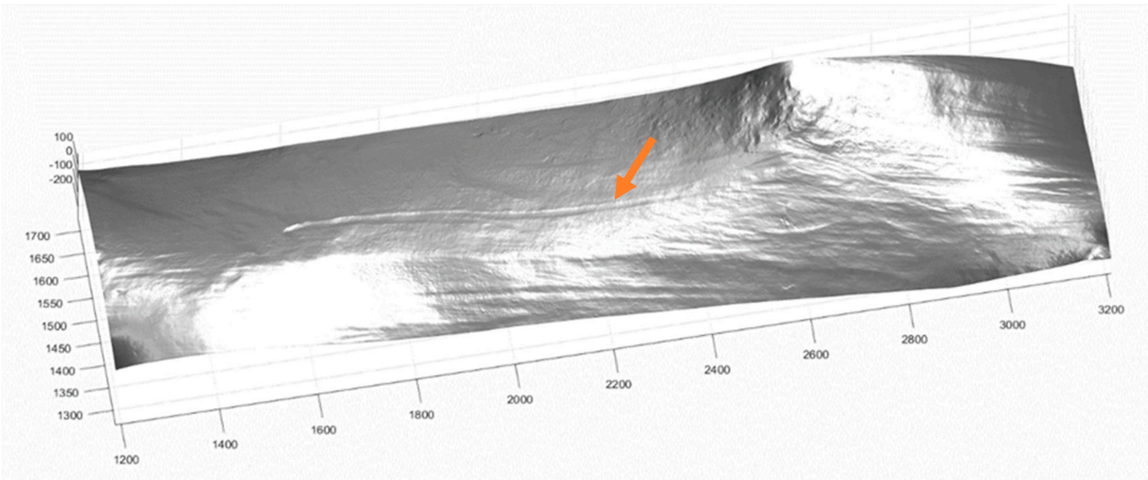


Figure 8. 3D reconstruction of the wood surface. The red arrow identifies the point where the surface scratch depth profile was reconstructed.

From the 3D model shown in Figure 8, we were able to measure the depth of the scratch at the position marked in Figures 7 and 8 with a red arrow. The results are shown in Figure 9.

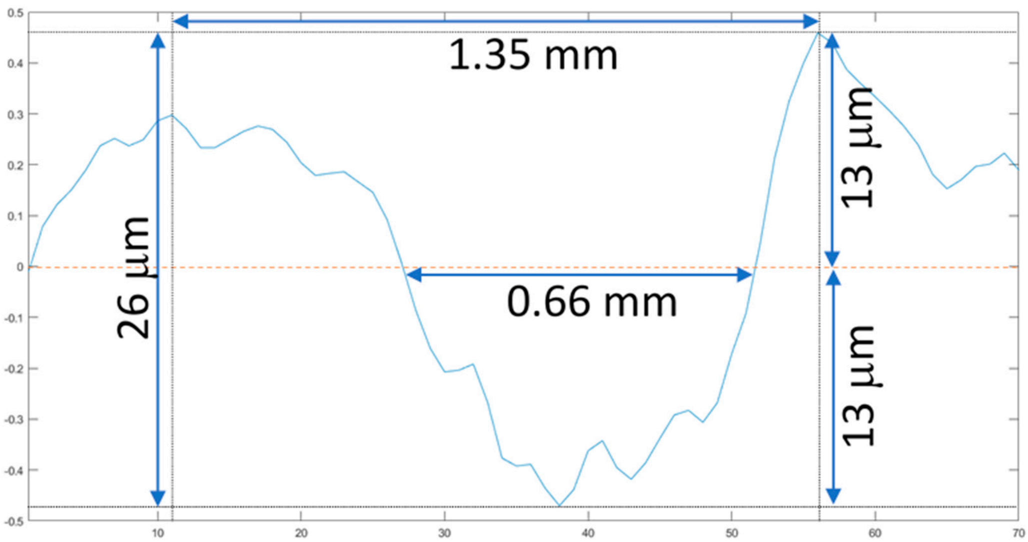


Figure 9. Profilometry of the scratch on the surface of the digging stick replica, obtained from the 3D model of the surface shown in Figure 8.

4. Discussion

The analysis of the RTI image and the reconstruction of the surface profile obtained from PSI allows for making some considerations on the suitability of this approach for the in situ analysis of fragile archaeological items. The RTI instrument realized at the Applied and Laser Spectroscopy Laboratory in Pisa operates without contact on relatively large surfaces, allowing to quickly locate zones of interest that can be visualized with a resolution comparable to that of a digital microscope, at a lower cost. Moreover, the possibility of metrically reconstructing the surface profile exploiting the photometric stereo imaging technique, although quite complex and time-consuming, gives well-resolved depth profiles with a micrometric resolution, which is better than conventional photogrammetry and comparable to much more complex techniques which are not suitable, for cost and dimension of the instrumentation, to be used in the field.

5. Conclusions

The application of RTI to fragile archaeological objects offers a cheap but powerful tool for documentation and study of objects that cannot be easily removed or manipulated. The non-contact nature of the method and the robustness of the instrument, without mobile parts, envisage the possibility of using this system, minimizing the manipulation of the objects, for a quick in situ documentation and assessment, to be eventually studied in greater detail at later times, if needed, using the PSI approach.

Author Contributions: Conceptualization, V.P.; methodology, V.P., S.F., A.R. and B.A.; software, V.P.; validation, V.P., S.F., A.R. and B.A.; formal analysis, V.P., S.F., A.R. and B.A.; investigation, V.P., S.F., A.R. and B.A.; data curation, V.P., S.F.; writing—original draft preparation, V.P.; writing—review and editing, V.P., S.F., A.R. and B.A.; supervision, V.P., A.R. and B.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Italian Institute of Prehistory and Protohistory (IIPP) and is part of the IIPP project "VIWA_P–Visual Imaging for Wooden Artefacts in the Palaeolithic".

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Benvenuti, M.; Bahain, J.J.; Capalbo, C.; Capretti, C.; Ciani, F.; D'Amico, C.; Esu, D.; Giachi, G.; Giuliani, C.; Gliozzi, E.; et al. Paleoenvironmental context of the early Neanderthals of Poggetti Vecchi for the late middle Pleistocene of central Italy. *Quat. Res. (U. S.)* **2017**, *88*, 327–344. [CrossRef]
2. Aranguren, B.; Grimaldi, S.; Benvenuti, M.; Capalbo, C.; Cavanna, F.; Cavulli, F.; Ciani, F.; Comencini, G.; Giuliani, C.; Grandinetti, G.; et al. Poggetti Vecchi (Tuscany, Italy): A late Middle Pleistocene case of human–elephant interaction. *J. Hum. Evol.* **2019**, *133*, 32–60. [CrossRef] [PubMed]
3. Florindi, S. *Arheologia Sperimentale, digital imaging e analisi delle tracce. Un approccio integrato per l'analisi dei digging stick di Poggetti Vecchi (GR)*; University of Pisa: Pisa, Italy, 2019. (In Italian)
4. McCarthy, J. Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. *J. Archaeol. Sci.* **2014**, *43*, 175–185. [CrossRef]
5. Earl, G.; Martinez, K.; Malzbender, T. Archaeological applications of polynomial texture mapping: Analysis, conservation and representation. *J. Archaeol. Sci.* **2010**, *37*, 2040–2050. [CrossRef]
6. Rich, S.A.; Watts, R.; Momber, G. Mesolithic woodworking, experimental archaeology & underwater heritage in Hampshire and the Isle of Wight (UK). *Meseolithic Misc.* **2016**, *24*, 3–12.
7. Newman, S.E. Applications of Reflectance Transformation Imaging (RTI) to the study of bone surface modifications. *J. Archaeol. Sci.* **2015**, *53*, 536–549. [CrossRef]
8. Malzbender, T.; Gelb, D.; Wolters, H. Polynomial texture maps. In *SIGGRAPH '01: Proceedings of the 28th annual conference on Computer graphics and interactive techniques*; Association for Computing Machinery: New York, NY, USA, 2001; pp. 519–528.
9. Cosentino, A. Macro Photography for Reflectance Transformation Imaging: A Practical Guide to the Highlights Method. *e-conservation J.* **2013**, *1*, 70–85. [CrossRef]
10. Mytum, H.; Peterson, J.R. The Application of Reflectance Transformation Imaging (RTI) in Historical Archaeology. *Hist. Archaeol.* **2018**, *52*, 489–503. [CrossRef]

11. Woodham, R.J. Photometric method for determining surface orientation from multiple images. *Opt. Eng.* **1980**, *19*, 191139. [CrossRef]
12. Earl, G.; Beale, G.; Martinez, K.; Pagi, H. Polynomial texture mapping and related imaging technologies for the recording, analysis and presentation of archaeological materials. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2010**, *38*, 218–223.
13. Abdrabou, A.; Abdalla, M.; Shaheen, I.A.; Kamal, H.M. Investigation of an ancient Egyptian polychrome wooden statuette by imaging and spectroscopy. *Int. J. Conserv. Sci.* **2018**, *9*, 39–54.
14. Munteanu, M.; Crina, I.; Sandu, A.; Lupascu, M.M.; Vasilache, V.; Sandu, I. The importance of a complete and modern information gathering protocol in the conservation process of a XVIII-th century icon. *Int. J. Conserv. Sci.* **2016**, *7*, 995–1008.
15. Karsten, A.; Earl, G. HMS Stirling Castle, Kent: The Stirling Castle Wood Recording Project: A pilot study to compare traditional and innovative recording techniques for waterlogged wood: Archaeological conservation report. *English Herit. Res. Reports* **2010**, *65*, 1–40.
16. Aranguren, B.; Revedin, A.; Amico, N.; Cavulli, F.; Giachi, G.; Grimaldi, S.; Macchioni, N.; Santaniello, F. Wooden tools and fire technology in the early Neanderthal site of poggetti vecchi (Italy). *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 2054–2059. [CrossRef] [PubMed]
17. Quéau, Y.; Durou, J.D. Edge-preserving integration of a normal field: Weighted least-squares, TV and L1 approaches. In *Scale Space and Variational Methods in Computer Vision. SSVM 2015*; Springer: Berlin, Germany, 2015; Volume 9087, pp. 576–588.
18. IRIT-ENSEEIHT/VORTEX Photometric Stereo. Available online: http://ubee.enseeiht.fr/photometricstereo/ (accessed on 24 October 2020).