

Monitoring and conservation of archaeological wooden elements from ship wrecks using 3D digital imaging

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Abstract — In marine archaeology, many artifacts made of metallic or organic material are found in different state of conservation depending of the environment in which they are discovered. Once brought to the surface for study or display purposes, the artifacts need to be treated properly otherwise they deteriorate in a short lapse of time. The fragility of organic artifacts and the volumetric variation caused by the marine life on or surrounding them and water lead to the need for measuring the physical dimensions soon after an artifact is extracted from the sea. In an ideal context, it would be appropriate to preserve and restore the archaeological elements rapidly and with the latest methods but due to the large number of artifacts, the cost of complete restoration activities becomes prohibitive for the funding available in public institutions. For this reason, many public laboratories are resorting to digital technologies for documentation, restoration, display and conservation. In this paper, we illustrate the experience of the University of Salento in this area of archaeology using 3D imaging technology. The interest sprang from the need to develop a protocol for documentation and digital restoration of archaeological finds discovered along the coast of Torre S. Sabina (BR) Italy.

Keywords—Marine archaeology, 3d imaging, 3d modeling, metrology, wooden artifacts, underwater

I. THE UNDERWATER SITE IN SANTA SABINA (BR), ITALY

The University of Salento, Italy, has been conducting underwater archaeological work in the bay of Torre Santa Sabina in the Province of Brindisi in Italy since 2007 [1]. The historical reconstruction of the site is based on the large collection of artifacts that was discovered there. Many of which are intact or complete. The reconstruction allows one to conclude that the site was visited and used from the Bronze Age until the Middle Ages. This information resulting from investigations carried out on the site from the 70s until today attests to the full inclusion of the Salento region in the routes, the network of contacts and exchanges in the Mediterranean [2] (see fig.1 for a map). The water depth of the bay of Torre S. Sabina preserved remains of cargo ships and hulls, quarry materials and artefacts resulting from port activity [3, 4]. In the inlet, at least five wrecks have been identified and, in particular, the wreck "Torre S. Sabina 1" see Figure 1- area A is a site of great interest, amongst the best preserved Roman

ship in the Mediterranean region [5]. Its study is decisive for both the historical (shipbuilding, cargo, routes, etc.) and the geo-archaeological aspects. The wreck has wings and seems to have been progressively submerged by a rise of the sea level. Similar considerations apply to the remains of the cargo of boats that through the centuries were shipwrecked along the rocky escarpment (area B), creating a massive deposit of heterogeneous archaeological materials, often in an excellent state of preservation [6, 7].

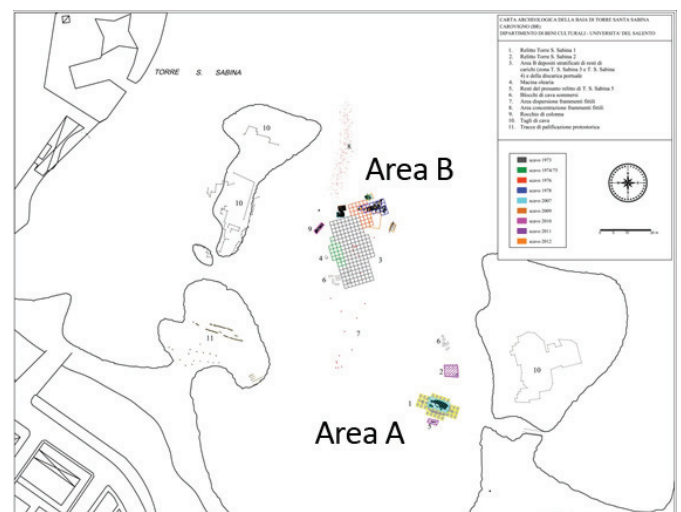


Fig. 1. Map of the underwater site of Torre. S. Sabina (BR), Italy

In area B of the bay, at about 5 m deep, during the excavation of 2012, some fragments of waterlogged wood were found. One of which is particularly interesting and it seems to be the result of intense shipbuilding activities. The element in question, though fragmentary, is 110 cm long, 12 cm wide and on average between 6.5 and 10 cm high. Along the edges of the top face, one can see two rows of mortises, staggered (size 6.7 cm x 1.2 cm), 4-6 cm away from each other, with tenons broken inside them. At mid-length there is a circular through-hole (diameter 1 cm), with the lower end eroded by the *Teredo navalis* (shipworms). A wooden peg is visible at one end of the element and has a diameter similar to the hole described. At

approximately 3 cm from this object, the concretion of the head of a round nail appears.

As a hypothesis, one could identify the piece with an element of the axial carpentry, maybe a section of the keel, straight, bow stem or sternpost. The almost vertical orientation of the mortises and the small size of the wood is a particularity of the artefact. Radiocarbon dating performed by CEDAD (Centre for Dating and Diagnostics) at the University of Salento estimated a chronological window of 510-350 BCE (with a probability of 65.4%) and 300-200 BCE (with a 20.8% probability).

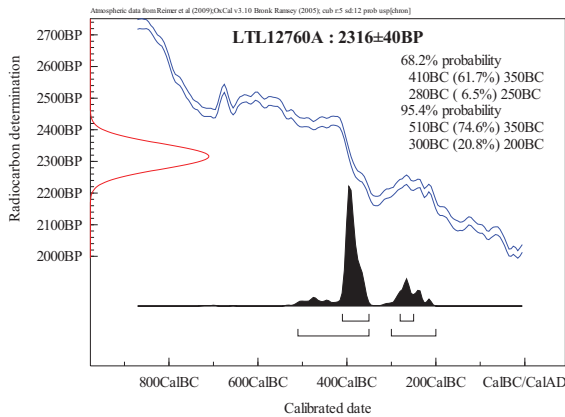


Fig. 2. Graph representing the calibration of the conventional radiocarbon dating of the sample from Torre Santa Sabina.

The xilatomic analysis carried out with the collaboration of the Chair of Materials and Technologies for Restoration of the University of Salento allowed establishing that the waterlogged wood is of “*Quercus Ilex*” (Holm Oak)¹. The artefact, recovered from the sea, is currently in a process of desalination at the restoration laboratory of the Department of Cultural Heritage of the same University. In order to better preserve its morphological features from the very moment of its recovery from the sea, the artifact along with other fragments of smaller sizes have been immersed in fresh water inside a special tank. The fresh water is changed on a regular basis.

In this paper, the experiments performed by the University of Salento in this area of archaeology using 3D imaging technology is illustrated with two small artefacts taken from an actual shipwreck. These experiments with 3D imaging stem from the need to develop a protocol for 3D documentation and also to test digital restoration techniques of waterlogged wood.

Section II explains the motivation for using 3D imaging for preservation and restoration. Section III presents the 3D survey methodology used. It is followed by a discussion on the advantages of 3D ‘metric’ imaging for marine archaeology and of determining the time frame within which one can operate out of water without the artifact suffering significant

¹ The analyses were carried out as part of a specific thesis assigned to Mr. Marco Colazzo by Dr. Maria Enrica Frigione on "Characterization and study of the degradation of the wooden objects from underwater findings".

morphological changes. Some concluding remarks complete this paper.

II. THREE-DIMENSIONAL SURVEY FOR PRESERVATION AND PHYSICAL RESTORATION OF WATERLOGGED WOOD

The archaeological elements of organic nature that have been submerged for a long time have survived only thanks to the special underwater anoxic environment and hence the waterlogged wood has not deteriorated since it was immediately covered by sediment. They remained in this condition until the archaeological excavation took place. The tunneling created by shipworms found into the artefacts assumes short periods of exposure of the wood to the attack of xylophagous animals [8].

The wooden specimens, once recovered from the sea, in the absence of appropriate conservation and restoration operations would face their natural deterioration caused by desiccation, bacterial and fungal decay, and wood boring organisms [9, 10, 11, 12]. Even after a first consolidation treatment they still require a frequent and continuous monitoring before their final consolidation, i.e., reinforcement or stabilisation of wooden artefacts. The techniques of wood restoration are expensive and usually irreversible. Therefore, they do not always yield the best results [13]. We considered necessary, in this case, to record and document the size of the organic specimens at the "time" of their recovery using 3D digital imaging technology.

III. 3D SURVEY: METHODOLOGY AND ANALYSIS OF THE ACQUIRED DATA

Three-dimensional (3D) digital technology applied to the restoration of wooden cultural heritage artefacts is not a new practice [14, 15] and even its application to relics found in an underwater excavation [16, 17]. Laser scanners have been used on several occasions to monitor changes of waterlogged materials before and after a treatment [18, 19, 20]. In our case, however, it was necessary to prepare a protocol to be applied to materials which would immediately be restored. The 3D acquisition of the artefact, for obvious logistical reasons, was carried out at the Laboratory of Applied Science Archaeology. In order to proceed with the 3D scans, the water was first drained and the wood was left resting on the perforated base of the washing tank. A Minolta® Vivid 900 from the 3D Laboratory of SIBA of the same University was used for the laser scans [21].

The wood was extracted from the water at around 10 o'clock in the morning. After a series of preliminary scans to determine the optimal distance from the work piece and the required resolution, we proceeded to the digitization. This phase was alternated with the pre-alignment, each time, of a series of 3D images captured. The operations lasted until 19:20, after which the artefact was again put back into water.

In the following days, first in the alignment phase and later in the modeling phase (merging and final mesh creation), the presence in the 3D model of particularly “noisy” points and in some areas of the presence of ‘double surfaces’ indicated that the artefact had suffered dimensional changes throughout the

day, revealing a general shrinkage but also a bulging in certain areas.



Fig. 3. Minolta ® Vivid 900 from the 3D Laboratory of SIBA of the University of Salento that was used for the 3D laser scans.

Four tests were carried out (two on small areas and two on the entire artefact) to verify the extent of the dimensional variations. But considering the size of the piece and since each side was scanned at different times over a period of about 2 hours, the changes were progressive and the results did not give a clear answer, just a general shrinkage and bulging in certain areas. On average, the deformation varied by a few mm (see fig. 4).

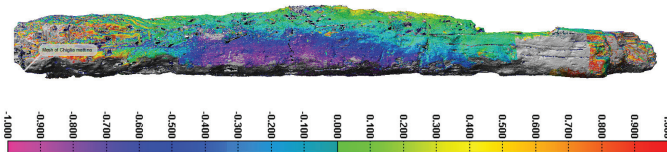


Fig. 4. Colour coding showing the dimensional variations between morning and afternoon.

To determine with certainty whether the dimensional changes were caused by the progressive desiccation of the artefact or by a mechanical cause e.g. the handling or crushing of the wood under its own weight, we have decided to carry out tests on a smaller sample (approx. 15 cm. in length) that detached from the rest of the main artefact of interest. The tests were carried out this time at the 3D Laboratory of SIBA. The creation of the 3D models of the sample was performed with a 3D laser scanner from ShapeGrabber ® [22] (configuration AI300 + SG102). This scanner is suitable for high-resolution acquisitions of small objects. This scanner is equipped with a rotating base which allows 3D scans all around individual artefacts in a completely automatic way. This, in turns, minimizes the time in handling these fragile artefacts. The structure resolution (as per VDI/VDE 2617.6.1) is as follows, lateral position resolution was set at 0.1 mm (depends on laser line width and imaging CCD subsystem; *diameter of a human hair is about 0.08 mm*) and the axial resolution which depends on the signal-to-noise ratio and laser penetration is about 0.01 mm on a cooperative surface but because of the darker material and the presence of water, it was estimated at about 0.08 mm. The rotation base has an angular resolution in the micro-radian range. InnovMetric Polyworks ® Modeler and Inspector were

used for 3D image alignment, modeling and data verification [23].

The test sample was weighed at the beginning and at the end of the tests. Its weight was 848 g and that just when it was extracted from the water tank and drained for excess water. It was positioned on a support built *ad hoc*. It consists of metallic scaffolding that crossed it in four points. The artefact also rested on a metal object of known size (Fig. 5). On the first day, five series of scans, at intervals of two hours were performed. Each series consisted of 12 individual scans in automatic mode with a rotation of the base by 28 degrees. In the following days, two scans at an interval of approximately 6 hours were performed. Temperature (range of 4.9°C) and relative humidity (range of 12%) were constantly monitored but not controlled.



Fig. 5. Test sample positioned on top of a control object (see below test sample) and on a rotating stage to automate the 3D scan acquisition phase.

The test was concluded after eight days from the start day. The test sample was still wet and weighed now only 264 g. Over a period of 7.5 hours during the first day, the dimensional variations have been fairly uniform.

	Scan#	Temperature(C)	Relative humidity
Day 1	Scan_01 (h. 10.30-11.10)	25.5°	46%
	Scan_02 (h. 12.30-13.10)	25.5°-25.6°	49-51%
	Scan_03 (h. 14.30-15.10)	25.9°	52%
	Scan_04 (h. 16.30-17.10)	26.3°	50%
	Scan_05 (h. 17.45-18.25)	26.3°	50%
Day 2	Scan_06 (h. 9.10-9.50)	25.4°-25.6°	51-47%
	Scan_09 (h. 14.25-15.05)	26.1°-26.2°	41%
Day 3	Scan_10 (h. 9.15-11.00)	22.5°-22.8°	49-48%
	Scan_11 (h. 16.10-16.45)	26.9°	40%
Day 4	Scan_12 (h. 9.10-9.45)	26°	51%
	Scan_13 (h. 13.18-13.45)	26.5°	51%
Days 5-6	Saturday and Sunday – no scans performed	---	---
Day 7	Scan_14 (h. 9.10-9.50)	26.3°	50%
	Scan_15 (h. 15.35-16.15)	27.4°	46%
Day 8	Scan_16 (h. 9.20-10.00)	26.8°	48%

The alignment of the 3D images related to the first series of scans gave typically double bell or bimodal histograms (see Fig. 6). The test sample was probably still too saturated with water or it has suffered a shock when it was removed straight out of the water tank. The alignment of successive scans has instead given near symmetrical bell-shaped histograms (see Fig. 7).

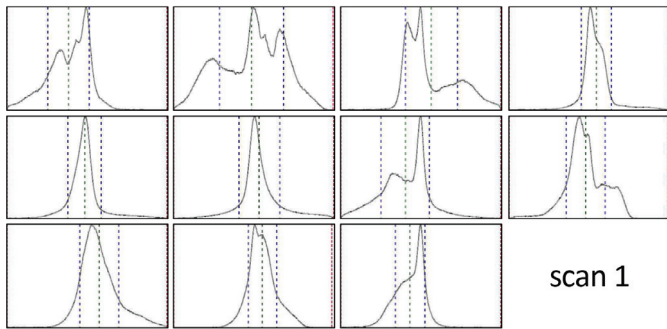


Fig. 6. Histograms after the alignment of the 3D images from the first series of scans (day 1).

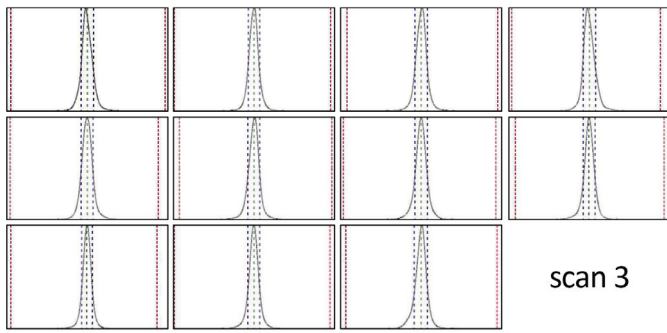


Fig. 7. Histograms after the third alignment of the 3D images (day 1).

The difference between the first and the second overlapping scans is approximately -0.1 mm on the whole surface except for some points. For example the difference is positive (0.1 mm) where the wood had a crack that gradually enlarged. It is interesting to note that the fracture started to accentuate right away. More or less the same values were recorded between scans 2 and 3, 3 and 4, 4 and 5 of the same day.

In total, during the first day of scans, the average dimensional variations that the test sample has suffered (comparison between the first and fifth series of scans) amounted to about -0.6 mm. In some points instead, where they were already clear fractures present, the test sample had positive displacements (see fig. 8 and fig. 9). These values are consistent with those seen on the larger waterlogged wooden relic and confirmed that in a day, due to the evaporation of water, there was a general decrease in volume, although modest (-0.6 mm) in the proximity to the deep fractures.

Instead, there has been a progressive "detachment" of a portion of the test sample from its original position by about 2 to 5 mm.

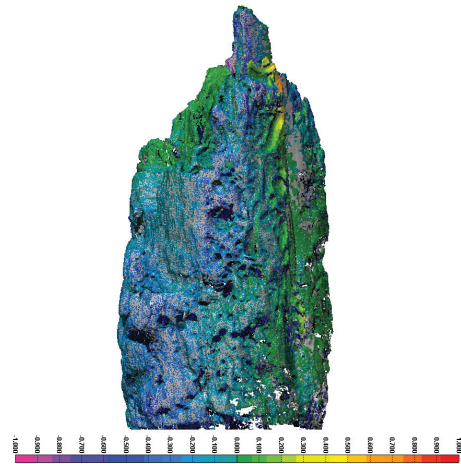


Fig. 8. Colour coding of the dimensional variations between the start and the end of the day mapped onto the 3D model (from the morning). Scale +/-1 mm.

The changes that occurred in the following days instead were much greater. It was not possible to use software for mechanical control like those specialized for Geometrical, Dimensional Tolerancing (GD&T) because the artefact is not a CAD model. It is a freeform object and the distortions are subjected to internal forces within the object that are not isotropic.

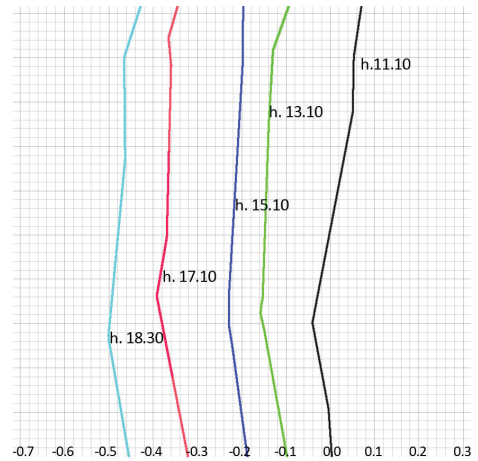


Fig. 9. Dimensional variations on some profiles acquired during the whole day. (Timestamp indicated).

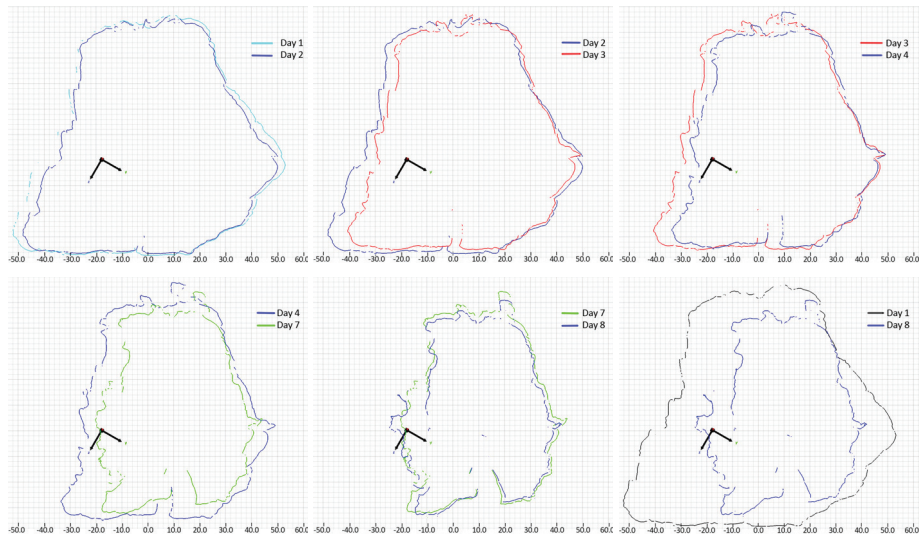


Fig. 10. Typical dimensional variations that took place over a period of 8 days. (Typical sections were used here to illustrate the changes).

IV. DISCUSSION

The application of 3D technology to underwater wooden artefacts has proved to be very useful. The advantages of the digital surveys using 3D laser scanners are well known in the context of various disciplines like mechanical engineering and also archaeology. A digital 3D model not only facilitates the detailed study of the artefacts apart from being non-contact, but it also offers innovative analysis tools ranging from the possibility to zoom in on the model to examine and measure tiny surface details or to detect traces left by tool marks, understand woodworking, to the possibility of creating sectional views on the object without destroying it. The technology also ensures the reproducibility of the same physical archaeological artefact through the use of rapid prototyping technologies aimed at museum displays. Together, rapid prototyping and 3D digital models offer the unique opportunity to study remotely the artefact and enjoy it virtually.

With regard to the specimens from the boat of S. Sabina, the operation has allowed us to confirm the progressive decrease in the volume of wood extracted from the water, something which is already known but it has allowed us to determine the time frame within which one can operate out of the water without the artefact suffering significant morphological changes. This is useful for example to schedule a 3D survey and a restoration. Thanks to this work, we are in a better position to start defining a protocol to follow for all waterlogged wooden artefacts that need to be documented and restored. The restoration will be carried out after a complete 3D survey at a very high resolution has been done. The resolution is critical because one needs to measure in detail the surface of the artefact. In the scanning process, a verification tool/object of known size will always be added in the field of view near the artefact. The consolidated specimens will be resubmitted to a 3D scan to monitor changes in form and size as a result of consolidating treatment performed. The specimen will be measured in 3D with the same tool and in the same manner as before restoration. In reality, any restored pieces should be the

subject of a periodic digital 3D survey to confirm the success of the restoration.

During the experiments with our 3D imaging equipment, we were confronted with the fact that rapid scanning and modelling were hindered by the absence of flow through between hardware and software. The equipment was indeed designed for general purpose tasks. In the present situation, a scanning system where the scan head is fully integrated with the modelling software would be desirable. Real-time acquisition, data cleaning, mesh generation and visualisation, as 3D data is gathered, would have reduced our task by a large factor. From our evaluation, the latest commercial 3D imaging systems can reduce the scanning and model generation time by about a factor of five with respect to our current technology. Future projects will consider acquiring such type of equipment.

At the moment, we have already realized the 3D reference models of three small waterlogged wooden artefacts belonging to a similar wreck, i.e., two pulleys and one ring. These other artefacts serve to further test a protocol. This protocol once completed will be applied to larger projects. As noted by many authors, 3D imaging does not provide a complete picture. The examination of artefacts should be done by a wood specialist. Therefore, 3D imaging should not be seen as a replacement to the conservation and curation of wooden artefacts [24, 25, 26, 27].

V. CONCLUSIONS

The UNESCO Convention 2001 (Law 157/2009) states that for the protection of underwater cultural heritage, the *in situ* conservation should be considered as the first option for protection. As for the organic artefacts, however, *in situ* conservation is not compatible with the protection and enjoyment of the property. For this reason it is very important, before embarking on the twisty roads of expensive restorations, to meticulously measure the size and the characteristics of

artifacts from the sea. The experience of conservation and restoration on the artefacts from the excavations of the Chair of Underwater Archaeology and experience of the SIBA 3D Lab of the University of Salento has placed us in the position of having to find solutions in parallel to the physical restoration of waterlogged artefacts. The solution identified for the virtual restoration has determined the chance to experience new fields of application of 3D laser surveys and 3D processing. This has opened up the possibility of extending the virtual restoration to new forms of dimensional analysis and to ensure remote fruition of the artefacts.

Digital modelling using 3D imaging technology (e.g. 3D laser scanners for the acquisition) which can be used to facilitate a detailed study of the artifacts without direct contact with the fragile surfaces offer innovative analysis tools ranging from the possibility to zoom in to examine and measure tiny details of the surface or detect traces left by tool marks. Furthermore, the possibility of creating sections of the artefact without destroying it, ensuring the reproducibility of the archaeological artefact using rapid prototyping technology and offering the opportunity to study remotely and virtually bring about a new way of understanding our past and hence open a door into that past for future generations.

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