Comparison and deformation analysis of five 3D models of the Paleolithic wooden point from the Ljubljanica River

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***Abstract*—The article describes the comparison and analysis of five 3D models of the hunting tool from the Ljubljanica River found near Sinja Gorica. The 40,000 years old Palaeolithic point, discovered by underwater archaeologists during a preventive archeological survey, was made out of yew wood. Five 3D models of the point were taken over the period of ten years, two before and three after the conservation process. The comparison of the 3D models serves two purposes. The primary goal is to evaluate the changes of the artifact that occurred during this period and, specifically, to compare its shape before and after the treatment. Conservation of waterlogged wood is still a delicate and somewhat uncertain process in regards to the long term survivability of such artifacts. The second goal is to asses which software tools are currently available for such comparison, what are technical problems that need to be addressed, and how to effectively present or visualize the sometimes small but critical changes of shape.**

***Index Terms*—3D models, 3D model analysis, CloudCompare, deformation monitoring, deformation analysis, palaeolithic wooden point, Ljubljanica River**

I. Introduction

In 2008 underwater archaeologists discovered a pointed object made of Yew wood (*Taxus sp.*) in the Ljubljanica river near Sinja Gorica in Slovenia. Its shape is reminiscent of Palaeolithic leaf-shaped stone and bone points. Two wood samples were dated using the AMS ^{14}C method. Te first gave an age estimate of >43,970 years (Beta-252943), while a repeat measurement gave 38,490±330 BP (OxA-19866). At the same time, dendrological examinations were conducted and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) was performed to determine which chemical elements were on the point. After analyzing the wooden point from different points of view it became clear that the point was carved by Homo Neanderthalensis or Homo Sapiens [1].

This wooden point is so far just one of only eight known wooden paleolithic artifacts found in Europe: Clacton-on-Sea, GB 1911 (424-374ka date secondary [2]; Lehringen, Germany 1948 (115-125ka by stratigraphy) [3]; Abric Romani, Spain 1992 (45-49ka secondary) [4]; Schöningen, Germany 1995 (337-300ka secondary) [5]; Mannheim, Germany 2004 (∼18ka BP AMS) [6]; Sinja Gorica, Slovenia 2008 (∼40ka BP AMS) [1]; Poggetti Vecchi, Italy 2012 (∼171ka secondary by UDM) [7]; Aranbaltza [8], Spain 2014 (∼90ka secondary by OSL) [9].

After this lucky find and after the artifact's true importance was finally determined, it's preservation was necessary. It is well known that the conservation of waterlogged wooden artifacts is very challenging. The conservation process of waterlogged wood can induce substantial changes to the shape and size of the artifacts [10]. However, it was decided to conserve the paleolithic wooden point using conventional methods by treat the artifact with melamine and was sent to the Römisch-Germanischen Zentralmuseum in Mainz where the preservation procedure was performed.

Protection of the world's archaeological cultural heritage

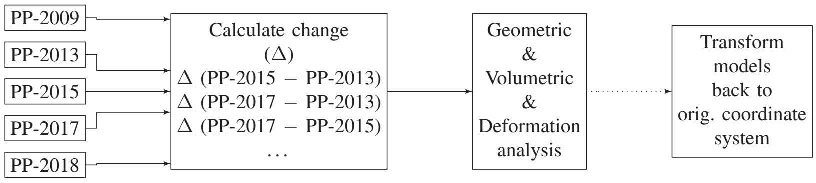


Fig. 1. Flowchart of the key steps used in model deformation analysis of 3D models

(CH) has become a special responsibility of scientific and state institutions in the 21.st Century. Artifacts made from organic materials (e.g. wood, leather, textiles etc.) are especially prone to degradation and are therefore rare archeological finds. CH artifacts are constantly exposed to natural and human-made influences that can compromise their cultural value. Archaeologists and other CH professionals are faced with the problem of protecting and analyzing these artifacts as well as preserving them for future generations. In order to do so, they need reliable data on their state of preservation.

Based on our extensive experience in underwater archaeology and with waterlogged wood [11] we knew that such artifacts, when they are excluded from its natural environment and deposits, can even under expertly performed conservation processes undergo unwanted changes (i.e. bending and other shape deformations, changes of cross-section, size, volume, color, texture etc.). Having at our disposal 3D models of the studied artifact we could quantify these changes. Our hypothesis was, therefore, that we will be able to measure and control the changes that the 40,000 years old paleolithic wooden point has undergone since its discovery and exclusion from its natural environment and deposits in the Ljubljanica River and to highlight in this way the danger of unwanted changes in artifacts of terrestrial and underwater CH after being extracted from their original environment and after the conservation processes.

Since the essential element in this study are the 3D models of the artifact [12], this article serves also as an illustration and case study of how computer technology, computer tools and methodologies are used in the interdisciplinary context of CH [13].

II. Data, tools and methods

Five 3D models of the paleolithic wooden point are available to us. The first 3D model was made in 2009 (PP-2009), a year after the artifact's discovery. The point was scanned again in 2013 (PP-2013) before undergoing a conservation treatment by melamine. Until the conservation process was started, the wooden point was stored in distilled water in a cool and dark environment. After the conservation process the artifact is stored in requested museum climate conditions and was scanned again in 2015 (PP-2015), 2017 (PP-2017), and finally using a Micro-CT scanner in 2018 (PP-2018). The 3D models PP-2013 (scanner ATOS III), PP-2015 (scanner ATOS III) and PP-2017 (scanner ATOS TRIPPLE SCAN) were stored in *.ply* format by the Kompetenzbereich Wissenschafliche IT des Romisch-Germanischen Zentralmuseums in collaboration with i3mainz, the Institut for Raumbezogenen Informations- und Messtechnik der Hochschule Mainz, University of Applied Science (Germany) (PP-2015 and PP-2017). The models PP-2009 (ZScanner 800) by Intri d.o.o. (Slovenia) and PP-2018 (Micro XCT 400) by the Slovenian National Building and Civil Engineering Institute Ljubljana, were stored in *.stl* format.

Our particular goal is to compare and analyze vertices and polygons of five 3D models in *.ply* and *.stl* formats to compute the differences in dimensions, volumes and cross-sections of the models (Fig. 1). The comparative analysis of the data and parameters of all 3D models was performed with CloudCompare version 2.9.1. (see: *http://www.danielgm.net/cc/*), an open source graphical computer program (Fig. 2).

CloudCompare (CC) can process 3D point clouds and triangular meshes. It was originally designed to perform comparisons between two dense 3D point clouds (such as the ones acquired with a laser scanner) or between a point cloud and a triangular mesh. It relies on a specific octree data structure dedicated to this task. Later, it was extended to a more generic point cloud (C2M and M3C2) processing software, including many advanced algorithms (i.e. registration, resampling, color/normal/scalar fields handling, statistics computation, sensor management, interactive or automatic segmentation, display enhancement, etc.), (see: *https://en.wikipedia.org/wiki/CloudCompare*). To date, this software tool has been used primarily in mechanical engineering, in the automobile industry, geology, medicine and by design and construction companies, especially for quality control of products or materials and in determining differences and errors between 3D models. While the attention of 3D model research in archeology has been focused so far on visualization and reconstruction, systematic comparisons of different 3D models, for deformation analysis and deformation monitoring of artifacts, have not been very common so far.

The five 3D models of the point were imported into CC and subjected to geometric comparisons and volumetric measurements. Many different algorithms can be used to compare 3D models including the popular ICP [14]. CC provides a set of basic tools for manually editing and rendering of 3D point clouds and triangular meshes. It also offers various advanced processing algorithms [15]. A dynamic color rendering system helps the user to visualize the per-point scalar fields in an efficient way. The *.ply* and *.stl* formats are the most appropriate for further comparison and processing of 3D cloud points in CC since they can be compared without any compromises and differences. However, we prefer the *.ply* format since a larger

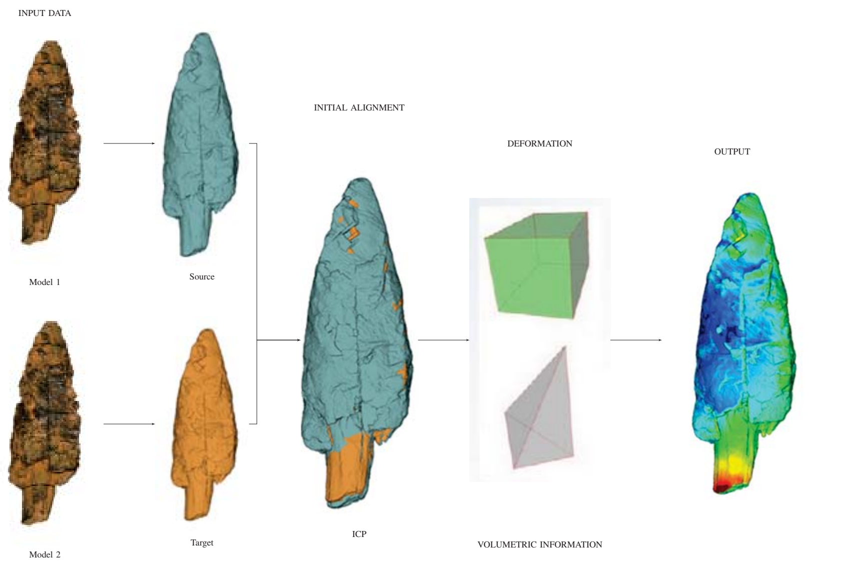


Fig. 2. The process of comparing 3D models (CloudCompare). Source: volumetric tetrahedral mesh. Target: volumetric shape defined by voxels. ICP: Iterative Closest Point Algorithm

set of comparisons is available in CC. Since the model PP-2018 was initially stored in two separate 3D clouds—due to the limited size of the work space of the scanner—we had to combine and integrate both files into a single one.

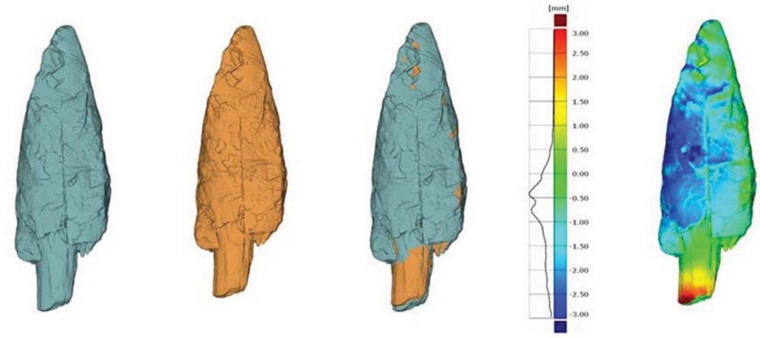
We first performed the registration of input data. The basis for determining the transformation parameters of the photogrammetric 3D model was the 3D point cloud consisting of scanned points. This was followed by the calculation of the distance between the cloud points and the planes of the 3D model (Fig. 1). Measurements expressed in μm, μm^2 and μm^3 of models of the point using CC and statistical comparisons of data were performed. The comparisons were made between models PP-2009 and PP-2013 (before preservation), between PP-2013 and PP-2015 (end of preservation), between PP-2013 and PP-2017, between PP-2015 and PP-2018, between PP-2017 and PP-2018 and between PP-2009 and PP-2018.

III. Results

The most striking comparison is between models PP-2013 and PP-2015, this is just before and after the conservation process of the wooden point was finished (Fig. 3 and Table I). The pronounced change of the point occurred during the treatment. A larger deviation in dimensions in the PP-2013 model is due to the above-mentioned circumstances (irrigation, swelling, adding consolidation, etc.). All volumetric measurements indicate that the selected preservation method has a strong (decisive) effect on the tip deformation process. Two years after the conservation was concluded (2017), the process of deviation due to the conservation process has stabilized and apparently subsided. Changes in dimensions in the PP-2015, PP-2017 and PP-2018 models show a certain moderation, not stabilization. This may also be due to the final stage of preservation (intensive heat and then controlled natural drying) and the use of selected consolidating agents (eg. melamine resin). CT scanning of the artifact (PP-2018) warned that the internal structure of the point was severely degraded and that certain parts were not evenly preserved. We can conclude that the uncontrolled operation of internal peak forces with a different degree of dynamics and response in the longitudinal, radial and tangential direction of archaeological wood is still underway. Two years after the end of preservation, the point is thinner by 1.14% (0.2 mm), shorter by 0.62% (0.9 mm) and narrower by 0.5% (0.3 mm). Archaeologists were confronted with similar problems also with the Clacton Spear Point (England) and the Neanderthal wooden tools from Aranbaltza (Spain) [8].

The deformation monitoring of the point was carried out with the C2M (cloud-mesh) algorithm. The results of the comparison of all five models (Table I) show that during the entire ten year monitoring period the artifacts length was reduced by 3.3% (5.171 mm), width by 3.31% (1.655 mm) and thickness by 11.3% (2.890 mm), while the volume of the point decreased by 9.60% or 6.781 mm^3. Due to intensive irrigation (preparation for canning) of the point, the second model (PP-2013) indicates swelling of the wood and the dimension of the point increased (length + 3.44%, width + 1.41% and thickness 12.53%). Since the end of the conservation in 2015, the process of deformation and change of dimension has slowed down and the artifact is now mostly stable. Still, shrinkage of the point continued and between 2015 and 2018 the length of the point decreased by 1.49%, the width by 4.42% and the thickness by 4.89%. There was also some bending and deformation, both at the base and at the tip of the point. Since wood is a natural organic material, some oscillations in dimensions are normal and expected. This is a sign that the consolidant does not fix the wood into an unnatural shape, but instead lets it ”breathe”.

Although the first signs of deformation of the point were



PP-2013			PP-2015			Δ (PP-2015 − PP-2013) / PP-2013
Length:	160,958	μm	Length:	152,709	μm	-5.12%
Width:	52,274	μm	Width:	50,594	μm	-3.21%
Thickness:	28,810	μm	Depth:	23,956	μm	-17.20%
Volume:	80,404	μm^3	Volume:	66,383	μm^3	-17.44%

Fig. 3. Comparison between models PP-2013 and PP-2015. On top from left to right: PP-2013, PP-2015 and difference between the two models.

TABLE I
VOLUMETRIC COMPARISON OF THREE 3D MODELS OF THE PALEOLITHIC WOODEN POINT FROM THE LJUBLJANICA RIVER

	PP-R2008	PP-2009	PP-2013	PP-2015	PP-2017	PP-2018
	0	1	2	3	4	5
	μm	μm	μm	μm	μm	μm
Length	160000	155606	160958	152709	151768	150435
Width	51000 48000	50014	52274	50594	50348	48359
Thickness	25000 24000	25579	28810	23856	23585	22689
	+-μm / %	+-μm / %	+-μm / %	+-μm / %	+-μm / %	+-μm / %
Length+-% (l)		α	+5352 +3,44%	-897 -1,86%	-3838 -2,47%	-5171 -3,3%
			α	-8249 -5,12%	-9190 -5,74%	-10523 -6,54%
				α	-941 -0,62%	-2274 -1,49%
					α	-1333 -0,88%
Width+-% (b)		α	+2260 +1,41%	+580 +1,2%	+334 +0,68%	-1655 -3,31%
			α	-1680 -3,21%	-1926 -3,68%	-3915 -7,49%
				α	-246 -0,49%	-2235 -4,42%
					α	-1989 -3,95%
Thickness+-%		α	+3230 +12,63%	-1724 -6,74%	-1995 -7,8%	-2890 -11,3%
			α	-4954 -17,2%	-5225 -18,34%	-6121 -21,3%
				α	-217 -1,14%	-1167 -4,89%
					α	-896 -3,80%
	μm^3	μm^3	μm^3	μm^3	μm^3	μm^3
Volume		70653,6	80404,1	66382,8	65238,9	63871,9
	+-μm^3 / %	+-μm^3 / %	+-μm^3 / %	+-μm^3 / %	+-μm^3 / %	+-μm^3 / %
Volume +-%		α	+9751 +13,80%	-4271 -6,05%	-5414 -7,66%	-6781 -9,60%
			α	-14022 -17,44%	-15166 -18,86%	-16532 -20,56%
				α	-1145 -1,72%	-2511 -3,78%
					α	-1367 -2,1%

partially indicated in the PP-2015 model, the deformation process of the point at the tip and at the base can be clearly identified in the PP-2018 model. The measurements show that two shape deformation processes (Fig. 4) are taking place: bending and shrinkage of the point. The bending of the point is more prominent, indicated by the shift of the cross section contours at the tip and at the base (Fig. 5).

The C2M algorithm found in the PP-2018 model some bending at the tip of the point, which was not observed until then. 3D CT scans additionally highlighted the possibility that the deviation at the tip of the point is the result of two opposing internal processes in the upper and middle part of the artifact. The first is shrinkage, the second is bending. These two processes were intensified as indicated by PP-2018. Color comparison of the middle part of the point (Fig. 4) additionally indicates that the wood is unevenly shrinking which causes bending of the upper part of the point. In addition, the coloring of PP-2018 manifests that the base of the point is bending out of the point's central axis.

IV. DISCUSSION

Comparison of five 3D models confirms our initial hypothesis that the paleolithic point underwent changes after its discovery and exclusion from its natural environment in the deposits of the Ljubljanica River. After ten years, the length, width and thickness of the point, as well as its volume, were reduced. The largest changes occurred during the process of conservation. These dimensional changes may well be within the expected changes during the prevailing methods of conservation of waterlogged wood. But since the dimensional changes were not completely uniform, this resulted also in changes of shape. We believe that periodic monitoring of the paleolithic point is necessary since advancing changes of shape may lead to breakage of the artifact, as unfortunately exemplified by the Clacton wooden paleolithic point [2].

The changes that we identified using the CloudCompare software tool highlight the need for careful, thoughtful, responsible and planned conservation and protection of CH objects. Especially for those rare high CH valuable artifacts which due to the special features of their composition (such as organic materials) are more exposed to the risk of deformation.

We presented the changes between the 3D models using tables with numerical data (Tab. I), color coded 2D images from several orthogonal viewpoints (Fig. 4), and with 2D

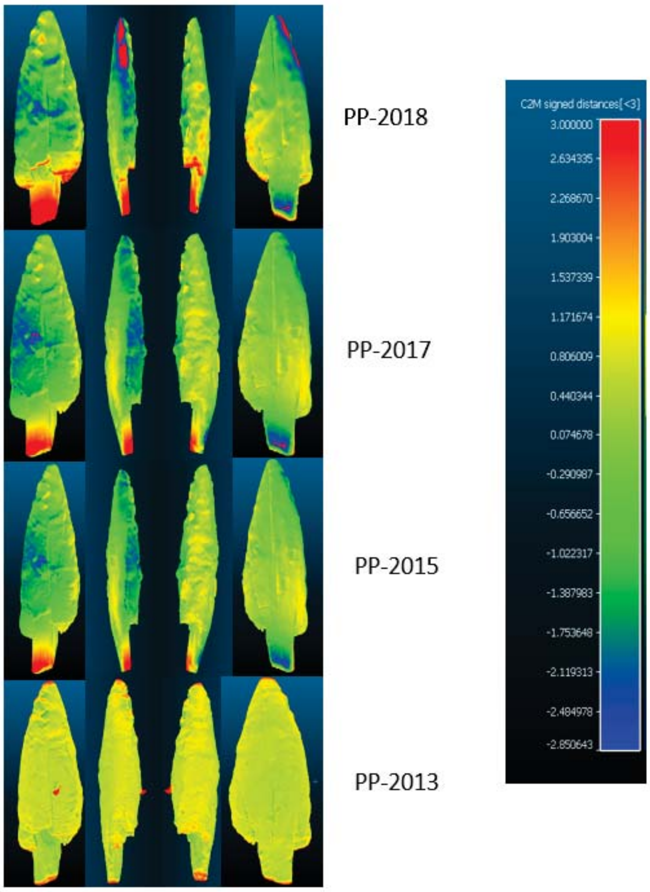


Fig. 4. The deformation process of the Paleolithic point after 2009. The colors show by how much the given models (PP-2013, PP-2015, PP-2017, PP-2018) differ from PP-2009 in millimeters, as indicated by the color chart. Colors at the base of the point of the top three models indicate extension on one side and compression on the opposite side, reflecting that the base part is bending off the center axis.

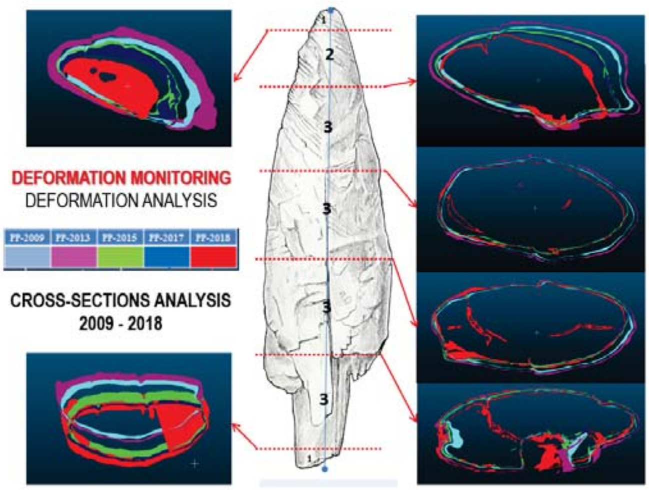


Fig. 5. Changes of the point at five different cross-sections (2009-2018). The cross sections are not shown at the same scale to better see the details.

cross-sections (Fig. 5), which often requires tedious close observation and comparison. Innate property of the human visual system, however, is to detect differences through motion. Having at our disposal 3D models of the artifact from different time periods, one could present the changes as variations on a common shape, using blend animation to show the change smoothly into another by interpolation.

This case study illustrated the need for a closer interdisciplinary cooperation between archeology and computer science on a technological and methodological level. An important shift in the relationship between archeology and computer science as well as their co-responsibility for CH at the national and international level are two documents, namely The London Charter (2009) (see: *http://www.londoncharter.org/*) for the computer-based visualization of CH and the Seville Principles of Virtual Archeology (2011) (see: *http://smartheritage.com/seville-principles/seville-principles*). Among the eight fundamental principles of the Seville document, the principle of **interdisciplinarity** is laid down, which requires modern archeology to include the use of new technologies related to computer visualization of the remains of archaeological heritage in all archaeological research.

A. *Recommendations*

Open-source 3D graphical software tools (e.g. CloudCompare, Meshlab, Blender, etc. [9]) and technologies for recording of 3D data (e.g. structured light scanners, multi-image photogrammetry) have brought in recent decades radical changes to the field of archeology. Archaeologists now have a greater degree of authority in evaluating, reconstructing, reading, describing and documenting artifacts. 3D models, replicas and virtual models of artifacts allow us to study, compare and analyze them while keeping the original intact.

The software (CC – CloudCompare) and the applied algorithms confirmed their suitability and usefulness in analytical shape monitoring. They also confirmed to be an appropriate basis for further archaeological analyses and interpretations of 3D models of CH artifacts. Expectations for greater precision of artifact measurements and also for reconstruction and preparation of models for later visualization were also fulfilled. Open source tools, such as CC, can provide archaeologists with the necessary reliable data for further analysis and interpretation at a low cost. It also provides them with more reliable and accurate information (up to μm) by measuring x, y, and z points of artifacts. CC could be an important standard for future archaeological treatment of artifacts and analysis of degradation.

The collected findings and lessons highlighted by the comparison of 3D models of the Paleolithic wooden point from the Ljubljanica River indicate that a careful and responsible approach is required by archaeologists as well as by computer scientists which should be reflected also by forming guidelines that should be set by national state institutions. Only in this way credible preservation and presentation of artifacts, such as the 40,000 year old wooden point, one of only eight known wooden paleolithic artifacts found in Europe, can be preserved for the future. Efficient use of 3D graphic software tools [16] presents both the archaeological and computer science professions with a number of new challenges. Our research has highlighted the following challenges [13]:

- inclusion of 3D scanning, modeling and measurement techniques already during initial archaeological field research,
- standardization of 3D models in *.ply* or *.bin* formats,
- establishment of national and transnational digital collections of 3D artifact models (digital glyptothek),
- using CloudCompare etc. and similar open source software in analytical and preventive archaeology,
- permanent monitoring of dimensional changes and deformation processes of artifacts using 3D models,
- definition of standard procedures for 3D deformations analysis in the treatment and protection of worldwide archaeological CH.

Our case study fully confirmed the appropriateness of the computer and information technologies and tools in modern archeology. In accordance with the London Charter and the Seville Principles, it would be appropriate to include the suggested approach for the analytical treatment of 3D models with open-source computer graphic tools in national guidelines that define and regulate methods, procedures and techniques for finding archaeological remains and the use of technical means in it.

Based on the presented case study, we found that CC is an appropriate tool for:

- accurately determining the dimensions of artifact, its volume and the texture characteristics;
- volumetric measurements and their basic statistical treatment;
- graphic processing and comparison of a point cloud or a triangulation network of 3D model artifact points;
- comparing two or more 3D models to perform deformation monitoring in archeology.

CC can provide for different types of 3D data (LiDAR, TLS and GIS) means of processing and analysis that can not be achieved reliably with analogue tools. But CC is inadequate for all 3D data formats. The most suitable formats are PLY and BIN. Since CC is on top of it an open source program we recommend its use in archeology.

For periodical monitoring of 3D shape of a particular artifact we advise the persistent use of the same device. For deformation (volumetric) analysis, 3D recorders ATOS III and ATOS TRIPPLE SCAN are advisable. For small artifacts (up to 15 cm) Mini XCT 400 are ideal for deformation and degradation analysis. It is advisable that for each artifact a specially made clamp or cradle is constructed so that the artifact can be consistently locked in the same position during 3D scanning.

B. Conclusions

It is obvious that in the future the protection of underwater cultural heritage will be impossible to imagine without digitized collections of 3D models, the visualization of artifacts, virtual museums, new analytic methods, deformation analysis, deformation monitoring etc. In that way, artifacts will be safely stored but will live globally.

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