3D Point Clouds for Documentation, Analysis and Promotion of Cultural Heritage Artifacts

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New sensors and methods for recovering the 3D shape of cultural heritage can generate huge amounts of 3D data, mostly as clouds of 3D points covered by photographic texture. Such data can partially replace classic forms of documentation in cultural heritage. But in this moment in time, 3D data demonstrates its usability primarily for presentation and visualisation of cultural heritage. This is a very important and worthy goal for promotion of cultural heritage first and foremost for the general public. But how can all this digital heritage trend be used by professionals, such as archaeologists and art historians, to facilitate their principal job of interpretation and understanding of cultural heritage? Computer vision, as a part of artificial intelligence, offers many useful tools and methods for analysis of visual information. The article illustrates how some of those tools can help in the analysis of cultural artefacts in the context of underwater archaeology and monitoring of the preservation of water-logged wood. At the end, the challenges when the cultural heritage domain fully enters the big data era will be discussed.

Key words:
Computer vision, 3D point clouds, Volumetric models, Virtual enhancement, Preservation.

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INTRODUCTION

New digital devices for capturing visual information, such as mobile phones carried nowadays by the majority of population and Internet with its wide variety of applications for sharing information are making pictorial information more pervasive in our daily life but also in many different application areas. Taking a picture to inform or make a statement is usually faster and easier than writing a statement which is also restricted to a particular language. This trend of visual information overtaking written information is referred to as pictorial or iconic turn [Boehm and Mitchell 2009].

Cultural heritage is from its inception heavily dependent on pictorial information for documentation, analysis and promotional purposes. Older analogue formats of pictorial information are gradually digitised and new formats, in particular 3D data formats, are being introduced. Most pictorial information is still identified and searched for by means of key words describing the pictorial information. However, methods of computer vision make possible to search directly for the information contained in the pictures themselves. Some methods of analysis of visual information, such as finding and identifying of human faces made huge advances due to the increasing security demands [Wang and Deng 2018]. Developing algorithms for analysis of particular types of visual information used to be a demanding and lengthy hand crafted operation. The use of machine learning methods, however, in particular the use of deep neural networks, made the development of solutions to typical computer vision problems much faster. Using training examples deep neural networks learn to recognise similar objects in new images.

Typical computer vision tasks in the cultural heritage context are:

- Digitalisation of existing image databases and segmentation of objects versus background
- Identification or categorisation of objects
- Searching for similar objects based on visual similarity (size, colour, texture, structure, shape etc.)
- Detection of forgeries and authentication based on visual/stylistic properties
- Computational aesthetics (quantitative and formal evaluation of the pictorial content)

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CAPTURING AND USE OF 3D DATA

New active sensors and automated photogrammetry approaches enable routine and fast capture of 3D shape of individual objects and entire scenes. Capture of 3D data has become a routine operation, used very often in field work for documentation purposes. Sensors can be hand held or carried by autonomous platforms, such as aerial flying platforms. The initial format of such 3D data are 3D point clouds. These dense 3D point clouds can be covered with photographic texture and observed from any direction. 3D data can be observed either on screen, with virtual reality googles, holographic displays etc. 3D data in its basic format is therefore useful in particular for promotion of cultural heritage, for games and education, for protection and monitoring by comparing 3D data taken at different points in time. An example of a physical object virtually enhanced in the context of interactive art can be seen in Fig. 1. No special equipment on the side of the observers is needed to observe such virtual enhancements. It is also straightforward to use 3D data to make 3D physical copies using either additive methods, such as 3D printing, or by robotic sculpting methods.

For more advanced analysis of 3D shapes, such as search for similar objects and shape comparison, advances in computer vision methods are required, involving segmentation of shapes and modelling of shapes with surface or volumetric geometrical models.

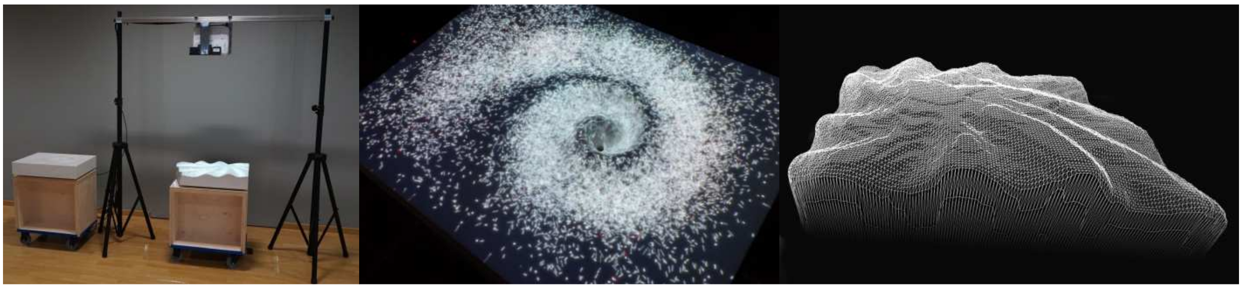

Fig. 1. Stone sculpture virtually augmented with running ``water'' drops. This art installation [Solina and Meden 2017] offers an interactive user experience: the Kinect range sensor captures constantly the 3D shape of the sculpture. Virtual drops that rain on the sculpture run down the greatest gradient and behave as physical water droplets. They are observed by means of a video projection on the surface of the sculpture. The observer can reach into the projection cone, touch the sculpture, and manipulate the flow of the virtual water drops.[1] Such virtually enhanced 3D models could be used also for better presentation and understanding of cultural heritage artefacts.

3D PHOTOGRAMMETRIC DOCUMENTATION IN UNDERWATER ARCHEOLOGY

In underwater archaeology the only practical and cost effective method of 3D documentation remains multi-image photogrammetry. The method is cost-effective since standard underwater photo/video equipment can be used. The matching of corresponding points in overlapping images and camera calibration is done automatically with computer vision methods. It is also fast and efficient and by reducing the number of underwater hours makes the documentation process safer. Many software applications exist, also free and open source software solutions for 3D reconstruction from sets of images resulting in dense 3D point clouds.

Our team has participated in two underwater archaeological explorations where multi-image photogrammetry was used to obtain a 3D model of the scene and artefacts and subsequent analysis of the 3D models for interpretation purposes. The first case involved the explorations of an early Roman barge in the Ljubljanica River, the second case was the study of sarcophagi cargo from a Roman shipwreck near island Brač in the Adriatic sea.

EARLY ROMAN BARGE FROM THE LJUBLJANICA RIVER

Wooden remains of an old vessel were found in the Ljubljanica River near Sinja gorica and partially uncovered in the period of 2008-2012. It was determined that this were the remains of an Early Roman barge built after 3 AD [Erič et al. 2014]. Since the remains of the vessel were extending under the banks of the river which could not be uncovered, the barge remains in situ, covered with sand. The exposed parts of the barge were during the exploration documented using multi-image photogrammetry (Fig. 2). Experiments in bringing various range scanning methods underwater are being made, but it is automated photogrammetry, based on structure from motion principle, that has

[1] https://youtu.be/y6NAiXlNm20

most advantages for underwater documentation [Drap 2012]. The recording equipment can consist of standard photographic cameras for underwater use and one of the software packages for 3D reconstruction from a series of overlapping images. Underwater photogrammetry does not differ from terrestrial or aerial photogrammetry but the water medium introduces specific constraints, especially turbidity of water and presence of suspended particles [Drap et al. 2013].

A detailed analysis of the ship could be performed only on the recovered 3D data. Only during later careful analysis of the 3D model, indentations in the bottom wooden planks were found. These indentations indicate that wooden boxes were probably routinely used for cargo. We made 3D models of wooden boxes after the boxes in the Archaeological Artefact Museum, Sforza Castle, Milan, to test such use in virtual space. For analysis and processing of the 3D data we used MeshLab, a software program for 3D mesh visualisation, processing and editing.

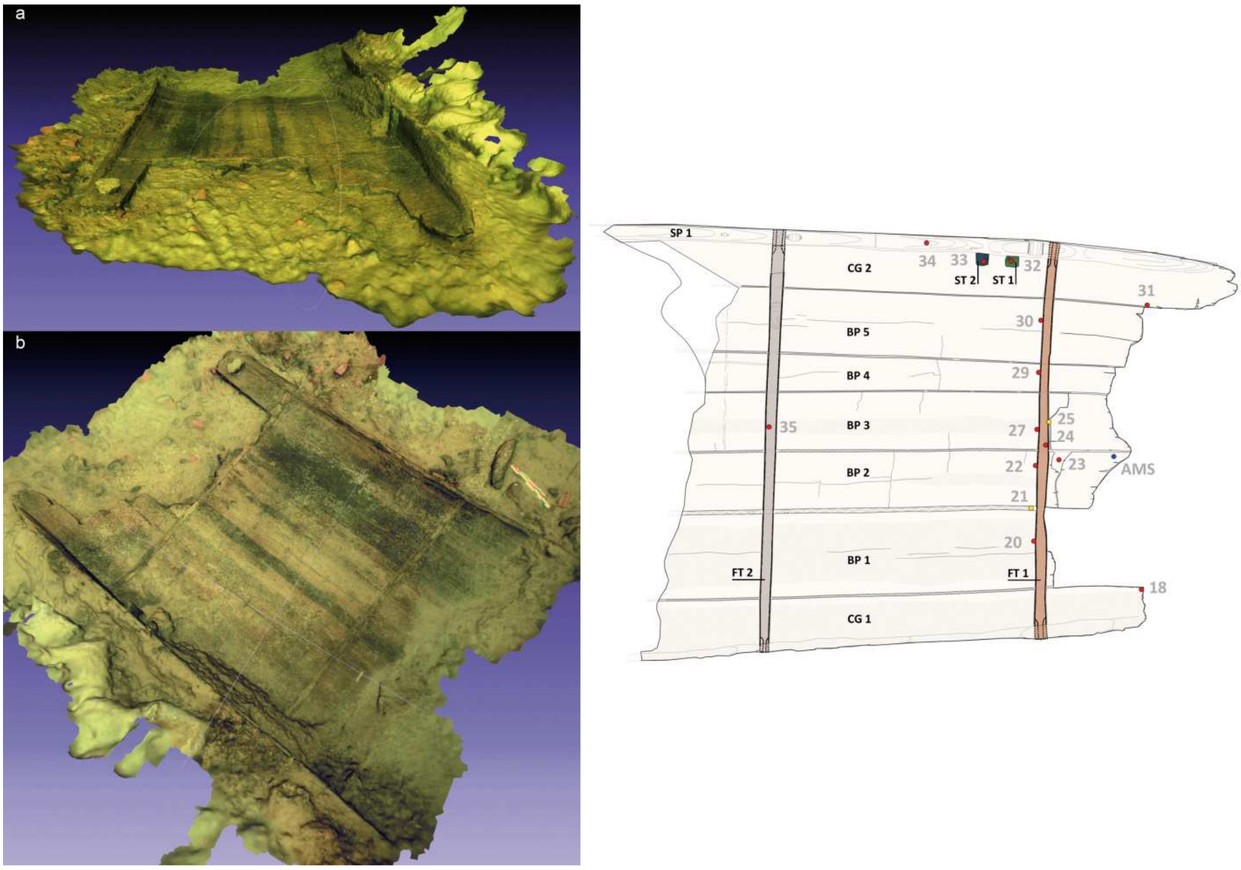

Fig. 2. A 3D model of the Roman barge in the Ljubljanica River was obtained under-water using multi-image photogrammetry (left). The 2D archeological drawing on the right was derived from the 3D data

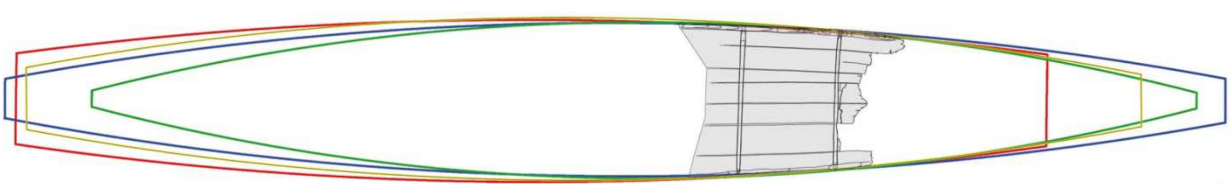

Fig. 3. Comparison of the documented barge segment with the outlines of other Roman ships from the same period

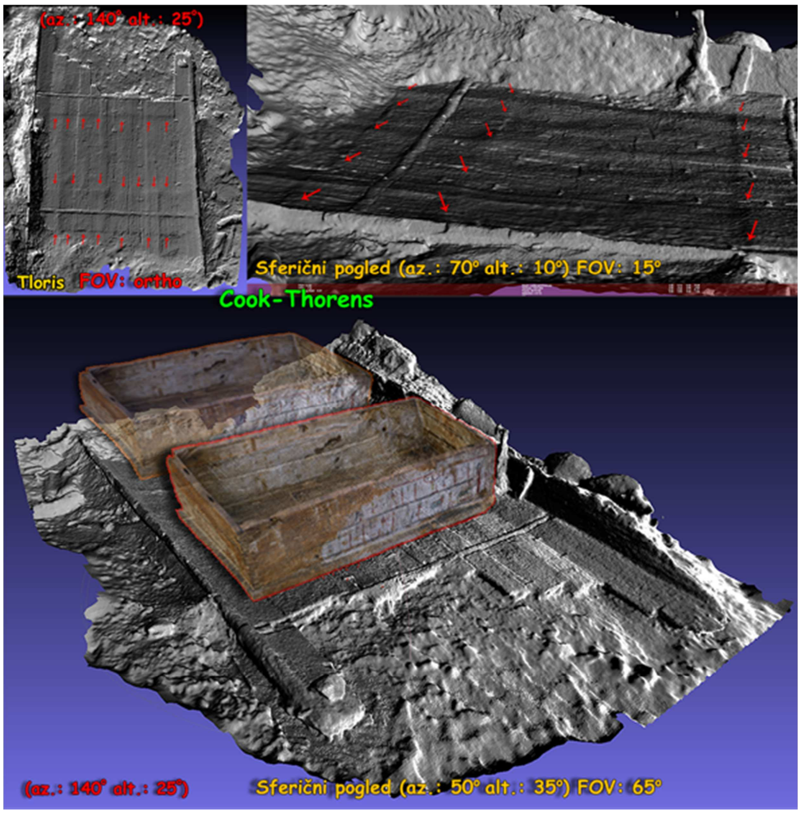

Fig. 4. Indentations in the bottom wooden planks indicate a continuous use of wooden boxes for cargo. 3D models of wooden boxes were made after boxes in the Archaeological Artefact Museum, Sforza Castle, Milan

SARCOPHAGI CARGO FROM A ROMAN SHIPWRECK NEAR ISLAND BRAČ

Our research team participated in the survey of a sarcophagi cargo from a 2nd/3rd century AD Roman shipwreck near island Brač in the Adriatic sea in Croatia. The survey took place in time period of 2010-2012. Both, manual and photogrammetric under-water documentation was used. This offered a nice opportunity to compare both methods of documentation (Fig. 5).

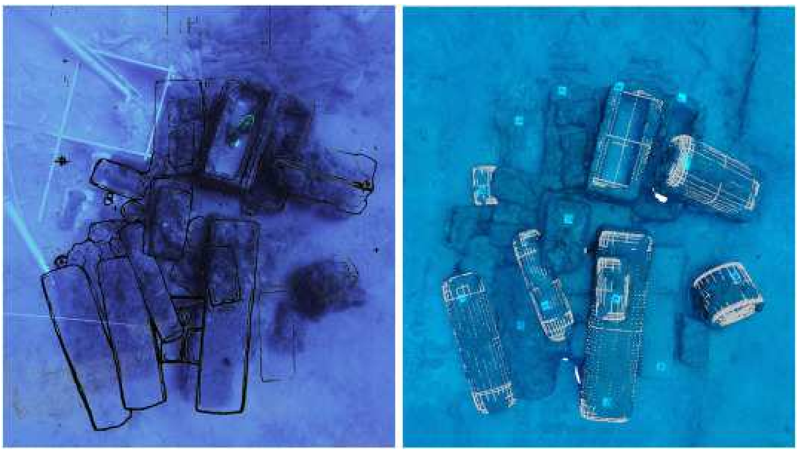

Fig. 5. Sarcophagi cargo from a 2nd/3rd century AD Roman shipwreck near island Brač, Croatia. On the left are the results of the initial manual documentation of the site. Several divers and many hours underwater were needed for manual documentation of the 110 m2 area. On the right is displayed the 3D point cloud obtained with multi-image photogrammetry which is covered with photographic texture. On top of it are displayed the superquadric volumetric models of individual stone blocks. For the photogrammetric documentation 900 photos were used which were captured by a single diver in about one hour of diving time.

The wooden construction of the ship have disappeared long ago, fortunately just a few small wooden segments were preserved which helped in establishing the time of the ship's construction. The size and shape of the ship could therefore be ascertained only by the volume and the layout of its cargo. For such analysis and reasoning about the size and shape of the ship, volumetric models of its cargo offer a better level of abstraction than the small grained and unsegmented 3D point clouds. From the 3D point cloud volumetric models of individual stone blocks [Jaklič et al. 2015] were reconstructed using the standard method for recovery and segmentation of superquadrics [Jaklič et al. 2000], as can be seen in Fig. 6.

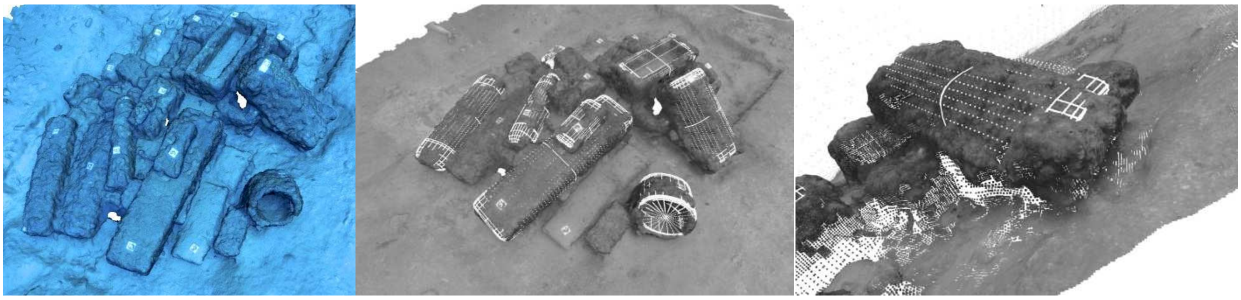

Fig. 6. 3D point cloud covered with photographic texture (left), superquadric volumetric models of individual stone blocks (centre), a detail from the same scene on the right (cover of a sarcophagus)

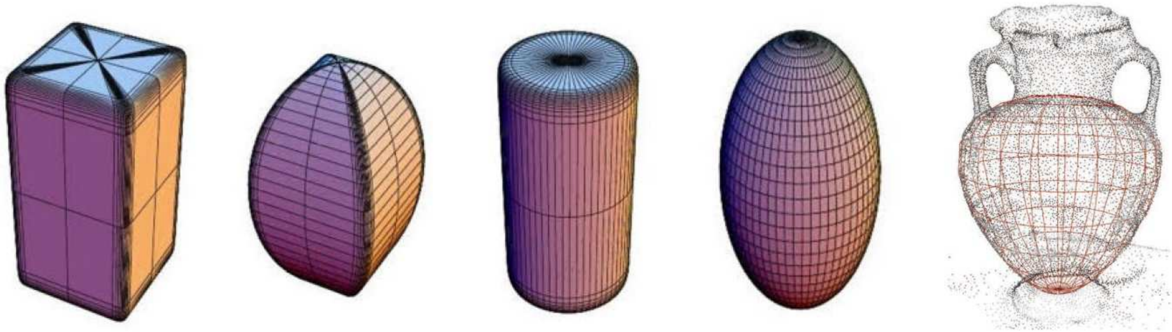

Fig. 7. Four typical superquadric volumetric models on the left, and the 3D point cloud of an amphora on the right, whose body is modelled with a superquadric

Superquadrics are a family of volumetric models which enable a uniform representation of cuboids, cylinders and ellipsoids (Fig. 7). Their shape expressive power can be further enhanced by global and local deformations. The body of the amphora in Fig. 7, for example, is modelled with a tapered ellipsoid. The original method for concurrent segmentation and model recovery from 3D points [Jaklič et al. 2000] is used most often in robotics research for grasp planning and object avoidance. Recently, research has started on replacing the original method for superquadric recovery with a deep neural network approach to make it faster [Oblak et al. 2019].

What are the benefits of using superquadric models in archaeology? Superquadrics offer a level of abstraction which is advantageous for reasoning about the overall structure of a given scene – for example, how many parts there are, how they are interconnected/supported and what is the volume of these parts. The shape of superquadrics is defined by just five parameters which is a very compact description, making comparisons very efficient. Measuring point-to-point distances directly on the 3D point cloud can be difficult if the edges and corners are not well defined because of their rough shape and other imperfections. By the nature of the superquadric fitting process the average dimensions of an object are recovered. Although superquadric parameters cannot be compared directly since the parametrization of same shapes is not unique, nevertheless, superquadrics could be used for shape indexing and searching for similar shapes at the same archaeological site and in databases from other archaeological sites.

MONITORING THE PRESERVATION PROCESS OF WATERLOGGED WOOD

Fig. 8. A palaeolithic wooden point, made out of yew wood, found in the Ljubljanica River near Sinja gorica, radiocarbon dated to 40.000 years

In 2008 underwater archaeologists discovered a pointed object made of yew wood in the Ljubljanica River near Sinja Gorica, Slovenia (Fig. 8). Radiocarbon dating determined the age of the artefact to 40.000 years [Gaspari et al. 2011]. The wooden artefact was waterlogged. Due to the size of the point, its preservation in situ was not sensible and the waterlogged wood had to undergo a conservation process. Conservation of waterlogged wooden artefacts is still evolving. It was decided to apply to the Palaeolithic wooden point one of the conventional conservation method that is to infuse melamine into the object to replace the water. Due to their extensive experience in conservation of waterlogged wood, the point was sent for conservation to the Römisch-Germanisches Zentralmuseum in Mainz. To monitor the conservation process several 3D models of the wooden point were taken: before, during and after the conservation process and compared (Figs. 9, 10, 11) [Guček Puhar et al. 2018].

The goal was to compute the differences in dimensions, volumes and cross-sections of the 3D models. The comparative analysis of the data and parameters of all 3D models was performed with CloudCompare, an open source graphical computer program. Comparison of the 3D models indicates that the Paleolithic point underwent changes after its exclusion from 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 be well 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 the shape of the point which may lead to its breakage at some point in the future.

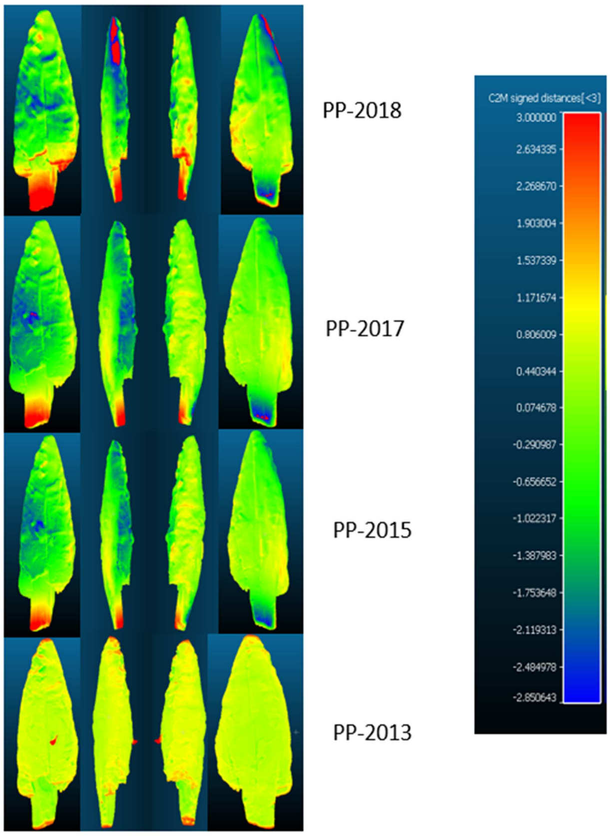

Fig. 9. Five 3D models were taken during the entire conservation process. Left: comparison of 3D models against the first model PP-2009 from 2009. CloudCompare software application, which was initially developed for mechanical products, was used to monitor shrinkage and bending of the wood

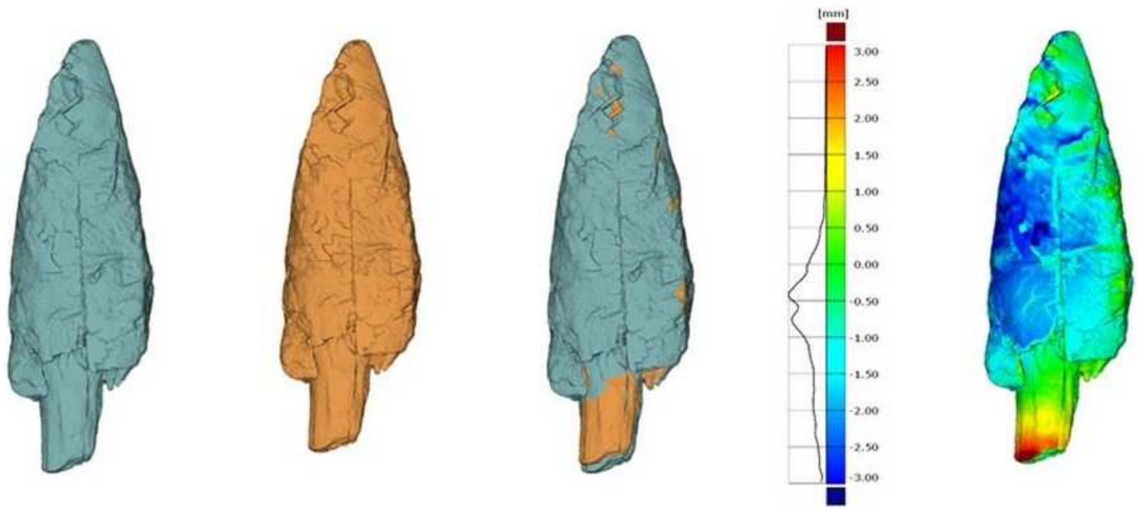

Fig. 10. Comparison of two 3D models of the wooden point, taken just before (2013) and immediately after (2015) of the conservation process. Shrinkage of the wooden artefact and bending of the base can be observed.

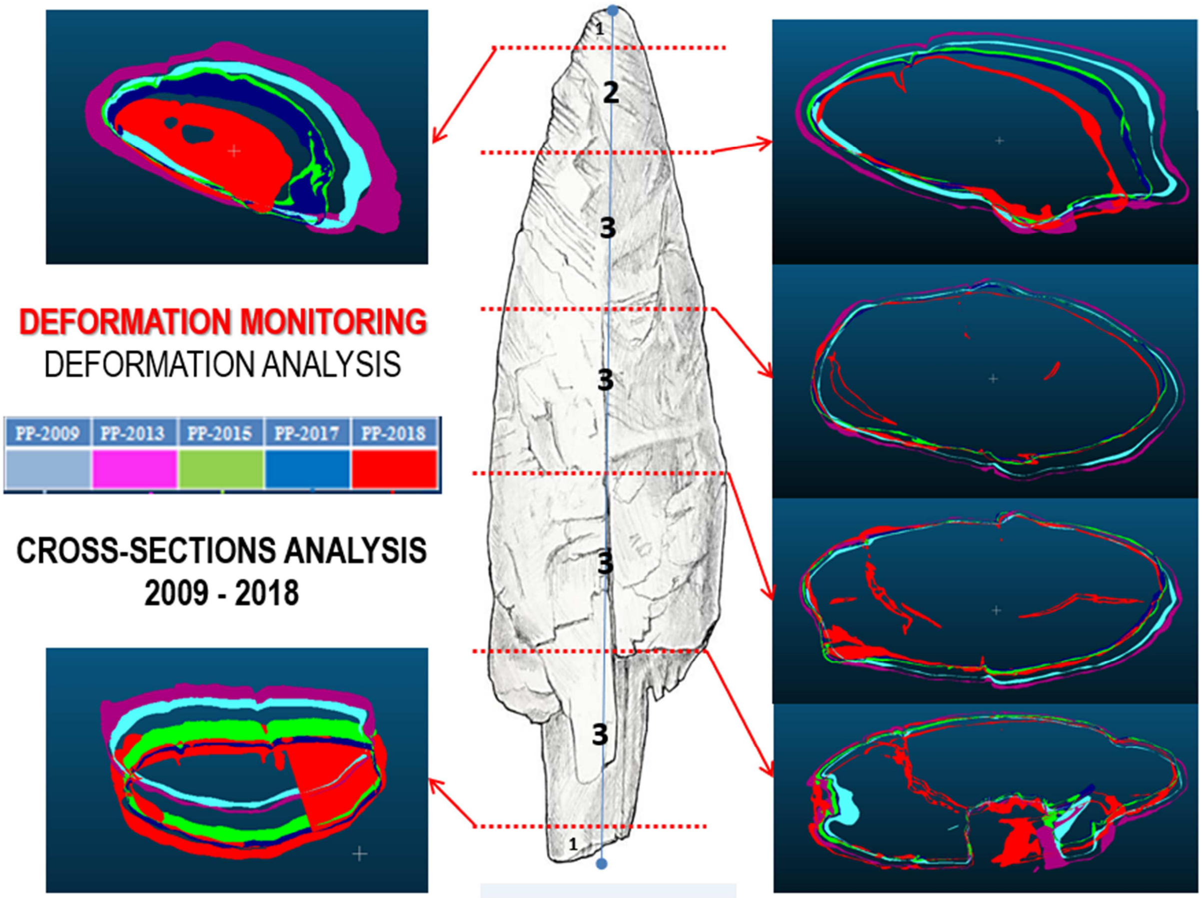

Fig. 11. Comparison of cross sections of all five 3D models of the palaeolithic wooden point at six positions (cross sections are not shown at the same scale). Shrinkage and bending of the artefact can be observed again.

CONCLUSIONS

In agreement with the pictorial turn paradigm the profusion of pictorial data will continue to increase in general. Existing 2D image collections in the heritage domain will eventually all be completely converted into digital formats. Searching through digital 2D image collections is already very efficient. The next challenge in cultural heritage is making 3D scans of all existing collections of 3D objects and environments. Although the technology for 3D scanning has progressed tremendously, this is still a time consuming task. Still, 3D scanning is in lieu of classical documentation approaches now already routinely employed in field work of archaeologists and art historians.

The real challenge from a scientific point of view is how to make the already massive collections of 3D data useful not only for viewing or promotion, but to use the 3D data for better analysis and study of artefacts and of complete historical environments. Some typical tasks that could benefit from better or new analytical methods for 3D data are monitoring of artefacts, modelling of their structure or deriving their part-based physical composition to better understand the production and usage of artefacts, to better follow stylistic developments etc. When cultural heritage enters the big data era when most of the 3D artefacts will also be available in digital form, efficient automatic search for similar artefacts will be of crucial importance. While computer vision methods for comparison of 2D images are already quite efficient, methods of comparing 3D shapes in various scenarios are still under development. This is closely connected to the problem of segmentation of 3D point clouds since in order to analyse individual objects or artefacts they must be first isolated from the 3D point clouds of the entire scenes.

To help and simplify the understanding and analysis of 3D data in the cultural heritage domain, computer vision should develop stable, robust and interactive (semi-automatic) methods for coherent part-level segmentation and modelling of 3D data.

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