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Reconstruction of 3D models from microtomographic images of archeological artifacts

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***Abstract* – The article[1] describes an example of using an iterative algorithm to reconstruction 3D models from two-dimensional (2D) microtomographic (μCT) computer images of archaeological artifacts. The object of the tomographic reconstruction was a 40,000-year-old Paleolithic hunting weapon found in the Ljubljanica River near Sinja Gorica (Slovenia) [1, 2].[2] Between 2013 and 2017, the point was conserved using a traditional waterlogged wood processing technique with melamine resin. Using computer volumetric analysis of five surface 3D models, taken before, during and after the conservation [3, 4], it was found out that volumetric changes and deviations of the point have occurred. The point bent visibly. Surface changes on 3D models did not answer the question: in what condition is the point after the conservation procedure nor the causes of the established deviation. Therefore, we developed an iterative algorithm (IR) with which we rendered a volumetric 3D model from 2D microtomographic images. With the volumetric 3D model, we were able to supplement the information of the surface 3D model and volumetrically and graphically confirm the actual and critical state of the internal structure of the artifact.**

Reconstruction of 3D models from 2D microtomographic images and results obtained from volumetric 3D model highlighted the importance of computed tomography as a non-invasive imaging technique in archaeological treatment, and especially in the planning and implementation of procedures for conservation [5, 6, 7, 8, 9, 10], restoration and storage of valuable objects of archaeological cultural heritage.

[1]This research was supported by ARRS (SRA - Slovenian Research Agency) Research Program P2- 0214 “Computer Vision”.

[2]The paleolithic wooden point was found in 2008 in the Ljubljanica river bed near Vrhnika in Slovenia. It is made out of yew wood. This wooden point is so far just one of only eight known wooden paleolithic artifacts found in Europe.

I. INTRODUCTION

Traditional radiology and, after 1975, computed tomography have been present in archaeology since their inception as non-invasive imaging techniques for dealing with delicate and valuable artifacts (eg. mummies, Paleolithic and ancient remains, papyrus scrolls, wood, metal tools [11], jewelry, weapons, ceramics, wall paintings, Oetzi - Italy [12], etc.).

The second decade of the 21st century is marked by developmental and methodological processing of images in archaeology. The 1st CAA-GR Conference in Crete [13] was dedicated to the use of new technological imaging methods in the preservation of cultural heritage. At the same time, the conference was the concluding act of the twenty-year development of the idea of virtual archaeology. This is the period when archaeologists confirmed interest in the use of new information technologies (LiDAR, photogrammetry, computer modeling, additive manufacturing, visualization and hypertext). It is surprising, however, that computed tomography as a non-invasive imaging technique has received no attention from the greatest authority on archaeological information science. And this after the use of computed tomography has already indelibly marked the archaeological and museum work in preserving the most valuable and sensitive artifacts of cultural heritage.

It is true, as says professor of physics and electrical engineering Jeremy J. O’Brien [14], that the use of computed tomography in archaeology and in the preservation of archaeological cultural heritage after in 1979, was more due to the curiosity and individual interests of the archaeological and egyptological elite than to the planned and systematic research work. It is therefore not surprising that the interest in rendering surface and volume 3D models from two-dimensional tomographic or micro tomographic images has so far not been clearly defined in archaeology. A greater interest in the use of computed tomography in archaeology started only after 2015.

In recent years (2016-2020), archaeologists and computer scientists have been developing new computer algorithms for rendering, segmenting and visualizing surface and volume 3D models in archaeology. At the forefront is also an interest in the internal geometric features of 3D models of artifacts. However, computed tomography is becoming increasingly important as a working diagnostic tool for planning and selecting more appropriate conservation and restoration procedures of artefacts. Some French [7] (eg: Introspect project[3]), British (RTISAD project), American (eg: EDUCE project; Mummy project) [10], Canadian, Israeli, Austrian [9] and German [8] university research centers, specialized laboratories of state museums and some private companies already use computed tomography as an important part of the regular procedures of conservation and restoration of museum and archaeological exhibits.

Reconstruction of 3D models of archaeological artifacts has so far in archaeology been limited primarily to surface 3D modeling, using photogrammetry, laser recorders, and structured light recorders. Various computer vision algorithms have been used (eg: intuitive algorithms for calculating similarities or distances, SIFT, ICP, self-learning algorithms, SfM, SfS, SfL, algorithm segmentation, stereo-reconstruction algorithms, self-learning algorithms, algorithms of CNN, deep learning, etc.). This is also the reason why the use of information technology in archaeology has focused on virtual archaeology [15, 16], additive production of copies of artifacts from surface 3D models, and the digitization of basic archaeological documentation.

For archaeological applications there are no specialized algorithms for the reconstruction of surface and volumetric 3D models from tomographic images. Commercial algorithms are used instead, but they are mostly adapted to the needs of clinical diagnostics and industry. In the reconstruction of tomographic images in medicine, additive manufacturing, material analysis and industrial controlling, the filtered back projection algorithm (FBP) has been standardized for some time. In recent years, the somewhat forgotten algorithms of iterative reconstruction have re-emerged in industrial tomography [17, 18, 6]. Their use has become interesting with the increasing processing power of computers. Comparisons and research have pointed to certain advantages of iterative reconstruction algorithms over the FBP algorithm. New iterative reconstruction algorithms show certain advantages over the use of the FSB algorithm (AIDR, ASIR and ASIR-V, IRIS, SAFIRE, ADMIRE, etc.). New iterative algorithms are already built into the latest generations of CT readers (e.g. Siemens, Toshiba, GE Healthcare, Philips, Canon, etc.) [19]. In most cases they represent a business secret.

Over other modeling techniques, the advantage of tomographic imaging and modeling of artifacts is that we can visualize both surface and volume models from tomographic images. With both models, we can more comprehensively assess the condition of the remains of the archaeological cultural heritage. Since we had microtomographic images of the Paleolithic wooden point and because the previous surface 3D models [3, 4] did not answer the question about the actual state of the artifact, we decided to make a volumetric 3D model. The volumetric 3D model of the point is supposed to explain if there have been changes in the internal structure of the artifact that could jeopardize the existence of the artifact. With this aim, we planned to create an algorithm for the reconstruction of surface and volume models from microtomographic images.

Also in our case, although it is only a further processing of already processed 2D μCT images, we decided to use an iterative form of the algorithm at rendering volume and surface 3D model. Our algorithm is one of the first specialized algorithms for easy use in archaeological treatments and in the processes of conservation, restoration and storage of archaeological artifacts. It is intended to be used - in addition to the ICP algorithm - in the deformation monitoring of archaeological cultural heritage objects. It's use is very simple. An archaeologist can adapt it to his current work goals and needs without the help of a radiologist or a computer scientist.

II. VALIDITY OF DEVELOPMENT AND USE OF SPECIAL ALGORITHMS FOR RECONSTRUCTION OF 3D MODELS OF ARCHAEOLOGICAL OBJECTS FROM MICROTOMOGRAPHIC 2D IMAGES

In the conceptual design of the reconstruction of the spatial and surface 3D model of a selected archaeological object from microtomographic 2D images was substantiated the question of the suitability and necessity of designing a special algorithm that would be adapted to professional, research, analytical and work goals of archaeologists and conservators. This is supposed to be already a routine task in materials science. The position is justified, but archaeologists and conservators, who do not yet have the opportunity to use specialized microtomographic recorders and algorithms to reconstruct 3D models of archaeological objects, must adapt their research objectives to algorithms and techniques of 3D modeling or visualization. As a rule, these are automated and adapted to the very specific goals of medical and industrial computed tomography. To address these shortcomings and limitations of use (hardware and algorithmic) such as warnings against the use of computed tomography on wood, special recorders and special algorithms adapted to the needs of wood experts were de-

[3]The INTROSPECT project is a research collaboration between researchers in computer science and archaeology made up of about fifteen people from France (the IRISA and CReAAH laboratories, Inrap and the company Image ET), UniversitÃ© Laval and INRS-ETE. Source: https://anr.fr/Project-ANR-16-FRQC-0004

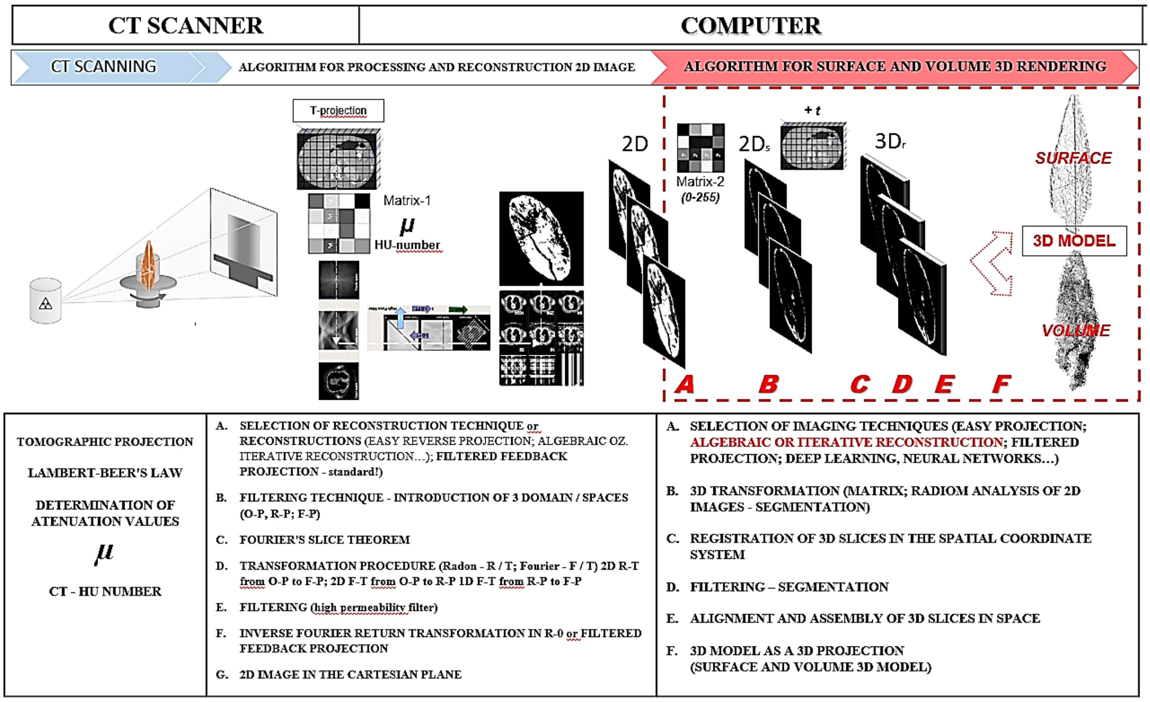

Fig. 1. Algorithm workflow protocol for the reconstruction of surface and volumetric 3D models from 2D microtomographic images.

veloped [20, 21].

Despite the concerns and reservations, we estimated that there are also specific research and work goals of archaeologists and conservators in the processing of microtomographic 2D images. Current practice in the field of computed tomography draws attention in both medicine and industry to the development of customized algorithms (more than 130 different algorithms), which are intended for specific purposes (diagnostics, control and analysis of certain types of material, measurements, etc.). Therefore, we believe that it is appropriate to provide also for archaeology a tool and procedure for independent reconstruction of 3D models from original microtomographic 2D image records.

III. METHOD, HARDWARE AND SOFTWARE ENVIRONMENT AND INPUT DATA

The input are reconstructed two-dimensional (micro) tomographic images of the archaeological object in TIFF format, which were made on the basis of a matrix of attenuation values (HU-number) and filtered back projections with a microtomographic reader MicroXCT 400.[4] Number of μCT images: 3577. Number of μCT slices: 3577. Input format: TIFF. 3D rubber thickness: 36 μm. Output data: 3D model type: surface and volume. Output format: OBJ.

The algorithm is made with a software package for numerical analysis—the fourth generation programming language—MatLab.[5] The algebraic or iterative algorithm is adapted to specific archaeological research goals. In the selected test case, these are: volumetric data; identification of openings, damages, deformations, cracks and fractures in the internal structure of the artifact. The archaeologist defines his research goal through the segmentation process. In doing so, he uses an RGB matrix of grayscale (0-255). The surface and volumetric 3D models are rendered with the open source MeshLab and CloudCompare software.

Procedure - workflow: image register, segmentation, transformation of 2D image into 3D slice, registration of

[4]Microtomographic two-dimensional images of the Paleolithic wooden point were made for research purposes by The Laboratory for Cements, Mortars and Ceramics, Slovenian National Building and Civil Engineering Institute. Dimičeva ulica 12, SI-1000 Ljubljana.

[5]MATLAB is an on-line system providing machine aid for the mechanical symbolic processes encountered in analysis. It is capable of performing, automatically and symbolically, such common procedures as simplification, substitution, differentiation, polynomial factorization, indefinite integration, direct and inverse Laplace transforms, the solution of linear differential equations with constant coefficients, the solution of simultaneous linear equations, and the inverson of matrices. It also supplies fairly elaborate bookkeeping facilities appropriate to its on-line operation. The MathWorks, Inc.

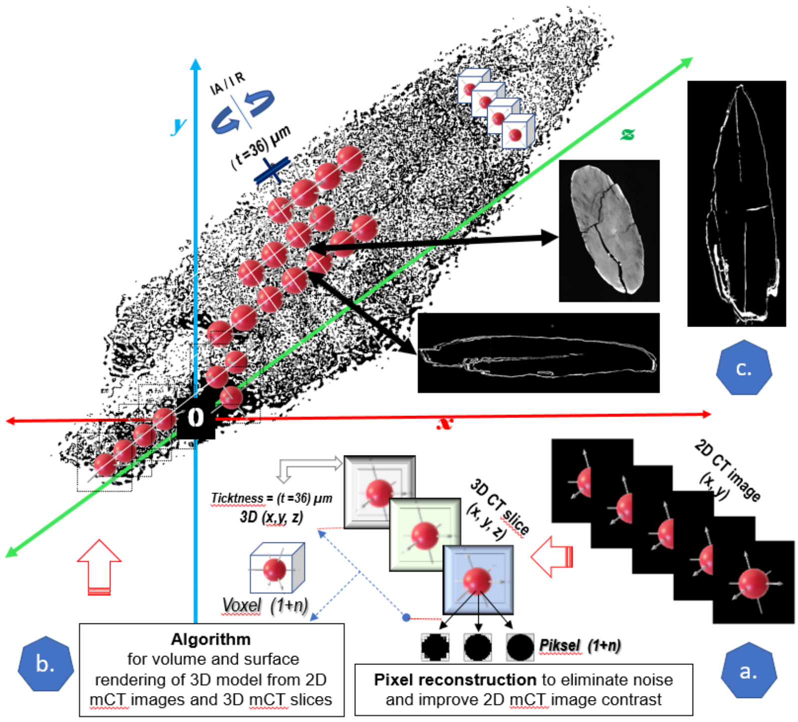

Fig. 2. Reconstruction workflow of volumetric 3D models from 2D microtomographic images.

3D slices in a volume coordinate system, filtering and combining 3D slices, 3D model representation. An additional transparency filter is used in the final visualization of the 3D volume model.

In the phase of computer processing of microtomographic 3D slices, we developed two algorithms: a direct algorithm for the reconstruction of a 3D volume model based on the gray HU scale and a segmentation algorithm for the reconstruction of a 3D volume model based on the gray RGB scale. The direct reconstruction algorithm is robust and can be used to achieve results comparable to related commercial algorithms. The segmentation algorithm is completely adaptable to the target needs of archaeologists and conservators when dealing with an archaeological object.

The workflow of the algorithms are shown in Figures 1 and 2.

IV. RESULTS

In the experimental part, we tested the algorithm on the example of a Paleolithic wooden point, where we investigated and located changes in the wood structure, identified and located critical points (dislocations, inclusions, pores, cracks, openings, damage, chips, deformations and fractures), identified damage or. changes that previously could not be obtained from the point cloud or triangulation grids of a surface 3D model of a Paleolithic wooden point.

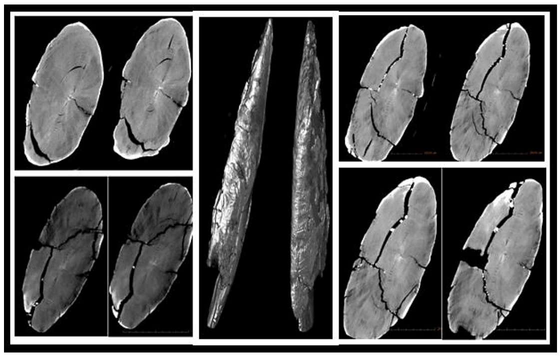

Fig. 3. Examples of textural and structural features of transverse cuts plane of the Paleolithic wooden point - after conservation

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With the volume 3D model, we were able to indisputably identify, investigate and document the internal structure of the artifact. Deformation changes (cracks, fractures, decay) are clearly visible and located (Figure 3). We volumetrically determined and marked critical points in the internal structure of the artifact on the model (Figure 4). Two pronounced internal deformations were found.

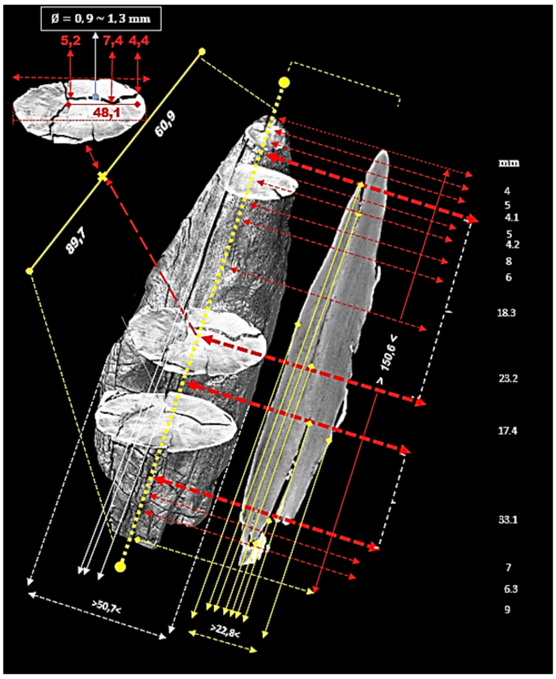

Fig. 4. Microlocation of a large crack and fracture in three plane sections of a Paleolithic wooden point - after conservation.

V. DISCUSSION

The algorithm used to reconstruct 3D models from 2D μCT images met our expectations. The results answered the working questions asked (internal deformation of the artifact). We successfully discovered and microlocated critical points and pointed out the insufficiently analytically thought-out approach in the design and implementation of traditional canning with melamine resin.

With the volume 3D model, we were able to accurately identify, investigate, and document the internal structure of the artifact. Deformation changes (cracks, fractures, decay) are clearly visible and located.

The developed algorithm after experimental verification of its usability and efficiency in the case of the Paleolithic wooden point significantly complements the deformation monitoring method presented at the IEEE conference in 2018 in Monte Casino [3]. Complementing the deformation monitoring method with an iterative algorithm for reconstructing a volumetric 3D model can enable archaeologists to make a comprehensive analysis of the archaeological object before and after the conservation process, and provide conservators with relevant information for selecting appropriate methods, techniques and means of stabilizing valuable archaeological objects.

VI. CONCLUSION

The volumetric 3D model together with the surface 3D model provides the complete information about the state of the original. The model can be used successfully for the selection of conservation techniques [5, 4, 9, 10], analysis and evaluation, in the visualization of the spatial representation of the artifact, additive archaeology [13] and in the timely planning of procedures for the storage and protection of the artifact. The 3D models supplemented with this information and data will gain in importance in the coming years not only in the field of cultural heritage preservation, but also in industry, medicine, etc., as 3D is becoming one of the fundamental standards of the 4th Industrial Revolution [18, 22, 9].

The importance of 3D models and computer spatial and surface 3D visualizations include the London Charter [15],[6] the Seville Principles [16][7] and ratified international treaties among the archaeological and cultural heritage protection standards.

It would be appropriate for the archaeological profession to use non-invasive computed tomography more often than before. In particular, when dealing with sensitive remains and for the production of volumetric 3D models for inclusion into documentary archaeological collections. Spatial and surface 3D rendering from 2D CT images not only expands the knowledge about the screened objects, but also enables further analysis, identification, expands the field of archaeometry, enables better quality 3D rendering and addition.

For archaeologists, conservators and restorers, however, computed tomography can provide a timely and reliable additional information for planning, selecting and implementation of more efficient ways for preservation of cultural heritage remains.

The approach to the reconstruction of the volume 3D model from microtomographic images could be tested, upgraded and developed in the future on new algorithmic paradigms, which in recent years—in the interaction of artificial intelligence, computer vision and radiology—are indicated and offered by artificial intelligence algorithms. These could completely replace the human analytical function in dealing with and evaluating the internal structure and characteristics of 3D models of the remains of human cultural heritage.

[6] `http://www.londoncharter.org`

[7] `http://smartheritage.com/seville-principles/seville-principles`

REFERENCES

[1] Boris Kavur. Palaeolithic wooden object from the Ljubljanica at Sinja Gorica and its siginificance for cultural history. In Andrej Gaspari and Miran Erič, editors, *Potopljena preteklost, Arheologija vodnih okolij in raziskovanje podvodne kulturne dediščine v Sloveniji*, pages 239–242. Didakta, 2012.

[2] Andrej Gaspari, Miran Erič, and Boštjan Odar. A Palaeolithic wooden point from Ljubljansko barje, Slovenia. In Benjamin J, Bonsall C, Pickard C, and Fischer A, editors, *Submerged Prehistory*, pages 186–192. Oxbow Books, Oxford, 2011.

[3] Enej Guček Puhar, Miran Erič, Katja Kavkler, Kristijan Celec, Anja Cramer, Lidija Korat, Aleš Jaklič, and Franc Solina. Comparison and deformation analysis of five 3D models of the Paleolithic wooden point from the Ljubljanica River. In *2018 Metrology for Archaeology and Cultural Heritage (MetroArchaeo)*, pages 449–454. IEEE, 2018.

[4] Miran Erič, Enej Guček Puhar, Aleš Jaklič, and Franc Solina. The necessity of changing the methodology of preserving waterlogged wooden objects. *SKYLLIS Zeitschrift für maritime und limnische Archäologie und Kulturgeschichte*, 2018(2):174–185, 2018.

[5] Rene Van Grieken and Koen Janssens. *Cultural heritage conservation and environmental impact assessment by non-destructive testing and micro-analysis*. CRC Press, 2014.

[6] Andreas Schindler, Rozemarijn Vliegenthart, U Joseph Schoepf, Philipp Blanke, Ullrich Ebersberger, Young Jun Cho, Thomas Allmendinger, Sebastian Vogt, Rainer Raupach, Christian Fink, et al. Iterative image reconstruction techniques for CT coronary artery calcium quantification: comparison with traditional filtered back projection in vitro and in vivo. *Radiology*, 270(2):387–393, 2014.

[7] Théophane Nicolas, Ronan Gaugne, Cédric Tavernier, Emilie Millet, Renaud Bernadet, and Valérie Gouranton. Lift the veil of the block samples from the Warcq chariot burial with 3D digital technologies. In *2018 3rd Digital Heritage International Congress (DigitalHERITAGE) held jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018)*, pages 1–8. IEEE, 2018.

[8] Nicole Ebinger-Rist, Christina Peek, Jörg Stelzner, and Florian Gauß. Computed tomography: a powerful tool for non-destructive mass documentation of archaeological metals. *METAL 2010*, page 458, 2010.

[9] Daniel Jungblut, Stephan Karl, Hubert Mara, Susanne Krömker, and Gabriel Wittum. Automated GPU-based surface morphology reconstruction of volume data for archaeology. In *Scientific Computing and Cultural Heritage*, pages 41–49. Springer, 2013.

[10] Emma Marie Payne. Imaging techniques in conservation. *Journal of conservation and museum studies*, 10(2), 2013.

[11] M Rossi, F Casali, P Chirco, MP Morigi, E Nava, E Querzola, and M Zanarini. X-ray 3D computed tomography of bronze archaeological samples. *IEEE Transactions on Nuclear Science*, 46(4):897–903, 1999.

[12] William A Murphy Jr, Dieter zur Nedden, Paul Gostner, Rudolf Knapp, Wolfgang Recheis, and Horst Seidler. The iceman: discovery and imaging. *Radiology*, 226(3):614–629, 2003.

[13] Paul Reilly and Gareth Beale. Additive archaeology: the spirit of virtual archaeology reprinted. In *Archaeological Research in the Digital Age: Computer Applications and Quantitative Methods in Archaeology*, pages 122–130, Rethymon, Crete, Greece, 2015. Institute for Mediterranean Studies–Foundation of Research and Technology.

[14] N Applbaum and YH Applbaum. The use of medical computed tomography (CT) imaging in the study of ceramic and clay archaeological artifacts from the ancient near east. In *X-rays for Archaeology*, pages 231–245. Springer, 2005.

[15] Hugh Denard. A new introduction to the London Charter. In *Paradata and transparency in virtual heritage*, pages 83–98. Routledge, 2016.

[16] PRINCIPLES OF SEVILLE, International principles of virtual archaeology, 2013.

[17] Sapienza-Polo Pontino. State of the art: Iterative CT reconstruction techniques1. 2015.

[18] Sameer Tipnis, Ashok Ramachandra, Walter Huda, Andrew Hardie, Joseph Schoepf, Philip Costello, Thomas Flohr, and Martin Sedlmair. Iterative reconstruction in image space (IRIS) and lesion detection in abdominal CT. In *Medical Imaging 2010: Physics of Medical Imaging*, volume 7622, page 76222K. International Society for Optics and Photonics, 2010.

[19] Martin J Willemink and Peter B Noël. The evolution of image reconstruction for CT-from filtered back projection to artificial intelligence. *European radiology*, 29(5):2185–2195, 2019.

[20] Voichita Bucur. Techniques for high resolution imaging of wood structure: a review. *Measurement Science and Technology*, 14(12):R91, 2003.

[21] Voichita Bucur. *Nondestructive characterization and imaging of wood*. Springer Science & Business Media, 2003.

[22] Klaus Schwab. *The fourth industrial revolution*. Currency, 2017.