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Democratisation of archaeological sites through digital technologies: the "Oltreaquileia" website

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Abstract

Archaeological artefacts are essential in heritage studies, but are hardly available. Having this concept in mind, the creation of 3D models, of archaeological materials and sites, is a way to make them available online for both the general public and specialists. Using the open-source software package 3DHOP, everyone can now appreciate the models in the website "oltreaquileia". This "democratization of archaeology" brings with it many advantages, but there are also challenges. The creation of the 3D models was possible thanks to the use of specific digital tools and technologies: structured-light scanner; Structure from Motion Photogrammetry and the X-ray computed microCT. A virtual reconstruction of the external fortification of the San Rocco Republican Roman camp, recently created in collaboration with 3D modelers, has been included in the website. The website Oltreaquileia, implemented with 3D models of artefacts and sites, the catalogue of the exhibition with the same name and the demo of the virtual reconstruction of San Rocco external fortification, can be considered a flexible and engaging tool for dissemination and scientific purposes.

Contents

Introduction

Artefact's digitisation

Digitisation could be the future. Digitisation could be the way in which we satisfy the "need to preserve the 'fragile' and 'non-renewable' past for 'future generations'"[1]. Harrison wrote that heritage is "not about the past, but instead about our relationship with the present and the future"[2]. It is clear that, in the very definition of heritage, there is already the concept of the future within.

In the past we have already 'saved' lots of artefacts thanks to previous pictures and analyses of them before they were getting mauled by external factors. Now we have more powerful technologies, so we have to take advantage of that to preserve more but also also more easily.

In addition, there is the fact that cultural goods are unfortunately ephemeral. There are threats like weather phenomena, changes made by man or animals, wars, iconoclastic phenomena, and more. In recent years there is more awareness of the possible loss of material heritage. "Even where a building or object is under no immediate threat of destruction, its listing on a heritage register is an action that assumes a potential threat at some time in the future"[3], so one necessary aim is to preserve the cultural and archaeological heritage. In which way? It is best not to stop at physical preservation; rather, it is important to develop ideas for digital preservation.

Remondino and Rizzi have stated in their work that "according to UNESCO, a heritage can be seen as an arch between what we inherit and what we leave behind"[4]. In the last years, people are much more careful with the cultural heritage they inherit and with the related documentation, so there is an increasing attention for documenting and preserving them also in digital ways[5].

Thanks to digital preservation, in fact, artefacts will not cease to exist, so they could be passed down to future generations, but more importantly, they can be available in multiple parts of the world at the same time.

[1] Laurajane Smith. "Discourses of heritage: implications for archaeological community practice". In: *Nuevo mundo mundos nuevos* (Jan. 2012). DOI: 10.4000/nuevomundo.64148.

[2] R. Harrison. *Heritage: Critical Approaches.* Heritage studies. Routledge, 2013. ISBN: 9780415591959. URL: https://books.google.it/books?id=2bIluenegmgC.

[3] Ibid.

[4] Fabio Remondino and Alessandro Rizzi. "Reality-based 3D documentation of natural and cultural heritage sites—techniques, problems, and examples". In: *Applied Geomatics* 2.3 (2010), pp. 85–100.

[5] Ibid.

With digitisation of archaeological assets, virtual preservation is made possible, but also its fruition. Archaeological artefacts in digital format are valuable for the general public for the public enjoyment; for professionals for research (for example, they may need to study archaeological artefacts that are not easily accessible), but also for teachers for educational purposes.

"Oltreaquileia" website

In this work I want to discuss the effects of making cultural artefacts accessible to the general public and specialists. This theoretical discussion is accompanied by a practical case, in which 3D models of archaeological artefacts were created and placed within the "Oltreaquileia" website.

Created for the exhibition of the same name dedicated to the Republican Roman fortifications of Trieste and sites related to them, this website was used as a platform to make the exhibition catalogue accessible to the public. The exhibition "Oltre Aquileia" ran from 16 October 2021 to 28 February 2022 and was held at the Speleological Museum of the Grotta Gigante and at the Visitor Centre of Val Rosandra in the Municipality of San Dorligo della Valle/Dolina. The exhibition was realised by the Societač Alpina delle Giulie, il Centro di Fisica Teorica Abdus Salam (ICTP), l'Istituto di Archeologia dell'Accademia Slovena di Scienze e Arti, il Comune di San Dorligo della Valle Občina Dolina within the framework of the 'Progetto espositivo multidisciplinare: Castra, accampamenti militari romani a Nordest'.

In addition to making the catalogue accessible, the site was also designed to make the multimedia contents, related to the exhibition (such as: 3D models, films, etc.), accessible. Now the goal is to continue using the site and expand it to create a platform where the public and specialists can interact with 3D models of a selection of significant artefacts from Trieste's military sites.

In this way, everyone can log on to the site and interact with archaeological artefacts for educational and outreach aims.

3D technologies

This work was an occasion to test and compare different 3D technologies, considering similar artefacts as targets. In fact, each digital tool has its own minimum and maximum scan volume (therefore some scanners can recognise larger objects than others), different processing times and results. Considering the advantages and difficulties of the available methods, but also the size of our artefacts, the digital tools selected for creating the 3D models were: structured-light scanner (specifically, the Artec Eva 3D scanner) with related software to create the 3D models; the Structure from Motion Photogrammetry and the X-ray micro-computed tomography.

3DHOP opensource software package was used to upload the models into the site.

An explanation for each of these technologies will be given in the dedicated chapters.

3D modelling of San Rocco camp

The project aims to test the use of augmented and virtual reality to improve the public understanding of the remains of the Republican Roman military camps of the Trieste area and, at the same time, to engage students, specialists and the general public in a virtual reality project. In fact, although the Trieste fortifications have a considerable historical and archaeological significance also at an international level, their remains are not easy to identify on the ground since in most cases they correspond to modest bumps and ridges. In this way, users are able to view via mobile devices a 3D photogrammetric-derived reconstruction of part of the external rampart of San Rocco (excavated in 2021 and now covered) (Fig. 1) and, at the same time, a hypothetical but scientifically sound reconstruction of the original appearance (Fig. 2) of the fortified walkway and associated defence works.

Figure 1: Excavation of part of the external fortification of San Rocco, seen from the north-east, with a complex defensive system

This project has been done thanks to the work of Federico Bernardini, archaeologist, researcher and professor at Ca' Foscari University; Fabio Belardi, senior 3D modeler and founder of Fabelar and Davide Radin, 3D modeler and programmer. Using various modelling software, such as 3dsMax and Mudbox, the fortified walkway and associated defence works were reconstructed on the basis of the archaeological evidence. This was followed by *polycount reduction, retopoly* and *non-overlapping unwrap* of the meshes for the *baking* of lighting and shadows. This technology permits to store lighting and shadow information of the objects separately in some data structure and away from their materials. This information can be retrieved efficiently at run time; so user can change the material itself or modify some proper-

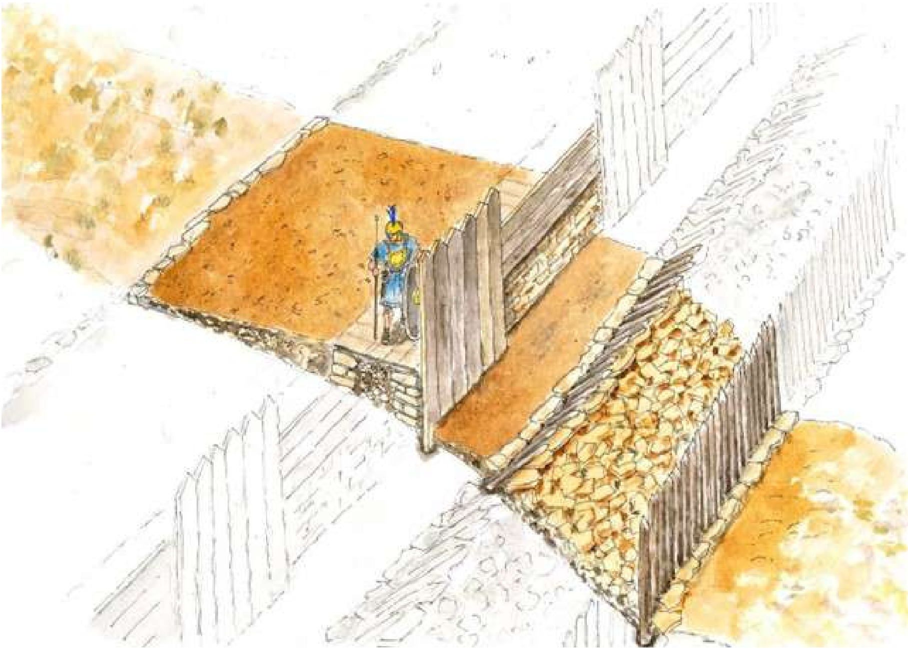

Figure 2: Hypothetical reconstruction of part of the external fortification of San Rocco. Drawing by G. Zanettini

ties without the need to re-bake it again and again[6]. Adobe Photoshop and Adobe Substance 3D Painter were used to create photorealistic textures and materials to be applied to the 3D models. The DTM of the landscape with 50 cm resolution and the 3D model of the excavation allowed the virtual reconstruction to be correctly aligned with the real site.

[6] Dario Seyb et al. "The design and evolution of the UberBake light baking system". In: *ACM Transactions on Graphics (Proceedings of SIGGRAPH)* 39.4 (July 2020). DOI: 10/gg8xc9.

Chapter 1

Archaeological framework and selected evidence

Before going into the details of the methodologies used and the processes implemented, it is best to describe the subjects in question. There is also a need to specify the archaeological setting and context of the artefacts. By knowing simple information such as the location of the recovery, but also the date, it is possible to understand the characteristics of the artefact and the reasons for finding it there, but also its purposes of use and to answer other questions. Experts and scholars, thanks to the archaeological setting and context, can frame archaeological artefacts in an easier way.

The following sections are dedicated to the archaeological framework of the project's artefacts and sites.

Scientific research as background

The Trieste Roman military fortifications were recently discovered through remote sensing and later investigated through surface surveys and small-scale excavation between 2019 and 2021 by an international team[1]. The scholars have been interested in uncovering and reconstructing the history of "the conquest and romanization of the Karst"[2]. The research was conducted in areas east of Aquileia. The sites are located south east of Trieste in front of northern Istria. The fortification system consists of a large military camp on the San Rocco hill, flanked by two smaller structures, those of Grociana piccola and Monte d'Oro[3].

Archaeologists and researchers have intertwined excavations and archaeological surveys with analysis of literary sources. They also used new technologies, like *Airborne Laser scanning* and *Ground Penetrating Radar*, to identify the sites and understand their plan and topography.

[1] Federico Bernardini and Alessandro Duiz. *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*. 2021.

[2] Ibid.

[3] Ibid.

This intensive work has uncovered archaeological evidence showing "the presence of military camps, land division, roadways and more"[4]. The remains found on the surface could seem insignificant to a general audience, because they are small, they are often in pieces, and many of them belong to everyday objects. Actually these artefacts are able 'to introduce us' to Karst history and Roman military architecture during the 2nd and the 1st century BC. In fact, the identified camps, and the related finds, demonstrate early clashes with indigenous peoples. Moreover, some of the fortifications found in the Trieste area can be considered among the oldest known Roman military camps.[5].

After bringing to light an almost unknown history, there was the idea of presenting the results of the work done in an exhibition. The exhibition, which ran from October 16, 2021 to February 28, 2022, was divided into 2 sections. The first section was devoted to artefacts from the San Rocco and Grociana Piccola camps, as well as artefacts from battlefields and fortifications, in the area east of Aquileia, including the both Italian and Slovenian territory. The second section presented the scientific methodologies that enabled all this discovery[6].

Historical background

In the early 2nd century BC, the coastal strip of Trieste and the Istrian peninsula was controlled by the Histri, who occupied the *castellieri*, which are fortified villages. Towards the end of the 3rd century BC Roman expansionism in this area began. Ancient historians wrote that the first conflict between Romans and Histri took place in 221 BC. Further clashes occurred when Aquileia was founded in 181 BC, although, Istria was subdued a few years later (between 178 and 177 BC). Traces of the clash were found in the territory that roughly corresponds to the present-day province of Trieste. Other archaeological findings show that, after the conquest of Istria, a contingent of Latin allies was sent to the Istrian territory. In this way they could "control the indigenous population and prevent possible attacks against Aquileia"[7]. Thereafter, partly because of continuing military expeditions against populations, the whole area continued to be politically unstable until the middle of the 1st century BC[8].

Our artefacts

We have selected several pieces of different materials and sizes. In detail, the selected artefacts were:

- a javelin tip or catapult bolt of heavy artillery; this is a javelin tip or heavy artillery projectile with a square section, socked haft and a through-hole for

[4]Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.
[5]Ibid.
[6]Ibid.
[7]Ibid.
[8]Ibid.

fixing. It is made of iron; the place of discovery is Grociana Piccola (TS) and its measurements are: length 12.8 cm; max. width 3 cm[9];

- a tent peg; this is a tent peg with rectangular cross-section, enlarged oval head with through-hole, in which part of the ring is retained. It is made of iron; the place of discovery is Mount San Rocco (TS) and its measurements are: length 21 cm; max. width 1.8 cm. Dating is between the 2nd and 1st centuries BC[10];

- a rim of wine amphora of Tyrrhenian production (Grecoitalica); this is a rim of late Greco-Italic amphora of probable Campanian production[11]. "Macroscopic external observation and X-ray computed microtomography (microCT) of the sample have shown the presence of abundant very dense inclusions that have been later recognized as igneous silicate phases. Microscope observations and microprobe analyses have shown that their heavy mineral assemblages are different from those of local pottery productions, being characteristics of the Roman Magmatic Province, including both Latium and Campania, which are among the main original production centers of these transport vessels"[12]. The place of discovery is Mount San Rocco (TS) and its measurement is: max. length 7 cm. Dating is in the first half of the 2nd century BC[13];

- "a fragmented amphora lid"[14]; this is a circular lid of Italic production, with slightly flared margin and hollow bottom. The material of which it is composed is a yellowish clay; the place of discovery is Mount San Rocco (TS) and its measurements are: diameter 7 cm. Dating is between the 2nd and 1st centuries BC[15];

- a rim of wine amphora of late Greco-Italic or early Lamboglia 2 type (RR19-Grecoitalica); this artefact is part of a group of 11 amphorae rims of Italic production. It is composed of depurated yellow-pink-orange clay with rare inclusions, characterised by a triangular, more or less flattened section. These are forms of transition between the Greco-Italic and Lamboglia 2 types. The place of discovery is Grociana Piccola (TS) and its measurements are: max. length 10 cm, min. 5 cm. Dating is in the 2nd century BC[16];

- 2 rims of wine amphora; The material of which they are composed is depurated yellow-pink-orange clay with rare inclusions, characterised by a triangular, more or less flattened section. These are forms of transition between the

[9] Ibid.
[10] Ibid.
[11] Ibid.
[12] Federico Bernardini et al. "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529." In: *Proceedings of the National Academy of Sciences of the United States of America* 112 (Mar. 2015). DOI: 10.1073/pnas.1419175112.
[13] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.
[14] Bernardini et al., "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529."
[15] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.
[16] Ibid.

Greco-Italic and Lamboglia 2 types. The place of discovery is Mount San Rocco (TS) and the dating is different[17]:

- Lambolia 2 (archaic), "An amphora rim, attributable to the archaic Lamboglia 2 type has been discovered close to the late Greco–Italic one"[18]. It is "probably datable between the end of the second century BC and the beginning of the first century BC"[19];
- Lambolia 2, "belongs to a late banded Lamboglia 2 type and can be therefore dated within the first century BC Lamboglia 2 types, in fact, were produced along the Adriatic coast until approximately the third decade BC"[20].

• a memorial stone with military helmet; this is a limestone tombstone, consisting of a small column tapered in the centre and surmounted by a helmet with a hemispherical cap. There are 2 circular motifs in relief, symbolising eyebrows and paragnatids tied with a lace. The helmet may refer to the Port type, widespread in the Caesarian period. Its characteristics are inspired by Celtic forms, at a time when legionary equipment was evolving. In the course of the 1st century BC, in fact, as Caesar's conquests in Gaul progressed, there was a gradual abandonment of the Montefortino-type helmets in favour of forms inspired by the Gallic tradition. The material of which it is made is limestone; the place of discovery is Aquileia (UD) and its measurements are: height 60 cm; max. diameter 19 cm. Dating is in the 1st century BC[21];

• dedication to Timavo; this inscription had been placed in Aquileia by the consul in 129 BC. Gaio Sempronio Tuditano on the occasion of the triumph over the Japodes, celebrated in Rome following victorious campaigns against various populations of the eastern Alpine arc, including the Tuarisci and possibly also the Carni. There are 2 fragments of the dedication: the left and right sides. The material of which they are made is limestone; the place of discovery is Aquileia (UD) and its measurements are[22]:

  - height 28 cm; lenght 34 cm; thickness 33 cm[23];
  - height 28 cm; lenght 22 cm; thickness 33 cm[24];

• epigraph of the Legio XIII; this is a block of semi-processed limestone, which relates to the Roman bridge that crossed the Locavaz Canal, near the mouth of the Timavo River. Given the inscription 'LEG XIII', it was possible to attribute the inscription of the block to the soldiers of the thirteenth Caesar's legion, later called *Gemina* in the imperial age. It is made of limestone; the

[17] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.
[18] Bernardini et al., "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529."
[19] Ibid.
[20] Ibid.
[21] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.
[22] Ibid.
[23] Ibid.
[24] Ibid.

place of discovery is Locavaz (TS-GO) and its measurements are: height 40 cm; length 93 cm; depth 345 cm. Dating is in the second half of the 1st century BC[25];

Our sites

The areas where the archaeological artefacts were found are: Grociana Piccola and San Rocco. Both archaeological sites are largely covered by meadows, shrubs and tall vegetation, even though they stand on geological formations of different age and nature[26].

Grociana Piccola

Grociana piccola is located on a very strategic hill, because from that position it can control the bay of Muggia and a portion of the Karst plateau. Two large, roughly rectangular structures were identified in the area of Grociana Piccola in a fortuitous way, in fact they were discovered by processing high-resolution terrain models derived from LiDAR data. The LIDAR-derived digital terrain models disclosed the presence of an archaeological site which is different from the one previously hypothesized[27].

During this analysis two large structures have been discovered. The larger one is a trapezoidal structure with rounded corners oriented in an east-west direction and within it is a smaller rectangular structure with a different orientation. The remains of the outer wall are not easily recognisable on the ground and can be identified with a modest bump. The remains of the inner structure are more visible, at least where they have not been affected by recent military works[28]. (Fig. 1.1).

The structures have a regular shape and are built on an irregular terrain, so it is easy to see that they were designed using advanced tools such as the *groma*. This instrument has been used by Romans for tracing orthogonal alignments and it is composed by a vertical staff with horizontal cross-pieces mounted at right angles and a plum line[29].

In order to clarify the precise chronology of the site, two trenches were opened in 2019, after repeated surface surveys. During excavations in the inner fortification, abundant amphorae and pottery fragments datable to the 2nd century BC have been discovered, suggesting a chronology of the second century BC. The amphorae were used by the legionaries to conserve and transport oil and wine and other precious

[25] Ibid.

[26] Federico Bernardini. "Fortificazioni militari repubblicane nell'area di Trieste (Italia nord-orientale): materiali archeologici da Grociana piccola e San Rocco rinvenuti nel corso della prima campagna di ricognizioni". In: Oct. 2019, pp. 139–153. ISBN: 978-88-7140-957-3.

[27] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.

[28] Bernardini et al., "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529."

[29] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.

Figure 1.1: Terrain model derived from laser data of the hill of Grociana Piccola. The two sub-rectangular Roman fortifications are clearly visible. Elaborated by Federico Bernardini. (Image taken from the article "Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)")

liquids[30]. Among these amphora fragments there are two rims of Lamboglia 2 amphorae[31]. Also beakers and other vessel forms of Roman origin have been discovered together with the amphorae[32].

The inner fortification of Grociana Piccola probabily was built in the 2nd century BC and had the function of lookout for the camp of San Rocco (in fact it was in visual connection with this camp). In this way, Grociana Piccola was able to control a wide area of the Karst plateau. Then it lost importance and was abandoned before the beginning of the 1st century BC.

In the 1st century BC, the hill of Grociana Piccola was occupied again by a larger Roman military fortification. This fortification "is characterized by internal, *clavicula*-shaped, narrow openings on each of its four sides, thus protected internally by a curvilinear wall"[33].

The presence of amphorae and pottery fragments outside of the inner fortification is very low. In this area the archaeological surface surveys retrieved a javelin point or catapult bolt, a bronze coin and more than 100 *caliga* hobnails[34]. These hobnails were used to increase the durability of the soles of the shoes and to improve the grip on the ground.

The external fortification was probably a temporary camp because the construction technique of the fortification was rough, there were a great amount of *caliga* hobnails

[30] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.
[31] Bernardini et al., "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529."
[32] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.
[33] Ibid.
[34] Ibid.

of the same type, but an absence of ceramic fragments. The origin of this camp could be dated in the mid-1st century BC as Roman military reaction due to the attack suffered by Tergeste in 52 BC, probably on behalf of the Iapodes, an ancient population who inhabited the north-western Balkans[35].

San Rocco

The hill of San Rocco rises in a strategic position, near the innermost and most protected part of the gulf of Trieste. The San Rocco site is located in a central strategic area, only two km away from the innermost present-day shore of Muggia Bay, and next to a safe source of water, because is surrounded by the Rosandra River[36]. On this hill is located a Roman camp with a complex and irregular plan, which covers over thirteen hectares. The main fortification structure is roughly semicircular in shape and there are several other structures inside, including a rectangular fortification on the top of the hill[37]. (Fig. 1.2).

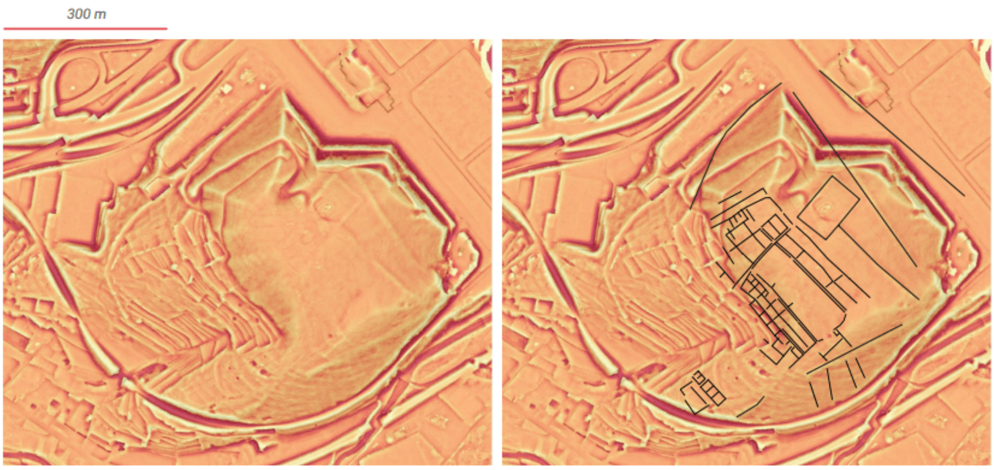

Figure 1.2: Terrain model of the San Rocco hill derived from laser data, with a reconstruction of the site plan based on the structures visible in the laser data and aerial photography. Elaborated by Federico Bernardini. (Image taken from the article "Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)")

Unfortunately, since the first identification of the archaeological structures, the morphology of San Rocco hill has been altered due to interventions of various kinds[38]. Even though these alterations of the morphology it has been possible to visualize the plans of the surviving emerging structures thanks to the elaboration of terrain models derived from laser data. Through the use of historical aerial photographs it was possible to reconstruct the original appearance of the site, especially in the most damaged parts. Instead, a geophysical prospecting campaign provided information

[35] Ibid.

[36] Bernardini et al., "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529."

[37] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.

[38] Bernardini et al., "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529."

regarding the construction techniques and hypothetical buried features. The ruins are characterised by a limited height development, generally less than one metre, and a considerable width, in fact in some places they exceed 20 metres. The first hypothesis was that walls with these characteristics were used as a fortified walkway. In the latest excavations conducted, this hypothesis was only partially confirmed because they revealed much larger and much more complex structures than originally hypothesized[39].

Archaeological excavations were conducted in 2019 to investigate an inner portion of the fortification. The result of these excavations was the discovery of a Roman terracing, made of stones and sustained by preparation layers and a retaining walls towards the valley. This structure corresponds to traces of structures visible in post-World War II aerial photographs; so it is probable that the encampment was organized in terraces. The army probably used these terraces for setting up barracks or tents. Thanks to excavations and surface survey, archaeologists could identify several artefacts, like for example: *caliga* hobnails, a Roman peg, a bronze coin and amphorae fragments belonging to the Roman Republican period from the 2nd to the 1st century BC. Most of the amphorae and pottery fragments have been discovered in the southeastern sector of the hill. Through the study of archaeological data obtained in this area, it was possible to evaluate the chronology of the site. San Rocco was probably occupied in the first half of the 2nd century BC, as suggested by some fragments of Greek-Italic amphorae imported from central Italy[40], and would have continued to be occupied until the middle of the first century BC, but probably not only for military purposes[41].

For its exceptional size and its imposing fortification structures, San Rocco is the main known Roman evidence of the 2nd century BC discovered in the area of Trieste.

[39] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.

[40] Bernardini, "Fortificazioni militari repubblicane nell'area di Trieste (Italia nord-orientale): materiali archeologici da Grociana piccola e San Rocco rinvenuti nel corso della prima campagna di ricognizioni".

[41] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.

Chapter 2

3D models publicly available

Oscar Montelius states that the possibility to access to material forms is prioritized over authenticity[1]. According to him, whether an artefact is authentic or not is less important than whether it can be easily used.

Only if we can see a cultural artefact we can remember it and we can learn. Gabriel Wyner wrote in his book, "Come imparare qualsiasi lingua", that we have a visual memory, so for us, is not useful to use just the imagination, we need to see the material to learn effectively[2].

Usually, in the archaeological discipline, it is difficult to have different kinds of archaeological artefacts always available to be analyzed or shown to students during lectures. When artefacts are found, they follow a cataloging and archiving process and then they are stored in protected areas.

Access to archaeological collections is often limited because of the fragility of the object or because of its unique research use, so any individual will not easily be able to see and touch them. Modern 3D visualization technologies help in these situations because they give the possibility to make the artefact available for a community of stakeholders and "represents an additional opportunity for identifying and (virtually) sharing an even larger number of significant features and elements contained within the single artifact"[3].

Technologies to create 3D models have facilitated the dissemination of artefacts in general, but at the same time they have raised numerous questions regarding legislation. Whose property rights do we have in the case of a 3D model? Is it possible to scan a work of art and then reproduce it with a 3D print? With this last question it is useful to present the case study of the website "Scan the world". This is project of Google Arts & Culture, which contains a collection of 3D printable cultural artefacts, that are free to download. The intention of this work is to increase the sense of cultural identity of people, through an open platform for anyone who wants to access 3D heritage or to contribute with new models[4]. A test was made

[1] Fredrik Ekengren et al. “Dynamic Collections: A 3D Web Infrastructure for Artifact Engagement”. In: *Open Archaeology* 7.1 (2021), pp. 337–352. DOI: doi:10.1515/opar-2020-0139. URL: https://doi.org/10.1515/opar-2020-0139.

[2] Gabriel Wyner. *Come imparare qualsiasi lingua. Il metodo smart*. Jan. 2015.

[3] Ekengren et al., “Dynamic Collections: A 3D Web Infrastructure for Artifact Engagement”.

[4] *Scan the World*. https://artsandculture.google.com/story/egWRnanxkLB0zg.

with the David's head at the FabLab in Castelfranco Veneto; after downloading the 3D model from MyMiniFactory, it was easily printed with a 3D printer (Fig. 2.1), (Fig. 2.2).

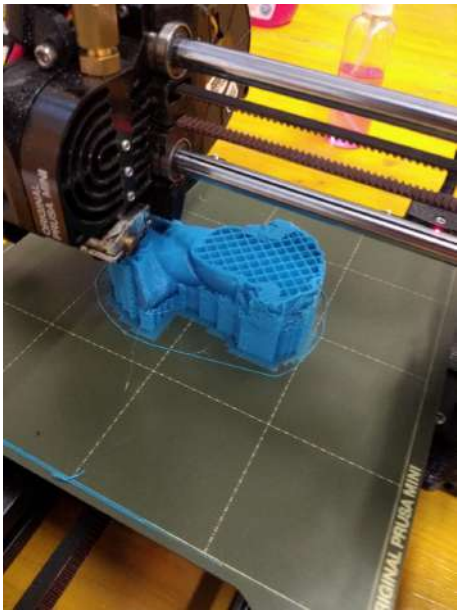

Figure 2.1: 3D printing of the David's head with the Prusa Mini printer (experiment made at the FabLab in Castelfranco Veneto)

At the legal level, in this case, the 3D models are downloadable from MyMiniFactory, which is the largest repository of 3D printable objects and so they have the appropriate Creative Commons licenses[5]. The Creative Commons licenses are useful for the 'user' of a copyrighted work, who wants to know 'What can I do with this work?'. "Creative Commons licenses give everyone from individual creators to large institutions a standardized way to grant the public permission to use their creative work under copyright law"[6].

This definition speaks of 'creative work', so the result of a person's creative idea. It does not speak about copies; therefore can a consumer take a work of art (protected by copyright) and scan it for himself and then reproduce it? Can they share it with others? What can be done with a 3D model? What are the boundaries in terms of legislation? As far as 3D models are concerned, there are still no well-defined laws regulating them. Current protection instruments (like copyright, design, trade mark) do not seem easily applicable to the new technological reality, or they are not enough.

In the following section we will find out what are the advantages of having 3D models of artefacts and sites available for free, but also what are the challenges.

[5] *Scan the World*.
[6] *Creative Commons Licenses*. https://creativecommons.org/about/cclicenses/.

Figure 2.2: The 3D printed David's head (experiment made at the FabLab in Castelfranco Veneto)

Advantages

The possibility to physically (if possible) or virtually handle an artefact is very useful for learning, studying and understanding.

Especially in archaeological discipline, the archaeological collections are necessary. "Archaeological collections are crucial in heritage studies and are used every day for training archaeologists and cultural heritage specialists"[7].

But what is a collection? Collection is defined as a group of objects arranged in a certain order and generally offering special access to history, art and science. Indeed, especially in the 17th and 18th centuries, the assembling and curating of collections was intended to order and understand the world and its past. The study of these collections and then their dissemination led to the foundation of many of the scientific disciplines known today and their methods. Collections are not static, but change over time as a result of new ideas, new technologies and new media[8].

A 3D collection is also a form of knowledge representation and, like the other collections, it "implies some reasoning behind the choice of the pieces, their properties

[7] Ekengren et al., "Dynamic Collections: A 3D Web Infrastructure for Artifact Engagement".
[8] Ibid.

and qualities (with respect to their target use), and the way they are arranged and catalogued"[9].

In recent years it is possible to find 3D collections online, where the user can discover the technical details of the model (like in a 2D collection) but also interact with the virtual model (for example by rotating it 360° or by zooming in). One example is the Smithsonian Museum, which has dedicated a section of its website to 3D collections.

In the website, it is possible to discover the project: '3D scanning frontier', where a group of technologists, working within the Smithsonian Institution Digitization Program Office, tries to increase and spread the knowledge through the use of three-dimensional capture technology, analysis tools, and distribution platform[10] (Fig. 2.3).

Figure 2.3: Home Smithsonian 3D Digitization

From this home page it is possible to see, in the header menu, the item "collections", which contains different 3D collections (Fig. 2.4).

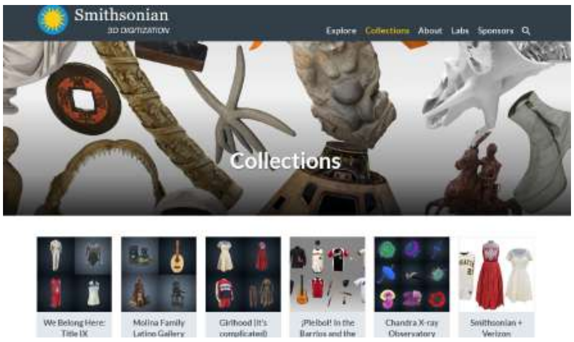

Figure 2.4: Page Smithsonian 3D Collection

The 3D collections available are very different from each other; from prehistoric artefacts to numismatics, from coral collections to hominin fossils (Fig. 2.5).

When an user chooses one of the 3D collections, a new window will open with all the 3D models inside, like for example the "Hominin Fossils" collections, which contains models of human skulls (Fig. 2.6).

At this point, the user can see and interact with one model at a time. Each model is presented with a 3D viewer and its data sheet containing details and information about that model (Fig. 2.7).

[9] Ekengren et al., "Dynamic Collections: A 3D Web Infrastructure for Artifact Engagement".
[10] *Smithsonian 3D digitization website*. https://3d.si.edu/.

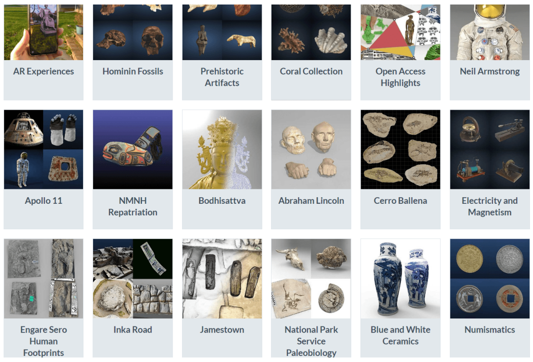

Figure 2.5: Smithsonian 3D Collection

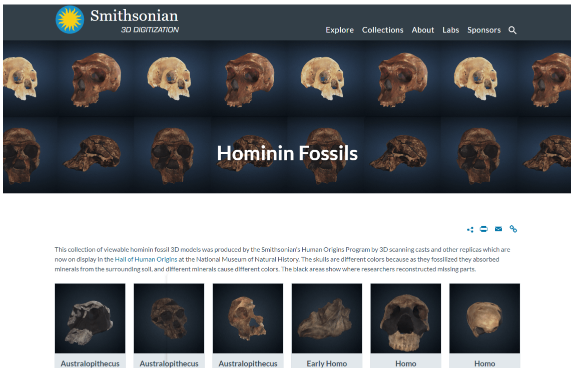

Figure 2.6: Page Hominin Fossils Collection

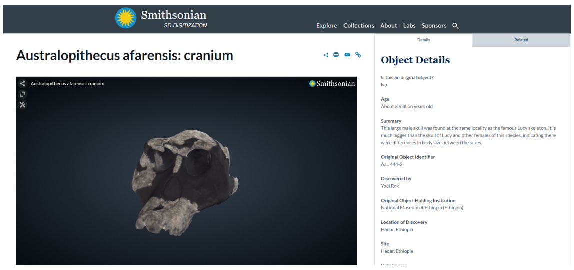

Figure 2.7: Example 3D model with data sheet

Another example is the African Fossils website. It is a virtual laboratory, which presents a large collection of fossils and artefacts found mostly on Lake Turkana in East Africa. This website offers the possibility to interact and explore a spectacular 3D collection of animals, human ancestors, as well as ancient stone tools. The website also allows users to download 3D models to be printed, as well as to comment on and share photos of the printed fossils. This is a way of being close to all possible users, not only professionals and scholars[11].

From the home page it is possible to see, in the menu, the item "3D models", which contains different 3D collections (Fig. 2.8).

Inside this page it is possible to discover a collection of 3D models, which users can filter by category or by timeline (Fig. 2.9).

[11] *African Fossils website*. https://africanfossils.org/.

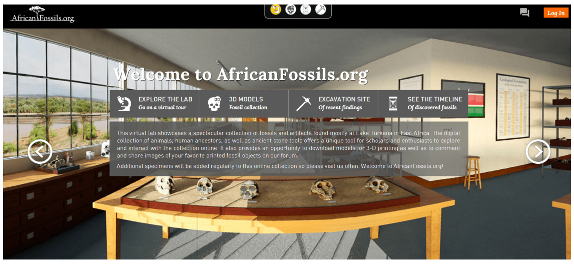

Figure 2.8: Homepage African Fossils

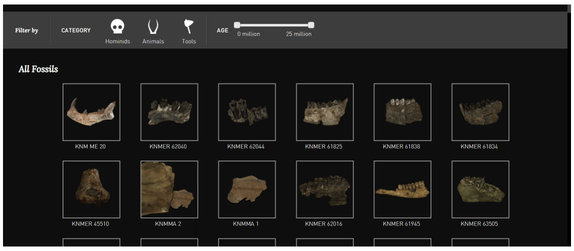

Figure 2.9: African Fossils 3D Collection

These could be two simple examples to understand that, in recent years, new technologies have made it possible to create a huge amount of 3D models and collections, bearing in mind that collections are very important in archaeological research. This production process permits the **"democratization of data"**[12] and **produce new knowledge**[13].

The democratization of data is realized by the fact that 3D collections are often available online. Any student who needs to study an archaeological artefact could find it online and interact with it. Thanks to the various tools, it is possible see its dimensions or take measurements, to turn it around, to get inside the material of which it is composed.

The production of knowledge is possible thanks to a common share of digital models across museums and other interested subjects. This could lead to a general enrichment, since everybody would be able to show its exposed 3D representations, which would be common from New York to Moscow.

Moreover, Appiah states that "The object's aesthetic value is not fully captured by its value as private property"[14]. It is worthwhile to give people the incentive to share the artefacts. Creating 3D models and making them available online turns out to be the best way to fulfill the production of knowledge.

In this way, another benefit could be realized: the original artefacts remain on its original site. It is not necessary to move the artefacts around the world.

Regarding this argument, it is necessary to make some considerations, because some-

[12] Ekengren et al., "Dynamic Collections: A 3D Web Infrastructure for Artifact Engagement".
[13] Ibid.
[14] Kwame Anthony Appiah. "Whose Culture Is It?" In: *Whose Culture?: The Promise of Museums and the Debate over Antiquities*. Ed. by James Cuno. Princeton University Press, 2012, pp. 71–86. DOI: doi:10.1515/9781400833047-005. URL: https://doi.org/10.1515/9781400833047-005.

times the artefacts are not safe if they are in the original site. "Heritage is usually utilized during war periods as a weapon in propaganda battles"[15]. Cities like Palmyra have lost a large part of their cultural and archaeological heritage to the war unleashed by Isis.

But why? "These violent acts and their high-tech mediatic representation accomplished many goals at once: from humiliating the local communities to broadcasting a radical ideology of religious fanaticism in order to recruit new transnational militants all the way to defying the common values attached to cultural heritage in the globalized world"[16]. One of the motivations of this destruction is to annihilate the sense of heritage.

It is clear that sometimes the cultural and archaeological heritage is not safe. There are many different threats, from simple weather phenomena to wars.

Renfrew, C. and Bahn, P.G., in their book, said that there are two main types of destruction of the past, but both are man-made: the construction of buildings, roads, dams, etc, and the agricultural intensification. These systems do not seem to bring instant damage, but they do bring long-term damage[17]. The agent of destruction that quickly destroy everything is conflict. In war zones, the artefacts related to the past could be easily and directly damaged with weapons. The authors listed other threats in the book that should not be overlooked, such as: the tourism and the looting of archaeological sites.

In both cases the aim is to make money by taking advantage of the evidence of the past. Even if some of these threats are not easily recognisable, they all lead to the damage of remarkable archaeological evidence[18].

Another weapon of destruction of cultural heritage is vandalism. A direct act that degrades the integrity of cultural property, as happened this year in Venice where the façade of the Basilica del Redentore was smeared red or in Parma where the cathedral door and the baptistery were defaced[19]. Another incident happened inside the Vatican Museums in Rome, where an American tourist threw two marble busts from the Roman era to the ground.

The list could go on, because these acts of vandalism are not new. Indeed, one may recall the famous episode of the Austrian geologist who hit Michelangelo's Pieta inside St. Peter's Basilica with a hammer on 21 May 1972[20].

[15] Nour A. Munawar. "Reconstructing Cultural Heritage in Conflict Zones: Should Palmyra be Rebuilt?" In: 2 (Dec. 2017), 33–48. DOI: 10.32028/exnovo.v2i0.388. URL: http://archaeopresspublishing.com/ojs/index.php/EXNOVO/article/view/388.

[16] Ömür Harmanşah. "ISIS, Heritage, and the Spectacles of Destruction in the Global Media". In: *Near Eastern Archaeology* 78.3 (2015), pp. 170–177. DOI: 10.5615/neareastarch.78.3.0170. eprint: https://doi.org/10.5615/neareastarch.78.3.0170. URL: https://doi.org/10.5615/neareastarch.78.3.0170.

[17] C. Renfrew and P.G. Bahn. *Archaeology Essentials: Theories, Methods, Practice with 303 Illustrations*. Thames & Hudson, 2018. ISBN: 9780500841389. URL: https://books.google.it/books?id=ruHEvAEACAAJ.

[18] Ibid.

[19] Rebecca Lavinia Baldin. *Cultura sfregiata: il vandalismo contro la nostra arte*. https://www.sintesidialettica.it/cultura-sfregiata-il-vandalismo-contro-la-nostra-arte/. May 2022.

[20] Manuela Pelati. *Musei Vaticani, turista Usa getta a terra due busti. «Voleva incontrare il*

Even if art and the cultural heritage in general are not in extreme situations, they always play an important role in conveying messages. Since the past, works of art have been used to convey strong messages or to demonstrate something to people[21]. A very recent example is what happened on 14 October 2022 at the National Gallery in London. Two activists of *Just Stop Oil* (a British protest movement against the use of fossil fuels) threw tomato soup on Van Gogh's famous painting *The Sunflowers*. They did this act of protest against rising gas prices and the handling of the climate crisis[22]. A similar episode of protest against the climate change occurred at the Uffizi Gallery in July of the same year. Three of *Ultima Generazione* activists glued themselves with their own hands to the glass protecting the painting *La Primavera* of Sandro Botticelli[23].

Art is therefore considered a powerful tool, and should be preserved as such. If we want to preserve the existence of an artefact it is useful to create a digital model and make it available online. It is possible for a computer to be destroyed, but if the model is online or if it exists in different copies saved in different computers, there is less risk of losing it than with the unique material model.

It is clear that digital models of artefacts, monuments, works of art, etc. are useful. Think about the simple conservation of cultural heritage. The conservation of cultural heritage can be explained as the set of preventive measures taken to extend the life of cultural heritage (so maintain the physical and cultural characteristics of the object); but also to spread its values and messages for future generations. Fundamental is the reference to future generations and it will be easier to spread the message of the cultural good if it is in digital format, since we are now in a globalised world. It is of utmost importance to educate young people to respect heritage and its importance also as a source of economic development, progress, work and also peace among peoples[24]. Digital 3D models can be a perfect medium in the education of the younger generation.

The public and the governments have the duty "to avoid unnecessary destruction of that heritage"[25], and this responsibility is expressed around the world in various protective legislation. In Italy, for example, there is the D.L. 22 gennaio 2004, n. 42 "Codice dei beni culturali e del paesaggio", in which one of the principles of Art. 1 state that: the State, regions, metropolitan cities, provinces and municipalities ensure and support the conservation of the cultural heritage and promote its public enjoyment and valorisation[26].

Papa». https://roma.corriere.it/notizie/cronaca/22_ottobre_05/musei-vaticani-squilibrato-getta-terra-due-busti-che-vanno-frantumi-fermato-polizia-e3906246-44b4-11ed-b1df-7473c7dbd1a7.shtml?refresh_ce. Oct. 2022.

[21] Desirée Maida. *Agli Uffizi tre ambientalisti si incollano per protesta alla Primavera di Botticelli*. https://www.artribune.com/arti-visive/archeologia-arte-antica/2022/07/uffizi-tre-ambientalisti-incollano-protesta-primavera-botticelli/. July 2022.

[22] Desirée Maida. *Una zuppa di pomodoro sui Girasoli di Vincent van Gogh. A Londra la protesta degli ambientalisti*. https://www.artribune.com/dal-mondo/2022/10/zuppa-pomodoro-girasoli-vincent-van-gogh-londra-protesta-ambientalisti/. Oct. 2022.

[23] Maida, *Agli Uffizi tre ambientalisti si incollano per protesta alla Primavera di Botticelli*.

[24] Baldin, *Cultura sfregiata: il vandalismo contro la nostra arte*.

[25] Renfrew and Bahn, *Archaeology Essentials: Theories, Methods, Practice with 303 Illustrations*.

[26] *D.L. 22 gennaio 2004, n. 42 "Codice dei beni culturali e del paesaggio"*. https://www.beniculturali.it/mibac/multimedia/MiBAC/documents/1226395624032_Codice2004.pdf.

Although cultural heritage in 3D format is not mentioned in this D.L., as it is a recent phenomenon, the 3D models facilitate the valorisation and dissemination of cultural heritage. They can be applied in different disciplines, and they can be used for many scopes such as archaeological documentation, AR/VR applications, digital conservation and restoration, 3D museum's collections, web geographic systems, etc[27].

Moreover, with digital model you can perform operations that are impossible with the real material object. This is due to the fact that the 3D model of the object contains lots of data, which is sometimes not possible to see with the naked eye[28]. With new technologies (for example with X-ray computed microCT), it is possible to visualize the microstructure of the analysed sample (but not the chemical composition) without damaging it. The object remains intact and the data can be saved and archived.

Furthermore, with 3D model you have the possibility to experiment different "form of engagement with the represented material"[29].

It is possible, for example, to take the digital model and cut it out virtually; or transport it virtually to remote places (in the desert, on top of a mountain, etc.). Furthermore, user could shrink or enlarge it, rotate it, but also add it to a virtual museum.

A first example of involvement with the 3D model that can be cited is one of the experiments created by Google Arts & Culture Experiments. In this website, artists and creative coders have created simple games at the crossroads of art and technology and anyone can try out these experiments, without the need for specific knowledge[30]. Among this collection of games is one that involve 3D models of ancient pottery pot, in fact the goal of the game is to sculpt your own historical pot[31]. The first step is to create a hole, then the user has to give it the correct shape, so he has to sculpt and in the end he can add handles and paint (Fig. 2.10).

Figure 2.10: Replicating a 3D pottery pot with Google Arts & Culture Experiments

[27] Remondino and Rizzi, "Reality-based 3D documentation of natural and cultural heritage sites—techniques, problems, and examples".

[28] Ekengren et al., "Dynamic Collections: A 3D Web Infrastructure for Artifact Engagement".

[29] Ibid.

[30] *Arts & Culture Experiments*. `https://experiments.withgoogle.com/collection/arts-culture`.

[31] *3D pottery experiments*. `https://artsandculture.google.com/experiment/nwHg1DOriJ1ltA`.

Another 'magical' thing you can do with the digital model is: create a material copy of it! This is possible thanks to 3D printers, which print physical models from a digital model. The most common 3D printers print with PLA filament (Polylactic Acid, which is a biodegradable plastic material), but the printers that print most accurately are those that use liquid resin.

A further reflection can also be made on this aspect: 3D printed models can be used in museums or temporary exhibitions to make the experience more immersive. 3D printed models are not very valuable (certainly less than the original ones) so they can be made available for people to be touched. Children especially love to touch with their own hands, so this could certainly be a good way to bring them closer to the cultural world. But we may also think about people who cannot see. If they can touch archaeological objects, they can have the same possibilities that all sighted people have. And isn't this democratisation of cultural and archaeological heritage?

In short, if you have a digital model you can do almost anything you can imagine with it. With the real material artefact, you can't do all that! "Digital collections of 3D artifacts thus have the potential to revolutionize the way students, teachers, and researchers understand and engage with archaeological data"[32].

In the specific field of archaeological documentation, 3D modelling can be very useful for: identification, monitoring, conservation and restoration of sites, buildings and objects. In fact, if the archaeologists are dealing with a landscape, with 3D modelling, they can integrate different elements and document the area. In the case of an archaeological site or a monument, they can obtain information for the analysis of the state of the structure for future restorations and maintenance. Finally, with an artefact, 3D modelling allows to obtain a complete and accurate replica of the object, both digital and physical (through the use of 3D printers), so archaeologists can measure it, analyze it, restore it and show it to the public[33].

Challenges

Growth in the use of digital tools within archaeology brings with it several challenges.

The first challenge is connected to the concept of ethics, because ethics is mandatory in modern archaeology.[34]

The presence of digital tools and "the centering of digital methodologies in archaeology have created new areas requiring ethical consideration"[35], but digital archaeology as discipline is too recent, so it is difficult to define code of ethics.

[32] Ekengren et al., "Dynamic Collections: A 3D Web Infrastructure for Artifact Engagement".

[33] S. Gonizzi Barsanti, Fabio Remondino, and D. Visintini. "3D Surveying and Modelling of Archaeological Sites-some critical issues". In: *ISPRS photogrammetry, remote sensing and spatial information sciences* 5 (2013), W1.

[34] Meghan Dennis. "Digital Archaeological Ethics: Successes and Failures in Disciplinary Attention". In: *Journal of Computer Applications in Archaeology* 3.1 (2020), pp. 210–218. URL: `https://journal.caa-international.org/articles/10.5334/jcaa.24/`.

[35] Ibid.

Digital archaeology started only as a methodological approach for the discipline of archaeology; but then it became a real sub-discipline within archaeology. Now this discipline "is existing almost entirely without ethical oversight"[36].

There are different areas in which digital archaeology is operating without establishing clear ethics guidelines. The first area is related to the use of *black box* technologies, so the use of digital tools. Black boxes are employed when digital instruments are used without any knowledge of their internal workings and how they manage with data. More precisely, we are aware of how to use digital tools, but we are not aware of how they transform the data. For us, the end result is enough. "Complex algorithms may be activated with a single click that requires little or no knowledge of what is actually done to the data yielding a “black box” approach to data processing"[37].

Efficiency achieved through the use of digital tools, reinforces or obscures practice and methodology in the discipline of archaeology. In fact "black boxes hide certain processes or maneuvers either owing to their complexity, their routine character, or their location outside of the expertise of disciplinary work"[38].

Archaeologists use digital technologies because they make work so much easier: it is possible to collect data quickly; store thousands of pieces of information without the risk of losing it; share this information with anyone, anywhere in the world. Data collection is also facilitated by technology, which makes it possible to get to the most remote places. The implication is that: the more the digital technologies facilitate the archaeological work, "the more the aspects of archaeology become obscured by technology"[39].

Software like: Adobe Photoshop, ArcGIS, Agisoft Metashape, but also open source software packages like QGIS and packages such as R, and packages that require programming in Python are some examples of digital tools used in the discipline of archaeology that may result as black box technologies, because usually are used without a full grasp of the data and the processes that manipulate such data. These digital tools facilitate digital photography, geographic information systems, spatial mapping software and photogrammetric rendering[40]. Consequently, as these digital tools make work easier and faster, professionals and students are taught to use these tools to carry out archaeological work, leaving out manual techniques. Problems occur when digital equipment is not available, because the students and the digital archaeologists are unprepared for situations like these[41].

This is connected to another area in which digital archaeology is operating without establishing clear ethics guidelines: "Archaeologists are often teaching students to use digital tools without teaching the accompanying ethical consideration of those

[36] Ibid.

[37] Kenneth Kvamme. “Getting Around the Black Box: Teaching (Geophysical) Data Processing through GIS”. in: *Journal of Computer Applications in Archaeology* (2018), pp. 74–87. DOI: http://doi.org/10.5334/jcaa.14.

[38] William Caraher. “Slow archaeology: Technology, efficiency, and archaeological work”. In: *Mobilizing the past for a digital future: The potential of digital archaeology* (2016).

[39] Dennis, “Digital Archaeological Ethics: Successes and Failures in Disciplinary Attention”.

[40] Ibid.

[41] Ibid.

tools"[42]. Students learn to use digital tools but don't know how to use them in the right way in the right context, so they are unprepared "for the realities of working in a sector that by its very nature has ethical obligations to multiple publics"[43]. Students learn to be performative with digital tools but without learning the consequences of the digital methods.

They could be completely unaware of their own professional digital footprint in the communities, for example: if students were to do a research on indigenous peoples and, after collecting data, they put it online; this community could be at risk of threat if colonisers find and use that repository of data[44]. A negative footprint could be created also by the social media activities. If someone posts something inappropriate online against other people, they will be harmed because posts online impact an individual's current prospects and future careers. Connected to this point of social media, it is important to mention also the problems of digital remembrance and the power of internet memory. Sometimes it could be difficult to delete something from internet, so it is important to be aware of the content uploaded. Taking in consideration the digital remembrance, it is important to have a reflection also on how long the outputs of the research will be available to the public after their participants have concluded their active participation. Students should have to choose in advance a "predetermined cut-off date for public access to those reflections"[45].

All these considerations mentioned so far represent challenges to the effectiveness of the archaeologist's work. Digital tools and methodologies should be considered only a toolkit for the research designs. Which medium to use should be chosen after a careful analysis of the consequences and ethical implications there might be with the communities involved. The digital tools should only help the archaeological profession; "the use of a digital tool or method just because it is digital is not ethical scholarship"[46].

Other challenges are more related to practical work of archaeologists. The first big challenge is to select the appropriate methodology to design the workflow for the generation of the 3D model and to being able to display it[47].

If the project aims to acquire 3D data from large and complex sites or objects, it is necessary to be aware of the huge amount of data, which causes a time-consuming and difficult process at high resolution. On the contrary, if the process will be at low resolution, it creates problems in accuracy and a possible loss of geometric details. Another problem can be caused by the combination of data acquired with different sensors, or under different viewpoints. In fact, with the photogrammetry (it will be explained later) it is possible that the process of alignment of the photographs taken is not able to recognize the points of interest and the model can not be created. If the data are not well merged together, the entire model will be inaccurate. Moreover, if

[42]Dennis, "Digital Archaeological Ethics: Successes and Failures in Disciplinary Attention".
[43]Ibid.
[44]Ibid.
[45]Ibid.
[46]Ibid.
[47]Remondino and Rizzi, "Reality-based 3D documentation of natural and cultural heritage sites—techniques, problems, and examples".

the object has a complex shape, it is very likely that in the process of creating the 3D model, there will be some gaps and holes. This problem requires that someone fixes the model by filling and interpolating the surface and also this process is time-consuming[48].

If it is necessary to acquire satellite and aerial images, the weather conditions or restrictions on flights can be a problem for the availability of the data. In the case of terrestrial images, there can be: occlusions from plants, trees, sloped terrain with stones, rocks and holes, restoration scaffolds, bad weather conditions that cause problems in the accessibility of data. When the methodology used is an active sensors, the user has to take in consideration the object material because there can be problems of bad reflection or penetration and these 'behaviours' influence the acquired data[49].

Also the visualization of the 3D results can be a challenge. The generally large amount of data in a 3D model and its complexity, limits the possibilities for interactive and real-time visualization of the 3D results; so "the rendering of large 3D models is done with a multi-resolution approach displaying large textured meshes with different levels of detail and simplification approaches"[50].

All these procedural problems reveal that the 3D methodologies are still all in a dynamic state of development, with even better application prospects for the near future[51].

[48] Ibid.
[49] Ibid.
[50] Ibid.
[51] Ibid.

Chapter 3

3D technologies

There are different methods to produce 3D models: Structure from Motion Photogrammetry, X-ray computed microCT and scanners are some of them, but one can also create a model with dedicated softwares like Blender.

The term "scanner" is too general, because different types of scanners exist, like: laser scanners, structured light range cameras or time of flight range cameras.

Before making a detailed presentation of each of them, it is necessary to introduce briefly the main two categories of 3D survey methods: passive and active 3D survey (also called reality-based modeling) methods.

In simple words, if a system only uses the reflection of natural light on a given target to measure its shape and does not emit any radiation, it is a passive sensor; instead, if it emits external lighting source, then it is an active sensor[1].

The most important **passive** method is the Structure from Motion Photogrammetry, which will be explained in the dedicated section below.

The introduction of active sensors as recording tool has demonstrated to be very useful especially in the archaeological field. Laser scanners and other active sensors allow to record a complex site in 3D, generating an automatic output, which can be consulted afterward by scholars, "but also as entry point for accessing different types of archeological data"[2].

In the category of **active** systems there can be two principles:

- Triangulation: with one camera and a light source (a laser beam). A laser beam is projected from one position onto the object's surface. "The light spot that this creates is observed by a camera from a second position. Knowing the relative positions and orientations of the laser and sensor, plus some simple trigonometry allows calculation of the 3D position of the illuminated surface

[1]Silvio Giancola, Matteo Valenti, and R. Sala. "Metrological Qualification of the Intel D400™ Active Stereoscopy Cameras". In: June 2018, pp. 71–85. ISBN: 978-3-319-91760-3. DOI: 10.1007/978-3-319-91761-0_6.

[2]Fabio Remondino and Stefano Campana. *3D Recording and Modelling in Archaeology and Cultural Heritage - Theory and Best Practices.* Jan. 2014. ISBN: 9781407312309.

point"[3]. Active triangulation includes: laser scanners and structured light range cameras.

- laser scanners: in these case, it is necessary to move the laser spot over the scene through the use of a spinning mirror to gather thousands of points in a short period of time. Lenses or mirrors can be used to reshape the laser spot, creating multiple spots or stripes. This permits to measure multiple 3D points simultaneously[4]. These technologies provide highly accurate results but they are relatively expensive.
- structured light range cameras: this technology uses a bright figure instead of a bright spot and calculate the distance according to the distortion of the figure. Structure Sensor projects a light pattern to the target. Because the projected pattern is known by the sensor, when this pattern reaches the object, it distorts according to the morphology of the object and the sensor is able to interpret the distortion, providing the depth information. The stripes are the most used but there are other illumination patterns such as parallel lines, circles, cross hairs and dot grids. These technologies are cheaper than laser scanners and there are different options in the market[5].

• Time of flight: measures a distance by shooting a laser beam out to an object and measuring how long that laser beam takes to bounce back. Distance is given by travel time multiplied by the speed of light. Laser-based time of flight range sensors can be also called LIDAR (LIght Detection And Ranging)[6].

Lidar was not developed for the use of archaeologists, but then it has been adopted in the archaeological field thanks to its potential. In fact, lidar is able to calculate the distance, the speed, rotation or chemical composition and concentration of a remote target[7].

LiDAR instruments can be mounted on ground platforms (for example Terrestrial Laser Scanning) and airborne platforms (for example Airborne Laser Scanning). Airborne lidar is particularly suited to large-area survey, because for smaller areas lidar survey is still possible, but it becomes proportionally more expensive, therefore it is best to use other tecniques. In the process of airbone lidar, the laser beam is transmitted in pulses from a rotary aircraft or a fixed-wing. The location of the sensor is known and accurate because it derives from the data of the global navigation satellite system (GNSS) and from the data of the Inertial Measurement Unit (IMU). Lidar is able to calculate the time taken for a pulse of light to reach the target and return; as a result it

[3] Robert B Fisher, Kurt Konolige, and Artificial Intelligence Center. "Handbook of Robotics Chapter 22-Range Sensors". In: (2008).

[4] Ibid.

[5] Luca Ulrich et al. "Analysis of RGB-D camera technologies for supporting different facial usage scenarios". In: *Multimedia Tools and Applications* 79 (Oct. 2020). DOI: 10.1007/s11042-020-09479-0.

[6] Fisher, Konolige, and Center, "Handbook of Robotics Chapter 22-Range Sensors".

[7] S. Crutchley and P. Crow. *Using Airborne Lidar in Archaeological Survey: The Light Fantastic*. Historic England Guidance Series. Historic England, 2018. ISBN: 9781848025479. URL: https://books.google.it/books?id=IxCRuwEACAAJ.

is possible to record the location of points on the ground with a high degree of accuracy. The key element of lidar is light and being an active system, lidar is able to work also at night or in other circumstances when passive sensors would not work. The outcomes of airborne lidar is a quantity of high-precision 3D measurements of points in space (point cloud) in a short period of time. This collection of locational and height data enables the creation of a three dimensional model of the land surface, which can be examined in order to "identify historic features that exhibit some form of surface topographic expression"[8].

The 3D models which can be generated from the data retrieved through lidar's process are: Digital Surface Model (DSM), so the surface with also features such as buildings and trees and Digital Terrain Model (DTM), which is the three-dimensional model only of the ground. The most useful outcomes of lidar for archaeologists is the Digital Terrain Model (DTM), because of the information it can provide in woodland. The DTM is generated by filtering the points of the laser pulse using mathematical algorithms to calculate where features exist above the natural ground surface and removing them[9].

There are different time of flight systems, for example: pulsed wave and continuous wave laser scanners. In the case of pulsed wave, the speed of light is constant and known and this technology can be used for measuring very distant targets, up to a few km. The continuous wave system produces continuous light waves instead of short light pulses. After the reflection, the detected waves change and these changes will be taking in consideration. This technology is suitable for measuring medium distant targets, up to tens of m. Recently, a new type of time of flight range sensor called the "Flash LIDAR" has been developed. In this case the light is sent out from sensor and at the same time all the pixels of the camera are capable to calculate the distance of every object in the scene. The light pulse now has to cover to whole portion of the scene that is observed, so sensors typically use an array of infrared laser LEDs. The resolution is very low, so it useful more for virtual reality activities[10].

There is no best method for all the objects, all available methods have advantages and disadvantages. The most appropriate technique depends on the characteristics of the object or the area to be surveyed, on the budget and on the time available[11], but also on the purpose of the final digital model, on the environmental conditions in which the survey is to take place and on the experience of the operator or the person commissioning the work[12].

For example the Structure from Motion Photogrammetry is useful for the documentation of heritage, the stratigraphic layers during the archaeological excavation but

[8] Ibid.

[9] Ibid.

[10] Fisher, Konolige, and Center, "Handbook of Robotics Chapter 22-Range Sensors".

[11] Barsanti, Remondino, and Visintini, "3D Surveying and Modelling of Archaeological Sites-some critical issues".

[12] Michele Russo, Fabio Remondino, and Gabriele Guidi. "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico". In: *Archeologia e Calcolatori* 22 (Jan. 2011), pp. 169–198.

also artefacts[13], instead active sensors, like laser scanners, collect directly 3D data of artefacts or sites, which can be used to produce highly accurate 3D models[14]; and the methodology of X-ray computed microCT can be used to analyze the inner structure of an artefact or density of the materials making up the object.

If different technologies are integrated with each other, a much better result can be achieved, capable of adapting to different objects. In fact, individual tools have characteristics that are missing or inefficient for all objects and areas, and can therefore be complemented by the integration of other techniques. The integration of different tools allows the acquisition and modelling process to be optimised, using each individual tool to the best of its characteristics and performance[15].

In this chapter we will look at the processes of each technology used in this work in order to produce 3D models. The digital tools and technologies are: Structure-light scanner (Scanner Artec Eva 3D); Structure from Motion Photogrammetry and the X-ray computed microCT.

Scanner Artec Eva 3D

The first models were created with Artec Eva 3D Scanner. Artec Eva is a scanner based on structured-light scanning technology that can quickly obtain an accurate and already textured 3D model of medium-sized objects. The structured-light scanning is a system that sends pattern of light through the object and then the light is distorted according to the 3D morphology of the object's surface. "By measuring the deformation of these patterns the scanner is able to calculate XYZ coordinates for each pixel captured by the camera"[16], and so it is able to reconstruct the 3D model of the object. The patterns can be different, like for example: parallel lines, concentric circles, cross hairs and dot grids[17].

It is important to bear in mind that not all objects can be scanned, or not all are easy to scan, as it is written in the manual of the scanner (Fig. 3.1). Since Artec 3D scanners "capture 3D frames using optical technology"[18], some types of surfaces are difficult to scan, like for example: transparent or reflective objects; very dark or black surfaces, but also objects with thin edges; and the manual presents also possible solutions[19].

13 Maurizio Forte and Stefano Campana. "Digital methods and remote sensing in archaeology". In: *Archaeology in the Age of Sensing* (2016).

14 Barsanti, Remondino, and Visintini, "3D Surveying and Modelling of Archaeological Sites-some critical issues".

15 Russo, Remondino, and Guidi, "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico".

16 Shannon P. McPherron, Tim Gernat, and Jean-Jacques Hublin. "Structured light scanning for high-resolution documentation of in situ archaeological finds". In: *Journal of Archaeological Science* 36.1 (2009), pp. 19–24. ISSN: 0305-4403. DOI: https://doi.org/10.1016/j.jas.2008.06.028. URL: https://www.sciencedirect.com/science/article/pii/S030544030800160X.

17 Fisher, Konolige, and Center, "Handbook of Robotics Chapter 22-Range Sensors".

18 *Artec Studio 15 - User guide*. http://docs.artec-group.com/as/15/en/_downloads/25ad86ff3ec13dc8eae3208423c3eb81/Manual-15-EN.pdf.

19 Ibid.

Table 1: Hard-to-scan Surfaces

Surface Features	Possible Solutions
Black or very dark	Dust with anti-glare spray
Shiny or reflective objects	Dust with anti-glare spray, tilt scanner when capturing
Transparent (glass, certain kinds of plastic, etc.)	Dust with anti-glare spray
Thin edges	Add background geometry (e.g., crumpled paper)

Figure 3.1: Table with surfaces that are hard to scan and relative possible solutions

As written, with transparent objects it is necessary to use anti-glare spray. In the FabLab of Castelfranco Veneto, we made an experiment with a transparent jar (the typical jar used for jams). We sprayed the entire surface and after it dried, it was possible to scan it (Fig. 3.2).

Figure 3.2: Example of transparent jar dusted with anti-glare spray (experiment made at the FabLab in Castelfranco Veneto)

In terms of survey range, structured light scanning system have "limited survey range, usually from 0.5 m to maximum of few meters from the sensor"[20], so this system is not useful for large sites or whole buildings. If it is better used for small-medium sized objects and artefacts, the advantage is that this system "produces sub-millimeter accurate 3D representations with color information"[21].

In the data sheet of the scanner's manual, in which there are the technical details, (Fig. 3.3) it is possible to see that the size of the object must be greater than 10 cm, and we tested the scanner to its limits with our artefacts. In fact, we tried scanning some artefacts that measured about 10 cm.

[20] Forte and Campana, "Digital methods and remote sensing in archaeology".
[21] McPherron, Gernat, and Hublin, "Structured light scanning for high-resolution documentation of in situ archaeological finds".

Artec Eva technical specs

3D accuracy	Up to 0.1 mm
3D resolution	Up to 0.2 mm
Object size	Starting from 10 cm
Full color scanning	Yes
Target-free tracking	Hybrid geometry and color based
3D reconstruction rate	16 FPS
Output formats	All popular formats, including STL, OBJ, and PLY
Weight of scanner	0.9 kg

Figure 3.3: Data sheet Artec Eva

Our scanning process

In the scanning process we equipped ourselves with: a sufficiently lit room, a small table, a powerful computer with Artec Studio software installed, some foam rubber and markers. The scanner was connected to a laptop with Artec Studio, to visualize the scanning process in real-time.

After preparing the location, we placed our first artefact on the table, trying to make sure it was in the brightest part of the room. We chose a small table so that we could easily walk around it and scan the object entirely without blocking the scanning process (Fig. 3.4).

We had no objects with transparent or reflective surfaces so we did not need to cover them with powder coating or a special anti-glare spray. This was good news because most archaeological materials cannot sprayed with anti-glare spray.

While scanning it is better to pay closer attention to the object on the screen than to the actual object so it is possible to understand how you are scanning (Fig. 3.5). We tried a couple of times for each object and sometimes, especially in the beginning we happened to hear an alert sound and to see the screen displays with an error. In that cases, we returned the scanner to the area where it was stuck. The manual writes that “possible reasons for the ’Tracking lost’ error include the following:

- You are scanning simple geometric shapes;
- The part of the object you are scanning is too small;
- Scanner movement is too fast"[22].

[22] *Artec Studio 15 - User guide*.

Figure 3.4: Scanning arrangement with amphora of Altino

Figure 3.5: Scanning session

The smallest pieces were the most difficult to scan. We used some material we found in the room to make the scanning more effective; in fact, we put a roll of paper towels in the center of the table and put the artefact in the hole with foam rubber to support it. We also put markers and objects to help the scanner recognise the object (Fig. 3.6).

Figure 3.6: Scanning small artefacts

Then there was the process of alignment of the various scans. And the global registration (Fig. 3.7), (Fig. 3.8), (Fig. 3.9).

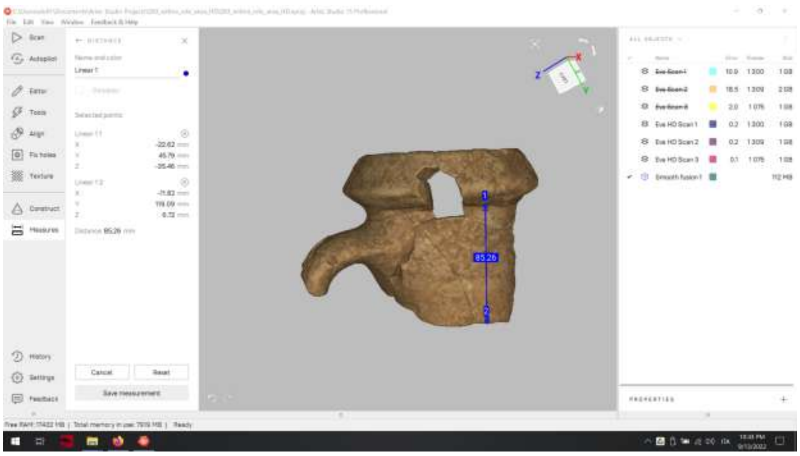

Figure 3.7: Processing 3D model in Artec Studio software

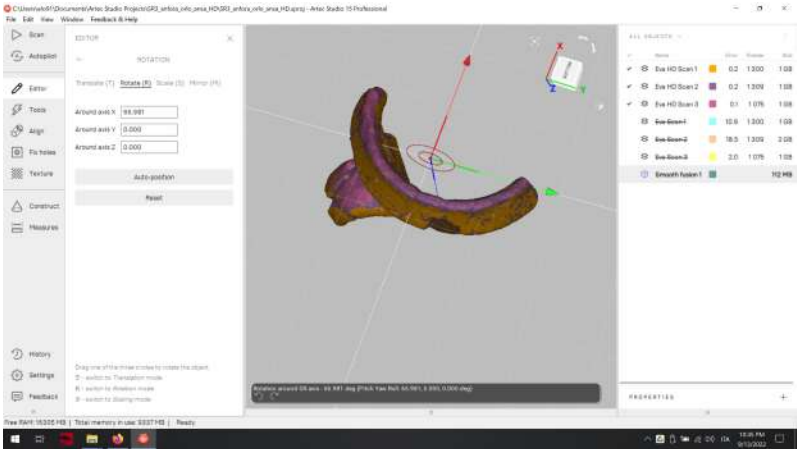

Figure 3.8: Processing 3D model in Artec Studio software

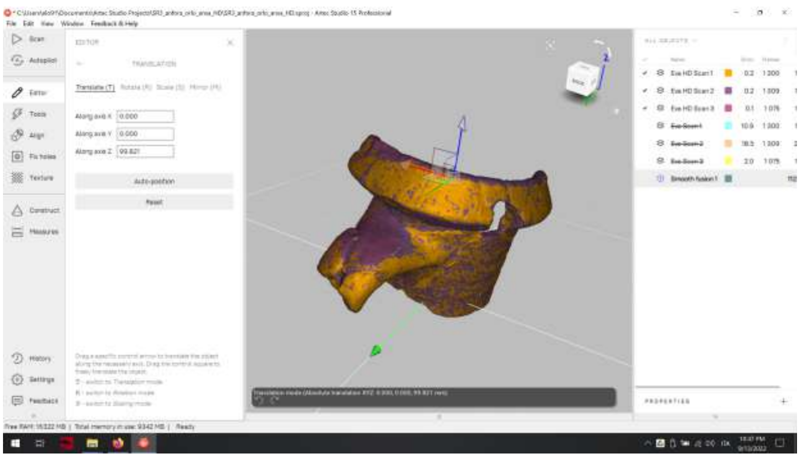

Figure 3.9: Processing 3D model in Artec Studio software

Structure from Motion Photogrammetry

Photogrammetry is an important image-based technique which allow the acquisition of accurate information from photographs. This technique basically turns 2D image data into 3D data, creating a 3D model[23].

It can be employed in different applications like mapping, 3D documentation, conservation, digital restoration, reverse engineering, animation, urban planning, deformation analysis[24].

The photogrammetric method generally employs minimum 2 pictures of the same target from 2 different perspective. Similar to human vision, if an object is seen in at least 2 images, "the different relative positions allow a stereoscopic view and the derivation of 3D information of the scene"[25].

Stereo analysis uses two or more input images to estimate the distance to points in a scene. The basic concept is triangulation: a scene point and the two camera points form a triangle, and knowing the baseline between the two cameras, and the angle formed by the camera rays, the distance to the object can be determined.

The two-camera model uses the same system used by our brain, in fact it is based on the biological model of stereovision itself, where thanks to the distance between the eyes, the depth can be estimated. Basically, we have 2 eyes with a space between them and this space is used by our brain to give us the perception of the depth and the third dimension. Each eye receives a slightly different image, which are processed together by the brain that calculates the distance to the object. So, stereoscopic vision is at the base of the Image-based 3D modeling.

"In recent years, Structure from Motion (SfM) complemented by dense image-matching algorithms embedded in Multi-View Stereo (MVS) approaches"[26], has revolutionized the archaeological survey and the excavation process recording.

In general, it is necessary to document the area before starting the excavation and also to record every stage of the digging process. In the past, the process was documented manually, in fact archaeologists had to draw for example the skeleton and grave in plan view (which is not simple), if they had to record the excavation of a burial. Now, with the development of new technologies, archaeologists have only to take a series of digital photos from as many angles as possible at every stage of the excavation. Because the Structure from Motion procedure is able to automatically define the position and orientation of the cameras, software like Agisoft Metashape can easily generate a 3D computer-generated model of the area comparing the photos

[23] Remondino and Campana, *3D Recording and Modelling in Archaeology and Cultural Heritage - Theory and Best Practices*.

[24] Remondino and Rizzi, "Reality-based 3D documentation of natural and cultural heritage sites—techniques, problems, and examples".

[25] Remondino and Campana, *3D Recording and Modelling in Archaeology and Cultural Heritage - Theory and Best Practices*.

[26] Lei Luo et al. "Airborne and spaceborne remote sensing for archaeological and cultural heritage applications: A review of the century (1907–2017)". In: *Remote Sensing of Environment* 232 (2019), p. 111280. ISSN: 0034-4257. DOI: https://doi.org/10.1016/j.rse.2019.111280. URL: https://www.sciencedirect.com/science/article/pii/S0034425719302998.

taken[27].

Photogrammetry is cheap and accessible to all, because this method requires only a simple camera (like a common mobile phone camera) and some softwares. On the contrary, the 3D laser scanning method, for example, needs expensive and specialized equipment[28]. Moreover, in recent years, new technologies have improved and facilitated this technique. In traditional photogrammetry, it is necessary to know in advance the positions of the camera and the positions of some points visible in more than an image; instead, the SfM used with MVS technique permits the generation of 3D models in an easier way, without knowing the imaging parameters and the network geometry[29].

Another advantage of photogrammetry is that it is possible to obtain 3D models, using archive images, objects or scenes that are no longer available or have been damaged. Compared to active sensors (such as laser scanner), photogrammetric surveys use images that contain all the information (geometry and texture) useful for rendering 3D models[30].

The basic procedure of creating a 3D model through the Structure from Motion Photogrammetry consists of different stages, some of which are generated automatically by the software, while others are produced by those working on the project. The general workflow is:

- planning and reconnaissance; sensors and digital cameras capable of acquiring images are normally used from the ground or mounted on aerial platforms (aero-planes, balloons, helicopters) or satellite[31];

- taking a large number of pictures from different perspective of the object, creating an overlapping set[32]; in the case of terrestrial shots, the operator must acquire the images covering the entire surface of the object to be surveyed, avoiding shaded areas and always ensuring a sufficient degree of overlap between the different images[33].

  Each part of the scene should be visible on at least 3 images, taken from different viewpoints, if they have to be reconstructed in 3D. This could be difficult in case of architectural structures because taking photos just from the ground level creates some shadows in upper parts of the architecture. The best solution is to use unmanned aerial vehicles (UAV) in order to reach parts

[27] Renfrew and Bahn, *Archaeology Essentials: Theories, Methods, Practice with 303 Illustrations*.
[28] Ibid.
[29] Luo et al., "Airborne and spaceborne remote sensing for archaeological and cultural heritage applications: A review of the century (1907–2017)".
[30] Russo, Remondino, and Guidi, "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico".
[31] Ibid.
[32] J. Bedford and Historic England. *Photogrammetric Applications for Cultural Heritage: Guidance for Good Practice*. Historic England Guidance Series. Historic England, 2017. ISBN: 9781848025028. URL: https://books.google.it/books?id=tdrMtQEACAAJ.
[33] Russo, Remondino, and Guidi, "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico".

of the structure that are not accessible from the ground level[34].

From the practical point of view, there are different photo-shooting strategies for a facade, an interior or an isolated objects, but concerning only the 'terrestrial' photo-shooting scenario, it is possible to recognise two basic methods[35]:

1. the walk-around method, which is suitable for recording objects outdoors, because the photographer has to move around the object. It is also used for documenting a solitary object in an indoor environment, but in this case it is necessary to do appropriate camera settings and chose the appropriate lighting conditions[36];
2. the turntable method, which is used for the documentation of portable object in an internal environment. This method is "based on photo-shooting in a single direction, from a camera mounted on a tripod"[37], so the position of the object has to be changed several times during the photo-shooting. The movement of the object is necessary because in this way it is possible to record all possible angles and sides of the object. The position can be changed manually but usually the photographer uses a rotating base[38].

Concerning the aerial and satellite images, the photo-shooting is more difficult so the photos are all acquired with parallel take axes[39];

- pre-processing images; all images should be checked before uploading them because this process can save time later. It is necessary to remove images that are of poor quality, "usually those that are comprehensively out of focus or exhibit significant motion blur as a result of either incorrect camera settings or the use of frames grabbed from video"[40];
- uploading the pictures in the software, like for example Agisoft Metashape, capable of identifying features or interest points (IPs) on the images. It is necessary to have the same interest point in different images, in fact: "the main requirement is that the definition of IPs should have good repeatability: the same IPs should be detectable across images under different lighting conditions and with different levels of image noise a quality known as invariance"[41].

  Usually the user set the number of IPs identified on each image through the software, but there are default values, for example in Agisoft Metashape is 40,000 per image[42].

[34] Predrag Novaković et al. *3D Digital Recording of Archaeological, Architectural and Artistic Heritage*. Dec. 2017. ISBN: ISBN 978-961-237-898-1 (pdf). DOI: 10.4312/9789612378981.
[35] Ibid.
[36] Ibid.
[37] Ibid.
[38] Ibid.
[39] Russo, Remondino, and Guidi, "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico".
[40] Bedford and England, *Photogrammetric Applications for Cultural Heritage: Guidance for Good Practice*.
[41] Ibid.
[42] Ibid.

Once a wide set of IPs has been identified and matched across image pairs, there is the process of triangulation. This process is able to calculate the relative position and orientation of the camera for each image in every pair and when there are overlapping pairs, they are combined to form a single block.

The optimisation of this process is achieved by a bundle adjustment, which "seeks to minimise the re-projection errors between observed and predicted image points"[43], and so to reduce the discrepancy in the image distance between the initial estimated position of a point and its real value;

- creating a sparse point cloud; for example, in Agisoft Metashape the IPs are called key points and the sparse cloud points seen in the model view after alignment are termed tie points. Tie points basically are key points (IPs) that have at least two projections each: "they are key points that have been matched on two or more images and therefore have become potential tie points"[44];
- creating a dense point cloud; once all the previous parts of the process are complete, the dense point cloud can be created;
- generating secondary product; a range of possibilities exists for the outputs, including ortho-images, digital elevation models (DEMs) and textured meshes;
- further processing and analysis of the outputs in other software (CAD, GIS, etc).

X-ray computed microCT

MicroCT is another way to produce a 3D model because it is a 3D imaging technique. This technique has the advantage of recording not only the outer surfaces (but without texture) of the analysed samples but also their inner microstructure. This is very important especially when the analysed samples are precious and cannot be damaged through traditional sampling techniques, so it is very used in the cultural heritage domain. MicroCT "gives non-invasive access to three-dimensional (3D) information"[45]. It can reveal the inner microstructural features of fossil remains and archaeological artefacts. The 3D models which are generated are characterised by different grey levels depending on the absorption properties of the materials, which are related to the density of the components of the samples. The lighter parts are the most dense, the darker parts the least dense.

Differences in resolution are given by the size of the samples, because higher is the resolution and smaller is the sample size. If you have a large sample, you can either:

[43] Ibid.

[44] Ibid.

[45] Federico Bernardini, Claudio Tuniz, and Franco Zanini. "Chapter 2 - X-Ray Computed Microtomography for Paleoanthropology, Archaeology, and Cultural Heritage". In: *Nanotechnologies and Nanomaterials for Diagnostic, Conservation and Restoration of Cultural Heritage*. Ed. by Giuseppe Lazzara and Rawil Fakhrullin. Advanced Nanomaterials. Elsevier, 2019, pp. 25–45. ISBN: 978-0-12-813910-3. DOI: https://doi.org/10.1016/B978-0-12-813910-3.00002-1. URL: https://www.sciencedirect.com/science/article/pii/B9780128139103000021.

analyse a small part at a very high resolution or analyse the entire sample at a medium-low resolution.

This technique makes it possible to see beyond the surface by revealing the internal microstructural characteristics of the samples analysed with micrometric resolution.

Analyses are applied to a variety of features on fossil dental and osteological material, artefacts in metal, glass/ceramics, wood/charcoal and stone, as well as archaeological food remains, textiles, leather, wood and paper. Other material of archaeological interest includes ancient musical instruments, prehistoric pottery ancient mummies, flint tools and wooden statues. X-ray microCT has been also used to check collagen preservation in archaeological bones, before the use of invasive methods such as those required for radiocarbon dating. Paleontological remains, more specifically paleoanthropological specimens such as crania, teeth and postcranial bones, are now frequently analysed with microCT, using both synchrotron radiation and microfocus tubes. An example could be represented by the analysis of the Neanderthal child mandible from a cave in Archi in Southern Italy. After the microCT process, it was possible to see the permanent teeth that were growing, in addition to the 5 teeth already out. The post processing permits the analysis of the mandible through a virtual reconstruction of all teeth but also the extraction of every single tooth and the separation of the dental tissue[46].

Another example could be the use of MicroCT to study pottery. In this case the microCT allowed to investigate both manufacture technology and provenance of the vases, but also to quantify and qualify the different components of the material (example: quartz inclusions, limestone fragments, etc.)[47].

Thanks to a few examples given here, it is possible to understand that the microCT method is very versatile for the 3D nondestructive investigation of materials and objects. A growing number of museums, universities and other institutions involved in archaeological and paleontological research are acquiring 3D imaging systems based on microCT. This X-ray technique evolved from conventional clinical CT scanning[48], with more than two orders of magnitude increase in space resolution and a great enhancement in image contrast. The past 20 years have been characterized by advances in microCT as a result of technological advances in X-ray and development is still in progress for the improvement of microfocus tubes and synchrotron radiation X-ray sources and techniques, as well as front-end microelectronics for data acquisition. Progress in computer processing speed and storage memory capacity has also been crucial for the development of microCT.

[46] Bernardini F. et al. "Microtomographic-based structural analysis of the Neanderthal child mandible from Archi, Southern Italy". In: *Proceedings of the European Society for Human Evolution* 2 (2013), p. 44. URL: http://hdl.handle.net/10278/3733680.

[47] F. Bernardini et al. "Neolithic pottery from the Trieste Karst (northeastern Italy): A multi-analytical study". In: *Microchemical Journal* 124 (2016), pp. 600–607. ISSN: 0026-265X. DOI: https://doi.org/10.1016/j.microc.2015.09.019. URL: https://www.sciencedirect.com/science/article/pii/S0026265X15002209.

[48] Bernardini, Tuniz, and Zanini, "Chapter 2 - X-Ray Computed Microtomography for Paleoanthropology, Archaeology, and Cultural Heritage".

The ICTP system

X-ray microCT scanners are available commercially but some groups are developing dedicated systems, specifically designed for applications in archaeology, palaeontology and cultural heritage, with space resolutions from sub-µm, for small mm-size objects, to tens of µm for 10-20-cm size objects. Portable systems for very large objects (e.g. archaeological items that cannot be moved from the museum) have been designed or are being planned. The ICTP X-ray microCT system is specifically designed for the investigation of relatively large objects (lateral dimension up to 20 cm and a weight up to 15 kg), with a voxel size of 50-100 µm. Smaller volumes can be studied with a voxel size of 5-10 µm. This system complements other instruments operated by Elettra, the synchrotron X-ray microCT setup at the SYRMEP beamline and two conventional stations. In the ICTP microCT system, X-rays are produced by a Hamamatsu microfocus X-ray source (150 kV maximum voltage, 500 µA maximum current, 5 µm minimum focal spot size). The detector is a Hamamatsu CMOS flat panel coupled to a fiber optic plate under GOS scintillator. The source-detector system and the sample manipulator are mounted on a flexible mechanical setup, which can be easily disassembled. Detector and movement system have been selected among several available choices to perform at high precision. A lead-shielded cabinet is being presently used to perform microCT experiments at the ICTP (Fig. 3.10).

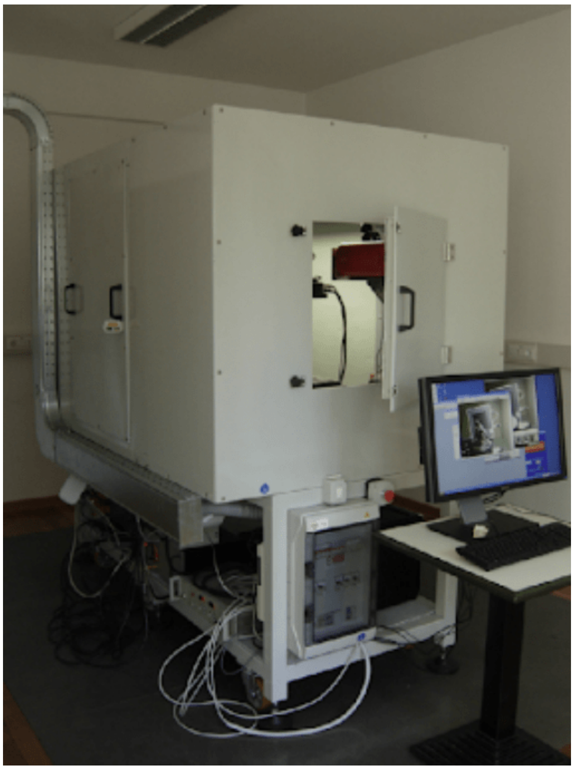

Figure 3.10: The lead-shielded cabinet used to operate the mCT in the ICTP laboratory (Image taken from the article "The ICTP-Elettra X-ray laboratory for cultural heritage and archaeology")

The system has been designed to allow large sample-to-detector distances to exploit phase-contrast effects. 3D images are generated from a large series (typically from 1440 to 1800) of 2D radiographs, using specific mathematical algorithms for slice reconstruction. Materials microstructure can be studied at the micrometre scale by using virtual sectioning, segmentation and rendering methods[49].

There are three main components in conventional microCT scanners, including the ICTP system (Fig. 3.11):

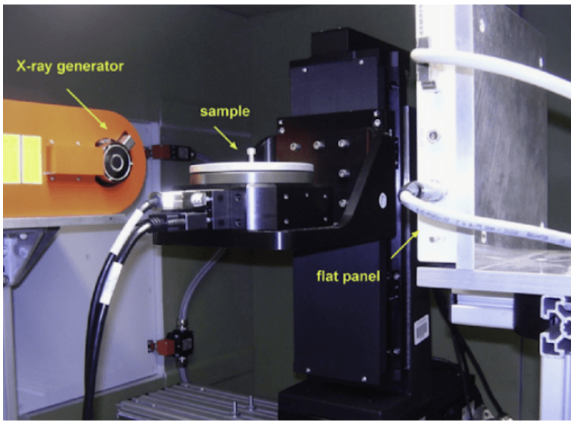

Figure 3.11: Inside the ICTP microCT system: the source–detector system and the sample manipulator are mounted on a flexible mechanical set-up (Image taken from the article "The ICTP-Elettra X-ray laboratory for cultural heritage and archaeology")

- x-ray tube, which produces the x-rays;
- rotation stage and positioning system (sample manipulator), to place the sample within the field of view of the detector;
- detector, which acquires radiographs.

The acquisition and data reconstruction process is as follows:

- place the sample on the rotation stage and be sure that it is fixed because it is important that the sample does not move during the acquisition (foam rubber can often be used with very small objects);
- acquire a large number of radiographs (typically from 1440 to 1800) turning the sample over 360° degrees;
- the next process is the transversal slices reconstruction through commercial software based on specific mathematical algorithms. Thanks to this reconstruction it is possible to create the 3D model, which is not a mesh but a stack of the obtained slices;

[49] Claudio Tuniz et al. "The ICTP-Elettra X-ray laboratory for cultural heritage and archaeology". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 711 (May 2013), 106–110. DOI: 10.1016/j.nima.2013.01.046.

- the final step is the rendering and the segmentation through commercial software. At ICTP, VG Studio Max 2.1 (Volume Graphics) and Avizo are used. In order to virtually separate parts with different density and then virtually extract all the components, it is necessary to do a long work of segmentation.

Some iron artefacts included in the present project have been scanned using microCT in order to obtain information about the state of preservation and original shape under corrosion layers. The next images show some 2D radiographs and virtual slices of the javelin tip (Fig. 3.12), (Fig. 3.13), (Fig. 3.14).

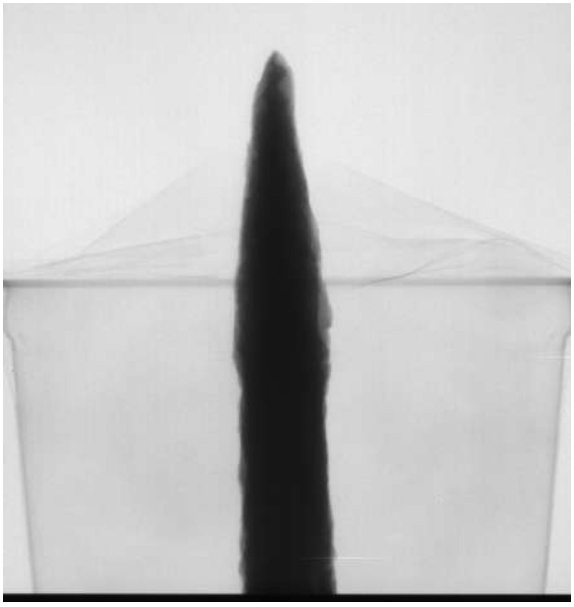

Figure 3.12: 2D radiograph of the javelin tip

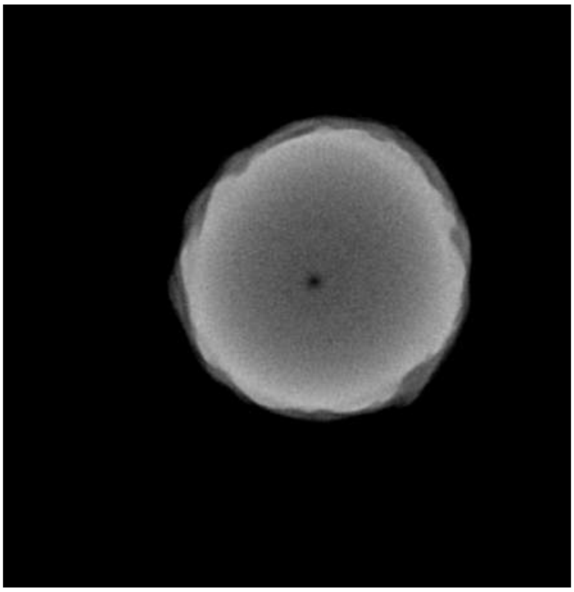

Figure 3.13: Virtual slice of the javelin tip

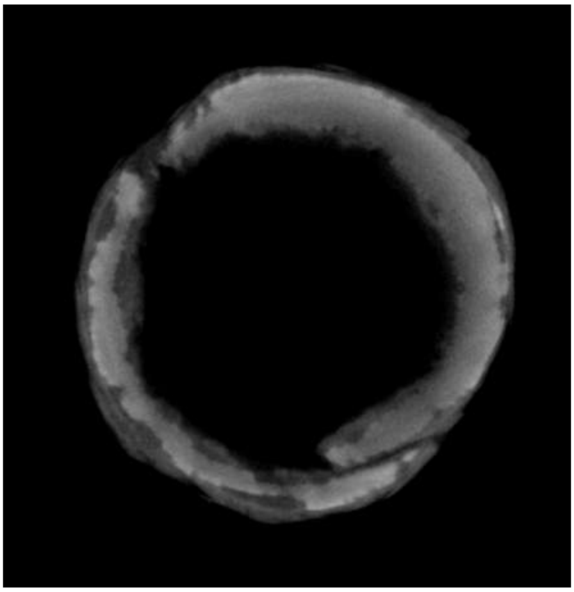

Figure 3.14: Virtual slice of the javelin tip

After the acquisition of the radiographs, the reconstruction of transversal slices was made through the commercial software DigiXCT (DIGISENS) (Fig. 3.15), (Fig. 3.16). The outcome of this reconstruction is a 3D model, made of a stack of the obtained slices, not a mesh.

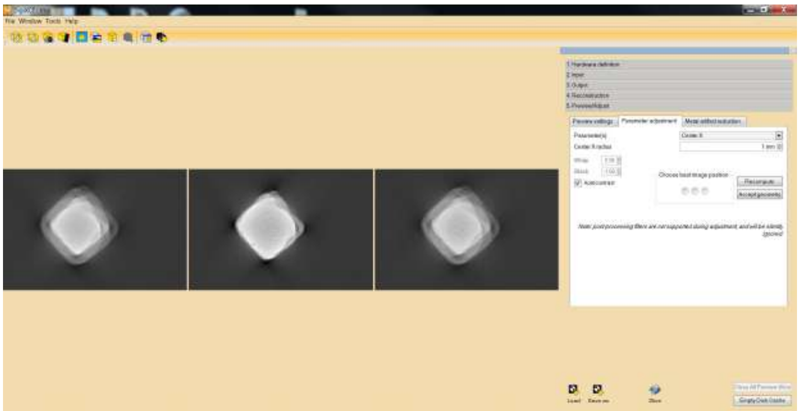

Figure 3.15: Transversal slices reconstruction of the javelin tip in DigiXCT

In order to visualise the 3D model and all the related radiographs, it was used the software VG Studio Max (Fig. 3.17).

Once the 3D data have been acquired, the whole volume of the artefacts has been selected in the software Avizo, assigned to a material and then exported as a surface (i.e. mesh) in order to use it to show just the external 3D aspect of the artefacts (Fig. 3.18), (Fig. 3.19), (Fig. 3.20), (Fig. 3.21), (Fig. 3.22).

Contrary to other 3D methods, microCT shows the inner structure of samples but does not allow to obtain a texture. This is why the 3D models obtained by microCT, included in the "Oltreaquileia" website, are without colour information.

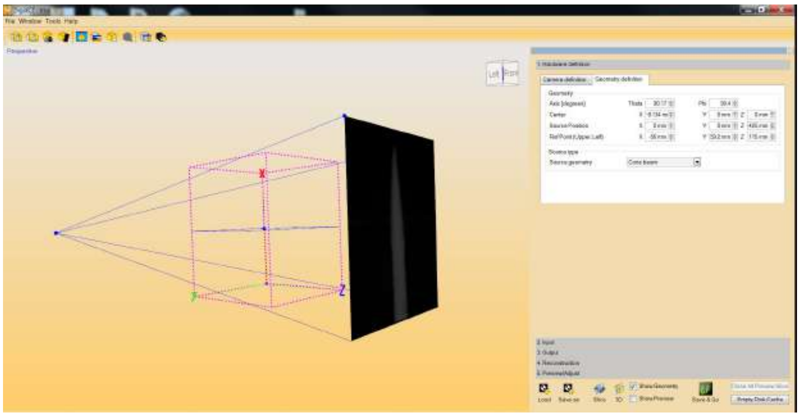

Figure 3.16: Transversal slices reconstruction of the javelin tip in DigiXCT

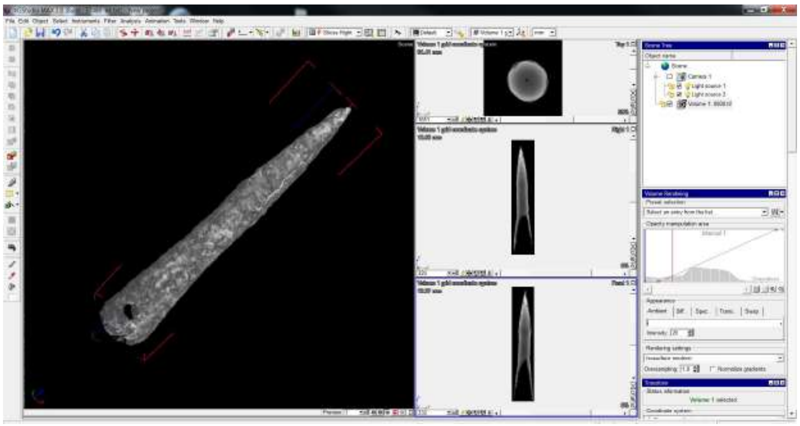

Figure 3.17: 3D visualization of the 3D model with all the radiographs in VG Studio Max

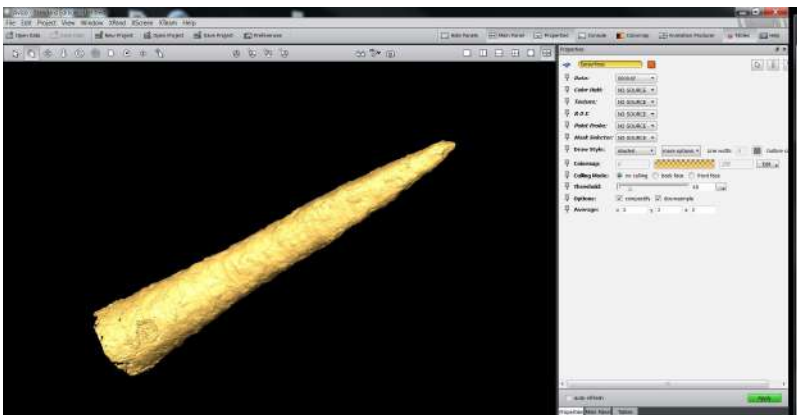

Figure 3.18: 3D visualization of the 3D model in Avizo

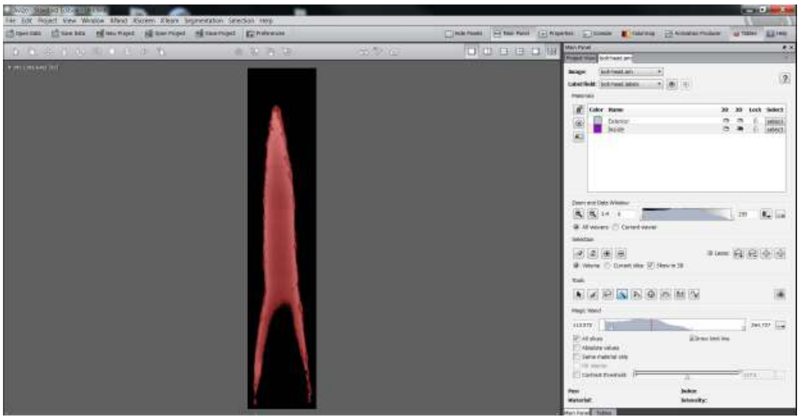

Figure 3.19: Process of segmentation of the 3D model in Avizo

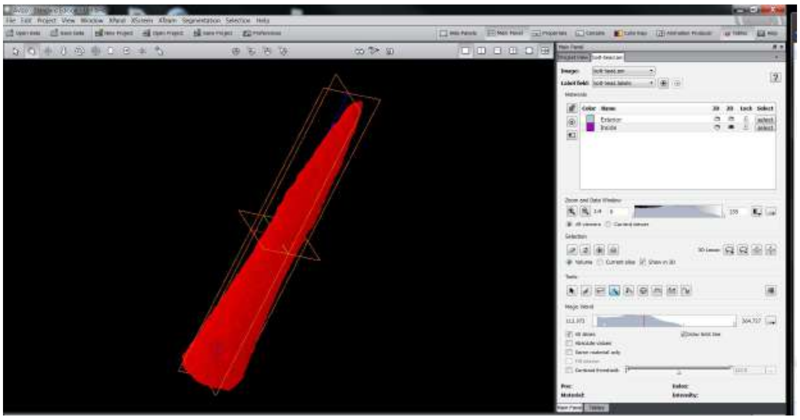

Figure 3.20: Process of segmentation of the 3D model in Avizo

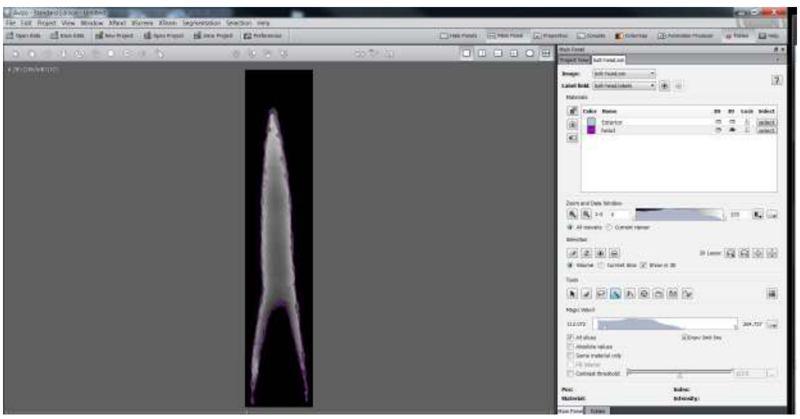

Figure 3.21: Process of segmentation of the 3D model in Avizo

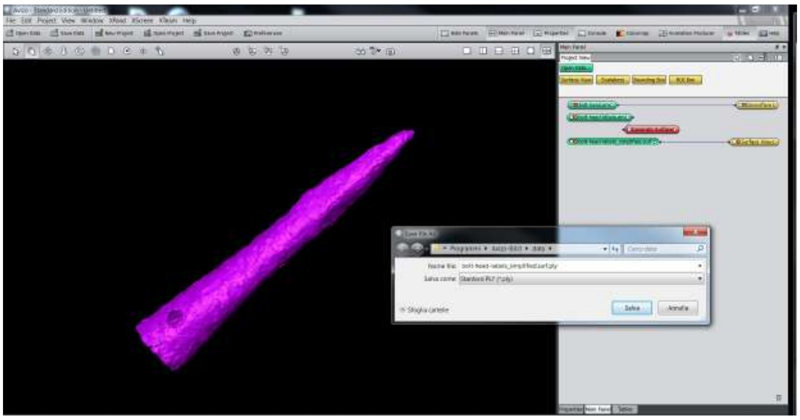

Figure 3.22: Exporting the 3D model in .ply format

Chapter 4

Specific outcomes

After finishing the preparation of the 3D models and the creation of the HTML pages (text files with html extension) for every 3D model, they had to be uploaded to the "Oltreaquileia" website.

Figure 4.1: Visualisation of an amphora rim generated through the structured light scanner in the "Oltreaquileia" website

We upload the models in the website and the following are the results. The first image is the result of a 3D model generated through the structured light scanner Artec Eva 3D. This technology permitted to display also the texture so it is possible to see the colours of the 3D model, like in reality (Fig. 4.1). The 3D model is an amphora rim and so we decided to present it as if it were in its actual position (if it was attached to the amphora). This decision have been taken for all the amphora fragments selected because in this way people can understand very easily what is the artefact displayed. Making the process of understanding simple is necessary because if users in general don't understand, they will not appreciate. For a public of specialists can be easier to understand, but it is always a good idea to display the artefacts in a correct way. Precisely because they are specialists, they may find it much more difficult to work with our materials if they are presented in the wrong way. For these reasons all the artefacts have been oriented in the correct position before the upload.

The second image shows the 3D model of the javelin tip generated with X-ray computed microtomography (microCT) (Fig. 4.2). Most of the archaeological pottery materials discovered in the considered sites were analyzed by microCT to produce 3D models and virtual sections[1]. The difference of these 3D models is that they don't have the texture, because microCT shows the inner structure of samples but does not allow to obtain a texture.

Figure 4.2: Visualisation of a javelin tip generated through the microCT in the "Oltreaquileia" website

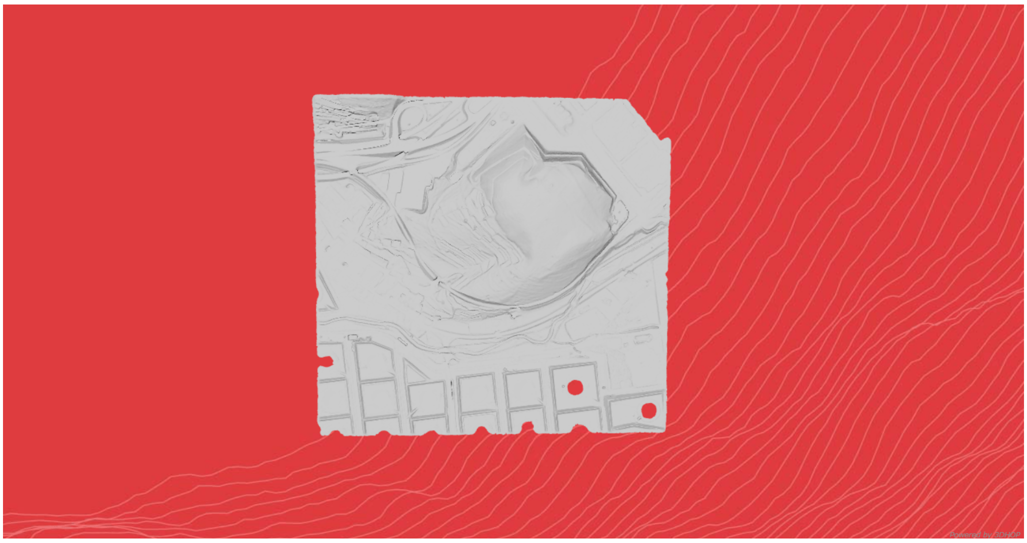

Figure 4.3: Visualisation of a 3D model of San Rocco created through lidar in the "Oltreaquileia" website

[1]Bernardini et al., "Early Roman military fortifications and the origin of Trieste, Italy. Proceedings of the National Academy of Sciences 112(13): E1520–E1529."

The next image represents the 3D model of San Rocco site generated through Lidar. The resulting point-cloud data of the acquisition process were classified in points related and not related to the ground through a filtering procedure. Then the points belonging to the ground were extracted[2] and a mesh has been created. In simple word, the vegetation have been removed from the surface of the site and the result is a model without texture (Fig. 4.3).

Figure 4.4: Visualisation of a 3D model of the dedication to Timavo generated through photogrammetry in the "Oltreaquileia" website

The following image shows the result of a photogrammetry process (Fig. 4.4). In this case the photos were taken for creating the 3D model of the dedication to Timavo. With photogrammetry it is possible to visualize also the texture.

Also the excavation of San Rocco was created with photogrammetry and the following image is the result with the texture (Fig. 4.5).

The website "Oltreaquileia" became an instrument to discover the archaeological sites selected from a different point of view. In fact users have the opportunity to discover the historical background of the archaeological artefacts and the related location but also the features of the artefacts through the catalogue. In the same website, they can interact with the 3D models uploaded thanks to the functions available (the functions will be explained in the following chapter). The website is designed to permit users to navigate in an easy way, because the functions are easily comprehensible.

[2] Ibid.

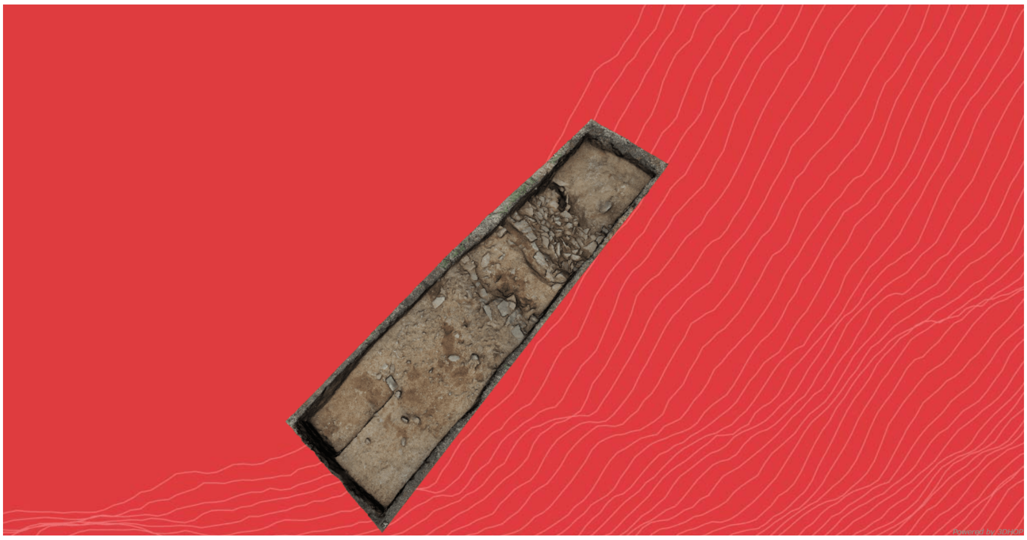

Figure 4.5: Excavation of San Rocco generated through photogrammetry in the "Oltreaquileia" website

Chapter 5

Visualisation of models on the web

With the idea of democratization of knowledge in mind, the idea of the present work was to implement the "Oltreaquileia" website with several 3D models of artefacts and sites related to the conquest and Romanization of the north-eastern Adriatic regions. In this way any individual can take advantage of the models directly in the website. It is possible to see them from both smartphones and PCs, as the website is responsive.

In my research I used the open-source tool 3DHOP, which is the acronym of 3D Heritage Online Presenter. This tool "is an open-source framework for the creation of interactive Web presentations of high-resolution 3D models"[1] and is mostly dedicated to the Cultural Heritage field.

3DHOP process

By using 3DHOP to create 3D model views, the user can interact with 3D models directly within a common web page. Its process is relatively simple because all you need to do is adding some HTML and JavaScript components in the web page source code.

The site presents the models without too much difficulty loading because the NEXUS model converter (which is explained later) converts and compresses the model. In fact, 3DHOP is able to work with very large 3D models (1-10-100 millions of triangles or points) with ease, also on low-bandwidth, because it uses NEXUS multiresolution format (.nxs or .nxz). Multiresolution models are streamed from remote and they are rendered adaptively and then optimised according to viewpoint and view distance. 3DHOP does not require a specialized server. It is only necessary to have some space on a web server and it works directly inside modern web browsers without plug-ins or additional components[2].

[1] Marco Potenziani et al. "3DHOP: 3D Heritage Online Presenter". In: *Computers & Graphics* 52 (2015), pp. 129–141. ISSN: 0097-8493. DOI: https://doi.org/10.1016/j.cag.2015.07.001. URL: https://www.sciencedirect.com/science/article/pii/S0097849315001041.

[2] Ibid.

The process started from downloading: 3DHOP framework and NEXUS model converter (for converting and compressing the 3D models). 3DHOP has been designed to work over the internet, with the webpage and data on a remote web server, accessed from the browser through the web. However, when developing web pages, it is much easier to work locally. This can be done in two ways and I have decided to install a local web sever: Apache HTTP Server. In order to install this web server software it is a good choice to use a web server solution stack package like XAMPP, which is free and open source[3].

For what concern the preparation of models is necessary to know that 3DHOP uses the NEXUS multiresolution format (.nxs or .nxz), so 3DHOP is able to manage with high-resolution triangular meshes.

The first step was to prepare the models and for doing that I used MeshLab, an open source system for processing and editing 3D triangular meshes. I applied a rototranslation to each 3D model, so I moved the model on the XYZ axes to put it in an easy-to-view position, which is the same position where users will see it on the website. This is possible because MeshLab uses the same reference system as 3DHOP (Fig. 5.1).

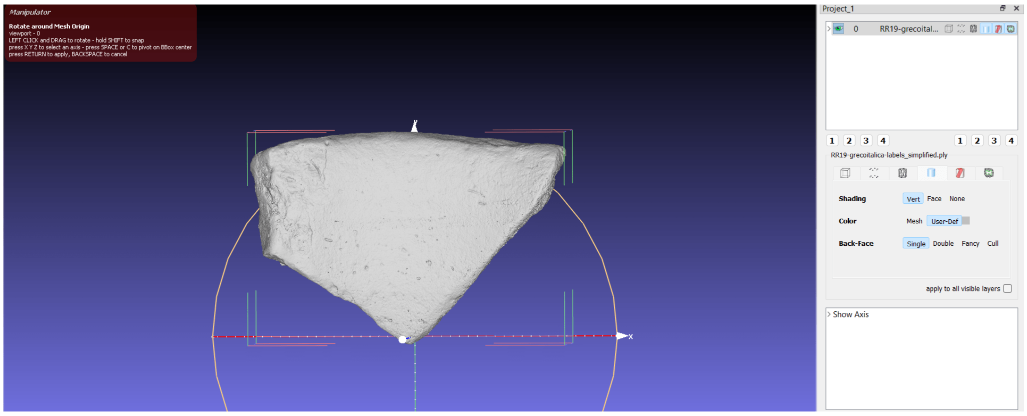

Figure 5.1: Process of rototranslation of a 3D model in MeshLab

In the end I had to freeze the matrix of the transformation and export the model in .ply format.

When I had my models ready (in .ply format), I had to drag and drop the file inside *nxsbuild.exe* (found in the NEXUS folder) to convert the model to .nxs format. Then it was necessary to compress the .nxs format to .nxz format by dragging and dropping the file inside *nxscompress.exe*. After creating the file in .nxz format, I was able to insert this file inside my .html file. For this part I decided to use Visual Studio Code, as a source-code editor.

For each model there has to be an .html page. In fact, in every .html page it is necessary to specify which model (in format .nxz) the function *setup3dhop* has to show in the webpage. Also the background had to be specified in the .html page, therefore, after saving the .jpg file in the folder dedicated only to backgrounds, a precise function allows our background to be shown.

[3]Potenziani et al., "3DHOP: 3D Heritage Online Presenter".

Then, I was able to open it to display the 3D model. First I had to activate the local web sever Apache HTTP Server from the XAMPP Control Panel (Fig. 5.2) and then I opened the 3DHOP folder (which I created on my PC) on localhost. At this point it is possible to see all the .html pages created and choose which one of them to open (Fig. 5.3).

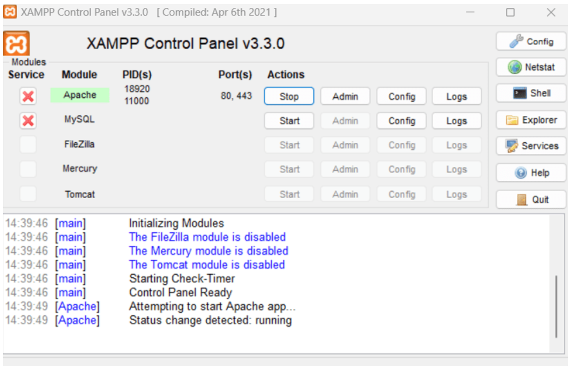

Figure 5.2: XAMPP Control Panel

Figure 5.3: 3DHOP folder on localhost

It is possible to open one of them at a time and see the model in our background (Fig. 5.4).

The model is not static in the page but the user can move and rotate it, thanks the function of *SphereTrackball*. Moreover, in every page, we decided to add different

Figure 5.4: Visualisation of an amphora fragment in the "Oltreaquileia" website

buttons, which allow the user to interact more with 3D model. Looking at the image, from top to bottom (Fig. 5.4), the first icon permits the user to return to the homepage and then there are the instruments to zoom-in and zoom-out. The following icon enable the lighting of 3D model and the next one enable the light control, so the user can choose the position of the light source. In basic terms, the user is able to hover over the model with the mouse and choose which side to illuminate. Then there is the icon with a ruler because it represents the measurement tool. This instrument permits the user to pick two points on the surface of the model and obtain the length. The following button enables the pickpoint mode, so user is able to pick a point on the surface of the model and retrieve the coordinates XYZ. Then there is the plane sections, a tool designed to allow user to section in real time the 3D models in the scene. If user clicks on the icon a toolbar, which represent the "sectioning" interface, will be open and it is possible activate/deactivate the X, Y and Z sectioning plane. After activating, the three sliders moves the corresponding sectioning plane across the extent of the scene. This tool can be used to see the inner structure of the objects or can be useful to perform more accurate measurement, removing some parts of the scene. The following tool is dedicated to the texture, in fact it enables the visualisation of the texture (if the model is provided) and the last one permits the visualisation of the model in an orthographic view.

"Oltreaquileia" website implementation

The exhibition "Oltre Aquileia" ran from 16 October 2021 to 28 February 2022 and was held in 2 different spaces: one section was displayed at the Speleological Museum of the Grotta Gigante and, the other one, at the Visitor Centre of Val Rosandra in the Municipality of San Dorligo della Valle/Dolina. The first section contained the material traces found from the Roman expansion and the second section was devoted to the interdisciplinary methods used[4].

[4] Bernardini and Duiz, *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)*.

This website was created on the occasion of this exhibition, as a platform to make accessible the exhibition catalog dedicated to the republican fortifications of Trieste and sites related to them, but it was designed also for future purposes. The aim, in fact, was and still is to expand it by adding other contents such as: 3D models or films, etc.

Figure 5.5: "Oltreaquileia" homepage

As we can see from the image (Fig. 5.5), the menu contains: *Home* with a description of the exhibition; *Catalog* with the full catalog; *3D models*, where some 3D models are already uploaded and *News* with published articles.

As has been said in the previous lines, the exhibition catalog was the first step into the website. The catalogue has been added in its entirety, complete with its cover, so users can browse through it as if it were in the printed version (Fig. 5.6).

Figure 5.6: Catalogue "Oltreaquileia" available on the website

Users can browse each page of the catalogue at a time or enter the page they want to view and the system will display the desired page. It is possible to zoom in, zoom out or share the catalogue, but also to print and download it.

The work of the catalogue was complete, so our aim was to add contents to another part of the website, in fact we have uploaded all the new models we have created to the *3D models* section. The user now has the option of scrolling through the menu that opens by clicking *3D models* and choosing which model to display. Every time the model will be opened in another window and it is possible to see the model one at time. Users can not view several models in one single window.

The website became an open platform for everyone. Now, researchers, specialists, students and the general public can have access to 3D models of artefacts from Trieste's military sites. In the future the site will be enriched with more content.

Conclusions

"The role of archaeology is: collective act of remembering"[5]. That said, archaeologists have developed several methods to achieve this goal. Over the years, archaeologists have endeavored to document their work by manually writing down their data on paper and the drawings on graph paper. With the advent of photography, archaeologists used to take photos of the excavation and then manually upload them to the computer once back home. Archaeologists spent several hours transferring the day's notes onto the computer and often did so during the night[6]. Later, with the advent of digital age, archaeologists integrated their work with other digital tools. New techniques and technologies are constantly being developed.

It is often the case that today's three-dimensional digital survey techniques seem to be more complex than most traditional methods to which the archaeologist was accustomed. This difficulty, mainly related to the use and management of 3D information, is however balanced by the great potential of these tools. These in fact make it possible to obtain geometric and colorimetric information much more complete than the information obtained through traditional survey techniques, but also with less time and with a much higher degree of accuracy. The application of these methodologies makes it possible to generate digital copies of real models, which are 'informative digital models' because they contain the information related to the artefact being analysed[7].

In recent months, archaeologists in Pompeii simplified their work by using the iPad, with a LIDAR scanner. During last summer's Pompeii I.14 project, where objects from an ancient Roman kitchen were unearthed, archaeologists used iPads to document and examine the findings, reconstructing the ways in which these artefacts were used by their creators. IPad pro has become a key tool in archaeology because as Allison Emmerson, a Tulane University professor who led the excavation, explains: archaeological excavations are a destructive process, because once excavated, that work can never be repeated in the same way. Therefore, the archaeologists in this project took care to record all relevant data from the excavation so that future researchers can reconstruct the site as it was interpreted. The iPad can record the

[5]Akira Matsuda and Katsuyuki Okamura. "Introduction: New Perspectives in Global Public Archaeology". In: July 2011, pp. 1–18. ISBN: 978-1-4614-0340-1. DOI: 10.1007/978-1-4614-0341-8_1.

[6]Giulia Giaume. *Ecco perché l'iPad sta cambiando il lavoro degli archeologi a Pompei.* https://www.artribune.com/arti-visive/archeologia-arte-antica/2022/11/ipad-lavoro-archeologi-pompei/. Nov. 2022.

[7]Russo, Remondino, and Guidi, "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico".

archaeological excavation automatically and digitally, including photographs, notes and drawings of the excavation trenches, while on smaller sites it can also create 3D maps that accurately record where each artefact was unearthed[8].

In any case, which method will be used is not very important, because for archaeological research, it is fundamental to record and document artefacts and sites in an accurate way, because only with a complete and precise digital documentation it is possible to interpret and analyze properly[9].

In order to best fulfil this purpose, it is important to be aware that digital analysis techniques and available digital technologies are becoming increasingly important in recent years. This is due to the fact that they facilitate knowledge and interpretation of the archaeological artefact. Consequently, knowledge (even minimal) about the existence of these technologies, their functioning and potential is increasingly required. This knowledge allows archaeologists to choose when to use these new technologies or when to use traditional techniques. It allows them to do the work themselves, without calling on external figures (such as 3D imaging experts), but also to be able to interpret the results obtained and assess their quality. Finally, it makes archaeologists capable of using the generated digital model and aware of the tools to interrogate it and extract useful information for ongoing analysis[10].

The figure of the archaeologist is becoming increasingly interdisciplinary, as different skills are required. It is important that they have the possession of the knowledge of archaeological methods because, if "the role of archaeology is: collective act of remembering"[11], archaeologists play a significant role in defining the past[12].

Our project could be considered an excellent example of interdisciplinary work in all the phases. During the excavation different methods have been used; archaeologists and researchers have intertwined excavations and archaeological surveys, but also new technologies, like *Airborne Laser scanning* and *Ground Penetrating Radar*. After the process of excavation, there was the idea of making cultural artefacts accessible to the general public and specialists. In order to reach that aim, different 3D technologies have been compared and tested so various skills were needed. After our work, the site became a platform where the public and specialists have the opportunity to interact with 3D models of a selection of significant artefacts from Trieste's military sites for educational and outreach aims. Furthermore, users can discover also a project of virtual reality of the reconstruction of San Rocco camp.

All these contents have been uploaded to the website because new technologies also make an active contribution in the valorisation of the artefacts through the web[13].

The work on this website does not end with these additions as it is a dissemination tool and will therefore be updated with new 3D models and other different contents.

[8] Giaume, *Ecco perché l'iPad sta cambiando il lavoro degli archeologi a Pompei*.

[9] Barsanti, Remondino, and Visintini, "3D Surveying and Modelling of Archaeological Sites-some critical issues".

[10] Russo, Remondino, and Guidi, "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico".

[11] Matsuda and Okamura, "Introduction: New Perspectives in Global Public Archaeology".

[12] Ibid.

[13] Russo, Remondino, and Guidi, "Principali tecniche e strumenti per il rilievo tridimensionale in ambito archeologico".

Credits

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>
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>
> *the experiences I have had, for bringing me this far.*

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[11] Federico Bernardini and Alessandro Duiz. *Oltre Aquileia. La conquista romana del Carso (II-I secolo a. C.)* 2021.

[12] Federico Bernardini, Claudio Tuniz, and Franco Zanini. "Chapter 2 - X-Ray Computed Microtomography for Paleoanthropology, Archaeology, and Cultural Heritage". In: *Nanotechnologies and Nanomaterials for Diagnostic, Conservation and Restoration of Cultural Heritage*. Ed. by Giuseppe Lazzara and Rawil Fakhrullin. Advanced Nanomaterials. Elsevier, 2019, pp. 25–45. ISBN: 978-0-12-813910-3. DOI: https://doi.org/10.1016/B978-0-12-813910-3.00002-1. URL: https://www.sciencedirect.com/science/article/pii/B9780128139103000021.

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