A 3D REPOSITORY OF DINOSAUR TEETH: THE GENERATION OF OPEN RESOURCES FOR THE CLASSIFICATION AND IDENTIFICATION OF SPECIMENS

J.M. Valle-Melón[1,6], J. Korro[1,6], J.C. Corral[2], B. García[1,6], X. Pereda-Suberbiola[3], E. Isasmendi[3], A. Torices[4], Á. Rodríguez Miranda[1,5] *

[1] Built heritage research group (GPAC), Universidad del País Vasco/Euskal Herriko Unibertsitatea (UPV/EHU), Vitoria-Gasteiz, Spain - (jm.valle, mirenjaione.korro, benat.garcia, alvaro.rodriguezm)@ehu.eus
[2] Museum of Natural Sciences of Álava, Vitoria-Gasteiz, Spain - ccorral@externos.araba.eus
[3] Departamento de Geología/Geologia Saila, Facultad de Ciencia y Tectonogía/Zientzia eta Teknologia Facultatea, Universidad del País Vasco/Euskal Herriko Unibertsitatea (UPV/EHU), Bilbao, Spain – (xabier.pereda, erik.isasmendi)@ehu.eus – xabier.pereda@ehu.eus
[4] Departament of Geodinamics, Stratigraphy and Palaeontology, Faculty of Geological Sciences, Complutense University of Madrid– atorices@ucm.es
[5] Department of Applied Mathematics, University of the Basque Country (UPV/EHU), Vitoria-Gasteiz, Spain
[6] Department of Mining Engineering, Metallurgy and Materials Science, University of the Basque Country (UPV/EHU), Vitoria-Gasteiz, Spain

KEY WORDS: Structured-light scanning, palaeontology, 3D recording, data preservation, 3D catalogue.

ABSTRACT:

Among the many valuable uses of the artificial intelligence in the field of museums, it may assist the classification of out-of-context items. This paper deals with the problem of the identification of dinosaur teeth (a type of fossil that is usually found scattered), which can be tackled by means of multivariate algorithms (such as the principal components, discriminant or cluster analyses) taking as a starting point a series of morphometric values (i.e., distances between specific points of the fossil tooth). A good interpretation requires some comprehension regarding the mathematical algorithms that are used, as well as the specific knowledge in palaeontology that permits appreciating the actual reach of the results. However, based on metric values as the computations are, there must also be some control over their precision and the possibility of checking the old measurements or complete the list of morphometric variables. This is an aspect that may be solved if the three-dimensional models of the teeth are made publicly available.
The text describes the 3D documentation of a set of twelve fossil teeth of the museum of Natural Sciences of Álava (Vitoria-Gasteiz, Spain) —approximately from 1 to 6 cm in size— using a structured light scanner and close-up photographs for recording some features smaller than the resolution of the scanner. The information about each tooth was then packed and uploaded to the university repository, from where it is also accessible via cultural and scientific aggregators (such as *Europeana*); likewise, reduced resolution copies are also accessible in the commercial platform *Sketchfab*®.

1. INTRODUCTION

Dinosaur teeth appear in many palaeontological contexts and are one of the most abundant fossils for supporting postulates about the taxa, distribution and feeding behaviour because, throughout their life, dinosaurs continuously grew new teeth to replace the former ones (Hendrickx et al., 2015, 2019; D'Emic *et al*., 2019). This is important in the case of theropod dinosaurs because their remains are usually scarcer and, sometimes, teeth are the only fossils we have to understand their diversity in the ancient ecosystems (Torices et al., 2015; Hendrickx et al., 2015, 2019).

However, the fact that teeth commonly appear isolated hinder their classification because in general appearance they look very similar among different taxa. A common way to support the systematic assignation of an isolated tooth to a certain taxon combines a set of linear measurements concerning some macroscopic features (in particular crown base length, crown basal width, crown height and apical length) in the millimetre/centimetre range and some submillimetre ones such as the denticle density (i.e., the number of peaks along the serrated edge per unit of length) (Hendricks, *et al*., 2019; Isasmendi *et al*., 2022). Qualitative features —as the shape of the denticles and the enamel texture— are also important for the expert classification, although the algorithms for automatic grouping often ignore them.

The database with the morphometric measures is subsequently processed by means of multivariate techniques in order to find a few (usually two, but they can also be three) new variables — factorial axes— which are linear combinations of the original ones showing as much as possible the variability of the data. These new factorial variables are represented in graphs where the elements for the same taxa appear clustered together. For example, the following 3D graph shows the result of the discriminant analysis of a set of 66 teeth belonging to five different taxa. The original database consists of five variables (crown height, crown base length, crown base width, mesial and distal denticle densities) that were reduced to three factorial variables.

* Corresponding author

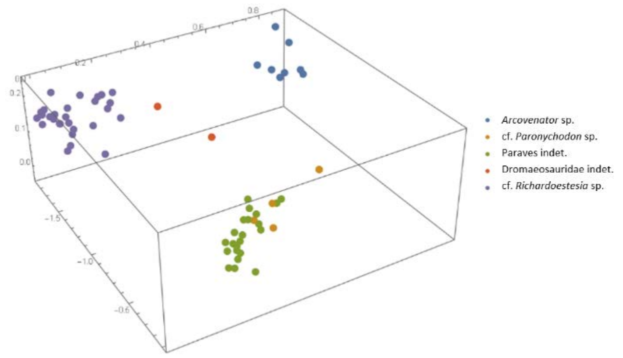

Figure 1. 3D scatter plot generated by discriminant analysis of a database containing morphometric values of 66 dinosaur teeth belonging to five taxa. This figure comes from the research project mentioned in the acknowledgements (Rodríguez Miranda, et al., 2022).

Although the main idea of this procedure is simple, the practical application becomes more complex since the selection of the morphometric values that are considered/ignored or the way that these characteristics are introduced in the computation entail significant changes in the obtained results.

Another point of concern is that the classification algorithms are often used as black boxes, that is to say, the users are given results, but they do not actually know why the specimens are located where they are in the scatter plot. To prevent this, it would be advisable that the analysis of the data counts on the expertise hereunder indicated:

- On the one hand, understanding of the algorithms is necessary (mathematical expertise). At least, it is essential to be aware of the purpose of the computation (what it does and what it does not). Likewise, the types of data that are expected (e.g., quantitative or qualitative values) and whether they need to be pre-processed or not (e.g., if they require to be normalized beforehand and how).
- On the other hand, field expertise (in this case, the paleontological one) is also necessary in order to interpret the results properly and assess their true scope. For example, if the specimens of two taxa appear mixed together… is there something incorrect in the classification or is it a sensible result since both taxa do not differ very much?
- In addition, as the algorithm used to distribute the elements in the new factorial space is based on the morphometric values that were recorded by some measuring techniques, the accuracy of the values and the propagation of the uncertainty may also be determining factors for the results. The present paper treats on some matters that fall within this metrical expertise.

The morphometric values of reference specimens that are used for comparison purposes are tabulated in scattered scientific papers. Moreover, there are several issues regarding the lack of consistency of the measurements recorded by different authors and the limitation to the study of the predefined features. These drawbacks could be sidestepped if precise three-dimensional models of the teeth were publicly available.

2. OBJECTIVE

The text presents the case of the three-dimensional documentation —by means of structured light scanning (VIGIE, 2022)— of a set of twelve dinosaur teeth from the upper Campanian Laño site (Condado de Treviño, Burgos) that are part of the collection of the museum of Natural Sciences of Álava —Arabako Natura Zientzien Museoa/Museo de Ciencias Naturales de Álava (MCNA)— (Corral et *al.*, 2016; Isasmendi *et al.*, 2022). The preparation of the 3D models and the dissemination via an open repository, with the aim of increasing the number of references for identification and classification purposes.

Furthermore, the 3D contents can help improve the visibility and community outreach of the museum. Indeed, the museum is situated in a medieval palace renovated in the late 1960s and early 1970, which creates a nice atmosphere for the visitors who, in return, suffer from a shortage of space and difficult accessibility. Moreover, the information provided on the website is poor and its palaeontological collection is yet to be included in cultural aggregators —such as the *Basque Museums' Collective Catalogue*, the *Digital Network of Collection of Spanish Museums* or *Europeana*— (although, in the near future, it is planned to upload part of the references to the *Global Biodiversity Information Facility* - GBIF).

3. MATERIALS AND METHODS

The teeth were documented in the facilities of the museum. These fossils are in the storage area —i.e., not in exhibition (Kęsik *et al*., 2023)— and, in general, they are in good preservation conditions, both facts facilitated the access to the specimens for this study. Apart from the technical staff of the museum, the team was composed of palaeontologists (for the choice of the specimens and the validation of the resulting 3D models), a conservator (for the handling of the fossils) and those entrusted of the geometric documentation. Moreover, advice from the part of the mathematics was also necessary, bearing in mind the subsequent use of these 3D models.

Attention should be drawn to the fact that the space available at the museum is limited to the one that can be released on the tables of the room that serves as laboratory and library, bearing in mind that many boxes and other fossils under study tend to compete for this finite space.

Therefore, the work required a portable equipment that could be quickly mounted in the laboratory of the museum, not taking up much space and that can be picked up at the end of the day. In particular, a short-range scanning device (“Scan in a box” fringe projection system) was selected. According to the technical specifications, the minimum size of the object that this equipment can document is 1 cm, with an attainable precision of 0.1% at the highest resolution, which is around 0.08 mm. This scanner records the colour of the surfaces but not very accurately; however, the main purpose of the models is to serve as geometric reference, thus the moderate quality of the texture was not considered a critical shortcoming.

https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1589-2023 | © Author(s) 2023. CC BY 4.0 License.

Figure 2. Preparation of the fossils (foreground) and set up of the scan area (background) at the laboratory of the museum of Natural Sciences of Álava.

The selection of the equipment and techniques for the three-dimensional documentation was based on examples about similar works but it also considered previous experiences (Rodríguez Miranda *et al.*, 2019). Looking at the references, mention must be made to many interesting examples of 3D geometric documentation of small and delicate archaeological objects and paleontological specimens, which make use of manifold approaches based on photogrammetric systems (e.g., Katsichti *et al*., 2019) or different types of scanners (time of flight, structured light, computed tomography…) (e.g., Miłosz *et al*., 2022). As examples of documentation of animal fossil teeth, sometimes as part of complete skulls, there are many references which uses a wide variety of the previous techniques: either photogrammetry (e.g., Santella & Milner, 2017; Stubbs-Lee *et al*., 2021; Sakaki *et al*., 2022), scanners (e.g., Das *et al*., 2017; Poropat *et al*., 2022) of both (e.g., Fahlke & Autenrieth, 2016; Ziegler *et al*., 2020).

Anyway, before starting the work at the museum, the system was set up in a laboratory at the university to check that the performance was adequate (as far as the time for the scans, the geometric definition of the features of the teeth and the size of the specimens to be documented are concerned). For these tests, three similar teeth lent by the University of La Rioja were used.

Fossils are brittle and need to be handled with care (Aymeric & Rull, 2021). Consequently, nitrile gloves and tweezers were used to avoid direct contact, as well as specific conservation materials (such as *Ethafoam*® and *Tyvek*®) for supporting the pieces in the different positions that were necessary for the successive scans. The foam was carved with a scalpel to create stable support of the fossil in each scanning position.

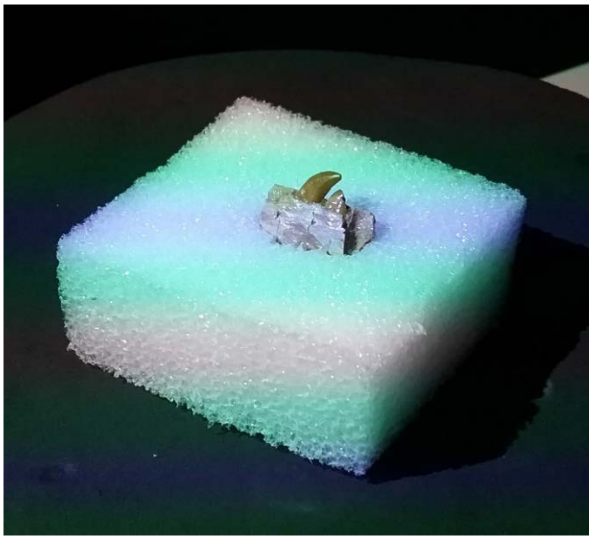

Figure 3. Set up for the scanning of a dentary fragment with two teeth (inventory number: MCNA 14624, Dromaeosauridae indet.). The fossil is supported on a piece of neutral foam.

The scan incidence was around 45º from the vertical and the distance to the object was set to 32 cm. The piece of foam with the tooth was located on a turntable that rotated in eight positions for each scan. Next, the fossil was relocated on the foam to make visible parts that were not in the previous scans. Usually, four to six different placements of the fossil were necessary to document its entire surface.

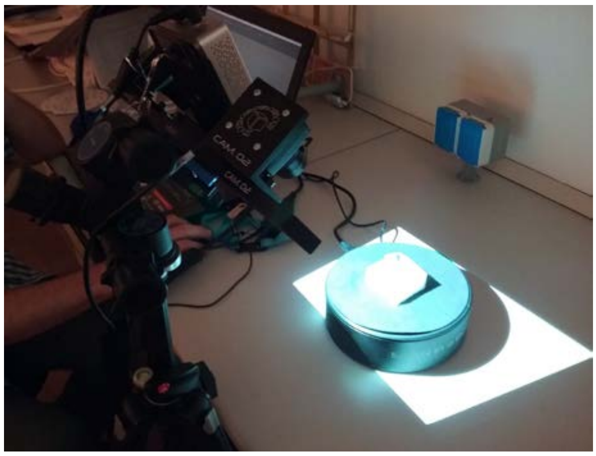

Figure 4. The scan is situated above the object and 32 cm far. It projects the strips obliquely at 45 degrees. The turntable rotates in eight positions showing different parts of the tooth in each scan.

The eight scans generated in each rotation of the turntable were automatically aligned by the software, thus generating a joint 3D model for that position. However, every time that the fossil was resituated on the foam the new partial 3D model was in a different reference system from the previous ones; therefore, it was necessary to align them, firstly with a preliminary manual definition of —at least— three common points, followed by a precise matching based on the common surfaces. The statistics generated by the software during the global alignment provided standard deviations of the distances of around 0.01 to 0.02 mm.

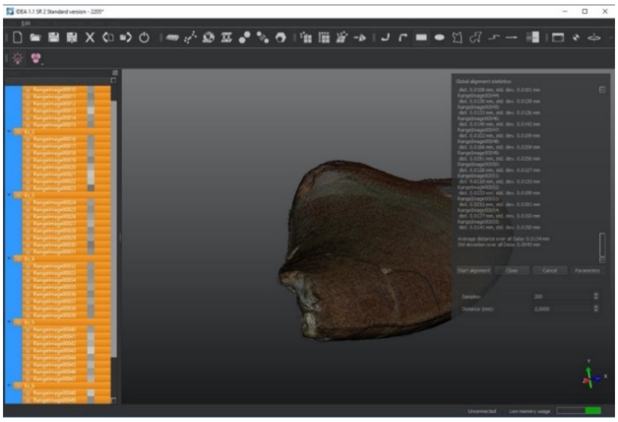

Figure 5. Global alignment. On the left panel the six groups of eight scans are indicated.

The alignments of the 3D models were done on-site for three reasons: firstly, because having the fossils in hand made easier to identify common points among the groups of scans; secondly, since the models were completed scan by scan and, being at the museum, made possible to decide whether the coverage of the surface was finished or, conversely, if more scans were necessary. Finally, problems that occurred during the scanning (for instance, due to unnoticed movements of the fossil on the foam during the spin of the turntable, a wrong configuration of the parameters of capture, unsuitable lighting conditions, etc.) could be detected as they arose. As a drawback, doing the alignments in the museum slowed down the productivity in terms of the number of documented teeth per day. Actually, we spent around two hours for each specimen.

Later, at the university laboratory, the models continue their processing from the alignment, going from the refining of the point clouds, the meshing and texturing.

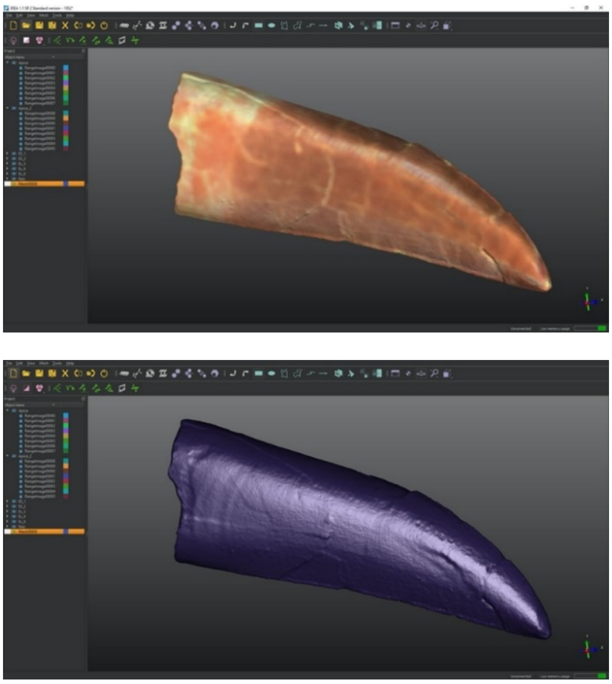

Figure 6. 3D model, final mesh with the texture registered by the scanner (up) and 3D model represented only with the shaded mesh (down) (specimen of *Arcovenator* sp. with inventory number: MCNA 1852).

As can be seen, the shaded model (without texture) is usually more adapted for the analysis of the geometry of the surfaces than the model with textures.

When the models were ready, they were checked on the screen. Then, we came back to the museum another day in order to verify that some irregularities were not due to artefacts during the 3D processing, but to real geometries caused by chipped parts, adhesive and fillers used in their restorations, patches of mineralized matrix, etc.

Figure 7. Parts of the model that needed revision (specimen MCNA 1853, *Arcovenator* sp.) (up) and visual inspection with the help of a magnifier (down).

4. RESULTS

4.1 3D models

After the alignment of the different scans necessary to complete the model of each tooth, the surfaces were meshed and cleaned. Thereupon, the models were exported in PLY (for visualization) and STL (for printing) formats, described and uploaded to the repository.

From that moment on, the 3D models can be used to measure distances either in the three-dimensional space or in orthographic 2D-views. Moreover, new metrics about the morphology such as surface and volumes (i.e., non only based on one-dimensional distances) can be also obtained. Likewise, the models are also useful for dissemination purposes, three-dimensional printing and so on.

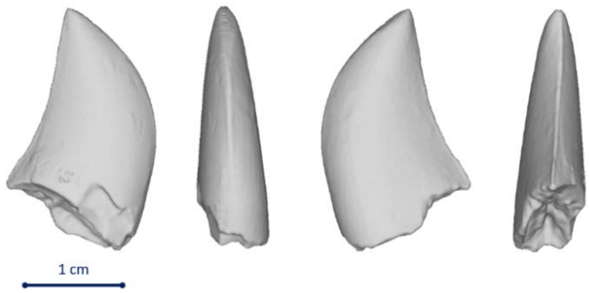

Figure 8. Four orthographic shaded views taken from the 3D model of one of the teeth (MCNA 14522, *Arcovenator* sp.).

4.2 Complementary photographs

A complementary collection of close-up photographs (between 6 and 10) for each piece was obtained. The aim was to document the texture, small imperfections, cracks and features with a size smaller than the resolution of the scan. After testing different camera types and configurations, the analysis of the data provided evidence about good results (regarding resolution, discernibility of details and depth of field) with the camera of a mobile phone (Xiaomi M2007J17G) with the "macro" option activated (35 mm equivalent focal length of 2 mm) and forced flash..

Figure 9. Photograph taken with a mobile phone in "macro" mode and flash for enhancing the details.

The photographs show the striation of the surfaces, deteriorations and some small features that are not properly recorded by the 3D scanning such as the denticles (density, size and shape) along the edges of the tooth.

Figure 10. Example of resulting photograph (tooth MCNA 14522, *Arcovenator* sp.). It complements the 3D model with the information about the texture of the surface, the identification of the denticles, etc.

The images were later enriched with descriptive IPTC metadata[1], which can be subsequently used for searching, classification and data retrieval.

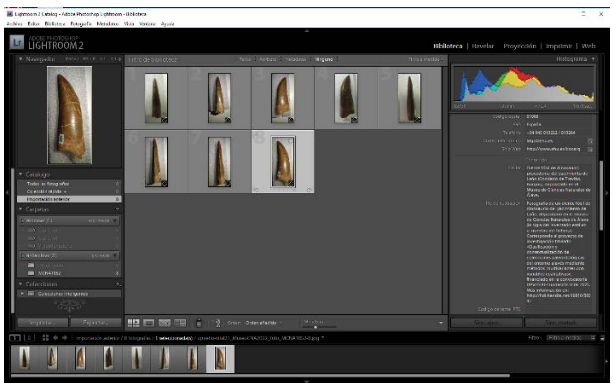

Figure 11. Detailed images of one of the specimens in the software for image management *Adobe Lightroom*®, the set of descriptive metadata is presented on the right panel.

In particular, the metadata include the following:

- In the block of "basic information", it is indicated that the photograph shows a fossil tooth from the site of Laño that is deposited in the museum of Natural Sciences of Álava (with a particular inventory number), that this image was taken in the context of the research project that is indicated in the section for acknowledgements of this paper and the permanent link to the register at the university repository (see below) where more images, the three-dimensional models and the scientific reports of the project are available.
- The blocks "IPTC content" and "IPCT creator" provide a short description of the tooth and the names of both the photographer and the description writer.

[1] Technical specifications and guidelines for the implementation of these metadata can be found at the website of the International Press Telecommunications Council (IPTC): https://www.iptc.org/standards/photo-metadata/

- In “IPTC copyright”, it is stated the names of the author of the photographs and the contexts of generation. On the other hand, the rights usage terms allow re-use under a Creative Commons-BY licencing.
- Finally, the blocks “IPTC image” and “Keywords” inform about the location of the museum and some content descriptors (in particular, the term “fossil” from the UNESCO thesaurus).

4.3 3D replicas

A collection of full-size printed replicas was generated and given to the museum. Replicas can be used for dissemination and for activities developed with the public to get closer and manipulate the specimens.

The printer used was an *Ultimaker S3*. The process started with the load of the STL file, which was rotated to a vertical position, this way, the arrangement of the successive layers of printing material generated a replica softer to the touch —tactile sensation is a quality factor for the appraisal of printed replicas (Wilson *et al*., 2018)—. Besides, the software calculated the material that is needed for support.

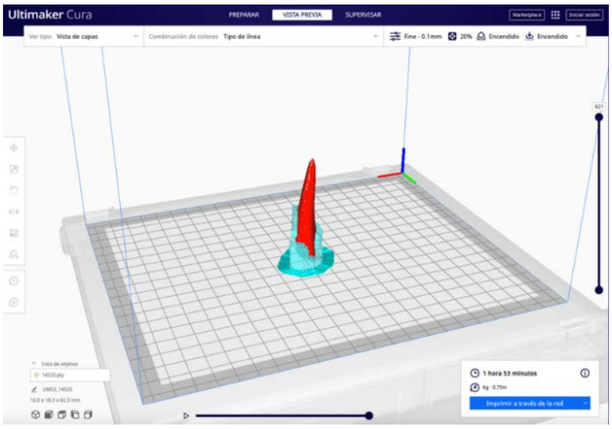

Figure 12. 3D printing software *Cura*®. The model of the tooth is represented in red while the supporting material is in cyan.

The thickness of the layers was set to 0.1 mm. The printer took from 60 to 90 minutes to reproduce each piece and then the product had to be immersed in water to remove the supporting material and release the printed model.

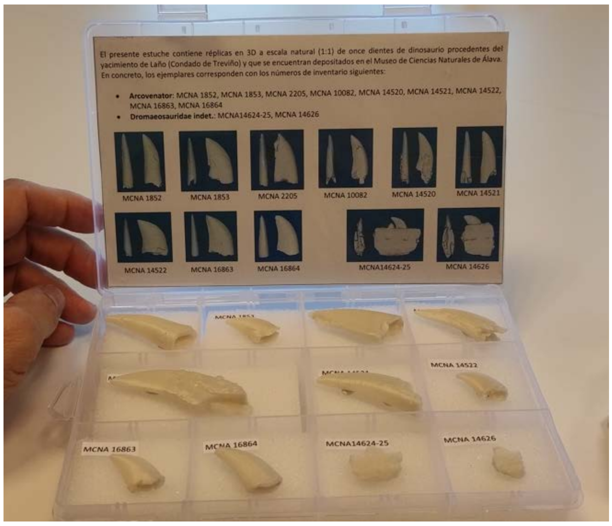

Figure 13. Box with the set of replicas.

4.4 Repository of 3D models

The dissemination of 3D contents can be channelled through a combination of two complementary systems: (1) public cultural/scientific repositories and aggregators and (2) by means of commercial platforms (Rodríguez Miranda *et al*., 2020).

An example of the former is *Europeana* —the collective catalogue for the European cultural institutions—, even though, nowadays, palaeontological collections are not widely represented. In our case, the information is provided via a record at the university repository (which is aggregated through the national point *Hispana*). This record contains the 3D models together with the reports with all the technical information about the digitization process and the characteristics of the results. The downloadable information from the repository consists of high resolutions 3D models in PLY format packed with the corresponding set of detailed photographs and a file with descriptive metadata (Dublin Core in XML). All the information is provided for re-use under a Creative Commons-BY licence.

Figure 14. Collection of 3D models at the university repository[2].

By contrast if we refer to commercial platforms for paleontological fossils, it is worth mentioning *Morphosource*® (Boyer *et al*., 2017); although the general purpose *Sketchfab*®

[2] http://hdl.handle.net/10810/58547

also contains an increasingly important number of models (e.g., Erolin *et al.*, 2017) and there are many other useful repositories (Cunningham, 2021). These platforms usually provide easier and quicker ways to disseminate the models, for instance they provide embedded interactive 3D viewers (something that is usually lacking in the cultural/scientific aggregators) and a huge and very active community of users. For this project, we resorted to *Sketchfab*®, where we created a collection with low resolution versions of the 3D models (for inspection) that are linked to the register at the university repository (where the full resolution models can be downloaded).

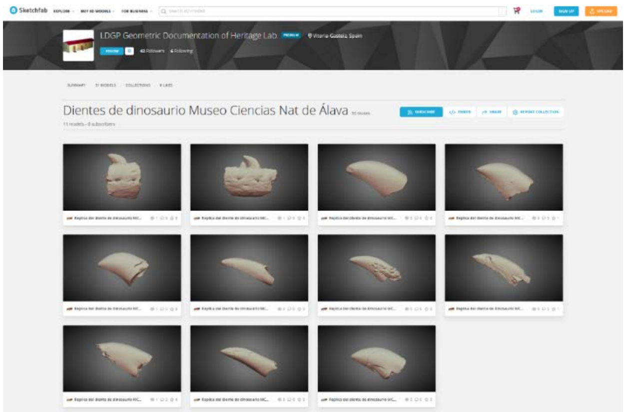

Figure 15. 3D models in *Skechfab*®[3]. The specimens of *Arcovenator* sp. correspond to the inventory numbers: MCNA 1852, 1853, 2205, 10082, 14520 14521 14522, 16863 and 16864; whereas the teeth of cf. *Paronychodon* sp. are the MCNA 14624-14625 and 14626.

5. DISCUSSION

The 3D models described in the previous sections were part of a more comprehensive study on the automatic classification algorithms in which 66 teeth for five different taxa (*Arcovenator* sp., Dromaeosauridae indet., cf. *Paronychodon* sp., Paraves indet. and cf. *Richardoestesia* sp.) were used. Nevertheless, only the specimens belonging to the two former taxa were large enough to be documented by means of the structured light scanner. In particular, the height of the specimens of *Arcovenator* sp. range from 20 to 60 mm and those assigned to Dromaeosauridae indet. are around 10 mm high. The teeth of the other three taxa —which were not modelled— do not exceed the 5 mm in height and are not suitable for the piece of equipment used in this project given their small size. In addition, even for the documented items the models are only adequate to reproduce the size and shape of the complete tooth and some macroscopic features. Conversely, some smaller characteristics (such as the form and number of denticles) falls below the resolution. That is why the models were complemented with the close-up photographs.

Apart from the previous techniques, the use of a portable digital microscope (*Aven Mighty Scope*®) was also considered during the preliminary stages. However, this system was discarded because the process of taking photographs was slow, in addition to its limited hardware capacities (low quality of the images due to softness of focus and poor lighting) and, finally, since the metric reference were the lines of a graph paper situated underneath, which introduced some metric distortions by the difference of height and perspective of the image.

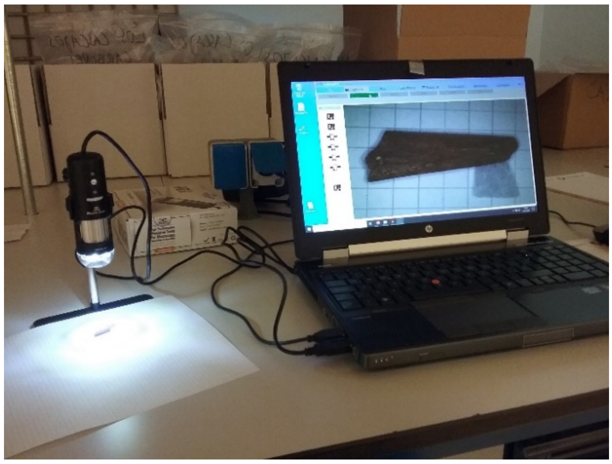

Figure 16. Photograph of a tooth taken with a portable microscope during the initial tests.

Although, in an ideal situation, the 3D models should register simultaneously both the macroscopic and the microscopic aspects, this is not an simple task for two reasons:

- On the one hand, it is difficult to be able to document features of very different sizes simultaneously and with a single type of equipment.
- Some parts of the tooth may require a particular resolution for the study of their specific characteristics. However, this improved resolution may be unnecessary for the rest of the model.

The combination of these two reasons calls into question the whole goal of having a large number of 3D models —generated by multiple organization and museums— that can be used for comparisons and classifications since we have acknowledged that some of the features that are important for such computations (the microscopic ones) will not be present in the 3D models.

This does not mean that the repositories of 3D models of dinosaur teeth are useless. On the one hand, we are still able to conduct comparisons based on the macroscopic characteristics of the fossils and this is something that can be most useful. On the other hand, we cannot disregard the other applications of the three-dimensional contents in education, dissemination, etc., which will help to make the investment profitable.

The availability of models in open databases allows contrasting the published values by means of the repeatability of the measures; on the other hand, we are free of selecting new measures from the 3D models instead of being limited to the specific values used by the previous authors. Indeed, three-dimensional models permit to go one step ahead from the analysis based on a set of linear features to the use of descriptive values concerning surfaces (e.g., roughness, local curvature, grooves, edge warp, etc.) and volumes.

[3] https://sketchfab.com/ldgp/collections/dientes-de-dinosaurio-museo-ciencias-nat-de-alava-77341b8f770446b295eac074709a0af3

Concerning the type of repository, it is possible to select (or to combine) between institutional public ones or commercial platforms. Our recommendation is to make use of the institutional repositories for the high-resolution models, because this decision does not make the re-use of the models contingent with the benefits of a particular company, it gives credit to the organizations which created the models, ensures the permanent availability of the datasets and permit to place the models in broader contexts (for instance, together with the technical reports about the documentation process). Nevertheless, it is evident that commercial platforms offer attractive possibilities that we should not ignore, let us use them… but do create a link to the institutional repository in case some users want to access the complete information.

6. CONCLUSIONS

The analysis of the results generated by the automatic classifications not only have to consider the inherent mathematics of the algorithms and the field knowledge (in the particular case presented here the paleontological one) but they also need to be aware of the influence of the characteristics of the metric values that the computations are using.

The availability of three-dimensional models of dinosaur teeth will help to further studies since it will permit different researchers to enlarge the number of specimens that can be used in their analyses. In any case, it is not possible to create models that are well adapted for all kind of research purposes. The recording technique and equipment used for the modelling will define the characteristics and limitations of the product.

Finally, it must not be overlooked that the models may also be useful for other purposes, such as dissemination or education, which make them particularly interesting for the promotion of the museums.

ACKNOWLEDGEMENTS

This work was supported by a grant of the University of the Basque Country (UPV/EHU) and the Fundación Vital Fundazioa in the framework of the call for research projects of the year 2021. Research of X. Pereda-Suberbiola and E. Isasmendi is financed by the Spanish Ministry of Science and Innovation (MCIN) and the European Regional Development Fund (FEDER) (research project PID2021-122612OB-I00), and by the Basque Country Government (research group IT1485-22). E. Isasmendi is supported by a PhD fellowship of the Basque Government/EJ (PRE_2019_1_0215). The participation of J. Korro is supported by the Basque Government through a grant for doctoral studies in the year 2019–2020 and its renewals.

REFERENCES

Aymeric, X, Rull, M. (2021) Una combinació difícil: grans dimensions i baixa mineralització. Manipulació, transport i mueïtzació d'espècimens fòssils. Unicum, 20: 71-84. https://raco.cat/index.php/UNICUM/article/view/399174

Boyer, D.M., Gunnell, G.F., Kaufman, S., McGeary, T.M. (2017) Morphosource: archiving and sharing 3-D digital specimen data. The Paleontological Society Papers, 22: 157-181. https://doi.org/10.1017/scs.2017.13

Corral, J.C., Pueyo, E.L., Berreteaga, A., Rodríguez-Pintó, A., Sánchez, E., Pereda-Suberbiola, X. (2016) Magnetostratigraphy and lithostratigraphy of the Laño vertebrate-site: Implications in the uppermost Cretaceous chronostratigraphy of the Basque-Cantabrian Region. Cretaceous Research, 5: 473-489. https://doi.org/10.1016/j.cretres.2015.07.015

Cunningham, J.A. (2021) The use of photogrammetric fossil models in palaeontology education. Evolution: Education and Outreach, 14:1. https://doi.org/10.1186/s12052-020-00140-w

D'Emic, M.D., O'Connor, P.M., Pascucci, T.R., Gavras, J.N., Mardakhayava, E., Lund, E.K. (2019) Evolution of high tooth replacement rates in theropod dinosaurs. PLoS One 14(11): e0224734. https://doi.org/10.1371/journal.pone.0224734

Das, A.J., Murmann, D.C., Cohrn, K., Raskar, R. (2017) A method for rapid 3D scanning and replication of large paleontological specimens. PLoS One 12(7): e0179264. https://doi.org/10.1371/journal.pone.0179264

Erolin, C., Jarron, M., Csetenyi, J. (2017) Zoology 3D: Creating a digital collection of specimens for the D'Arcy Thompson Zoology Museum. Digital Applications in Archaeology and Cultural Heritage, 7: 51-55. https://doi.org/10.1016/j.daach.2017.11.002

Fahlke, J.M., Autenrieth, M. (2016) Photogrammetry vs. micro-CT scanning for 3D surface generation of a typical vertebrate fossil – a case study. Journal of Paleontological Techniques, 14: 1-18,

Isasmendi, E., Torices, A., Canudo, J.I., Currie, P.J. and Pereda-Suberbiola, X. (2022) Upper Cretaceous European theropod palaeobiodiversity, palaeobiogeography and the intra-Maastrichtian faunal turnover: new contributions from the Iberian fossil site of Laño. Papers in Palaeontology, 8: e1419. https://doi.org/10.1002/spp2.1419

Hendrickx, C., Mateus, O., Araújo, R. (2015) A proposed terminology of theropod teeth (Dinosauria, Saurischia). Journal of Vertebrate Paleontology, 35(5): e982797. https://doi.org/10.1080/02724634.2015.982797

Hendrickx, C., Mateus, O., Araújo, R., Choiniere, J. (2019) The distribution of dental features in non-avian theropod dinosaurs: Taxonomic potential, degree of homoplasy, and major evolutionary trends. Palaeontologia Electronica 22.3.74: 1–110. https://doi.org/10.26879/820
palaeo-electronica.org/content/2019/2806-dental-features-in-theropods

Katsichti, V., Kontogianni, G., Georgopoulos, A. (2019) 3D documentation of frail archaeological finds using low-cost instrumentation. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives, 42 (2/W17): 157-164. https://doi.org/10.5194/isprs-archives-XLII-2-W17-157-2019

Kęsik, J., Żyła, K., Montusiewicz, J., Miłosz, M., Neamtu, C., Juszczyk, M. A. (2023) A Methodical Approach to 3D Scanning of Heritage Objects Being under Continuous Display. Applied Sciences, 13(1):441. https://doi.org/10.3390/app13010441

Miłosz, M., Montusiewicz, J., Kęsik, J., Żyła, K., Miłosz, E., Kayumov, R., Anvarov, N. (2022) Virtual scientific expedition for 3D scanning of museum artifacts in the COVID-19 period – The methodology and case study. Digital Applications in

Archaeology and Cultural Heritage. 26: e00230. doi: https://doi.org/10.1016/j.daach.2022.e00230.

Poropat, S.F., Frauenfelder, T.G., Mannion, P.D., Rigby, S.L., Pentland, A.H., Sloan, T., Elliott, D.A. (2022) Sauropod dinosaur teeth from the lower Upper Cretaceous Winton Formation of Queensland, Australia and the global record of early titanosauriforms. Royal Society Open Science, 9: 220381. https://doi.org/10.1098/rsos.220381

Rodríguez Miranda, A., Valle Melón, J.M., Torices, A., Lostado, R., Navarro, P., Elorriaga Agirre, G., Korro Bañuelos, J., Zornoza-Indart, A. (2019) 3D digitization of complex exhibition items (mounted skeletons of dinosaurs) and generation of virtual replicas for biomechanical studies. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Volume XLII-2/W15, 1015-1021. doi: https://doi.org/10.5194/isprs-archives-XLII-2-W15-1015-2019

Rodríguez Miranda, Á., Korro Bañuelos, J., Valle Melón, J.M. (2020) Archivo y difusión de contenidos 3D de elementos patrimoniales en repositorios institucionales y plataformas comerciales. Revista PH, 100: 78-80. https://doi.org/10.33349/2020.100.4641

Rodríguez Miranda, Á., Álvarez, M., Ferrero, A, García, B., Iñáñez, J.G., Korro, J., Lopetegi, A., López, I., Pereda-Suberbiola, X., Usategui, L., Valle-Melón, J.M. (2022) Informe del proyecto «Clasificación y contextualización de colecciones paleontológicas del entorno alavés mediante métodos multivariantes con variables cualitativas». Convocatoria de investigación UPV/EHU-Fundación Vital 2021. http://hdl.handle.net/10810/58547

Sakaki, H., Winkler, D.E., Kubo, T., Hirayama, R., Uno, H., Miyata, S., Endo, H., Sasaki, KJ., Takisawa, T., Kubo, M.O. (2022) Non-occlusal dental microwear texture analysis of a titanosauriform sauropod dinosaur from the Upper Cretaceous (Turonian) Tamagawa Formation, northeastern Japan. Cretaceous Research, 136: 105218. https://doi.org/10.1016/j.cretres.2022.105218

Santella, M., Milner, A.R.C. (2017) Coupling focus stacking with photogrammetry to illustrate small fossil teeth. Journal of Paleontological Techniques, 18: 1-17.

Stubbs-Lee, D. A., Stimson, M. R., MacRae, R. A., King, O. A. McAlpine, D. F. (2021) Conservation and photogrammetry of subfossil Quaternary walrus (Odobenus rosmarus) from the Bay of Fundy, Canada. Geological Curator 11 (5): 341-354.

Torices, A., Currie, P. J., Canudo, J. I., Pereda-Suberbiola, X. (2015) Theropod dinosaurs from the upper cretaceous of the south Pyrenees basin of Spain. Acta Palaeontologica Polonica, 60(3): 611-626. http://dx.doi.org/10.4202/app.2012.0121

VIGIE (2022) Study on quality in 3D digitisation of tangible cultural heritage: mapping parameters, formats, standards, benchmarks, methodologies, and guidelines. https://doi.org/10.2759/471776

Wilson, P.F., Stott, J., Warnett, J.M., Attridge, A., Smith, M.P., Williams, M.A., Warnick Manufacturing Group (2018) Museum visitor preference for the physical properties of 3D printed replicas. Journal of Cultural Heritage, 32: 176–185. https://doi.org/10.1016/j.culher.2018.02.002

Ziegler, M.J., Perez, V.J., Pirlo. J., Narducci, R.E., Moran, S.M., Selba, M.C., Hastings, A.K., Vargas-Vergara, C., Antonenko, P.D., MacFadden, B.J. (2020) Applications of 3D Paleontological Data at the Florida Museum of Natural History. Frontiers in Earth Sciences, 8: 600696. https://doi.org/10.3389/feart.2020.600696