

## Research

# Three 3D graphics engineering technologies for fallow deer antlers characterization in ecology and management approaches

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## Abstract

Numerous studies focus on creating 3D-models of biological elements for geometric evaluation using CAD tools. A crucial aspect is to obtain accurate geometrical data that is easy to obtain and cost-effective for analysis. The main objective is to evaluate the geometrical accuracy of 3D-models obtained with three graphical techniques of three-dimensional geometrical documentation that characterise the fallow deer antlers in an accurate 3D-model, which is used as input data in biological analyses estimating hunting quality, asymmetry and volume. Three technologies are evaluated: structured light scanning, multi-image photogrammetry (SfM), Structure from Motion, and spatial photogrammetric restitution using two photographs in a CAD system. The geometric accuracy of the 3D-models obtained and the deviation between relevant points of the antler structure, in the main beam, in the main tines and palm, are estimated. Subsequently, the suitability of each 3D-model is studied according to the type of biological application for which it is intended. Based on the results, solid and axial 3D-models, the applicability of the three techniques for the study of biological parameters such as hunting quality, asymmetry and volume is discussed. It concludes on the most appropriate procedure to define the digital characterisation of the antler, depending on the type of biological study to be carried out in order to obtain accurate results. Characterising a geometrically complex structure such as the fallow deer antler in a 3D-model quickly and accurately can help to quantify various biomarkers in populations of specimens, making it possible to infer internal and external influencing factors.

## Article highlights

1. The antlers of fallow deer are characterised using three technologies: 3D-scanning, 3D-photogrammetry (SfM) and a new technology (Bi-Photo CAD).
2. The geometrical accuracy of the 3D-models is evaluated by considering significant points of the antlers.
3. Based on the resources invested, the most appropriate type of 3D-model is defined according to the type of biological study to be carried out.

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## 1 Introduction

In the last three decades, various studies have investigated variables related to the size and quality of antlers in deer species such as red deer (*Cervus elaphus*), fallow deer (*Dama dama*) and roe deer (*Capreolus capreolus*) [1–9]. In Mediterranean areas, antlers growth is influenced by climate and population management, which affects the body condition and size of the deer as well as their antlers [3, 9]. The density value of antlers in cervids is a zoological biomarker of interest, related to their size and mineralization [10], and reflects their nutritional status during growth. The assessment of density requires the estimation of volume, combined with weight. [11] proposed measuring volume using the Archimedes method, but damage during handling and preparation affects accuracy. Estimating density in real antler models is labor-intensive [6, 12] and hampers volume precision due to manipulation. Additionally, obtaining their mass is challenging, especially if antlers come from hunting or natural shedding.

CAD systems, common in design and industry, achieve the extraction of geometric data from the antlers, extract geometric data, and directly provide volume. [13] propose a CAD method that creates a 3D-model from measured point coordinates on deer antlers, obtaining volume and density. This method is validated by comparing it with the hydrostatic Archimedes technique. Advanced graphic engineering techniques have enabled biomedical applications in CAD, ranging from modeling human bones and organs [14, 15] and designing personalized medical implants [16–19] to analyzing bone strength [18, 19] and providing guidance in bone pathology surgeries [20]. Among these techniques Coordinate Measuring Machines (CMM) stand out, enabling accurate 3D geometric data measurement of real objects through contact. These machines have been widely used in geometric morphometrics to study simian bones, temporal bones and human mandibles [21–23], as well as craniofacial regions [24]. Despite their high precision, these techniques are costly and require controlled laboratory conditions.

Another technique involves 3D scanning using a structured light scanner, which creates accurate models of real objects. These scanners have found applications in reverse engineering, industrial design, and biometrics, including human body geometry and craniofacial regions [24–28]. However, their high cost and the need for controlled laboratory conditions limit their use in the field and make it challenging to gather data from multiple specimens quickly.

On the other hand, structure from motion (SfM) photogrammetry techniques have stood out for being less costly and more flexible in terms of capture conditions. These techniques involve the 3D reconstruction of objects from photographs taken from various angles. Although they initially posed challenges in editing and optimizing the 3D-models due to the large number of captured points, software efficiencies and precision have addressed these issues [29, 30].

Despite these advantages, photogrammetric techniques require a significant number of photographs to generate 3D-models, which limits their application in the field where time to capture photos of numerous specimens is constrained. Although attempts have been made to reduce the number of photographs required [31–34], the limitation in rapidly modeling numerous specimens still persists.

Numerous authors used different 3D geometric documentation techniques in recent applications in various fields. Dörtbudak and Akça [35] made a comparison of photogrammetry and smartphone LIDAR for 3D documentation, demonstrating the feasibility of these technologies in field surveys with varying conditions. Similarly, Browning Jr. [36] investigated short-range photogrammetry for the analysis of rock relief detail, highlighting its application in the documentation of cultural symbols. Yakar and Dogan [37] used SfM photogrammetry for 3D reconstruction of residential areas, highlighting the importance of these techniques in geospatial documentation. Kabadayi et al. [38] compared different software for the documentation of cultural artefacts, while Kanun [39] showed the use of photogrammetric modelling in reverse engineering applications. Furthermore, Şasi and Yakar [40] applied photogrammetry in UAVs (Unmanned Aerial Vehicle) to model a historic mosque, demonstrating the flexibility and accuracy of these techniques in different contexts.

In this context, a technique proposed by [41] stands out for its effectiveness in capturing massive data in the field. This technique uses only two photographs taken from random angles to generate 3D-models through spatial photogrammetric restitution in a CAD system. This technique is particularly efficient in the field of hunting, allowing rapid data acquisition under non-ideal conditions. This optimization of tools and methodologies is particularly useful in biology studies that require data collection from numerous specimens in the field. For example, in the study of antler asymmetry, a biomarker related to the health of the specimen, these techniques can be quite valuable [42–47].

The objective of this research is to compare the accuracy in the geometry of fallow deer antlers using 3D-models generated by three relevant techniques: *3D structured light scanning*, *Structure from Motion* (SfM) multi-image photogrammetry based on multiple photographs, and spatial photogrammetric restitution in a CAD system using only two images. In addition to evaluating the accuracy of the resulting models, their suitability for various biological investigations, such as volume calculation, density assessment, hunting value estimation and asymmetry analysis will be discussed. The applicability of these techniques in the field for obtaining massive data and resource economy will also be considered.

## 2 Materials and methods

### 2.1 Object of study

In the present study, the geometric characterization of the fallow deer antler is proposed through its representation in a 3D-model using various technologies. Furthermore, the level of precision of the three 3D-models will be determined, along with their suitability for the intended biological application, highlighting their advantages and disadvantages.

Once the accurate 3D-model of the fallow deer antler is obtained, it can be utilized for:

- (a) Volume and density estimation: The antler's volume can be determined, serving as a biomarker to assess its development in relation to age and environment. Additionally, based on the volume and known weight of the antler its density could be estimated, another biomarker providing information about the health of the specimen and its relationship with other environmental factors. However, measuring weight is challenging as it may require antler shedding, with the added difficulty of locating both branches of the antler.
- (b) Descriptive analysis: 3D-models allow for the analysis of shape and geometry of different parts of the antler. These analyses are valuable in geometric morphometrics studies for comprehending changes in development and their relationship with environmental variables.
- (c) Analysis of antler asymmetry: Starting from the data of the 3D-model of the antler or its structure, relevant "homologous" points and considered antler parts are available: extreme points of main tines, bez tines, and trez tines, tips of the palms, lengths of bez tines and trez tines, lengths and widths of palms, etc. (Montalvo-Gil et al. 2022). This allows for future studies to relate this biomarker to other internal or external factors that influence development.
- (d) Estimation of cinegetic quality: From the 3D-model, the scores obtained for different elements of the antler can be assessed to evaluate its geometric development as described in official manuals for assessing cinegetic quality as a hunting trophy. Official assessments are performed by measuring different parts of the physical antler using a measuring tape; these distances and trajectories can be obtained by measuring on the surface of the 3D-model.

Having described various applications in which having the 3D-model as a starting point can be useful, the goal is to compare the geometric precision of the 3D-models obtained through the aforementioned technologies and highlight the advantages and disadvantages of each of them.

In the present study the biological applications will involve, on the one hand, determining the volume of the antler, a necessary variable for subsequent studies of its density, and on the other hand, assessing the hunting quality of the deer by metrically estimating the different parts of the antler's structure.

The main tasks are:

- Generation of 3D-models: 3D-models of deer antlers will be obtained using three technologies: structured light scanner, Structure from Motion (SfM) multi-image photogrammetry, and three-dimensional modeling based on the antler's structure obtained through spatial restitution photogrammetry from two photographs [41].
- Geometric precision evaluation: The precision of the three 3D-models obtained will be analyzed.
- Biological application: The 3D-models will be applied in biological contexts, particularly in calculating antler volume for density studies and in evaluating hunting quality by measuring different parts of the structure.
- Technology assessment: The three technologies used to generate the 3D-antler models will be evaluated, highlighting their advantages, disadvantages, and suitability for various biological applications.

## 2.2 Equipment used

The equipment used, both hardware and software, for obtaining the 3D-model in each of the three employed technologies is detailed below. For 3D-scanning, the '*EinScan Pro 2X*' scanner from 'Shining 3D' was employed, renowned for its speed and accuracy, capturing up to 1,500,000 points per second. Editing was carried out using its specific software. In Structure from Motion (SfM) photogrammetry, an 'Olympus' E-500 camera with a 28–80 mm focal lens was used. The 'Bentley ContextCapture' software was employed for spatial reconstruction of the model from the photos.

For 3D-modeling based on the antler structure obtained through Bi-photo photogrammetry, 'SolidWorks' was utilized. The software defined the virtual environment and generated the 3D-model from the structure. In the biological applications, such as determining antler volume and evaluating hunting quality, '*SolidWorks*' CAD software was used. It was also employed to measure the lengths of various parts of the structure.

The calibration procedure is performed automatically during the 'aerotriangulation' phase of the photogrammetric restitution procedure, resulting in the 'auto-calibration' parameters shown in Table 1, which serve, together with the distance measurement of known points on the antler, to establish the scale of the 3D-model and correct for deformations.

## 2.3 Definition of the 3D-model of the antler using various technologies

The process of obtaining the 3D-model, which characterizes the antler's geometry, through each of the three considered technologies is described below.

- (a) Using 'structured light scanning'.
- (b) Through '*Structure from Motion* (SfM)' multi-image photogrammetry.
- (c) Through 'Bi-Photo photogrammetry' and three-dimensional CAD modeling.

- (a) Obtaining the 3D-model of the antler of fallow deer by means of 'structured light scanner' technology

Structured light scanning technology was employed to obtain the 3D-model of the deer's antler. The main equipment used was the *EinScan Pro 2X* scanner (Fig. 1), renowned for its speed and precision. The objective was to create a reference model for comparison with others obtained through various technologies.

This scanner employs harmless radiation to capture contactless data. It operates at close range (0.5–1 m) and consists of a projector, geometric cameras, and texture cameras.

Its technical specifications are as follows:

- Ideal professional scanning tool for small to medium-sized objects.

**Table 1** Camera calibration results

| Name: OLYMPUS IMAGING CORP. E-500    |                   |                                    |                            |                            |          |        |          |    |    |
|--------------------------------------|-------------------|------------------------------------|----------------------------|----------------------------|----------|--------|----------|----|----|
| Model Type: Perspective              |                   |                                    |                            |                            |          |        |          |    |    |
| Image dimensions: 3264 × 2448 pixels |                   |                                    |                            |                            |          |        |          |    |    |
| Sensor size: 17.3 mm                 |                   |                                    |                            |                            |          |        |          |    |    |
| Number of photos: 32                 |                   |                                    |                            |                            |          |        |          |    |    |
| Calibration results                  |                   |                                    |                            |                            |          |        |          |    |    |
|                                      | Focal Length [mm] | Focal Length Equivalent 35 mm [mm] | Principal Point X [pixels] | Principal Point Y [pixels] | K1       | K2     | K3       | P1 | P2 |
| Previous values                      | 25.00             | 52.02                              |                            |                            |          |        |          |    |    |
| Optimized values                     | 23.96             | 49.86                              | 1639.45                    | 1209.21                    | − 0.1378 | 0.1192 | − 0.0983 | 0  | 0  |
| Difference Previous/optimized        | − 1.04            | − 2.16                             |                            |                            |          |        |          |    |    |

**Fig. 1** EinScan Pro 2X scanner in the laboratory on a tripod prior to data acquisition



- Scan speed (handheld rapid scan): 30 fps 1,500,000 points/s.
- Scan accuracy (fixed scan): 0.040 mm, (handheld HD scan): 0.045 mm.
- Volumetric accuracy (handheld scan modes): 0.1 mm + 0.3 mm/m.
- Minimum point distance (handheld HD/rapid scan): 0.2 mm.

The scanning process is based on triangulation through structured light [48, 49]. It projects two-dimensional patterns onto the antler, and by analyzing the deformation caused by its geometry the camera captures the shape and calculates the distance (Fig. 2).

The 'HD Manual Scanning' mode was used, the process consisted of moving the scanner around the antler, thus capturing the data at high resolution (HD) in a faster way, improving mobility and ease of use. It is not necessary to use adhesive markers on the surfaces of the antler, since, due to the performance and technical specifications of the equipment, an accurate 3D model with adequate resolution is obtained.

The process involves calibrating the scanner and capturing a point cloud, followed by creating a textured mesh and a solid 3D-model. Both the capture and editing were performed using the *EXScanPro-3.7.3.0* software.

The detailed steps are as follows:

- Calibration.
- Setting the scanning mode.
- Data capture.
- Cleaning, optimization, and mesh closure.

Calibration adjusts the scanner's precision and lighting. The handheld rapid scanning mode was chosen for the antler, enabling easy and accurate alignment.

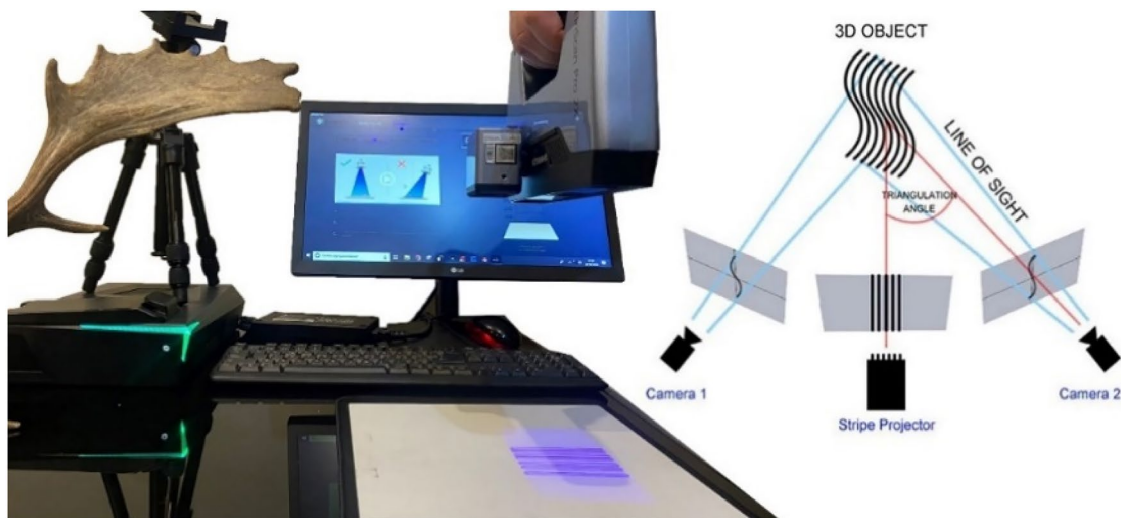


**Fig. 2** Structured light scanner and schematic diagram of its principle of operation

The capture was achieved by slowly moving the scanner around the antler. Real-time visualization aided in enhancing efficiency and correcting errors (Fig. 3).

The *EinScan Pro 2X* scanner achieved sub-millimeter accuracy of 0.05 mm and a resolution of 0.25 mm between points, generating a mesh of 7,254,322 triangles. The texture of the antler was also captured.

After the capture, the mesh was optimized to reduce the number of triangles to 6,134,900 (Figs. 4, 5). The optimized model was exported in various formats (STL, OBJ, PLY, ASC, 3MF, and P3) for use in other CAD software (Fig. 6).

Within the study of metric and volumetric analysis of deer antlers, it is necessary to be able to compare results obtained from the structured light scanner with other technologies. The goal is to have a validated method that serves as a reference.

- (b) Obtaining the 3D-model of the antler of the fallow deer by means of multi-image photogrammetry, SfM (structure from motion) technology

The SfM photogrammetric-3D methodology allows the creation of accurate meshes of real-world objects from photographs taken with conventional (non-metric) cameras. This technology makes it possible to obtain metric characteristics of the photographed objects, in this case the antlers of deer.

The technique involves capturing images under certain considerations: uniform lighting, preferably using DSLR cameras, and an appropriate environment. An *Olympus* camera with a 28–80 mm lens was used, maintaining a 35 mm equivalent. Photos were taken on a shaded terrace, with the object placed on a translucent pedestal (Fig. 7).

**Fig. 3** Structured light pattern on the antler of the fallow deer visualized in the software interface

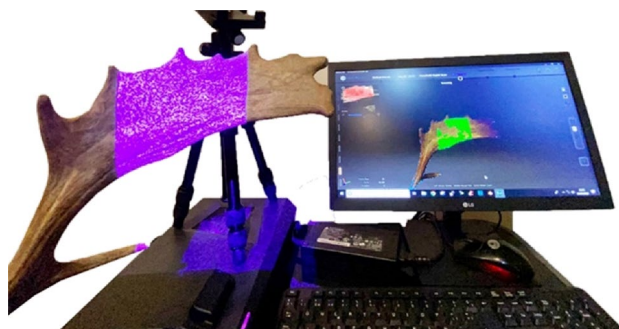


**Fig. 4** Mesh optimization: cleaning and hole filling



**Fig. 5** Level of detail of the optimized and closed 3D-model of the antler with and without texture

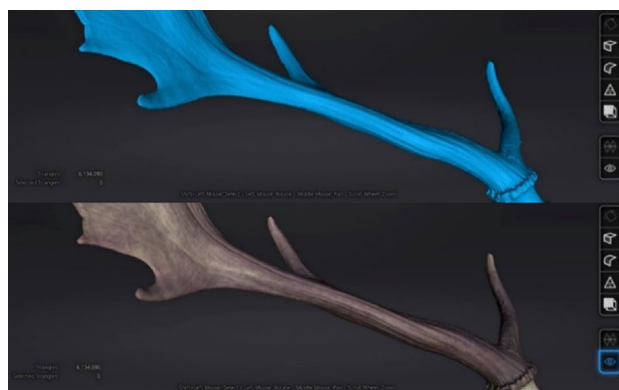


**Fig. 6** Final 3D-model obtained after applying the optimization processes



**Fig. 7** Location of the object



As for the shooting parameters with the Olympus camera, the focal length was set to 35 mm, the aperture to 5.6, while the shutter speed was set automatically by the camera, as the light conditions in such a small setup do not change during the shooting session.

The data capture process involves covering the object and overlapping images by 60%. A total of 32 photos were taken, describing two circles around the object (Fig. 8).

The process was carried out using *Bentley ContextCapture* software and consists of several steps (Fig. 9):

- Identification of photos and camera parameters.
- Identification of control points and metric constraints.
- Aerotriangulation.
- Model reconstruction.
- Visualization.

**Fig. 8** Distribution of photographic shots

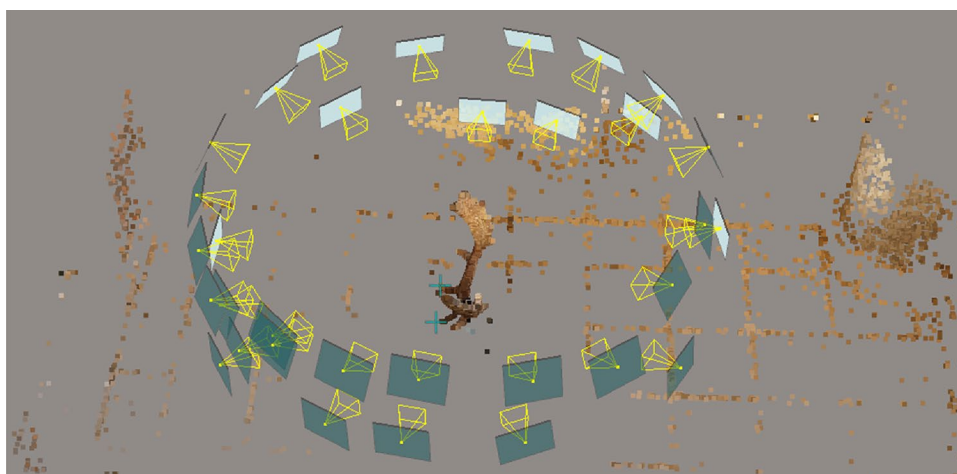


**Fig. 9** Modeling phases

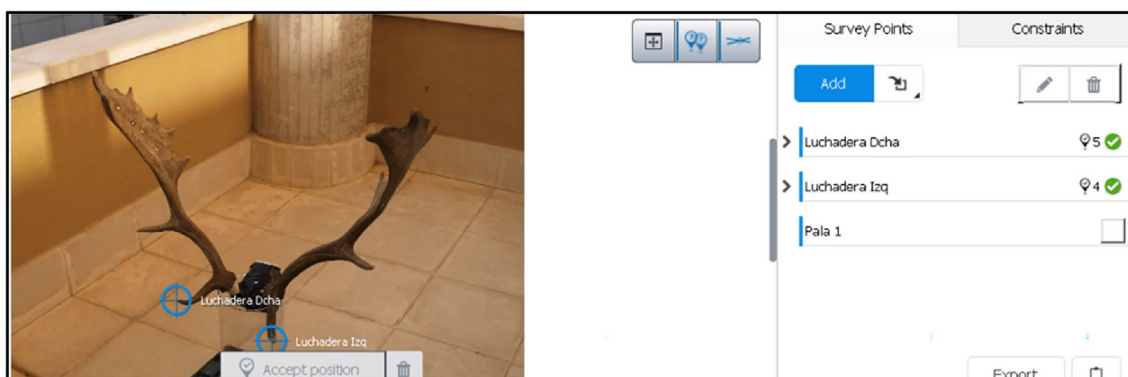


**Fig. 10** Identification of known points

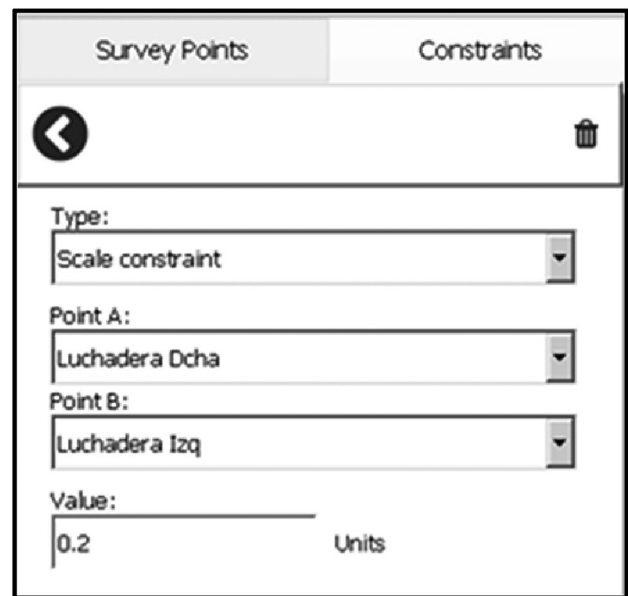
The photos are imported into the software, which identifies the camera and necessary parameters (Table 1). Control points are marked, such as the ends of the main antler points (Fig. 10). This enables "aerotriangulation," an automatic process that captures camera distortion and spatial positions of points accurately. Subsequently, the software spatially reconstructs the object (Fig. 11), assigning textures to the image meshes.

Before the reconstruction desired spatial elements are defined, and the 'Bounding Box' (Fig. 12) is used to delimit them. Once reconstructed, the object becomes viewable and usable in subsequent analyses (Fig. 13).

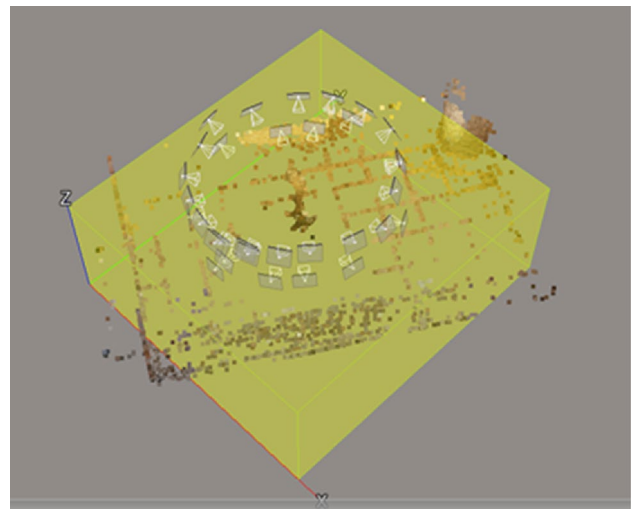
- (c) Obtaining the 3D-model of the fallow deer antlers by 3D-modeling from the axial structure obtained with Bi-Photo photogrammetry (Bi-Photo-CAD)

The term 'Bi-Photo-CAD' refers to the methodology used to obtain a 3D-model typology. The Bi-Photo photogrammetry technique begins by defining the central structure of the antler, which is the central fiber or axis of the main beam and tines. This axis passes through homologous points (*landmarks*) such as the base of the main beam, main tines; eye tine, trez tine, and palm. Then, the *SolidWorks* CAD software is used to create the 3D-model. Solid volumes of the main beam, main tines, and palm are obtained, defining contours of relevant cross-sectional profiles and using the 'overlay' command in *SolidWorks*.

The lateral tines, 'spellers tines' of the palm are modeled with surfaces based on side profiles and cross-sectional profiles. These surfaces are converted into solids and merged with the volume of the brow tine using the '*SolidWorks*' "boundary surface" command.

**Fig. 11** Metric constraints

The image shows a software interface with two tabs: 'Survey Points' and 'Constraints'. The 'Constraints' tab is active. It features a back arrow icon and a trash icon. Below these, there are four input fields: 'Type:' with a dropdown menu showing 'Scale constraint'; 'Point A:' with a dropdown menu showing 'Luchadera Dcha'; 'Point B:' with a dropdown menu showing 'Luchadera Izq'; and 'Value:' with a text input field containing '0.2' and a label 'Units'.

**Fig. 12** Bounding box

Each part of the antler is separately modeled, such as the 'main beam' and 'palm', 'main tines', 'eye tine' and 'trez tine'. Connection of junctions, 'burrs', and 'spellers tines of the palm' (Figs. 14, 15).

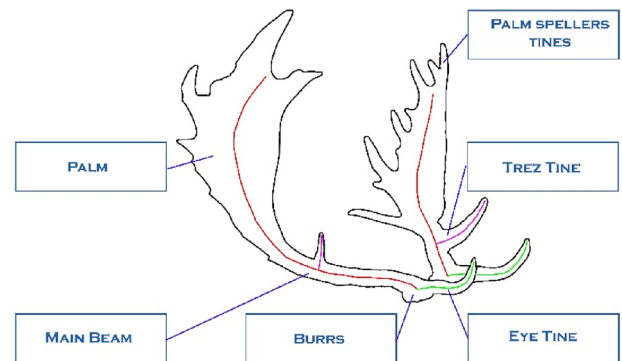
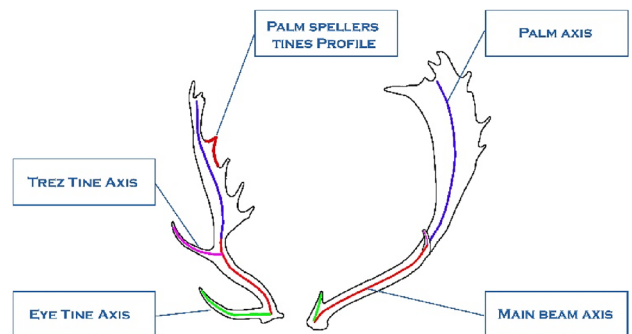
The modeling process is detailed in the Figs. 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27.

The final result, which includes all the modeled parts, is presented alongside the real model in Fig. 28.

## 2.4 Methodology for determining the geometric accuracy and volume of 3D models obtained with different technologies

### 2.4.1 Technologies used for 3D antler models (Fig. 29):

- Structured Light Scanner
- Multi-image Photogrammetry (SfM)
- 3D Modeling with SolidWorks from Photogrammetric Data [41].

**Fig. 13** 3D-model obtained**Fig. 14** Main elements of the antler**Fig. 15** Median axes of the antler

#### 2.4.2 Tools for evaluating precision

1. 3D-model comparison: software *Autodesk Netfabb 2023*
2. Statistical Analysis for Assessing Deviations

The 3D-model comparison process will consist of:

1. Reference 3D-model: very similar to the real model in terms of geometry and volume:

**Fig. 16** Antler structure

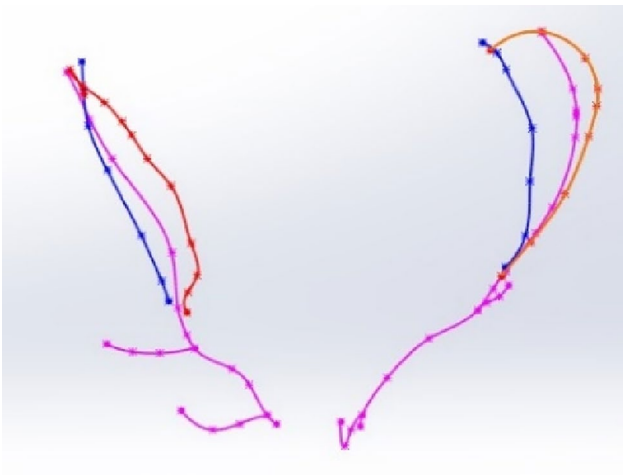


**Fig. 17** Antler structure and perimeters

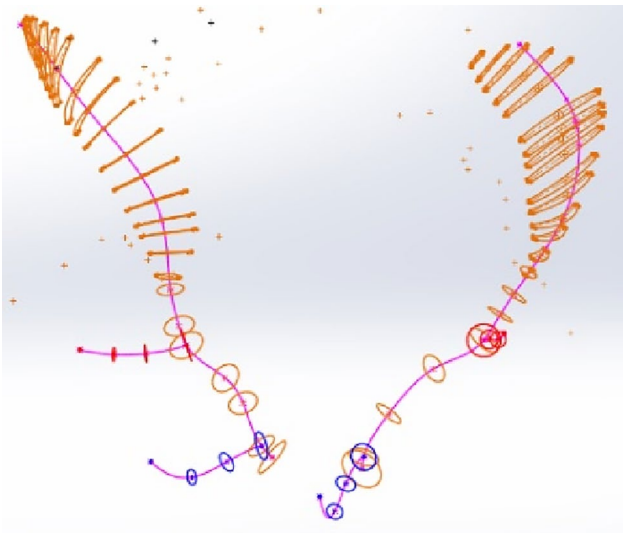


**Fig. 18** Main beam and palm central shaft

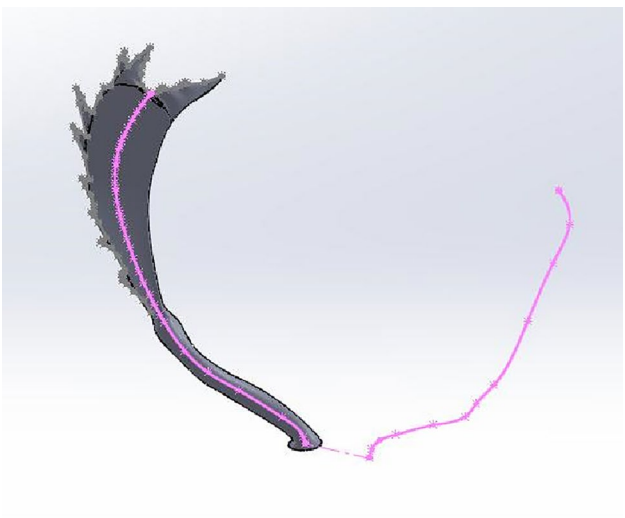
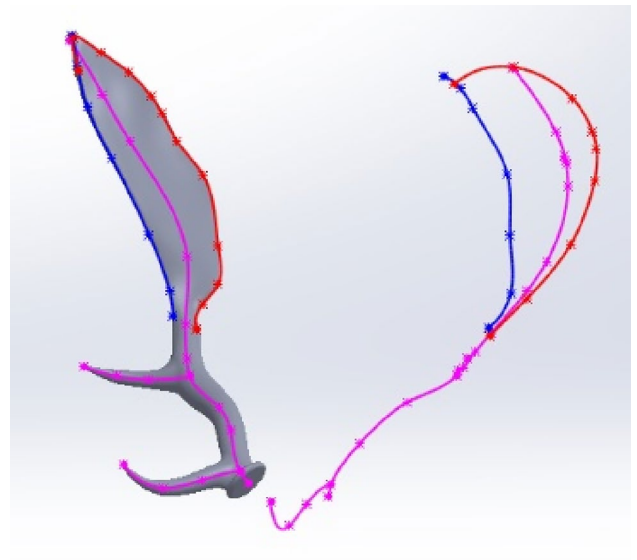
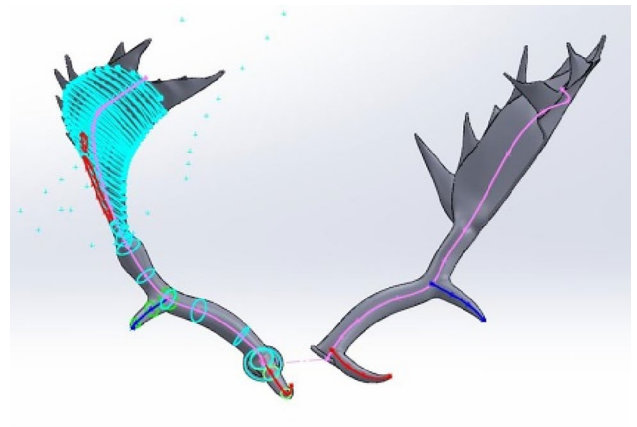
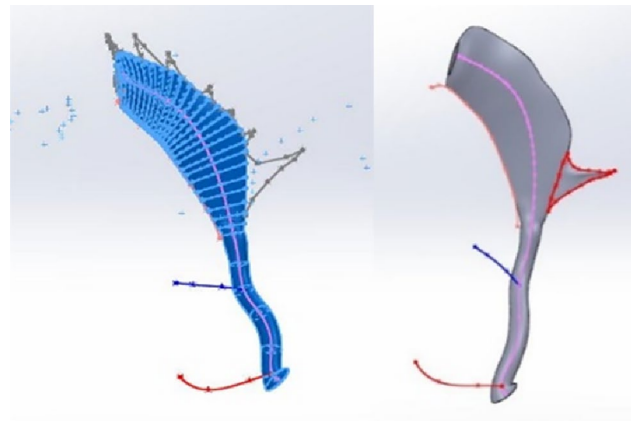


**Fig. 19** Palm contour curves**Fig. 20** Cross sections of the palm structure**Fig. 21** 3D-model of the main beam and the palm

- Obtained by Structured Light 3D-Scanner (Highest Accuracy).

2. Two comparisons: Carried out by superimposing 3D-models:

- Reference 3D-model (Escáner) vs. SfM 3D-model.
- Reference 3D-model (Escáner) vs. Bi-Foto-CAD 3D-model.

**Fig. 22** Structure and 3D-model of the eye tine

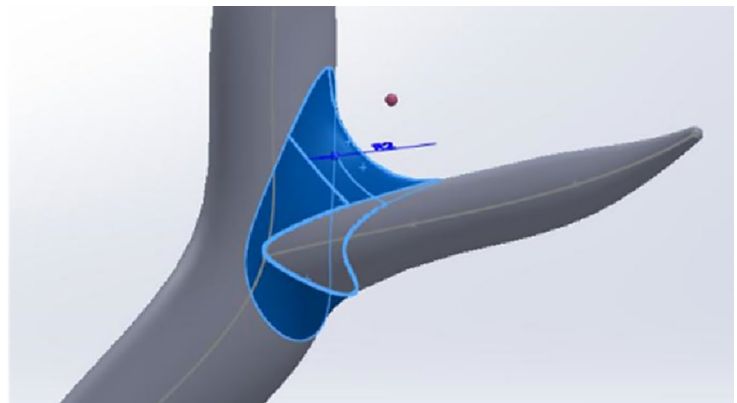
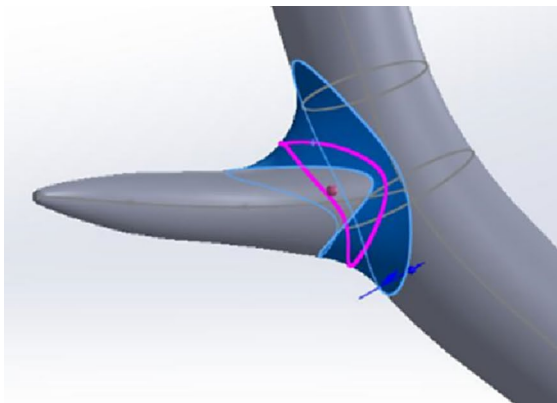
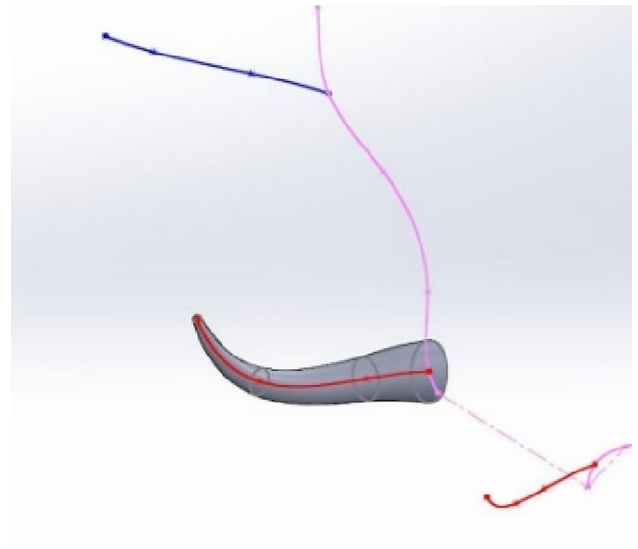
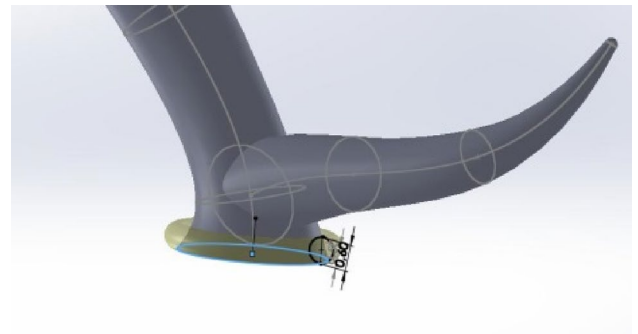


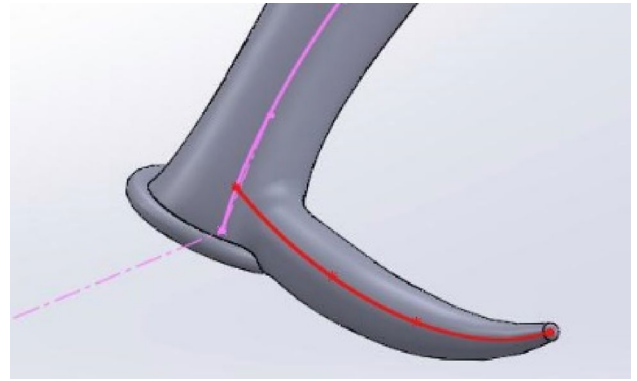
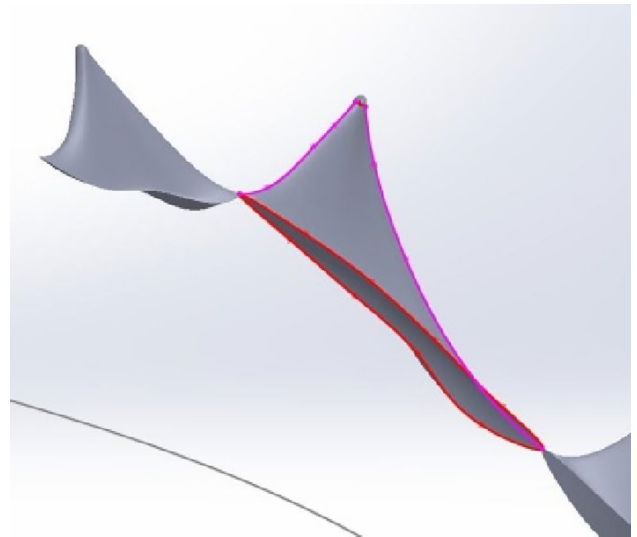
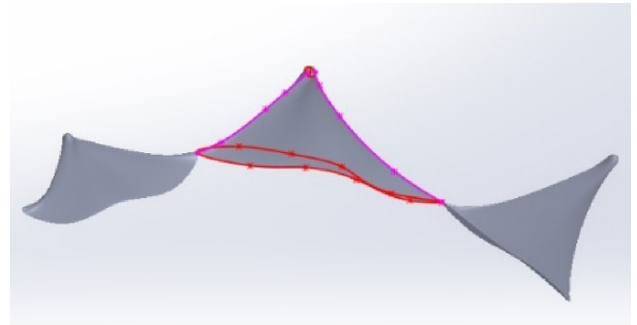
**Fig. 23** Connection of the main tines to the main beam

**Fig. 24** Burr structure



The methodology followed by the 3D-model comparison software, *Autodesk Netfabb*, is:

- Importation of 3D-models.
- Scaling of 3D-models.
- Choice of Reference 3D-model and 3D-model to be compared.
- Colour chart to visualise deviations.
- Maximum and minimum differences between 3D-models.

**Fig. 25** 3D-model of the burr**Fig. 26** Structure of the palm speller tine**Fig. 27** 3D-model of palm speller tine**Fig. 28** 3D model of the antler

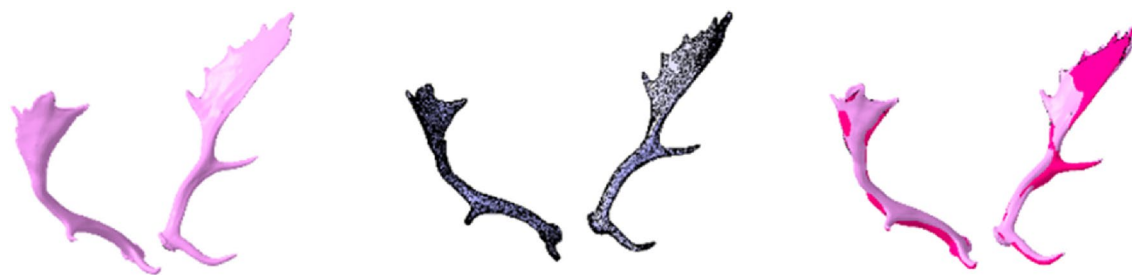


**Fig. 29** 3D-model of the antler obtained with different techniques

Following the comparison, the software displays a color-coded chart with both 3D-models overlaid. This allows for visualizing the deviations of the compared model in relation to the reference model. These deviations are highlighted in colors, red for positive deviations and blue for negative deviations (Fig. 30). Only deviations exceeding a predetermined tolerance value are considered. Additionally, the chart presents the maximum and minimum differences between the two models.

#### 2.4.3 Estimation of distances and deviations between selected points in the chart

In this study, 19 points from both branches of fallow deer antlers have been considered, corresponding to the ends of the main tines: eye tines, and trez tines, as well as the ends of the spellers of the palm. These deviation values between homologous points in the 3D-models will be used, through statistical inference techniques, to estimate the degree of geometric precision of the three 3D-models, taking into account all points of the antler.

- The methodology applied in each of the two comparisons is described:

First comparison: Model A-(3D-Scanner) vs Model B-(SfM):

Figure 31 shows the overlay of the two 3D-models of the antler made with 3D-scanner and photogrammetry (SfM) technologies.

**Fig. 30** 3D-model overlay and comparison

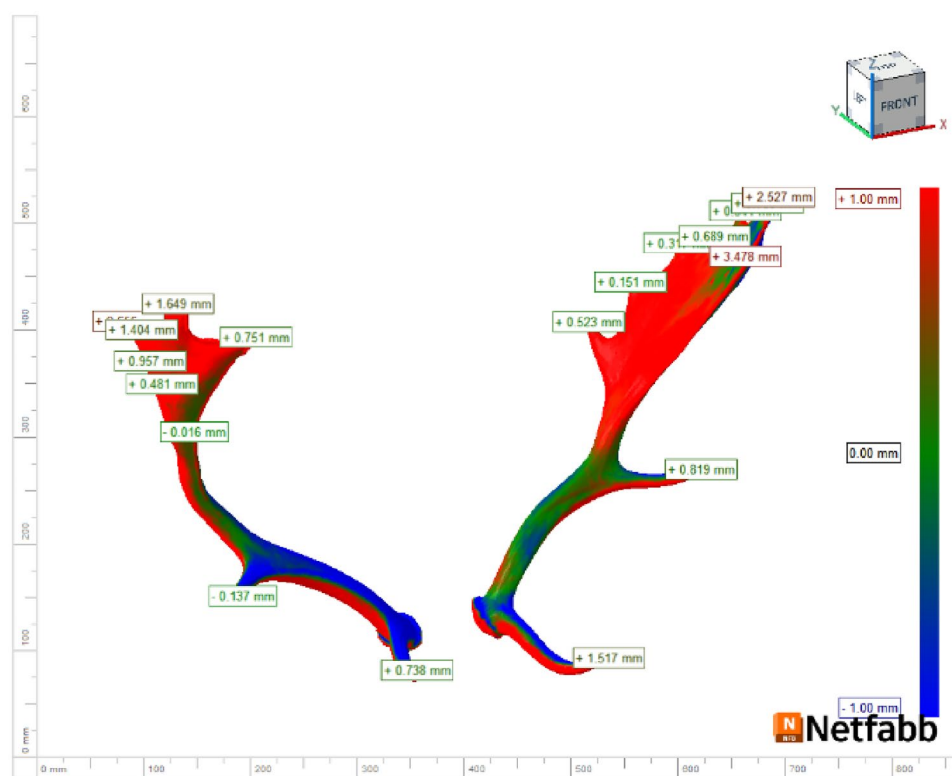




Fig. 31 3D-model overlay: obtained by '3D-scanner' and by 'SfM'

Fig. 32 3D-model overlay and comparison

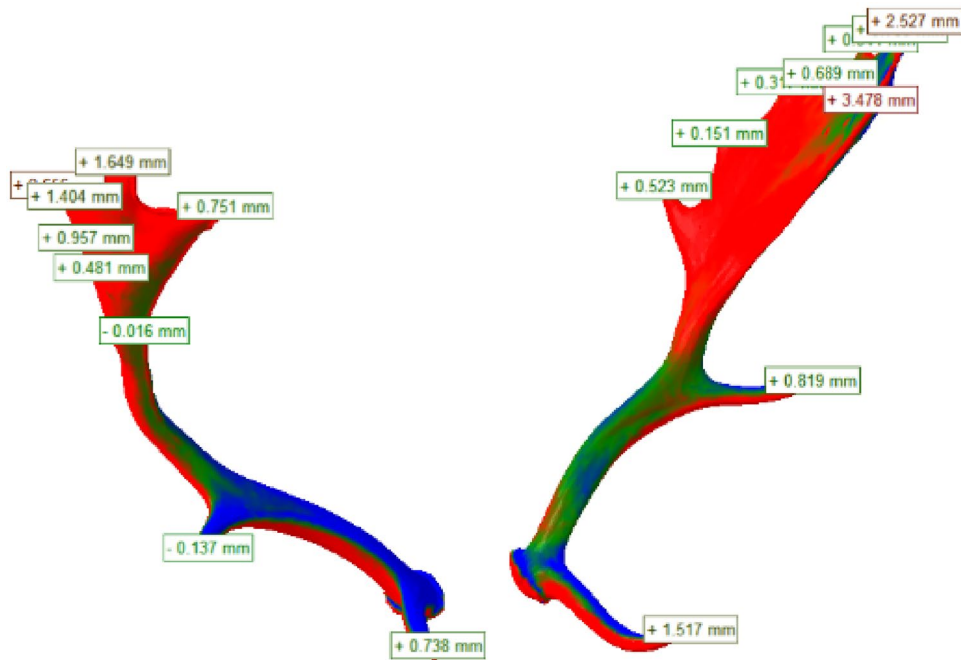


Figure 32 shows the deviations, at the reference points considered, that result from the two superimposed 3D-models of the antler.

| 3D-model (scanner)              | 3D-model (SfM)                  |
|---------------------------------|---------------------------------|
| Volume= 709.089 cm <sup>3</sup> | Volume= 702.042 cm <sup>3</sup> |
| Area= 1553.033 cm <sup>2</sup>  | Area= 1506.736 cm <sup>2</sup>  |

- Maximum positive distance (red color): + 7.179 mm
- Maximum negative distance (blue color): – 4.697 mm

Based on the superposition of the two 3D-models considered, Model A-(3D-Scanner) vs Model B-(SfM), the numerically quantified deviations of the considered significant points of the antler are shown in Table 2.

These deviation values between homologous points of the 3D-models will be utilized using statistical inference techniques to estimate the degree of geometric precision between both 3D-models.

- The graph displays overlap and deviations in specific areas.
  - Red color: SfM vs 3D-Scanner divergence.
  - Tolerance sets the limit for considered deviations.
- Deviation zones within a 1 mm tolerance (Fig. 33).

**Table 2** Differences between antler points of the 3D-models: A-(3D-scanner) and B-(SfM)

| Deviations between points (mm) |                  |
|--------------------------------|------------------|
| Right branch                   | Left branch      |
| +0.738 eye tine                | + 1.517 eye tine |
| -0.137 trez tine               | +0.819 trez tine |
| +0.751 palm                    | +3.478 palm      |
| +1.649 palm                    | +2.527 palm      |
| +1.404 palm                    | +0.739 palm      |
| +2.656 palm                    | +0.541 palm      |
| +0.957 palm                    | +0.689 palm      |
| +0.481 palm                    | +0.317 palm      |
| -0.016 palm                    | +0.151 palm      |
|                                | +0.523 palm      |

**Fig. 33** Overlay and comparison of 3D-models: with 1 mm tolerance

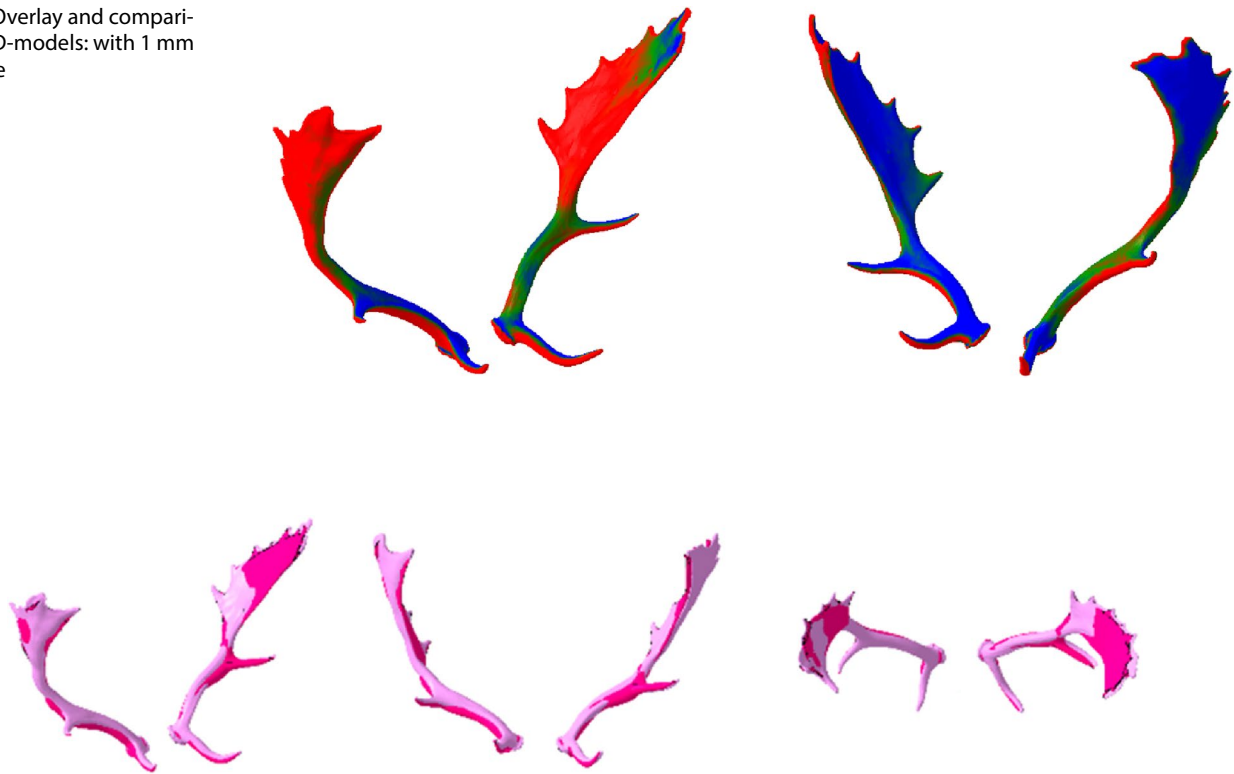


**Fig. 34** Overlay of 3D-models: obtained by '3D-Scanner' and by 'Bi-Photo-CAD'

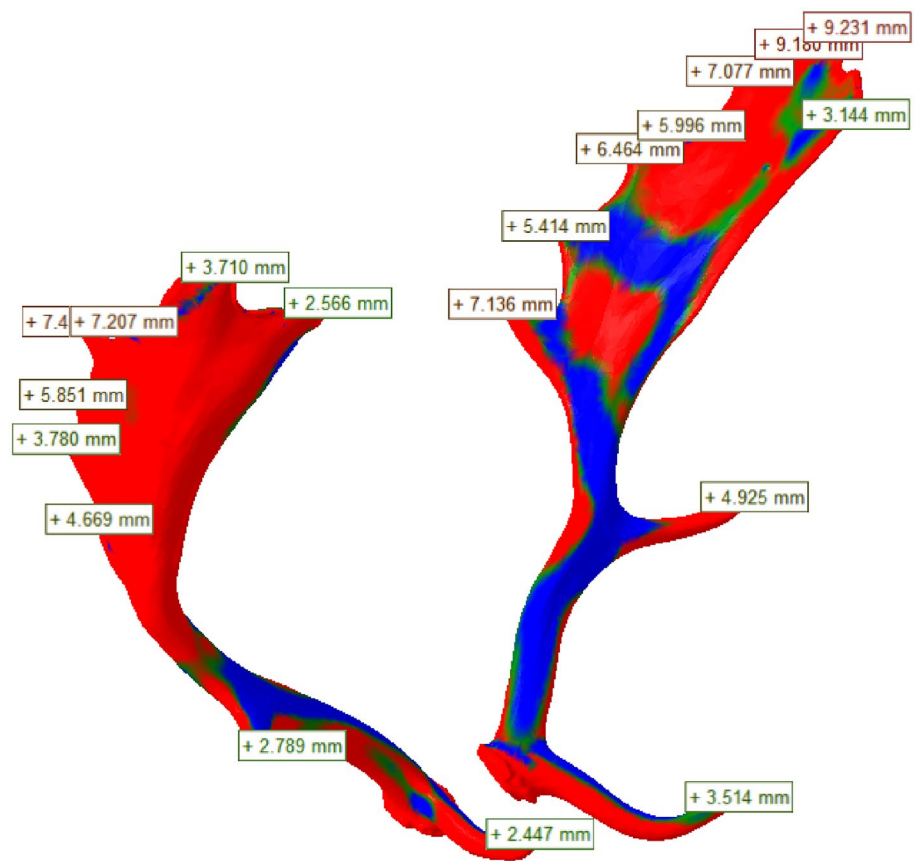
- Higher precision when considering deviations > 1 mm.
- Blue zones: Internal divergences in lateral areas.
- Red zones: Positive divergences in structural elements.
- Green zones: < 1 mm coincidences in central axis and internal part of the palm.

Second comparison: Model A-(3D-Scanner) vs. Model C-(Bi-Photo-CAD):

Figure 34 shows the overlay of the two 3D-models of the antler made with 3D-scanner and CAD-Bi-photo technologies.

Figure 35 shows the deviations, at the reference points considered, that result from the two superimposed 3D-models of the antler.

**Fig. 35** Overlay and comparison of 3D-models



| 3D-model ( <i>Scanner</i> )     | 3D-model ( <i>Bi-Photo-CAD</i> ) |
|---------------------------------|----------------------------------|
| Volume= 709.089 cm <sup>3</sup> | Volume= 581.078 cm <sup>3</sup>  |
| Area= 1553.033 cm <sup>2</sup>  | Area= 1476.371 cm <sup>2</sup>   |

- Maximum positive distance (red color): +20,959 mm
- Maximum negative distance (blue color): – 11.595 mm

Based on the superposition of the two 3D-models considered, Model A-(3D-Scanner) vs Model C-(Bi-Photo-CAD), Table 3 shows the numerically quantified deviations of the significant antler points considered.

**Table 3** Differences between antler points of the 3D-models: A-(3D-Scanner) and C-(Bi-Photo-CAD)

| Deviations between points (mm) |                  |
|--------------------------------|------------------|
| Right branch                   | Left branch      |
| +2.447 eye tine                | +3.514 eye tine  |
| +2.789 trez tine               | +4.925 trez tine |
| +2.566 palm                    | +3.144 palm      |
| +3.710 palm                    | +9.231 palm      |
| +7.207 palm                    | +9.180 palm      |
| +7.452 palm                    | +7.077 palm      |
| +5.851 palm                    | +5.996 palm      |
| +3.780 palm                    | +6.464 palm      |
| +4.669 palm                    | +5.414 palm      |
|                                | +7.136 palm      |

Just like in the previous comparison, these deviations between the points of both models will be used through statistical inference techniques to estimate the behavior of all points on the antler.

- 3D-model overlay graph displays deviations.
  - Red color: Divergence Bi-Photo-CAD vs Scanner.
  - Tolerance sets the limit for considered deviations.
- Deviation zones with a tolerance of 1 mm (Fig. 36).
  - Small area of coincidence (green color).
  - Predominance of red color: External divergences in prongs, main beam, and main tines.
  - Blue zones: Interior deviations in main beam and palms.

## 2.5 Methodologies for the assessment of 'hunting quality'

The 'hunting quality' assessment of the specimen analyzed is conducted by analyzing the degree of geometric development of its antlers and will be related to its greater antler development. The hunting quality assessment of the fallow deer's antlers, performed using digital procedures, requires the three-dimensional characterization of the antlers, either in their entirety or in their structure.

Two methods are presented for spatially characterizing the fallow deer's antlers.

### 1. 3D-Model-based Assessment:

- 3D data of antlers (accurate 3D-model from 3D-scanner or SfM photogrammetry); both methods validated previously.
- Use CAD software to measure trajectories, lengths, and perimeters on external surface.
- Quantify geometric elements metrically.
- Apply a scoring scale [50] to obtain the final score.
- Consider antler lengths and perimeters values (to achieve the final score of 'hunting quality assessment' [50]).
- Complete the score with non-geometric items from the official scale (color, number of spellers of palm, weight, and regularity).

Trajectories and perimeters considered are indicated on the mesh 3D-model in Fig. 37.

### 2. Antler structure-based assessment:

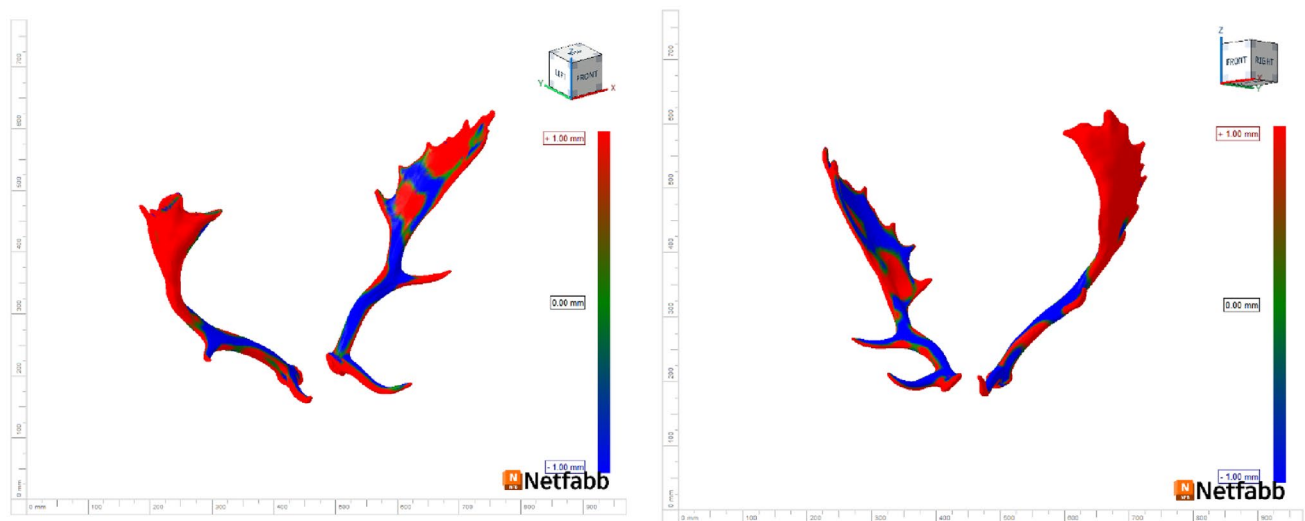


**Fig. 36** Overlay and comparison of 3D-models: with 1 mm tolerance

**Fig. 37** Trajectories and perimeters considered on the surface of the antler structure for hunting valuation

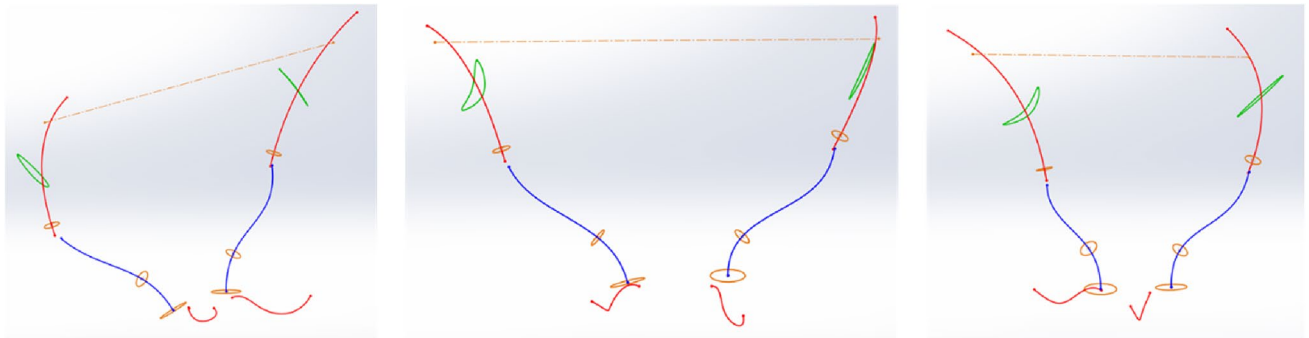
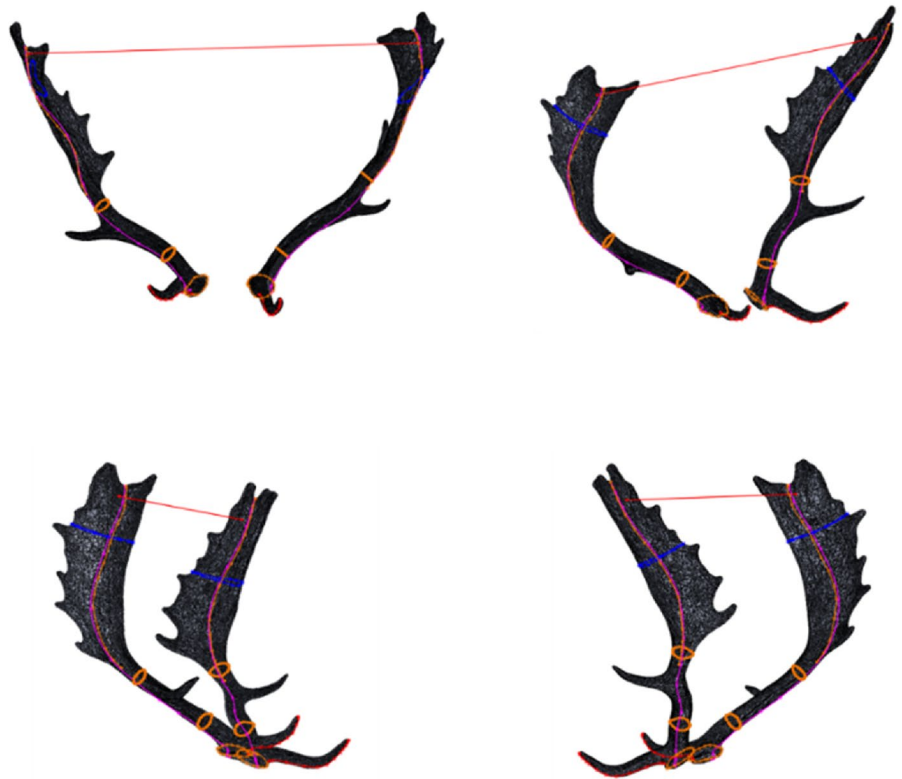
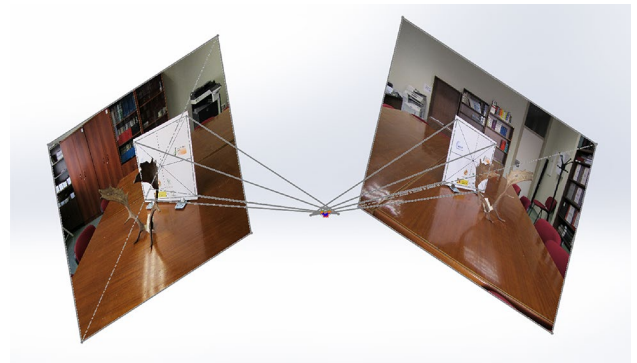


**Fig. 38** Spatial structure of the relevant parts of the antler required for 'hunting valuation'

**Fig. 39** Bi-Photo photogrammetric method that spatially restores points represented in two photographs by crossing projective rays



Obtaining an 'ad hoc' 3D-model as a starting point for the hunting valuation of antlers is not the most efficient methodology due to the required amount of time, monetary cost, and controlled conditions for its acquisition. It is more economical, at the level of resources invested to perform the 'hunting valuation', to work with the spatial structure of those relevant parts of the antler (Fig. 38) necessary to perform such valuation, as indicated in the 'Manual de homologación de Trofeos de caza' [50]. This spatial structure is obtained by applying the photogrammetric restitution methodology described in [41] (Fig. 39).

- Create a 3D-scenario in 'SolidWorks' CAD software.
- Obtain the axial structure of the antler.
- Measure lengths and perimeters of specific antler parts (Fig. 37).
- Obtain the final score according to the official scoring system.

### 3 Results

#### 3.1 Results of the 3D-models obtained

There is a certain similarity of the 3D-model obtained by 'Bi-Photo-CAD' with the physical model of the antler in terms of geometric definition; for the three-dimensional CAD definition of the antler we have started from a structure formed by homologous points, as in the study of the deer, significant of the geometry of the antler of the fallow deer like the starting points of the main tines, the axes of these, the axis of the main beam, the midpoint of the palm and that of the highest point of the palm. Subsequently, the degree of approximation of this 3D-model with others obtained with other technologies such as '3D-scanning' and 'SfM-Photogrammetry' is determined. From this comparison it is observed that there are differences in geometric accuracy and volume; this variable, together with density, represents a relevant biomarker that allows us to estimate the degree of anatomical development of the specimen, and, extending the study to populations, to evaluate the quality of ecosystems in specific climatic periods.

The degree of geometric deviation of the 3D-model, obtained by means of 'Bi-Photo-CAD', over the other two 3D-models obtained with the aforementioned technologies, which are very close to the real model, is due to the geometric complexity of the antler of the fallow deer. A series of assumptions and geometric simplifications have been made, aimed at facilitating the obtaining of the 3D-model using the three-dimensional CAD modeling tools with *SolidWorks* software, such as:

- Estimate constant palm thickness values in the central part and lower at the ends; transitions between the main beam and the beginning of the palm. Actually these thicknesses are not constant, and depending on each specimen the average thickness value may vary.
- Consider similar cross-section geometries of the palm, only varying the size depending on its position.  
Actually, the cross sections in the different positions of the palm are geometrically different, and do not maintain a constant pattern; this degree of variability will depend on the geometry of each specimen.

For the palm spellers tines, the thickness of the base that contacts the palm is supposed to be similar in all of them, but this is not really the case since this thickness adapts to the irregular surface edges of the palm.

The other parameters of the antler extracted from the photographs with the 'Bi-Photo-CAD' method, such as lengths: of the main beam, of the palm, central fibers of the eye tines and trez tines, profiles of the spellers tines of palm, and of perimeters: of burrs, and between tines, are almost exact to those of the physical model. Rubio-Paramio et al. [41] validate the degree of convergence of these lengths and perimeters obtained with the methodology of spatial restitution with photogrammetry from two photographs with the same data obtained on the physical model of the antler obtained in official measurements made by certified personnel with a tape measure in applications for the study of the hunting quality of deer antlers, and therefore demonstrate the accuracy and reliability of the 'Bi-Photo-CAD' method.

**Table 4** Differences between 3D-model points and statistical values

| Sample values (differences between related points) (mm): |         |       |         |       |                            |       |           |       |       |
|----------------------------------------------------------|---------|-------|---------|-------|----------------------------|-------|-----------|-------|-------|
| 0.738                                                    | 0.137   | 0.751 | 1.649   | 1.404 | 2.656                      | 0.957 | 0.481     | 0.016 | 1.517 |
| 0.819                                                    | 3.478   | 2.527 | 0.739   | 0.541 | 0.689                      | 0.317 | 0.151     | 0.523 |       |
| n                                                        | Average |       | S (n-1) |       | t-student                  |       | (a) error |       |       |
| 19                                                       | 1.057   |       | 0.941   |       | 2.101                      |       | 5%        |       |       |
| Confidence interval:                                     |         |       |         |       | Amplitude of the interval: |       |           |       |       |
| 1.057 ± 0.454 mm (0.604, 1.511)                          |         |       |         |       | 0.907 mm                   |       |           |       |       |

**Table 5** Differences between points of the 3D models and statistical values

| Sample values (differences between related points) (mm): |         |       |         |       |                            |       |           |       |       |
|----------------------------------------------------------|---------|-------|---------|-------|----------------------------|-------|-----------|-------|-------|
| 2.447                                                    | 2.798   | 2.566 | 3.710   | 7.207 | 7.452                      | 5.851 | 3.780     | 4.669 | 3.514 |
| 4.925                                                    | 3.144   | 9.231 | 9.180   | 7.077 | 5.996                      | 6.464 | 5.414     | 7.136 |       |
| n                                                        | Average |       | S (n-1) |       | t-student                  |       | (α) error |       |       |
| 19                                                       | 5.398   |       | 2.139   |       | 2.101                      |       | 5%        |       |       |
| Confidence interval:                                     |         |       |         |       | Amplitude of the interval: |       |           |       |       |
| 5.398 ± 1.031 mm (4.367, 6.429)                          |         |       |         |       | 2.062 mm                   |       |           |       |       |

### 3.2 Evaluation of the accuracy of the 3D-models obtained

In order to obtain an estimation of the geometric approximation of the 3D-models: B-(*SfM*) and C-(*Bi-Photo-CAD*) on the reference 3D-model A-(*3D-Scanner*), two comparisons will be established: that of 3D-model B-(*SfM*) on 3D-model A-(*3D-Scanner*) and that of 3D-model C-(*Bi-Photo-CAD*) on 3D-model A-(*3D-Scanner*). Thus 'statistical inference' techniques are established (Equation-1) to generalize the behavior of the whole data population, the differences of the means of all the antler points of the two 3D-models, starting from a sample of values.

$$\bar{D} \pm t_{1-\left(\frac{\alpha}{2}\right), n-1} \frac{S_{n-1,D}}{\sqrt{n}},$$

$\bar{D}$ : Difference between the mean values of the two samples.  $t$ : Distribution t-Student.  $S_{n-1}$ : Quasi-standard deviation.  $n$ : Sample values (differences between related points)

Equation (1) Determination of the 'confidence interval'.

In both 3D-model comparisons the 'confidence interval' will be obtained for each of them, establishing for them the same error ( $\alpha$ ) of 5% and therefore a 'confidence level' ( $1 - \alpha$ ) of 95%. The 'confidence level' of 95% indicates that, out of every 100 samples, 95 of them will contain the true value of the parameter, the difference of the means of all the points of both models compared; 95% of the samples are valid, understanding these as those in which the resulting 'confidence interval' contains the true value of the parameter.

Finally, the amplitude of the two confidence intervals obtained in both comparisons is compared, thus establishing the degree of deviation of the 3D-models B-(*SfM*) and C-(*Bi-Photo-CAD*) from the more accurate 3D-model A-(*3D-Scanner*) taken as a reference.

In each comparison, a sample of 19 values corresponding to the extreme points of the main tines: eye tines and trez tines and the palm spellers tines of both antler branches have been considered. These values correspond to the deviations of each pair of affine points of each of the two 3D-models compared, the extreme points of the tines, once they have been superimposed using the *Autodesk Netfabb 2023* software.

a. Comparison of 3D-models: A-(*3D-Scanner*) and B-(*SfM*):

Table 4 shows the statistical values, deviations of the antler points, obtained from the comparison of the 3D-models: Model A-(3D-Scanner) vs Model B-(SfM).

b. Comparison of 3D models: A-(3D-Scanner) and C-(Bi-Photo-CAD):

Table 5 shows the statistical values, deviations of the antler points, obtained from the comparison of the 3D-models: Model A-(3D-Scanner) vs Model C-(Bi-Photo-CAD).

In the comparison of the 3D-models A-(3D-Scanner) and B-(SfM), it is observed that the 'confidence interval' obtained is small, with a width of 0.907 mm with  $(\alpha) = 5\%$  and  $(1 - \alpha) = 95\%$ . In the second comparison, models-3D A-(3D-Scanner) and C-(Bi-Photo-CAD) are compared, obtaining a width for the 'confidence interval' of 2.062 mm with the same alpha value of 5%.

The amplitude of the interval of the first comparison is very small, indicating the great degree of geometric approximation of the 3D-model B-(SfM) with respect to the 3D-model A-(Scanner-3D) of greater precision. All this indicates that the differences between all the affine points of both antlers are very small, therefore, the differences of their means are also very close, with the amplitude of the 'confidence interval' obtained also quite small.

Comparing the width of the 'confidence intervals' obtained in the two comparisons, we obtain:  $2.062/0.907 = 2.3$ , with the result that the degree of deviation of 3D-model C-(Bi-Photo-CAD) is 2.3 times greater than that of 3D-model B-(SfM), both referred to the more accurate 3D-model A-(3D-Scanner).

### 3.3 Results of biological applications

1. Volume and area data of the 3D-models obtained

The volume and area results of each of the 3D-models provided by the *Autodesk Netfabb-2023* software are described:

Comparison of 3D-models: A-(3D-Scanner) and B-(SfM) in terms of 'volume' and 'area':

As for the volume:

$$\begin{aligned}\Delta - \text{Vol} &= [\text{Vol 3D-model B-(SfM)}/\text{Vol 3D-model A-(Scanner-3D)}] \\ &= (702.042 \text{ cm}^3 / 709.089 \text{ cm}^3) \\ &= 99\% \text{Degree of accuracy of both 3D-models: [B-(SfM) over A-(Scanner-3D)].}\end{aligned}$$

- There is a deviation in both volumes of 1%.

As for the area:

$$\begin{aligned}\Delta - \text{Area} &= (\text{Area 3D-model B-(SfM)}/\text{Area 3D-Model A-(3D-Scanner)}) \\ &= (1506.736 \text{ cm}^2 / 1553.033 \text{ cm}^2) \\ &= 97.02\% \text{Degree of accuracy of both models: [B-(SfM) over A-(3D-Scanner)].}\end{aligned}$$

- There is a deviation in both areas of 2.98%.

The degree of similarity of both 3D-models in terms of volume and area values, and therefore also geometry, is very significant. The 3D-model B-(SfM) has a volume value of 99% with respect to the 3D-model A-(3D-Scanner) and therefore there is very little deviation between them.

Comparison of 3D-models: A-(3D-Scanner) and C-(Bi-Photo-CAD) in terms of 'volume' and 'area':

In terms of volume:

$$\begin{aligned}\Delta - \text{Vol} &= (\text{Vol 3D-model C-(Bi-Photo-CAD)}/\text{Vol 3D-model A-(3D-Scanner)}) \\ &= (581.078 \text{ cm}^3 / 709.089 \text{ cm}^3) \\ &= 81.9\% \text{Degree of accuracy of both 3D-models: [C-(Bi-Photo-CAD) over A-(3D-Scanner)].}\end{aligned}$$

- There is a deviation in both volumes of 18.1%.

As for the area:

$$\Delta - \text{Area} = (\text{Area 3D-model C-(Bi-Photo-CAD)} / \text{Area 3D-model A-(3D-Scanner)})$$

$$= (1476.371 \text{ cm}^2 / 1553.033 \text{ cm}^2)$$

$$= 95.1\% \text{ Degree of accuracy of both models: [C-(Bi-Photo-CAD) over A-(3D-Scanner)].}$$

- There is a deviation in both areas of 4.9%.

The degree of divergence in the volume and area values between the 3D-models A-(3D-Scanner) and C-(Bi-Photo-CAD) is evident due to the difficulty of accurately reproducing the geometry of the antler, with 3D modeling, from the structure of this due to the irregularities that it presents in its different parts. The 3D-model C-(Bi-Photo-CAD) has a volume value of 82% with respect to the 3D-model A-(3D-Scanner), with a deviation of 18% between them.

## 2. Results of the 'hunting valuation'

### a Results obtained on the 3D-model

The results obtained (Table 6) in the evaluation of the hunting quality in the antler of the fallow deer considered on the surface of the 3D-model are indicated; the lengths of the trajectories of those parts of the antler have been measured as indicated in the official scale in the different items [50]. At the same time, for the same items of the antler structure, the measurement with a tape measure on the physical model by official approved personnel is indicated.

- The results obtained on the 3D-model converge precisely with the results obtained with a tape measure, demonstrating the accuracy of the 'Bi-Photo-CAD' method in spatially characterizing the geometric parts of the antler represented by two photographs [41].
- The reliability of the 3D-model and the reliability of the process of measuring trajectories and lengths on the surface of the model to perform the hunting assessment has been demonstrated, but it is not a practical procedure due to the time and controlled conditions involved in obtaining the 3D-model.
- Therefore, the most efficient procedure for the hunting valuation of the antler of fallow deer is to apply the 'Bi-Photo-CAD' method in order to obtain relatively quickly the spatial structure of those parts of the antler necessary to be measured and to obtain the final score that quantifies its hunting quality.

### b Results obtained on the 3D-model (antler structure)

**Table 6** Measurements on the 3D-model and on the physical model carried out with a tape measure

| Model-3D measuring (mm) |        |                |      |                              |
|-------------------------|--------|----------------|------|------------------------------|
| Length (1)              | 496.2  | Length (1)     | 485  | (1) Right main beam          |
| Length (2)              | 501.17 | Length (2)     | 495  | (2) Left main beam           |
| Length (3)              | 287.86 | Length (3)     | 293  | (3) Right palm               |
| Length (4)              | 279.90 | Length (4)     | 272  | (4) Left palm                |
| Length (5)              | 92.41  | Length (5)     | 92.5 | (5) Width right palm         |
| Length (6)              | 87.27  | Length (6)     | 90   | (6) Width left palm          |
| Length (7)              | 110.42 | Length (7)     | 107  | (7) Right eye tine           |
| Length (8)              | 130.51 | Length (8)     | 128  | (8) Left eye tine            |
| Length (9)              | 587.82 | Length (9)     | 581  | (9) Wingspan                 |
| Perimeter (10)          | 134.44 | Perimeter (10) | 140  | (10) Right burr              |
| Perimeter (11)          | 133.21 | Perimeter (11) | 138  | (11) Right burr              |
| Perimeter (12)          | 76.87  | Perimeter (12) | 78   | (12) Right cross section (1) |
| Perimeter (13)          | 74.31  | Perimeter (13) | 72   | (13) Left cross section (1)  |
| Perimeter (14)          | 71.8   | Perimeter (14) | 72   | (14) Right cross section (2) |
| Perimeter (15)          | 72.15  | Perimeter (15) | 70   | (15) Left cross section (2)  |

Cross section (1): thinner section of the main beam located between the eye tine and trez tine

Cross section (2): thinner section of the main beam located between the trez tine and the palm

**Table 7** Results of the hunting valuation for the sample of 15 fallow deer: Bi-photo-CAD and tape measure

(1): Met: Bi-Photo-CAD

(2): Met: Tape measure

|                | Fallow deer-1 |      | Fallow deer-2 |       | Fallow deer-3 |       | Fallow deer-4 |      |                              |
|----------------|---------------|------|---------------|-------|---------------|-------|---------------|------|------------------------------|
|                | (1)           | (2)  | (1)           | (2)   | (1)           | (2)   | (1)           | (2)  |                              |
| Length (1)     | 58.96         | 60   | 64.24         | 66    | 55.47         | 56.5  | 56.62         | 56   | (1) Right main beam          |
| Length (2)     | 57.91         | 57.5 | 64.12         | 65    | 57.99         | 57.5  | 59.78         | 61   | (2) Left main beam           |
| Length (3)     | 16.5          | 16.5 | 12.84         | 12.5  | 13.97         | 13.5  | 14.76         | 15   | (3) Right eye tine           |
| Length (4)     | 15.12         | 15   | 16.71         | 16.5  | 13.74         | 13.5  | 16.91         | 16   | (4) Left eye tine            |
| Length (5)     | 36            | 35   | 41.12         | 41.5  | 34.33         | 34    | 30.47         | 30.5 | (5) Right palm               |
| Length (6)     | 31.74         | 32   | 40.68         | 41    | 36.38         | 37    | 34.88         | 35   | (6) Left palm                |
| Length (7)     | 10.99         | 11   | 12.55         | 13.2  | 13.43         | 14    | 12.72         | 13   | (7) Width right palm         |
| Length (8)     | 13.51         | 13   | 16.53         | 16.75 | 14.26         | 14.75 | 12.74         | 13   | (8) Width left palm          |
| Length (9)     | 65.4          | 66   | 73.54         | 73    | 64.79         | 65    | 70.83         | 71   | (9) Wingspan                 |
| Perimeter (10) | 16.27         | 16   | 17.08         | 17    | 17.01         | 17    | 17.11         | 17   | (10) Right burr              |
| Perimeter (11) | 17.42         | 16.5 | 17.35         | 17    | 16.33         | 16    | 16.74         | 16.5 | (11) Right burr              |
| Perimeter (12) | 9.04          | 9.5  | 9.16          | 9.5   | 9.28          | 9.5   | 9.3           | 9.5  | (12) Right cross section (1) |
| Perimeter (13) | 9.76          | 10   | 9.37          | 9.5   | 9.31          | 9.3   | 9.48          | 9.5  | (13) left cross section (1)  |
| Perimeter (14) | 10            | 10   | 9.7           | 10    | 9.83          | 9.7   | 9.22          | 9.2  | (14) right cross section (2) |
| Perimeter (15) | 11.05         | 11.3 | 9.8           | 10    | 10.75         | 10.5  | 9.08          | 9.2  | (15) left cross section (2)  |

(1): Met: Bi-Photo-CAD

(2): Met: Tape measure

|                | Fallow deer-5 |      | Fallow deer-6 |       | Fallow deer-7 |       | Fallow deer-8 |       |                              |
|----------------|---------------|------|---------------|-------|---------------|-------|---------------|-------|------------------------------|
|                | (1)           | (2)  | (1)           | (2)   | (1)           | (2)   | (1)           | (2)   |                              |
| Length (1)     | 65.47         | 66   | 67.7          | 67    | 61.9          | 61    | 60.29         | 60.8  | (1) Right main beam          |
| Length (2)     | 68.38         | 68.5 | 67.2          | 66.5  | 64.2          | 65    | 59.98         | 60    | (2) Left main beam           |
| Length (3)     | 13.49         | 13   | 12.29         | 12    | 11.09         | 10.5  | 14.91         | 14.8  | (3) Right eye tine           |
| Length (4)     | 11.42         | 11   | 13.64         | 13.5  | 12.15         | 12.5  | 14.88         | 14.5  | (4) Left eye tine            |
| Length (5)     | 39.88         | 40   | 41.21         | 41    | 33.87         | 34.5  | 37.64         | 38.5  | (5) Right palm               |
| Length (6)     | 45.33         | 45.5 | 40.93         | 41    | 38.39         | 39    | 36.08         | 36.5  | (6) Left palm                |
| Length (7)     | 11.85         | 11.2 | 12.38         | 12.1  | 11.69         | 11.75 | 10.93         | 11.25 | (7) Width right palm         |
| Length (8)     | 11.5          | 12.1 | 12.35         | 12.25 | 11.77         | 12    | 11.47         | 10.9  | (8) Width left palm          |
| Length (9)     | 68.62         | 68   | 74.27         | 75    | 67.35         | 67    | 67.21         | 67    | (9) Wingspan                 |
| Perimeter (10) | 17.23         | 17   | 17.21         | 17    | 17.33         | 16.5  | 16.6          | 16.5  | (10) Right burr              |
| Perimeter (11) | 16.76         | 16.5 | 17.21         | 17.5  | 15.96         | 16    | 16.74         | 17    | (11) Right burr              |
| Perimeter (12) | 8.81          | 9    | 8.81          | 9     | 9.41          | 9.3   | 8.91          | 8.9   | (12) Right cross section (1) |
| Perimeter (13) | 9.37          | 9.5  | 9.66          | 9.4   | 8.8           | 8.6   | 9.34          | 9.2   | (13) left cross section (1)  |
| Perimeter (14) | 10.49         | 10.6 | 8.78          | 9     | 9.34          | 9.4   | 9.09          | 9     | (14) right cross section (2) |
| Perimeter (15) | 9.58          | 9.5  | 8.93          | 9.2   | 9.8           | 9.6   | 9.35          | 9.5   | (15) left cross section (2)  |

(1): Met: Bi-Photo-CAD

(2): Met: Tape measure

|            | Fallow deer-9 |      | Fallow deer-10 |      | Fallow deer-11 |      | Fallow deer-12 |      |                     |
|------------|---------------|------|----------------|------|----------------|------|----------------|------|---------------------|
|            | (1)           | (2)  | (1)            | (2)  | (1)            | (2)  | (1)            | (2)  |                     |
| Length (1) | 58.64         | 59   | 68.89          | 68   | 61.96          | 61   | 63.46          | 61.5 | (1) Right main beam |
| Length (2) | 62.97         | 62   | 65.81          | 64   | 62.13          | 62   | 66.37          | 65   | (2) Left main beam  |
| Length (3) | 0             | 0    | 14.04          | 13.7 | 16             | 15.4 | 19.3           | 18   | (3) Right eye tine  |
| Length (4) | 14.09         | 13.8 | 14.81          | 14.5 | 15.58          | 15.8 | 17.29          | 16   | (4) Left eye tine   |
| Length (5) | 36.89         | 37.5 | 43.52          | 43   | 32.92          | 32   | 33.5           | 33.7 | (5) Right palm      |
| Length (6) | 36.25         | 36.5 | 39.55          | 39.5 | 31.77          | 31.5 | 37.16          | 37.5 | (6) Left palm       |

**Table 7** (continued)

(1): Met: Bi-Photo-CAD

(2): Met: Tape measure

|                | Fallow deer-9 |       | Fallow deer-10 |      | Fallow deer-11 |      | Fallow deer-12 |      |                              |
|----------------|---------------|-------|----------------|------|----------------|------|----------------|------|------------------------------|
|                | (1)           | (2)   | (1)            | (2)  | (1)            | (2)  | (1)            | (2)  |                              |
| Length (7)     | 10.85         | 10.9  | 13.08          | 12.9 | 11.26          | 11.3 | 10.51          | 10.4 | (7) Width right palm         |
| Length (8)     | 10.43         | 10.75 | 13.96          | 14   | 13             | 13   | 13.59          | 14.2 | (8) Width left palm          |
| Length (9)     | 60.02         | 60    | 66.59          | 67   | 59.67          | 59   | 62.85          | 61   | (9) Wingspan                 |
| Perimeter (10) | 14.7          | 14.5  | 17.8           | 18   | 15.79          | 16   | 18.67          | 18.5 | (10) Right burr              |
| Perimeter (11) | 16.16         | 16    | 18.38          | 18.5 | 15.76          | 16   | 18.11          | 18.2 | (11) Right burr              |
| Perimeter (12) | 8.35          | 8.4   | 9.72           | 10   | 8.64           | 8.8  | 9.4            | 9.5  | (12) Right cross section (1) |
| Perimeter (13) | 8.23          | 8.4   | 10.51          | 10.5 | 8.37           | 8.5  | 9.82           | 10   | (13) Left cross section (1)  |
| Perimeter (14) | 8.4           | 8.6   | 10.2           | 10   | 9.18           | 9.3  | 10.24          | 10.5 | (14) Right cross section (2) |
| Perimeter (15) | 8.35          | 8.4   | 10.39          | 10.5 | 9.53           | 9.7  | 10.25          | 10.3 | (15) Left cross section (2)  |

(1): Met: Bi-Photo-CAD

(2): Met: Tape measure

|                | Fallow deer-13 |      | Fallow deer-14 |      | Fallow deer-15 |      |                              |
|----------------|----------------|------|----------------|------|----------------|------|------------------------------|
|                | (1)            | (2)  | (1)            | (2)  | (1)            | (2)  |                              |
| Length (1)     | 56.63          | 56   | 62.16          | 62.5 | 65.8           | 66   | (1) Right main beam          |
| Length (2)     | 55.53          | 54   | 66.1           | 64.5 | 68.4           | 68   | (2) Left main beam           |
| Length (3)     | 9.74           | 9.5  | 15.97          | 15.5 | 16.11          | 16.5 | (3) Right eye tine           |
| Length (4)     | 14.61          | 14.8 | 17.9           | 17.5 | 17.62          | 17   | (4) Left eye tine            |
| Length (5)     | 32.7           | 32.5 | 39.8           | 40   | 43.3           | 43   | (5) Right palm               |
| Length (6)     | 31.6           | 31.5 | 40.3           | 40.6 | 44.2           | 44   | (6) Left palm                |
| Length (7)     | 10.67          | 10.8 | 15.73          | 16   | 16.62          | 16   | (7) Width right palm         |
| Length (8)     | 11.34          | 11.6 | 16.75          | 17.6 | 17.03          | 17.3 | (8) Width left palm          |
| Length (9)     | 57.21          | 58   | 64.84          | 69   | 71.04          | 73   | (9) Wingspan                 |
| Perimeter (10) | 17.5           | 17.5 | 17.53          | 17.6 | 17.1           | 17   | (10) Right burr              |
| Perimeter (11) | 17.21          | 17.5 | 17.9           | 18   | 17.4           | 17.5 | (11) Right burr              |
| Perimeter (12) | 9.25           | 9.5  | 10.88          | 10.9 | 9.9            | 10   | (12) Right cross section (1) |
| Perimeter (13) | 8.83           | 9    | 11.46          | 11.5 | 11.05          | 11.1 | (13) Left cross section (1)  |
| Perimeter (14) | 9.38           | 9.5  | 12.31          | 12.3 | 11.3           | 11.5 | (14) Right cross section (2) |
| Perimeter (15) | 9.31           | 9.5  | 12.08          | 12.2 | 11.25          | 11.3 | (15) Left cross section (2)  |

Cross section (1): thinner section of the main beam located between the eye tine and trez tine. Cross section (2): thinner section of the main beam located between the trez tine and the palm

The results of the evaluation of the hunting quality of the fallow deer antlers are indicated in Table 7, applying the photogrammetric methodology of spatial restitution of the characteristic points of the parts of the structure of the antlers represented in two photographs, as indicated in the official scale [50]. At the same time, the measurement with a tape measure of the same parts of the antler considered, carried out on the real model by official approved personnel, is also indicated. These measurements were performed on a sample of 15 fallow deer antlers from real models obtained in taxidermy workshops which were from different hunting days and hunting grounds located in Andújar (Jaén), Spain during 2016. The taking of photographs, for the subsequent spatial restitution by photogrammetry of the significant geometric parts of the antler, was carried out in the taxidermy workshop itself.

Measurements with a tape measure were obtained from the official measurement, carried out by certified personnel.

- It is observed that the degree of approximation of the values of the different geometric indicators of the antlers, lengths and trajectories, considered for the assessment of the hunting quality of the specimen, is very similar in the

two methodologies; the values estimated in the spatial restitution carried out in CAD using photogrammetry with two photographs are very similar to, and considered very close to the real ones, those obtained by approved personnel measuring with a tape measure. Such validation of results, in terms of correlation and similarity of results in the two methodologies, was demonstrated in similar studies applied on deer specimens using statistical techniques [41].

- It is demonstrated that this procedure is the most efficient for the hunting valuation of fallow deer represented by its antlers over others, such as the representation of the antlers by means of 3D-models with different technologies, due to the greater resources and controlled conditions required to obtain such a 3D-model.

## 4 Discussion

The characterization of the 3D-model of the antler by means of the three technologies described above is used as input data for different biological applications. The 'suitability' characteristics that the input data has to meet depending on the type of biological analysis for which it is intended, 3D-model or axial structure of the antler; are:

- That it is precise, so that the results of subsequent analyses have the necessary reliability to be able to infer with other biomarkers.
- That the data collection is obtained under favorable conditions; in the hunting days themselves in situ, avoiding the use of costly resources in laboratories and controlled environments.
- Economy in resources to obtain them, in monetary cost and time invested in their definition.
- Ease of obtaining them in favorable environments so as to allow biological analysis, not only of specific specimens but also of populations of specimens that have developed in a given environment, allowing later inferences to be made with the results obtained about the quality of the environment in a specific period.

The attached Table 8 shows the degree of suitability of each result obtained for the geometric characterization of the antler of fallow deer defined by a 3D-model or by its axial structure depending on the biological application to which it will be implemented, either for the estimation of volume and density or for the evaluation of the hunting quality of the specimen.

1. For the biological application intended for volume determination, the degree of suitability of the input data is justified below

- 1.1 The 3D-model obtained by 'structured light scanner' is the 'most suitable' technology for its application, since it is the one that presents the greatest geometric precision and, therefore, the closest approximation to the real model. The equipment used has an accuracy of 0.045 mm (45 microns), meeting the requirement of obtaining a volume value and geometric approximation very close to that of the physical model.

On the other hand, the disadvantages that it may present are the following:

- The 'structured light scanner' may be suitable for the study of specific specimens, requiring the availability of the physical model from hunting trophies supplied in taxidermy workshops, but for the study of populations it is not the most suitable since on a hunting day the physical models are not available for data collection.
- It is necessary to work in laboratories and controlled environments.
- The cost of the equipment, hardware and software, can be high; it can be around 7000€.
- The implementation time can be high; ~ 2 h.

**Table 8** Degree of suitability of the data type according to the type of biological application to be implemented

| Application Biological | Technology         |                               |                                            |
|------------------------|--------------------|-------------------------------|--------------------------------------------|
|                        | Scanner (3D-model) | SfM photogrammetry (3D-model) | Bi-Photo-CAD (3D-model) (antler structure) |
| Volume                 | High               | Medium                        | Low (3D-model)                             |
| Assessment cynegetics  | Low                | Medium                        | High (antler structure)                    |

### 1.2 The 3D-model obtained with 'multi-image photogrammetry', SfM (Structure from Motion):

- It has a 'medium' degree of suitability, since this technology provides a 3D-model with an adequate degree of accuracy from a sweep of photographs, between 30 and 40, of the object. On the other hand, it does not require specialized equipment; an SLR reflex camera is enough to take the photographs, since these do not require subsequent editing treatments to correct deformation errors and, therefore, the use of more expensive metric cameras. Nor is the specific software that achieves the 3D-model through the spatial restitution of the object represented in the photographs too expensive.
- The time required to obtain the 3D-model is not high; it will depend on the characteristics of the software used.

The disadvantages that this technology may present are:

- It is not possible to obtain a 3D-model with the degree of approximation that the 'structured light scanner' has; such precision will depend on the performance of the spatial restitution software applied and on the number of photographs and their quality in terms of sharpness and deformation.
- For the study of features that require high accuracy, such as the estimation of the volume and density of deer antlers, 'SfM technology' may be applicable, but without being as accurate as the 'structured light scanner' implementation.
- It can be suitable for obtaining the 3D-model of the antler of a specific specimen. For the study of populations it is not suitable since it requires that the necessary photographs be taken in situ on the same hunting day, where the time and position of the antler for the capture of the photographs are significant limitations.
- For the taking of photographs, the conditions must be controlled; the luminosity of the environment must be acceptable, the object must have a minimum overlap of 60% in every two consecutive photographs, and the real model must be properly positioned so as to facilitate the taking of the sweep of photographs.

### 1.3 The 3D-model obtained by 'modeling with CAD software' from the axial structure of the antler by 'photogrammetry Bi-Photo' [41] is not suitable due to the drawbacks involved in its application:

- The 3D-model obtained is not close to the real model, neither in volume nor in geometry, and there are significant deviations due to the geometric complexity of the antler: different thicknesses and cross sections in all parts of its morphology make it very difficult to replicate them in a 3D-model from the 3D axial structure data obtained previously.
- In the three-dimensional modeling process a series of assumptions and geometric simplifications must be considered in order to facilitate the creation of the final 3D-model of the antler such as continuity and uniformity in the thicknesses, sections and shapes of the different parts of the antler, especially in the area of its palm; simplifications that are not adapted to the discontinuities and deformations that the antler actually presents in its different areas.
- The time required to obtain the 3D-model is high, requiring the definition of each geometric element of the antler separately using different solid and surface modeling options.
- The time to obtain the starting data, the axial structure of the antler, is significant; this is obtained by spatial restitution using photogrammetry from two photographs [41], making it difficult to study the volume of the antlers of populations of specimens.

One advantage is that the cost of the necessary computer equipment, in terms of hardware and software, is not high, since obtaining the 3D-model does not require major computer processing needs.

### 2. For the second biological application destined to the 'evaluation of the hunting quality' of the specimen, indicate that:

- Obtaining a 3D-model by any of the three technologies indicated for the evaluation of hunting quality is not the most appropriate, since it involves the investment of a lot of time and material.
- With the availability of a 3D-model, previously obtained for other types of analysis, it could be used as input for the evaluation of hunting quality, since the trajectories and lengths that are considered for the evaluation, indicated in [50], can be performed on the available 3D-model whether it is a mesh, solid or surface version.

- The 3D-model obtained with '3D-scanner' is not the most appropriate, since its definition requires expensive equipment and long computing times.
- The 3D model defined by 'photogrammetry (SfM)', could be more appropriate; this is less accurate than the one obtained by 'scanner-3D', but requires less expensive computer equipment.
- The most suitable technology for assessing the degree of hunting quality of the antler of fallow deer is the spatial restitution 'photogrammetric Bi-Photo' from two photographs [41].
- In a CAD-3D scenario, the spatial restitution of those necessary geometric elements, lengths and trajectories of the antler structure are obtained: lengths of the main beam and palm, of the eye tines, width of the palms, wingspan and perimeters of the main beam and of the burrs.

Depending on the magnitude of the value of these lengths and perimeters a score is obtained, as indicated in [50], which determines the degree of hunting quality of the antler of the specimen.

The implementation of this methodology has the following advantages:

- It is not necessary for the hunting valuation to spatially restore all the elements of the antler structure; only those parts of the antler specified in [50] are necessary.
- The necessary data to obtain spatially the elements of the antler are only two photographs showing the antler from two different points of view.
- The photographs are taken quickly during hunting days, so it is possible to take photographs of many specimens in the same day for later evaluation.

The three-dimensional definition of the antler structure elements and their metric quantification do not require laboratories or controlled environments for their implementation.

- The cost of the equipment, hardware and software, is moderate without requiring large processing and computer calculation requirements.
- The time needed to spatially obtain the antler geometric elements and their metric quantification is low.

## 5 Conclusions

This study has considered that for relevant biological and ecological applications such as the estimation of the volume and the evaluation of the hunting quality of fallow deer antlers, it is necessary to consider as input data for these analyses some models that accurately characterize the geometry of the antlers, so that the results obtained are considered accurate and relevant to allow subsequent correlation with other internal or external variables of the specimen. The process of obtaining the 3D model was initially described for each of the three technologies considered: '3D-scanner', 'SfM photogrammetry' and 'photogrammetry Bi-Photo-CAD', based on its structure. Subsequently, the degree of approximation of the three 3D-models was studied by comparing two of them with respect to the most accurate reference 3D-model, the one obtained by 3D-scanner, by superimposing and aligning two 3D-models in order to verify the degree of deviation of the pairs of significant related points considered in the antler: the ends of the main tines, eye tines and trez tines, and the spellers of the palm. For volume and density estimation studies an accurate 3D-model is needed, such as that provided by structured light scanner technology, or more quickly, although somewhat less accurately, with SfM technology.

For the study of the valuation of hunting quality we could take the lengths and perimeters necessary for the 'hunting valuation' on the external surface of a 3D-model, although this is not the most suitable method in terms of time, cost and controlled conditions for obtaining the 3D-model. The most efficient methodology is to work with the starting data of the geometric structure of those parts of the antler obtained quickly with photogrammetric spatial restitution of the antler from two photographs. The estimation of the antler volume, through its characterization in a 3D-model, can be relevant as a biomarker for determining the degree of development and health of the specimen. It may be more relevant to know the antler density value, which could be related to the degree of health and body development of the specimen according to the environmental conditions in which it has developed. To estimate the density value from the volume the mass or weight of the antler is needed; this variable is not easy to obtain since in antler samples taken from hunting trophies these are attached to the skull, making it difficult to estimate the mass of each part.

Another way of estimating it is through the water displacement procedure [13], although in this way there may be problems of deterioration on the surface of the antler. For the study of populations that have developed in a given location, one way to study density can be to study the weight of the samples available in the field in the periods when the specimens lose their antlers (late winter and early spring), called 'cast-off antlers', in order to assess the mass of the antler branch available. This tool, the spatial restitution from two photographs, makes possible the hunting assessment of fallow deer populations in subsequent studies in a specific period and location, since with it it is possible to take photographs in situ of many specimens on the same hunting day. Knowing the hunting valuation in populations makes possible its relationship with other biomarkers, such as age [3] and degree of asymmetry [47]. Therefore we can make inferences about internal characteristics of the specimen such as the degree of health along with other external variables such as the quality of the environmental conditions in which the fallow deer population has developed over a given period.

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**Author contributions** J.M.M.-G.: Methodology, software, review & editing. C.A.: Methodology, formal analysis, review & editing. D.F.G.-M.: software, Data curation & editing. J.M.V.-Z.: software, Data curation. M.Á.R.-P.: Methodology, review & editing, Conceptualization, project administration. All the authors wrote the paper and reviewed it for final approval. All authors have read and agreed to the published version of the manuscript.

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**Data availability** Data will be made available on request.

## Declarations

**Institutional review board statement** All specimens used in this study came from authorized hunts during the official hunting season in the study area. Current regulations on animal protection and bioethics were complied with. This study complied with all Andalusian, Spanish and European legal requirements and guidelines regarding experimentation and animal welfare. It was approved by the Committee on Ethics of Animal Experimentation of the University of Jaén and authorized by the General Direction of Agriculture and Livestock of the Ministry of Agriculture, Fisheries and Environment of the Junta de Andalucía. No special permits from the bioethics committees were required. The datasets and specimens of the current study, stored at the University of Jaén, may be available upon reasonable request to the corresponding author and head of the Research Group PAI-RNM-175 and Vertebrate Laboratory.

**Competing interests** The authors declare no competing interests.

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