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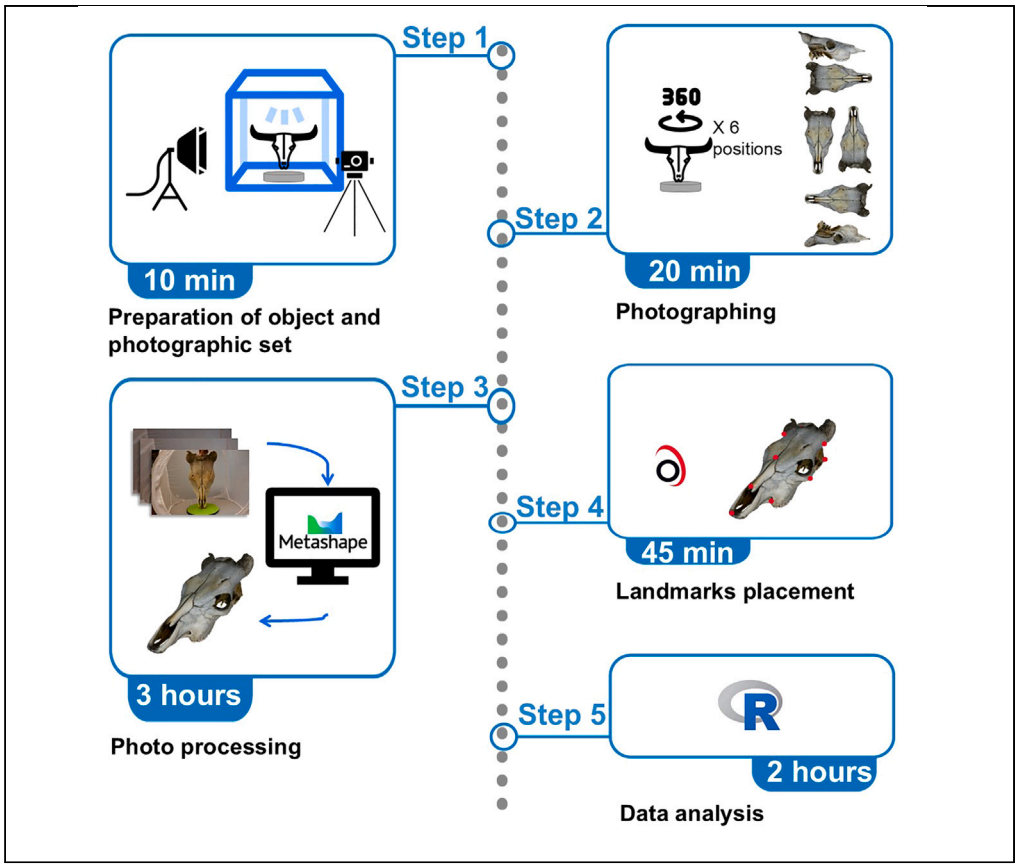
Protocol for 3D photogrammetry and morphological digitization of complex skulls



Here, we present a protocol for 3D photogrammetry and morphological digitization of skulls, including complex ones with tusks, antlers, and horns, which are challenging to reconstruct digitally. We describe steps for setting up specimens for image acquisition, including camera and lighting configurations, and the subsequent image processing to generate high-quality 3D models. We also outline the extraction of morphological data for accurate geometric morphometric analyses.

Publisher's note: Undertaking any experimental protocol requires adherence to local institutional guidelines for laboratory safety and ethics.

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Highlights

Setup for acquiring standardized images

Procedures for processing images into 3D models of complex skulls

Instructions for extracting shape-descriptive landmarks

Guidelines for obtaining morphometric data for geometric and statistical analyses

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Protocol for 3D photogrammetry and morphological digitization of complex skulls

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SUMMARY

Here, we present a protocol for 3D photogrammetry and morphological digitization of skulls, including complex ones with tusks, antlers, and horns, which are challenging to reconstruct digitally. We describe steps for setting up specimens for image acquisition, including camera and lighting configurations, and the subsequent image processing to generate high-quality 3D models. We also outline the extraction of morphological data for accurate geometric morphometric analyses.

BEFORE YOU BEGIN

This protocol is designed to create highly accurate 3D models of skulls, including problematic specimens with antlers,[1,2] horns,[3] and tusks,[4] using photogrammetry. The primary goal of digitization is to produce digital replicas that can be stored, manipulated, and analyzed without handling the original specimens.[5,6] This is particularly advantageous for large, complex, or valuable specimens,[7,8] as it reduces the risk of damage from repeated handling and allows museums and institutions to easily share their data with researchers worldwide.[9,10] Through digitization, research can be conducted more efficiently, and global collaboration is enhanced. Photogrammetry, being the most cost-effective technology for digitization, is often avoided for complex structures like bovid horns or cervid antlers due to the challenges in aligning multiple viewpoints, especially for objects with homogenous textures, elongated shapes, or very dark colors.[11–14] However, with a well-structured protocol, it is possible to achieve results comparable to those obtained using more expensive technologies (e.g., laser scanners, CT scanners). Relative costs for equipment, software, and tools are summarized in Table 1.

This protocol describes procedures for collecting morphological data deriving from standardized digital photographs of complex skulls. This includes recommendations for setting up the photographic environment, creating an exhaustive photographic library, and processing the images using specialized software. Detailed steps for generating 3D models through photogrammetry are provided, along with instructions for extracting morphometric data using appropriate tools.[15–17] The protocol also offers guidelines for performing statistical analyses using software packages tailored to the specific needs of the protocol aims.

Preparation of object and photographic set

Timing: 10 min

Table 1. Comparative cost between photogammetry and laserscanning

	Photogrammetry	Artec Spider (laser Scan)
Equipment		
Turntable	20$–100$	20$–100$
Box lights	30$–100$	–
Tripod	50$–500$	–
Camera	500$–2000$	–
LaserScan	–	20000$–30000$
Software		
Agisoft Metashape	180$–3500$	–
Artec Studio	–	Included with the scan

The costs presented are average market prices for 2024 and may vary depending on the specifications and type of equipment.

This section ensures proper preparation of the specimen and photographic setup for consistent image capture. It includes stabilizing the specimen and camera settings for optimal results. It will be useful for photographing the background and adjusting lighting in next steps.

1. Positioning the Specimen
   a. Place the specimen as close to the center of the rotating table as possible.
   b. Ensure that both the table and the specimen are securely positioned within a light-diffusing box designed to block direct light and distribute it evenly across the specimen.

   ⚠ CRITICAL: The light-diffusing box should eliminate strong highlights and shadows on the specimen's surface (Figure 1).

2. Lighting Adjustments
   a. If the ambient room lighting is insufficient, position adjustable directional lights outside the box.
   b. Adjust the light intensity to ensure even illumination of the specimen without creating harsh shadows or overexposure (Figure 2).
   c. Make a test shot to verify the lighting and eliminate any reflections.

   Note: The entire setup, including the light-diffusing box and the specimen, must remain completely stable throughout the entire process.

3. Camera Setup

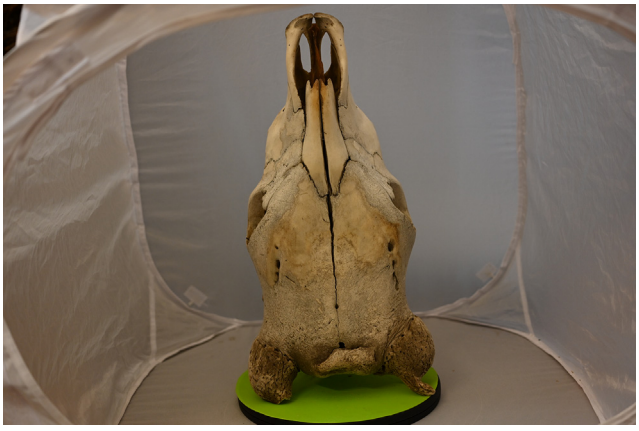

Figure 1. *Bos taurus* (AN.CO.ac0322) skull inside the light box

Figure 2. Example of bad lighting in *Bos taurus* (AN.CO.ac0322)
(A) Low exposure, (C) high exposure, and (B) the correct exposure inside the light box.

a. Put the camera on a tripod directly in front of the box opening. The tripod and camera should remain fixed as much as possible throughout the image capture process.
b. Adjust the camera's distance to ensure the entire specimen, along with the base and background, is within the frame during each rotation of the table.
c. Set the camera at an angle of at least 45° above the specimen.

Note: Deactivate the camera's flash to avoid unintended reflections and lighting inconsistencies.

⚠ CRITICAL: If the tripod is moved or the camera angle is changed during the process, take a photograph of the background and rotating table without the specimen for each new tripod/camera position to maintain consistent reference images. Additionally, an initial background photo should be taken to enable masking in the software, isolating the specimen from the background.

4. Special Considerations for Specimens with Antlers, Horns, and Tusks

For specimens with prominent antlers, horns, and tusks, attach adhesive markers at various points on the protruding portion of the specimens (e.g., close to the horn tip). Ensure that these markers remain in place throughout the photographic process (Figure 3).

⚠ CRITICAL: Consistent placement of these markers is essential for accurate photogrammetric reconstruction.

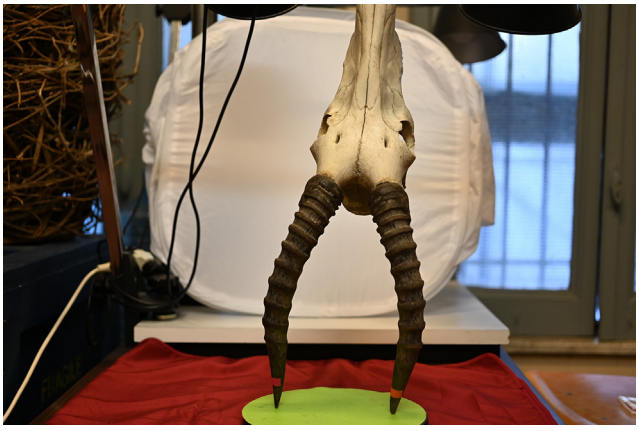

Figure 3. *Damaliscus lunatus* (AN.CO.ac0331) skull with markers (orange and pink) at the end of the horns

5. Camera Settings
   a. Adjust the camera settings carefully:
      i. ISO: Set the ISO value to no higher than 600 to minimize image noise.
      ii. Aperture: Set the aperture between f/6 and f/16 to avoid depth-of-field effects that can blur the edges of the image, which could interfere with software processing.
      iii. Shutter Speed: Ensure the shutter speed is not slower than 1/60 to avoid motion blur, especially when photographing with a tripod.

Note: Once chosen, these settings should remain consistent for all photographs taken during the session.

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental models: Organisms/strains		
Bos taurus	University of Rome - Sapienza	Bos_taurus_U_AN.CO.ac0322
Damaliscus lunatus	University of Rome - Sapienza	Damaliscus_lunatus_U_AN.CO.ac0331
Software and algorithms		
R, version 4.3.2	R Core Team[18]	https://www.r-project.org/
Geomorph package, version 4.06	Adams and Otárola-Castillo[19]	https://cran.r-project.org/web/packages/geomorph/index.html
Agisoft Metashape professional, version 2.1.3	Agisoft	https://www.agisoft.com/ Copyright 2022 Agisoft LLC
Checkpoint x64	Stratovan Encircle[20]	https://www.stratovan.com/products/checkpoint
MeshLab,[21] version 2023.12		https://www.meshlab.net/#description
Other		
Turntable		N/A
Neewer light box		N/A
Manfrotto MK190XPRO3-3W tripod		N/A
Nikon z6 ii reflex camera		N/A

STEP-BY-STEP METHOD DETAILS

Photographing

Timing: approximately 20 min

This section outlines the process of photographing the specimen from multiple angles to ensure complete 3D coverage. It includes capturing images from 360° around the object and performing multiple rotations for full coverage.

1. Capturing 360° Photographs
   a. Since the specimen is a three-dimensional volume, take photographs from 360° around the object from different positions by rotating the turntable.
   b. The number of photographs required varies according to the complexity of the specimen and the desired resolution of the digital model, but at least 90-120 total images from different vantage points are required to obtain highly accurate 3D models.
   c. Ensure that each image overlaps by at least 50% with the previous one by rotating the specimen approximately 20° between shots. This overlap is crucial for the software to accurately acquire anchor points.

Note: The images do not need to be taken or named in any specific order.

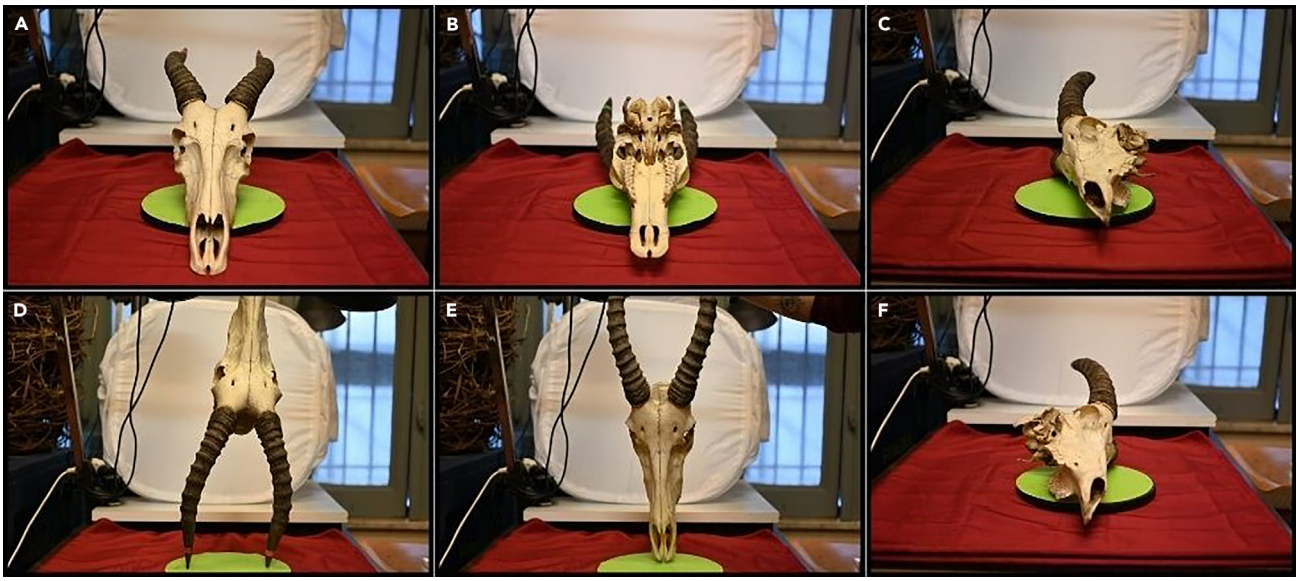

Figure 4. Six views of the *Damaliscus lunatus* (AN.CO.ac331) skull in different orientations
(A) Dorsal view; (B) ventral view; (C and F) right and left lateral views; (D and E) Vertical views.

⚠ CRITICAL: As mentioned in the 'before you begin' section, you need to take a background photo without the specimen every time you change the tripod or camera view (including the starting position).

2. Multiple Rotations for Complete Coverage
   a. Perform three pairs of rotations for each specimen (i.e., six rotations in total), with each set oriented on a different orthogonal axis (corresponding to the x-, y-, and z-axes to be photogrammetrically processed together following the one-chunk approach[22]).
   b. For each pair of rotations, the specimen should be rotated 180° between the first and second rotation to capture all necessary angles (Figure 4).

Note: For rotations where the object is in a precarious balance, the specimen can be held manually, or stabilized using materials such as modeling clay, cushions, or sand.

⚠ CRITICAL: If the tusks, horns or antlers are extremely complex, it is recommended to perform an additional rotation focused solely on the protruding region of the specimen, ensuring that a part of the skull is also included.

3. Lens and Focal Length Recommendations

For optimal results, use a 50 mm lens for full-frame cameras or a 30–35 mm lens for APS-C cameras. Photogrammetry software works better with these focal lengths because they produce minimal image distortion.

⚠ CRITICAL: Avoid using zoom lenses as they can introduce distortion, which may complicate the photogrammetric processing.

Photo processing

Timing: 3 h (depending on available computing power)

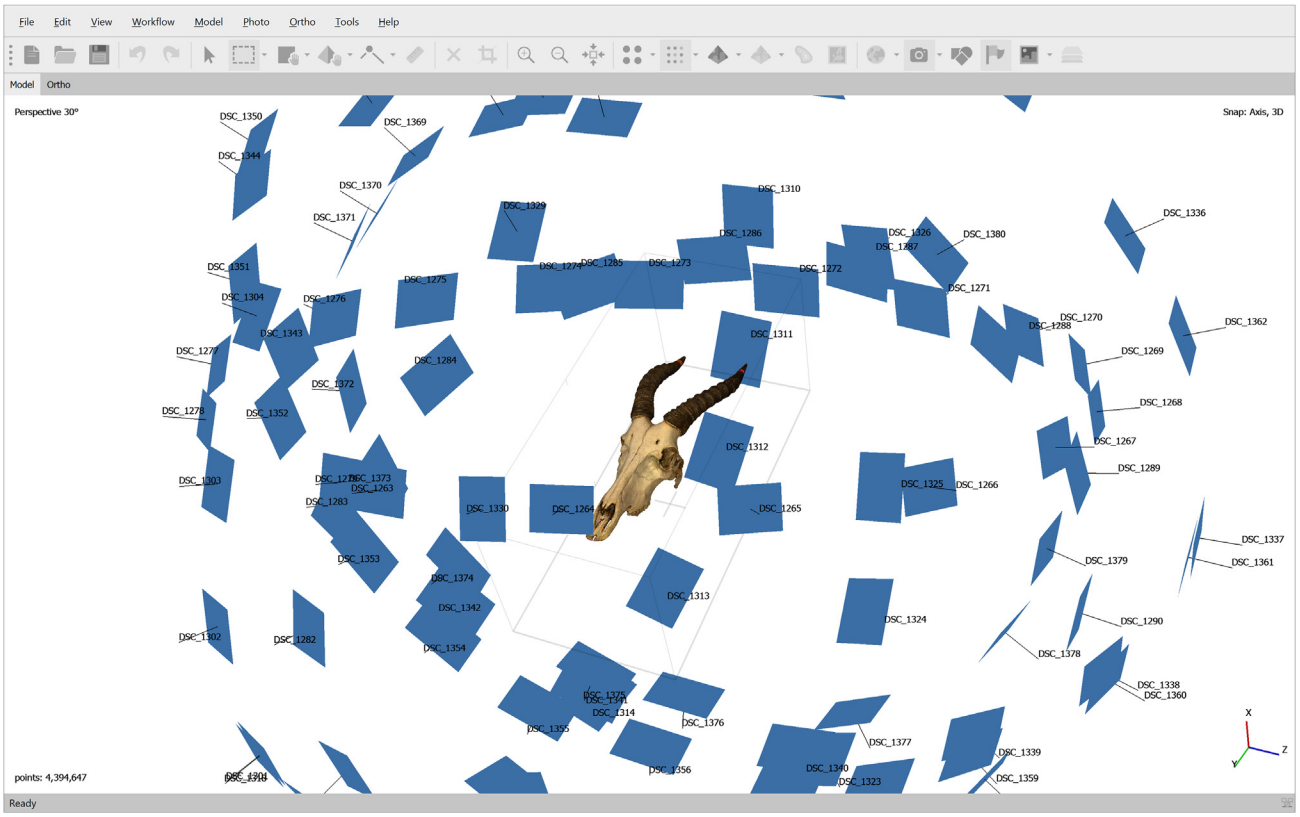

Figure 5. Screenshot from Agisoft Metashape showing the *Damaliscus lunatus* (AN.CO.ac331) skull after the photo alignment step
The circular arrangement of the cameras indicates successful alignment, matching the original 360° photo capture sequence.

This step outlines the process of organizing the images and creating a high-quality 3D model with Agisoft Metashape from the captured photographs.

4. Organizing images and project files
   a. Create a folder for each specimen, named with its unique identifier. This folder, after applying the procedure, will include:
      i. Photographs of the specimen
      ii. Background images (without the specimen)
      iii. Agisoft project files (.psx)
      iv. The 3D mesh model (.ply)
      v. The texture file
5. Importing images into Agisoft

Open Agisoft Metashape and import the specimen images, excluding the background photos.

6. Organizing images into chunks
   a. In Agisoft Metashape, images are processed within "chunks." Create a single chunk for the entire set of images captured during the six rotations.
   b. Apply the one-chunk method, importing all photographs from the six rotations into a single chunk.
   c. Advantages of the one-chunk method:
      i. Increases the statistical strength of the alignment process by processing all rotations simultaneously.

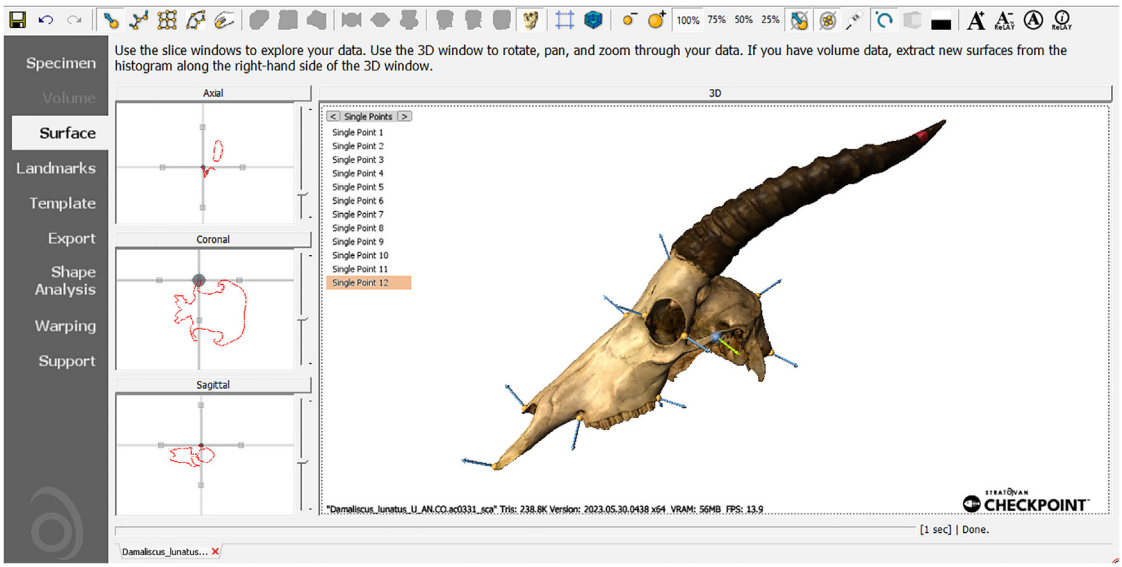

Figure 6. Example of single landmarking in *Damaliscus lunatus* (AN.CO.ac331) skull and Stratovan checkpoint main interface

ii. Ensures a uniform distribution of images in 3D space across the x, y, and z axes, avoiding unprocessed areas of the specimen.

Note: This method has proven effective for creating accurate and comprehensive 3D reconstructions, especially for complex specimens.[22]

7. Importing the mask (background removal)
   a. Select the images and right-click to choose **"Import Mask"**.
   b. Set the mask **filename template** and select the folder containing the background images.
   c. Adjust the **tolerance** level so that only the background is removed without affecting parts of the specimen.

⚠ CRITICAL: A more accurate mask leads to better alignment results. Test the mask on a single image first to ensure the tolerance settings are appropriate. If necessary, manually clean the images using tools such as "intelligent scissors".

Note: Masks may require different tolerance settings depending on lighting and contrast in the images.

8. Aligning photos
   In this process, the software compares and aligns the photos to match the angles they were taken from, generating "tie points" (anchor points) that link the images together.
   a. Go to **Workflow -> Align Photos** to start the alignment process.

⚠ CRITICAL: Ensure the accuracy is set to at least High or Highest for better results.

   b. After the alignment is complete, you can use the **"Show Cameras"** icon from the toolbar to visualize the sequence of photos as they were aligned. If the cameras appear arranged in a circular pattern, this confirms they are in the correct position, corresponding to how the photos were originally taken (Figure 5).
   c. **Cleaning noise:** Once the alignment is done, use the **selection tools** available (e.g., **intelligent scissors** or **lasso tool**) to clean up noise or unwanted points that are not part of the specimen.

Note: This step helps refine the accuracy of the alignment by removing irrelevant data that may interfere with further processing.

Note: The alignment process is key to successful reconstruction. Monitor the tie points generated to confirm they are evenly distributed across the specimen.

9. Building the Dense Cloud

After aligning the photos, the next step is to generate a dense cloud, which represents a detailed map of points based on the photo alignment. Go to **Workflow -> Build Dense Cloud** to initiate this process.

10. Constructing the Mesh

Once the dense cloud is generated, create the actual 3D model (mesh) of the specimen. Again, go to **Workflow -> Build Mesh**.

⚠ CRITICAL: Review the mesh to ensure it is free of gaps or distortions. Use the available tools to refine the 3D model, such as filling in holes or smoothing rough areas.

11. Applying the Texture
    a. Apply the texture from the original photographs onto the mesh to give it a realistic appearance.
    b. Go to **Workflow -> Build Texture** to apply the texture to the 3D model.
12. Exporting the final 3D model

Once the texture has been applied, the model is ready to be exported. Save the project files and export the 3D model (.ply format) along with the texture file for future analysis or sharing.

13. Scaling the 3D Model
    The 3D model exported from Agisoft is not scaled, so it needs to be manually scaled. This can be done using **Meshlab**.
    a. Launch Meshlab and open the recently created 3D model from Agisoft.
    b. Use the **"Measuring Tool"** from the toolbar to take a linear measurement on the model (e.g., total length of the palate). Ensure that the measurement is as straight as possible for accuracy.
    c. Using calipers, measure the same dimension on the physical specimen.
    d. Use the following formula to calculate the scaling factor:

$$\text{Scaling factor} = \frac{\text{Measurement from caliper (in millimeters)}}{\text{Measurement from Meshlab}}$$

    e. In Meshlab, go to **Filters -> Normals, Curvatures and Orientation -> Transform: Scale, Normalize.**
    f. In the window that appears, enter the calculated scaling factor into the **X-axis** field.

    Note: Ensure that the scaling factor uses a **period (.)** as the decimal separator.

    g. Check the flag for **"Uniform Scaling"** to apply the same scaling factor across all axes.
    h. Once scaled, press **CTRL + H** to center the model on the screen.
    i. After confirming that the model is correctly scaled, export the 3D model as a new .ply file containing the scaled model.

Note: Scaling could be done in Metashape, using markers and having a scale bar inside the images; but this could give problems in alignment phase if it is used the one-chunk method.

Landmarks placement

Timing: 15 min

14. Opening the specimen in Checkpoint

Open **Checkpoint** and load the *.ply* file from the specimen's folder.

15. Adding landmarks
    a. Click on **"Add Single Landmarks"** to place fixed landmarks (or choose alternative options if semi-landmark curves or patches are needed).
    b. Press **Shift + Left Click** to place each landmark on the specimen. Ensure that landmarks are placed on anatomically relevant points, and that can be consistently digitized on every specimen (Figure 6).
16. Exporting landmark coordinates

Once all landmarks are placed, export the point coordinates in the preferred format (e.g., .csv, .nts) for further analysis in R or other software. This operation should be repeated for each specimen.

Data analysis

Timing: variable

This step involves analyzing the morphometric data using the R programming language, for example with the *geomorph* package. It includes importing multiple files, performing Procrustes analysis, and further morphometric analyses based on the research objectives.

17. Loading the geomorph library and data

To import landmark coordinates for multiple specimens, export the coordinates in a format that supports batch import, such as Morphologika or .nts format. Place all the landmark files in the same directory, set it as the working directory in R, and use a function like read.morphologika() or readmulti.nts() to load them simultaneously.

```
>library(geomorph)

>landmarks <- read.csv("path_to_landmarks.csv") #for single specimen

Or

>landmarks <- read.morphologika(list.files(getwd()))

Or

> landmarks <- readmulti.nts(list.files(getwd()))
```

18. Performing Procrustes analysis

The *gpagen()* function could be used to perform Procrustes analysis on the landmarks in order to extract size and shape variables from landmark coordinates.

```
>procrustes <- gpagen(landmarks)
```

19. Additional morphometric analyses

geomorph functions can be used in a number of different scopes to manipulate and analyze size and shape variables resulting from the Procrustes analysis depending on the user aim (e.g., PCA, regression, ANOVA, etc.).

> ***Note:*** For further examples of morphometric analysis using R code, please refer to the supplementary materials section.

EXPECTED OUTCOMES

The expected outcome of this protocol is the production of high-quality 3D digital models of skull specimens, including those with tusks, horns, and antlers. These models will serve as accurate digital replicas that researchers can use for morphological studies, geometric morphometric analyses, and to facilitate global data sharing without the need to handle the physical specimens. Specifically, this protocol enables the capture of detailed and precise morphological data from complex structures that are traditionally challenging to digitize using photogrammetry. Researchers can produce highly accurate 3D models that can be scaled and landmarked for further morphometric and statistical analysis.

LIMITATIONS

Despite its advantages, this protocol may still face minor issues when dealing with specimens that have particularly homogenous textures, elongated shapes, or dark coloration. These factors can interfere with the alignment of images, leading to less accurate 3D reconstructions. For specimens with dark coloration, photographs can be taken in either JPEG or RAW format. The RAW format allows for post-processing adjustments, such as white balance correction, and is particularly advantageous for capturing extremely colorful textures (e.g., taxidermy birds); however, it requires significantly more storage space. On the other hand, the JPEG format has repeatedly proven suitable for photogrammetry of bones, offering a balance between file size and quality.[22] Additionally, the process may not always be reliable for specimens with intricate features, such as very fine or overlapping structures (e.g., closely intertwined antlers or horns), which may require additional manual intervention during the image processing phase on Agisoft. Environmental factors, such as inconsistent lighting or unstable camera positioning, can also affect the quality of the images and, consequently, the resulting 3D models. Furthermore, the computational demands of photogrammetry software like Agisoft Metashape may limit the protocol success on computers with insufficient processing power, potentially prolonging processing time and reducing output resolution.

TROUBLESHOOTING

Problem 1

Agisoft does not align the photos correctly (related to Step 8).

Potential solution

Try adjusting the **tie point** and **key point** settings in the alignment parameters. Additionally, increase the alignment quality to **Highest** for more accurate results. This may improve the software's ability to detect and align common features between the images.

Problem 2

Antlers, tusks, and horns are not correctly visualized in Agisoft (related to Step 9).

Potential solution

Use the **"Marker"** tool in Agisoft Metashape Professional. Consistently place markers at specific points on each photo (e.g., the tip of the antlers) to help the software align the images correctly.

This manual assistance can significantly improve the alignment for complex structures like antlers, tusks, and horns.

Problem 3

The mesh file does not open the texture during 3D visualization (related to Step 13).

Potential solution

Open the .ply file as a text file and modify the name of the texture file to match the exact name of the saved .jpeg texture file. Ensure that the texture file is in the same directory as the mesh file and that there are no discrepancies in the file names.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Naomi De Leo (naomi.deleo@uniroma1.it).

Technical contact

Technical questions on executing this protocol should be directed to and will be answered by the technical contact, Davide Tamagnini (davide.tamagnini@uniroma1.it).

Materials availability

This study did not generate any new unique reagents.

Data and code availability

The generated 3D models, Agisoft project files, landmark coordinate files, and additional code examples for data analysis can be found in the supplementary materials. They are also downloadable at the following link: https://figshare.com/s/4993b1beeb5be8f83588.

ACKNOWLEDGMENTS

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AUTHOR CONTRIBUTIONS

N.D.L., D.T., and C.C. established these protocols. N.D.L. wrote the initial draft and prepared all figures in this protocol. N.D.L., D.T., C.C., and L.M. revised subsequent drafts. L.M. acquired project funding, oversaw project administration, and provided all resources for this study. All authors granted final approval of the article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.xpro.2024.103572.

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