Instructions for photogrammetry pipeline and data collection

~~1. Prerequisites: Setting up the WebODM, finding help and additional software.~~

~~There are multiple ways ODM and WebODM can be installed. We opted to use the docker-based installation of the WebODM on our cloud server as it is the simplest to start.~~ ~~Please~~ ~~follow the instruction on setting up the WebODM at:~~
~~https://github.com/OpenDroneMap/WebODM/#getting-started~~

~~The official documentation and tutorials of ODM (and WebODM) can be found at:~~
~~https://docs.opendronemap.org/.~~

~~The user community form of ODM is at: https://community.opendronemap.org/~~

~~The postprocessing of the textured model and landmark data collection requires MeshLab and 3D Slicer with the SlicerMorph extension. MeshLab can be downloaded from https://www.meshlab.net/. For installing 3D Slicer and SlicerMorph, please see~~
~~https://github.com/SlicerMorph/SlicerMorph#installation~~

~~A python programming environment is necessary if the user wants to scale the specimen using Aruco markers. See description in Section 3.~~

[**Edit 3/18/25**: These prerequisite steps are no longer necessary, and handled entirely by the **SlicerMorph Photogrammetry** extension completely. See section 4 for more information and how to obtain SlicerMorph Photogrammetry extension.]

Equipment used:

- A DSLR camera (Canon EOS Rebel T6)
- A programmable turntable that can be controlled by a remote controller to set up how many steps it takes to finish a full circle and can be synced with a camera (The turntable we used was ComXim 12.6inch turntable with a shutter cable)
- Portable photo studio box (Amazon Basics) and lighting system (two UBeeSize V107 lights)
- Tripod (Amazon Basics)
- Putty
- A vertical stand for fixing the putty
- A remote shutter cable to connect the turntable with the camera, and a USB cable to connect the camera to the computers

2. Photography:

2.1 Equipment setup

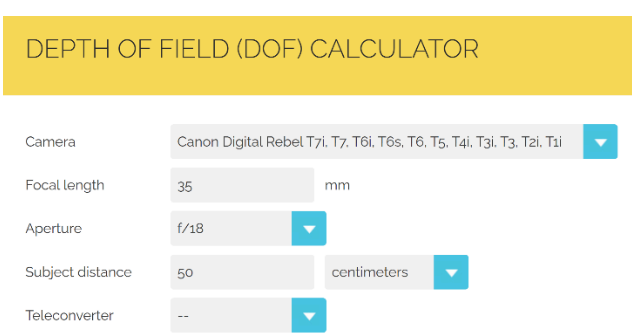
Setup the turntable and lighting in the photo studio. Attach the camera to a tripod that allows three degrees of freedom for movement.

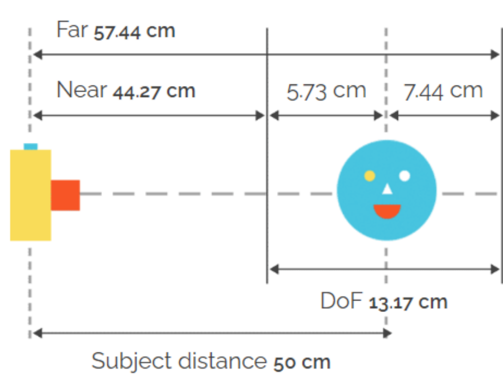
- We advise coverings the side walls and the studio floor in black and also paint or cover the surface of turntable black to minimize reflection and glare.
- Connect the camera and the turntable via the appropriate shutter cable.
- The camera is also synced with the computer using the DigiCamControl open-source software that works with Nikon and Canon cameras (http://digicamcontrol.com/). This allows direct transfer of photos to the computer from the camera.


Pictures show the camera set-up in the author CZ's office for this study.

2.2 Camera parameter setup

It is important to keep the entire specimen in focus throughout the photography session. This is best done by manually adjusting the settings on the camera (such as the aperture and focal ring) and creating a depth of field that will keep the specimen in focus in all orientations during photography session. This requires the knowledge of the subject distance to camera, the focal length of the objective and the aperture. These settings can be entered into a depth-of-field (DoF) calculator (e.g., https://www.photopills.com/calculators/dof) to calculate a working distance for the session (see the screenshots below).





- Subject distance is the distance between the center of the object to the camera sensor, which is marked on the body of the camera (see picture below)

Picture from:
https://3.bp.blogspot.com/-tjHpVMrsDeg/UoynJpZzuvI/AAAAAAAAIc4/zmzMtUyCdUc/s1600/focal-plane-mark-on-the-camera-body.jpg

- Ensure the specimen stays within the calculated DoF during the turntable rotation.
- Manually adjust the focus ring to ensure different parts of the specimen are similarly in focus.
- Adjust the shutter speed to control the exposure of photos to an appropriate level.
- We used 12MP setting on our camera (4608 × 3456)
- Once a set of camera parameters is achieved, take a few test photos of the specimen by rotating the turntable to different angles to ensure consistent sharpness of photos.

2.3 Taking photos

For this study, we took six sets of photos. The first five sets are the basis for the 3D model reconstruction. The sixth set is optional and is taken with Aruco markers to scale the reconstructed 3D model to its real-life dimensions automatically. Photos of the specimen UWBM39384 are provided as the sample data (https://osf.io/b39yx/, DOI: 10.17605/OSF.IO/B39YX). The folder "39384_raw_photos" contains the raw photos. The folder "39384_masked_photos" contains the masked photos submitted to WebODM (see sections 2.3, 3, and 4). The camera parameters for each set achieved from the DoF calculators are listed in the table below:

Set	Specimen Orientation	No. of pictures	Focal length (mm)	ISO	Aperture (F stop)	Shutter speed (sec)	Subject distance (in cm)	Depth of field (in cm)
1	Vertical	48	35	100	13	1/6 to 1/8	45	7.85 (41.41 to 49.27)
2	Vertical	48	35	100	13	1/6 to 1/8	45	7.85 (41.41 to 49.27)
3	Vertical	48	35	100	13	1/6 to 1/8	45	7.85 (41.41 to 49.27)
4	Horizontal	64	35	100	16	1/5	48	10.37 (43.23 to 53.96)
5	Horizontal	64	35	100	16	1/5	48	10.37 (43.23 to 53.96)
6	Horizontal (markers)	48	35	100	18	1/4	50	13.17 (44.27 to 57.44)

While they are optimized for our study and specific camera model, these parameters can be used as a starting point for other skeletal elements. Remember to recalculate the DoF every time the specimen to camera distance is changed.

Set 1. Place the specimen in a vertical position with the nose facing down. First, fix the nose on the putty on a vertical stand. Adjust the tripod height to make the lens faces approximately the center of the specimen. Take 48 equally spaced pictures (7.5^{o} of rotation at each step).

Set 2. Raise the camera to about 12 cm (approximately twice the AP length of the specimen) higher than Set 1 and rotate the camera down to approximately face the center of the specimen. Slightly adjust the focal ring if needed. Take 48 pictures.

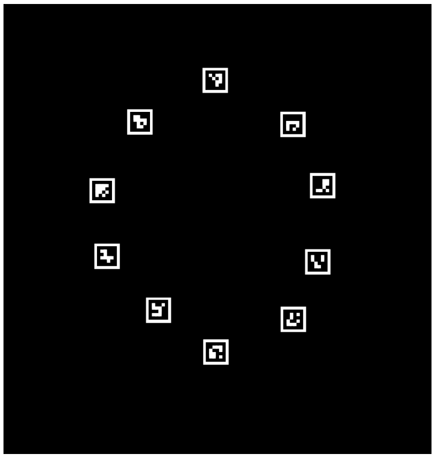
Set 3. Turn the skull upside down and fix the foramen magnum on the putty on the vertical stand. The camera parameters can stay the same as previous Set. Slightly adjusting the focus ring is needed. Take 48 pictures.

Set 4. Put the skull horizontally on the turntable with the ventral surface of the skull facing down and adjust the tripod to point horizontally to the center of the beaver skull. A small platform might be useful to elevate the specimen off the turntable a little. Slightly adjust the focal ring. Take 64 pictures.

Set 5. Turn the skull over to have the ventral surface facing upwards. Take 64 pictures.

Set 6. This set of photos is used for automatedly scaling using the Aruco markers.

- Design a sheet of Aruco markers (e.g., in Microsoft PowerPoint) with markers from ID 0 to ID 9 (markers can be generated at https://chev.me/arucogen/). We created each marker as 8mm wide, which was sufficiently large for our imaging protocol. Put a slightly larger white square below to create a contrast with the black background. An example PowerPoint is provided as part of the SOM.



A sample Aruco marker sheet

- Make sure the measurement units are metric, as we will use millimeters to describe the location of each marker in the next step.
- Record the horizontal and vertical position of the upper left corner of each marker from PowerPoint (Size and Position □Position) as the x and y coordinate into a text file (e.g., gcp_coord.txt). This assures that the distances calculated from these coordinates match the actual measurable distances between the markers. Enter these into a text file (e.g., “gcp_coord.txt”) following the convention below:
- The first column is the marker ID. The next three columns are x, y, and z coordinates of the marker (in millimeter units). Note that the z coordinate for each marker is fixed (1.00). This is because the markers are printed on a 2D surface.

gcp_coord.txt - Notepad

File Edit View

```
0 90.1 70.7 1.00
1 121.3 88.5 1.00
2 133.4 113.4 1.00
3 131.4 144.2 1.00
4 121.5 167.7 1.00
5 90.2 180.9 1.00
6 67.0 163.7 1.00
7 46.2 142.0 1.00
8 44.2 115.4 1.00
9 59.5 87.5 1.00
```

- In the sample data available at https://osf.io/b39yx/ (DOI: 10.17605/OSF.IO/B39YX), the sample “gcp_coord.txt” can be found in the folder “39384_raw_photo” that contains the raw photos.
- When processing, WebODM will assume the unit of input coordinates by default as meter, as that's the convention in geospatial coordinate systems. However, this does not influence actual data analysis-based 3D model because MeshLab and 3D Slicer correctly treat these values as millimeters.
- Cut the marker to a circular shape and put it on the turntable. Use tapes to keep the sheet as flat as possible.

- Put the specimen on the center of the sheet with its base facing down. Raise the camera about seven centimeters higher from the position for the photo sets 5 and 6 to take 48 pictures. Ensure four to five markers are visible in each picture.

3. Recognize Aruco markers from photos

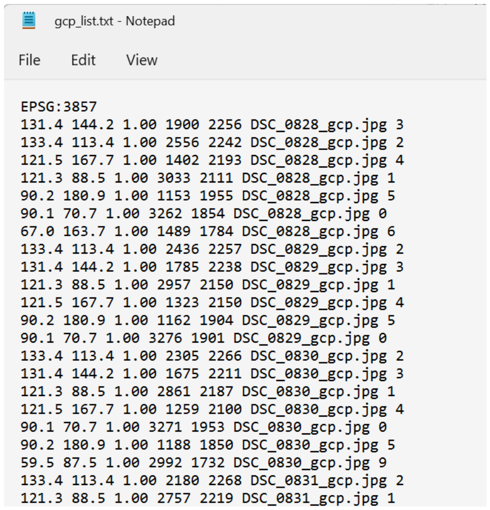
We use the "Find-GCP" python package (https://github.com/zsiki/Find-GCP) to recognize markers in each photo and record their pixel location of each marker's upper left corner.

- Install the OpenCV package (https://docs.opencv.org/4.x/df/d65/tutorial_table_of_content_introduction.html) in the terminal through `pip install opencv-python`
- Clone the Find-GCP GitHub repository `git clone https://github.com/zsiki/Find-GCP.git` to the designated directory or directly download the zip file.
- Run the following script in `python`

```
/path/gcp_find.py -t ODM -i /path/gcp_coord.txt --epsg 3857 -o
/path/gcp_list.txt `ls /path/photos_gcp/*.jpg`
```

  - The `/path/gcp_find.py` points to the python script `gcp-find.py` in the cloned `Find-GCP` repository.
  - The `/path/gcp_coord.txt` is the text file that stores the x and y coordinates of the upper left corner of each marker from the marker sheet. See step 6 of section 2.3.
  - EPSG 3857 is a commonly used geographical protocol adopted by ODM.
  - `` `ls /path/photos_gcp/*.jpg` `` lists all photos with markers from the photo (jpg format) set 6 stored in the folder `/path/photos_gcp/`.
  - The `/path/gcp_list.txt` is the output file `gcp_list.txt` stores the recognized marker, and its ID and coordinates in each picture from the photo set 6 of a specimen (see step 6 of section 2.3).
  - A sample output (`gcp_list.txt`) from the script is shown below (this text file can also be found in the sample data in "39384_masked_photos/set6" in the sample data available here: https://osf.io/b39yx/, DOI: 10.17605/OSF.IO/B39YX). The three leftmost columns are the coordinates of the recognized marker from the reference file (gcp_coord.txt) generated in the previous step. The fourth and fifth columns from the left indicate the pixel coordinates of the recognized marker (specifically coordinates of its upper-left corner) in the photo. The sixth column from the left indicates the filename

of the photograph marker is recognized from. Finally, the rightmost column is the ID of the recognized marker.



gcp_list.txt - Notepad

File Edit View

```
EPSG:3857
131.4 144.2 1.00 1900 2256 DSC_0828_gcp.jpg 3
133.4 113.4 1.00 2556 2242 DSC_0828_gcp.jpg 2
121.5 167.7 1.00 1402 2193 DSC_0828_gcp.jpg 4
121.3 88.5 1.00 3033 2111 DSC_0828_gcp.jpg 1
90.2 180.9 1.00 1153 1955 DSC_0828_gcp.jpg 5
90.1 70.7 1.00 3262 1854 DSC_0828_gcp.jpg 0
67.0 163.7 1.00 1489 1784 DSC_0828_gcp.jpg 6
133.4 113.4 1.00 2436 2257 DSC_0829_gcp.jpg 2
131.4 144.2 1.00 1785 2238 DSC_0829_gcp.jpg 3
121.3 88.5 1.00 2957 2150 DSC_0829_gcp.jpg 1
121.5 167.7 1.00 1323 2150 DSC_0829_gcp.jpg 4
90.2 180.9 1.00 1162 1904 DSC_0829_gcp.jpg 5
90.1 70.7 1.00 3276 1901 DSC_0829_gcp.jpg 0
133.4 113.4 1.00 2305 2266 DSC_0830_gcp.jpg 2
131.4 144.2 1.00 1675 2211 DSC_0830_gcp.jpg 3
121.3 88.5 1.00 2861 2187 DSC_0830_gcp.jpg 1
121.5 167.7 1.00 1259 2100 DSC_0830_gcp.jpg 4
90.1 70.7 1.00 3271 1953 DSC_0830_gcp.jpg 0
90.2 180.9 1.00 1188 1850 DSC_0830_gcp.jpg 5
59.5 87.5 1.00 2992 1732 DSC_0830_gcp.jpg 9
133.4 113.4 1.00 2180 2268 DSC_0831_gcp.jpg 2
121.3 88.5 1.00 2757 2219 DSC_0831_gcp.jpg 1
```

4. Photo pre-processing and 3D Model reconstruction

[**Revised 3/18/2025**. The older instructions for removing background and masking photographs through individual python scripts are now superseded by the new SlicerMorph Photogrammetry that integrates all the steps into a single streamlined workflow in 3D Slicer.]

The new preprint that compares output from the new SlicerMorph Photogrammety extension to the previous workflow is here: https://www.biorxiv.org/content/10.1101/2025.03.07.641939v1

The user guide for improved and streamlined photogrammetry pre and post processing in 3D Slicer: https://github.com/SlicerMorph/SlicerPhotogrammetry?tab=readme-ov-file#user-guide

- If you are using **Linux**, you can install the SlicerMorph Photogrammetry extension from the 3D Slicer extension manager. To obtain the extension, make sure you are using 3D Slicer version 5.8.1 (or later).
- If you are on **Windows** or **MacOS**, we highly recommend using **MorphoCloud On Demand Instances**, which provides powerful remote desktop sessions in which SlicerMorph Photogrammetry extension is already installed, and all you need to do is to upload your photographs to start processing.

MorphoCloud On Demand is free for all 3D morphology related tasks. See https://instances.morpho.cloud to learn more and request an instance.