TRIQUETRA

Toolbox for assessing and mitigating Climate Change risks and natural hazards threatening cultural heritage

3D Geometric Documentation of Cultural Heritage Sites for monitoring the impacts of Climate Change

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TRIQUETRA Workshop, Thessaloniki, Greece| 8 January 2025

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LABORATORY OF PHOTOGRAMMETRY

SCHOOL OF RURAL, SURVEYING AND GEOINFORMATICS ENGINEERING, NTUA

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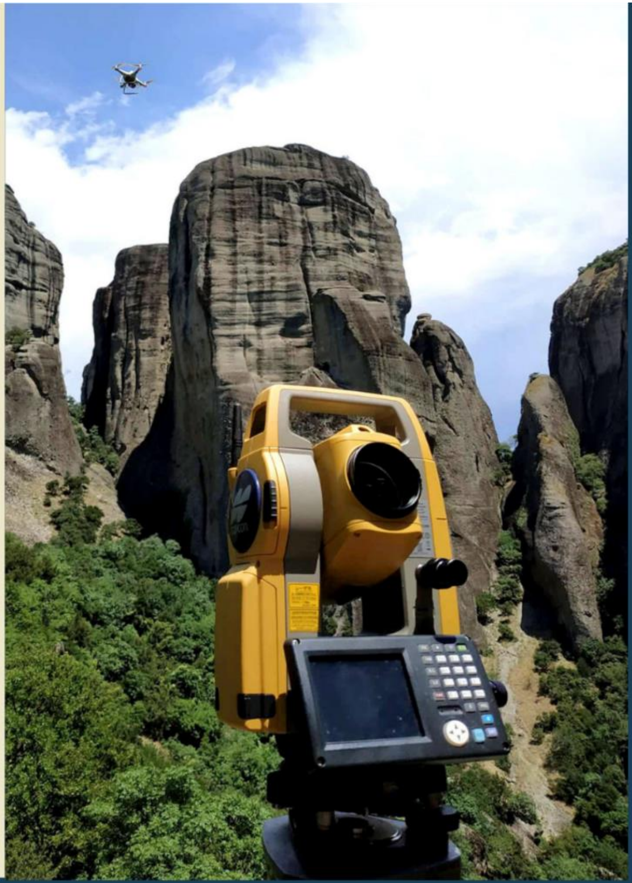
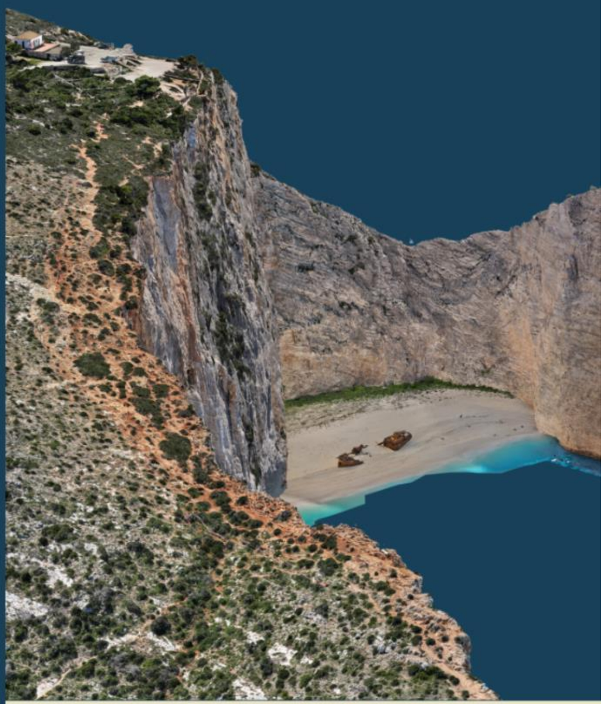
EXPERTISE

Photogrammetry & Computer Vision

- 3D Reconstuction and Mapping using Aerial, Satellite, Terrestrial & Underwater Imagery as well as LIDAR & SAR data
- 3D Geometric Documentation & Modelling of Tangible & Intangible Cultural Heritage
- Classification, detection & segmentation of unordered 3D point sets and images





- Historic Building Information Modelling (HBIM)
- Monitoring of dynamically changing environments
- Virtual & Augmented Reality
- Artificial intelligence

- Established in 1962
- Team: 5 academic staff, 4 teaching staff, 5 PhD researchers, and several collaborators
- Offers 10 undergraduate courses and participates in postgraduate programs
- Engaged in over 20 EU-funded projects (H2020)

Contents

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Verykokou, S., Soile, S., Ioannidis C. *“3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change.”* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

Introduction into multi-view 3D reconstruction

An overview of the basic stages

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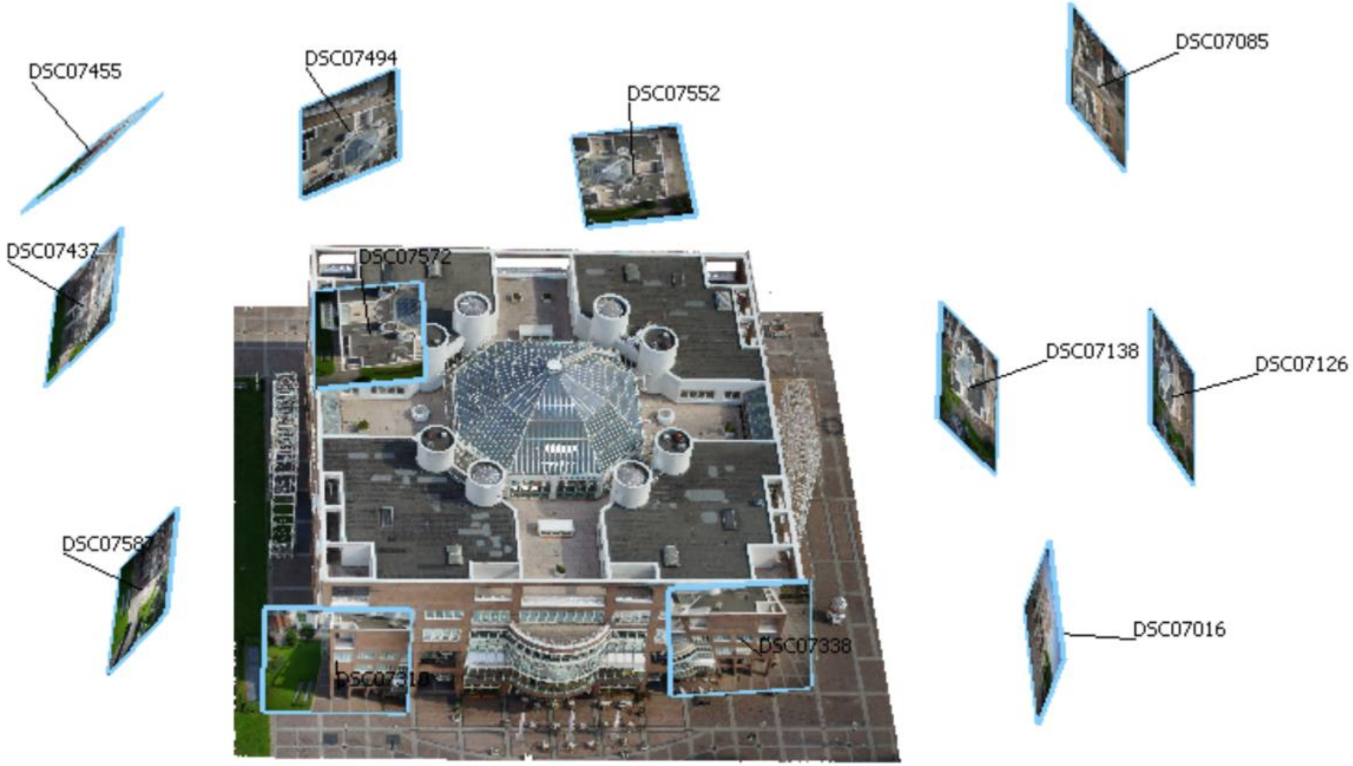

The process of multi-view 3D reconstruction from a set of images with unknown exterior (and interior) orientation involves:

- the calculation of interior and exterior orientation of images
- 3D reconstruction of the scene depicted in the imagery

Source of dataset for generating this product: ISPRS/EuroSDR Benchmark for Multi-Platform Photogrammetry

- Nex, F., Gerke, M., Remondino, F., Przybilla, H.-J., Bäumker, M. & Zurhorst, A. (2015). ISPRS Benchmark for Multi-Platform Photogrammetry. *The International Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-3/W4, 135-142. Doi: 10.5194/isprsannals-II-3-W4-135-2015.

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Stages of multi-view reconstruction

- Data collection stage
  - capturing of overlapping images
  - carrying out of topographical measurements
- Image orientation stage
  - calculation of exterior (& interior) orientation of images
  - producing a sparse point cloud

  } Detection of overlapping images
  Image matching and feature tracking
  Structure from motion (SfM)
- Depth map generation stage
  - Dense image matching for a subset of image pairs (or for all pairs)
- Dense point cloud generation stage
  - merging of depth maps or
  - densification of the sparse point cloud
- 3D surface creation stage
  - production of a polygonal (usually triangular) model (mesh)
  - using dense point cloud or depth maps
- Texture mapping stage
  - use of images of known interior & exterior orientation

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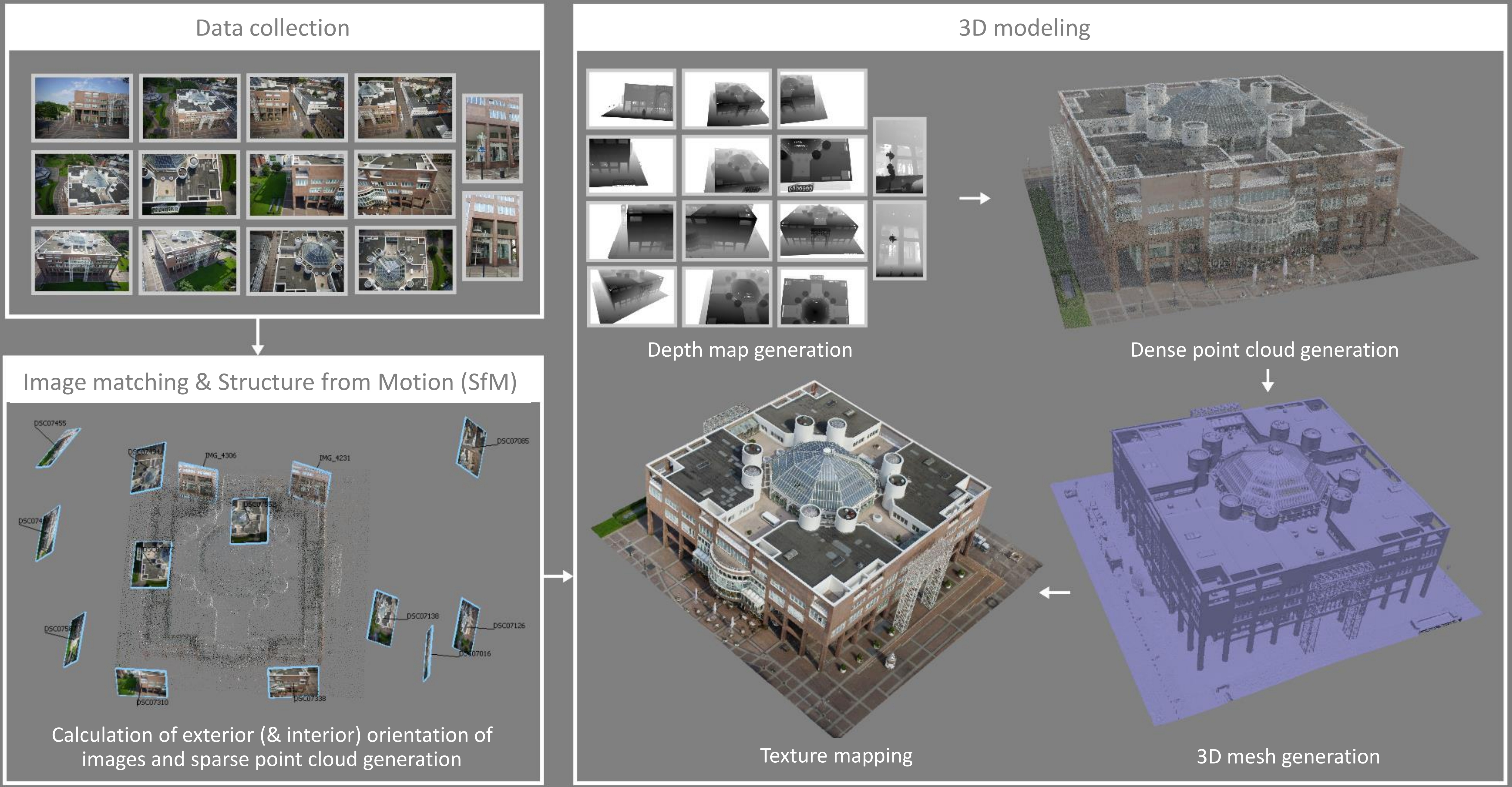

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Source of image: Verykokou, S.; Ioannidis, C. An Overview on Image-Based and Scanner-Based 3D Modeling Technologies. *Sensors* 2023, 23, 596. https://doi.org/10.3390/s23020596

3D modeling using images

- Reconstruction of objects from unordered image collections, which may have been captured:
  - from different cameras
  - with different perspectives
  - from different distances and
  - with different lighting conditions
- Reconstruction of objects from:
  - Simple images
  - Images from videos

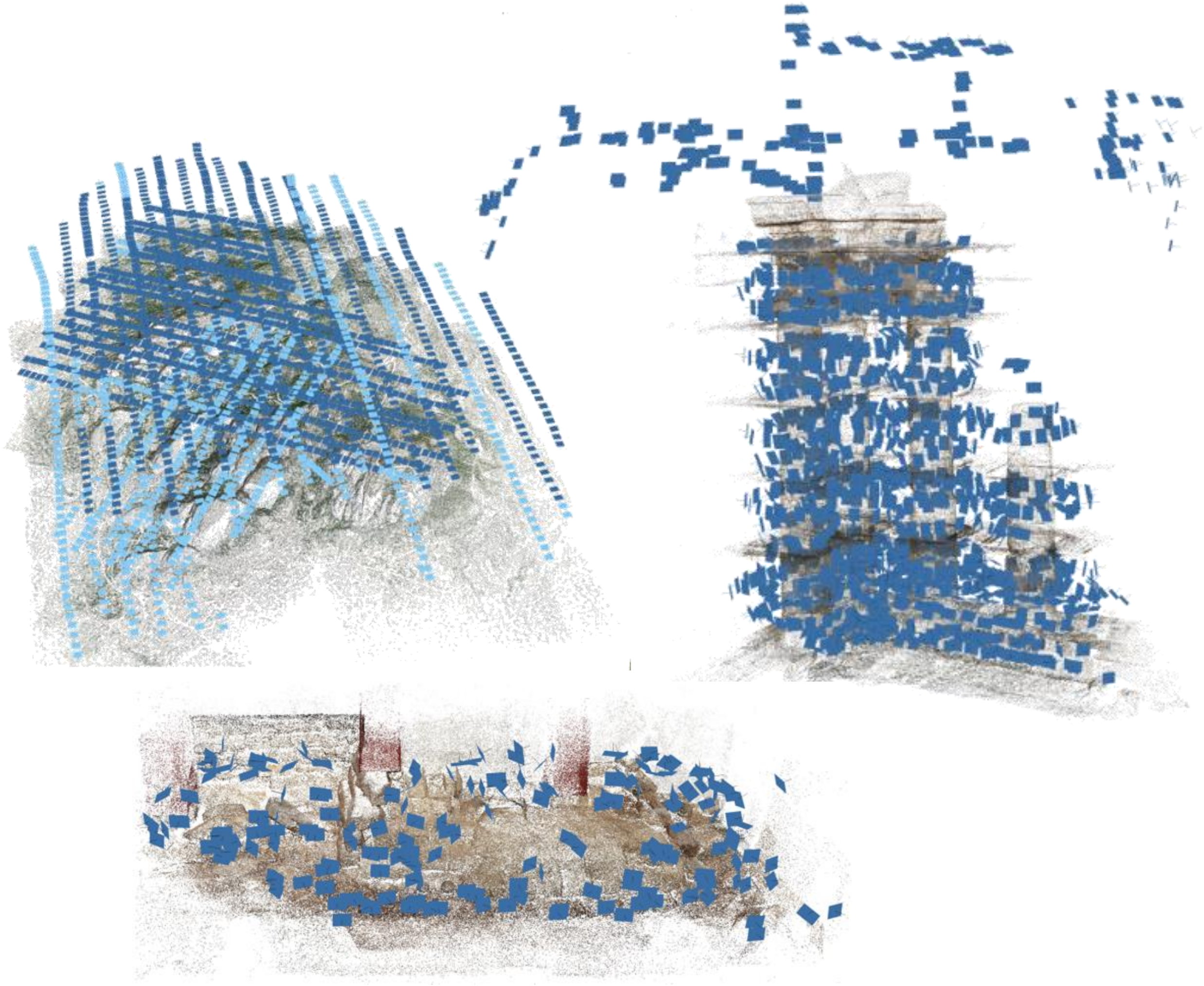

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Image matching

Overview, Categories, Feature-based matching, Outlier rejection

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Image matching

- The term “image matching” refers to the automatic establishment of correspondences between points, grayscale tones, features, relations, or other entities in overlapping images.
- It is a critical process for various photogrammetric and computer vision applications
  - such as the automatic detection of tie points for aerial triangulation, photo-triangulation or Structure from Motion (SfM) applications,
  - relative orientation processes, automatic collection of digital terrain/surface models (DTMs/DSMs),
  - augmented reality applications, and many other fields.

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Categories of image matching

Three main categories of image matching can be distinguished, depending on the entity being matched:

- Area-based matching

  Area-based matching identifies correspondences based on the similarity of intensity or color values within image regions.

- Feature-based matching

  Feature-based matching focuses on detecting and describing interest points that are robust under transformations such as scale, rotation and illumination changes.

- Relational matching

  Relational matching utilizes symbolic relationships between image structures, making it well-suited for template-based applications.

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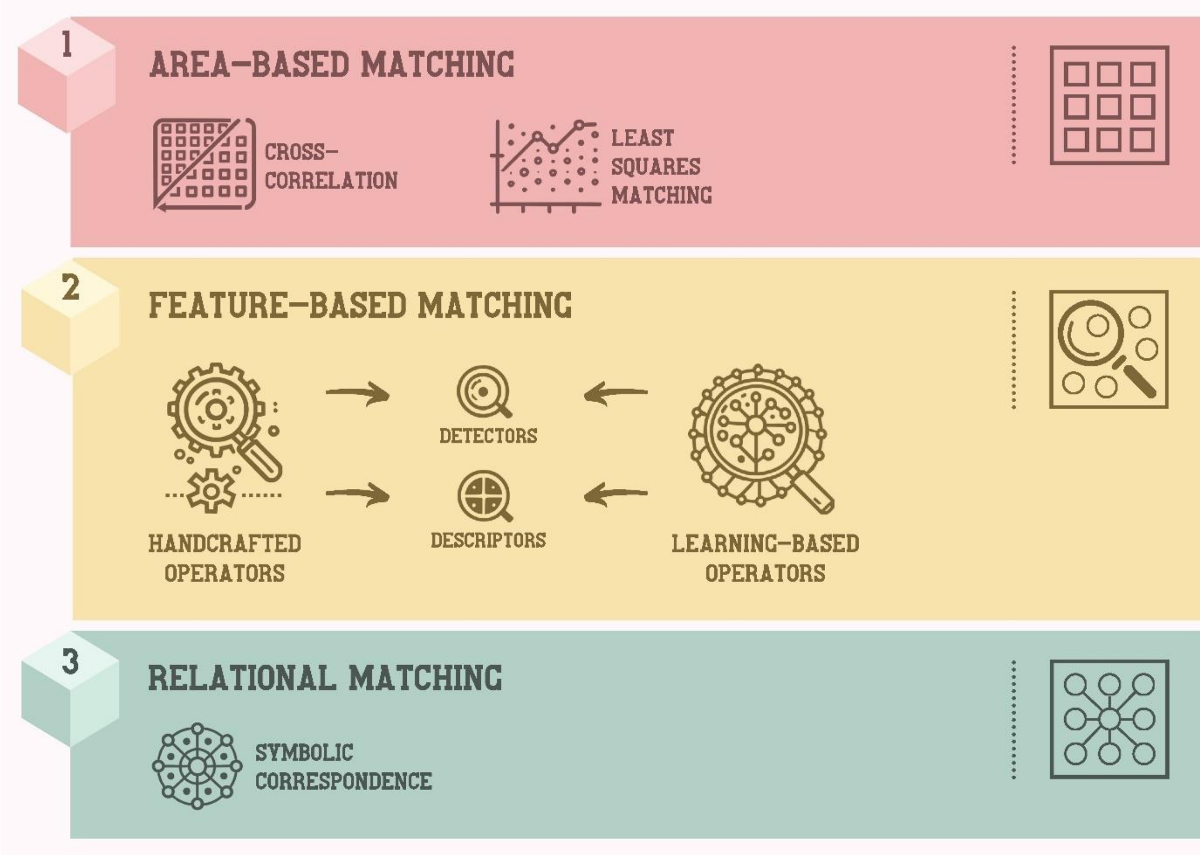
Categories of image matching

Image source: Verykokou S, Ioannidis C. Image Matching: A Comprehensive Overview of Conventional and Learning-Based Methods. *Encyclopedia*. 2025; 5(1):4. https://doi.org/10.3390/encyclopedia5010004

In the context of feature-based matching, two distinct subcategories can be identified: **conventional approaches**, which involve handcrafted detectors and descriptors, and **learning-based approaches**, which include training models to identify and describe features, while relying on the availability of high-quality training data.

- **Handcrafted operators** are manually designed algorithms that detect and describe features using predefined rules, mathematical models or methods (e.g., corner detection, gradient analysis) to extract distinctive features from images.
- **Learning-based operators** use machine learning techniques to detect and describe features after being trained on large datasets to learn feature representations and correspondences.



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Feature-based image matching

- Feature-based image matching involves **identifying features independently in each image** and then **matching them** based on local information from their neighborhoods
- The entities identified may be:
  - points (which are the most used entity)
  - edges or other linear elements
  - areas (surfaces/polygons).
- The matching takes place in **two main stages**:
  - **extraction (detection – description)** of the features independently in each image
  - **matching (finding correspondences)**
- Less sensitive to geometric and radiometric variations between images than area-based matching techniques

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Stages of feature-based matching

Feature detection and description algorithms, capable of locating and identifying features **independently of various image transformations**, including translation, rotation, scaling and affine deformations

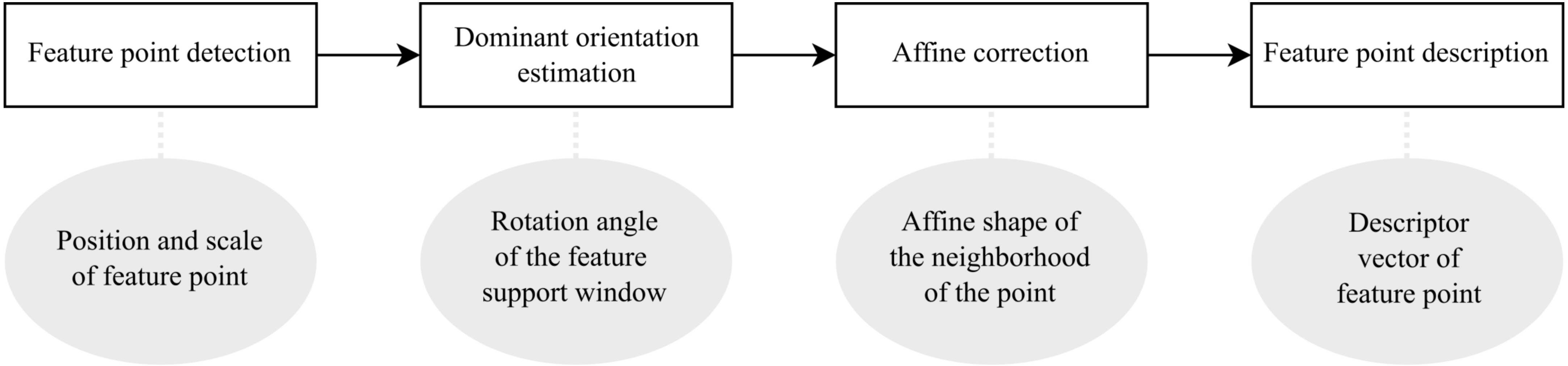

Image source: Verykokou S, Ioannidis C. Image Matching: A Comprehensive Overview of Conventional and Learning-Based Methods. *Encyclopedia*. 2025; 5(1):4. https://doi.org/10.3390/encyclopedia5010004

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Stages of feature-based matching

Feature detection

- "Scale space" → detection of points invariant to scale transformations

Estimation of the dominant orientation of each feature point

- Usually, based on the gradients (intensity changes) of the pixels in its neighboring region, the size of which usually depends on the scale of the point

Affine correction

- Calculation of the affine shape of the area around each point of interest

Description of points

- A "support window" around each point is calculated, to describe each point using local information from its neighboring pixels

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Finding of correspondences

- By **matching the descriptor vectors of the detected feature points**, using a similarity measure
- This measure is usually **a kind of norm** of the vector obtained as the difference of the feature vectors compared each time
  - **Euclidean norm** (Euclidean distance between the feature descriptor vectors)
  - **Manhattan norm** (sum of the absolute values of the elements of the vector resulting from the difference between the feature descriptor vectors)

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SIFT - Scale Invariant Feature Transform

- **Distinct image features from points scale invariants**
  - Lowe, D.G. (2004). Distinctive image features from scale-invariant keypoints. *International Journal of Computer Vision* , 60, 91-110
- **Detection of keypoints invariant to:**
  - Scale changes
  - Image rotations
- **and partially invariant to:**
  - Illumination changes
  - Changes in the viewpoint
  - Presence of noise

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SURF - Speeded-Up Robust Features

- Bay, H., Ess , A., Tuytelaars , T. & Van Gool , L. (2008). Speeded-up robust features (SURF). *Computer Vision and Image Understanding,* 110, 346-359
- Detection and description of feature points so that they are **invariant** to:
  - ► **scale** changes
  - ► **rotation** transformations
  - ► **lighting** changes
  - ► changes in **contrast**
- 64 dimensional feature vector → **faster than SIFT**

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Finding corresponding keypoints in image pairs

- The point correspondences returned by the matching algorithm can fall into one of the following four categories:
  - **True Positive (TP):** These are the correct correspondences returned by the algorithm.
  - **True Negative (TN):** These are non-correspondences correctly rejected by the algorithm and not considered matches.
  - **False Positive (FP):** These are incorrect correspondences returned by the algorithm.
  - **False Negative (FN):** These are correspondences that were not returned by the algorithm, even though the keypoints are homologous and visible in both images.

correct

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Finding corresponding keypoints in image pairs

- Common distance measure: **Euclidean distance between descriptor vectors**
- The simplest matching strategy considers points as homologous if the distance of their descriptor vectors is the **minimum** and **below a threshold** (maximum distance)
  - Setting a high threshold hides the risk of incorrect matches → increases the probability of returning many "False Positive" matches
  - By setting a small threshold, there is a risk that many homologous pixels are not identified , even though they are present in both images → high probability of an increased number of "False Negative" matches
- The **definition of a threshold is usually not sufficient**, and additional techniques, either in conjunction with or independent of the threshold, are often required to reject invalid correspondences (outliers)

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Outlier rejection

- The matching process often results in many **invalid correspondences**.
- Therefore, considering keypoints as homologous based solely on the minimum Euclidean distance is not sufficient → **additional techniques** are required to minimize invalid correspondences.
  - **Nearest neighbor distance ratio (ratio test)**
  - **Cross -check test**
  - **Thresholding of distances**
  - **Geometric Constraints (RANSAC)**

Usually **a combination** of the above methods is used

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Nearest neighbor distance ratio check (ratio test)

- For each keypoint in the first image, the two nearest keypoints in the second image are returned
- The **NNDR ratio is calculated** (Nearest Neighbour Distance Ratio)
- If the ratio is below a predefined threshold, the keypoints are considered homologous.

$$NNDR = \frac{\|v_1 - v_2\|}{\|v_1 - v_3\|}$$

v_1 feature vector of point 1 of image 1

v_2 1st closest to v_1 feature vector of point 2 of image 2

v_3 2nd closest to v_1 feature vector of point 3 of image 2

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Cross-check test

Pixels i and j are considered homologous if:

- for pixel i of image 1, pixel j of image 2 is closest to it

AND

- the closest to pixel j of image 2 is pixel i of image 1

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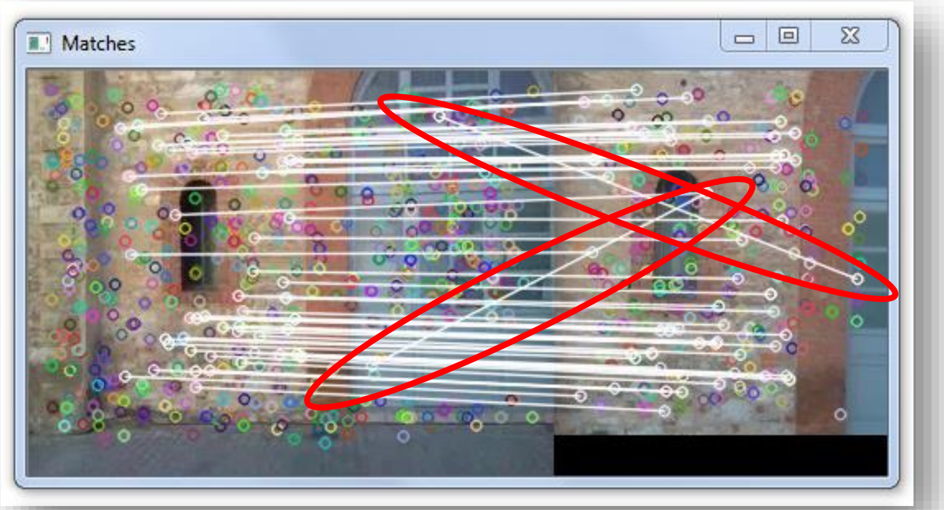
Thresholding distances

After applying the ratio test or the cross-check test, several gross errors remain

- Definition of the maximum allowed Euclidean distance
- Rejection of the pair of homologous points if the distance of their feature vectors is greater than the maximum allowed



Example of correspondences after applying the ratio test

A small percentage of gross errors remains

Elimination by estimating the geometric relationship of the two images

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RANSAC

- RANSAC: **RAN**ndom **SA**mple **C**onsensus
  - Fischler , M. & Bolles , R. (1981). Random sample consensus: A paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM* , 24, 381-395.
- In general: Estimating the **parameters of a mathematical model** from a set of data, **many** of which may be **incorrect**, relying on the use of the **minimum possible data**
- In image matching : Removing outliers in image pairs by computing the **epipolar matrix** between two images
  - **In the case of planar object images** , RANSAC can compute the **2D projective transform** (homography) between images

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RANSAC – epipolar matrix calculation

- Selection of a **random sample** of 7 or 8 correspondences (depending on the algorithm used for estimating the fundamental matrix).
- Estimation of the **fundamental matrix** based on the selected sample.
- Calculation of the number of valid correspondences (**inliers**) for the given solution → This indicates the quality of the computed geometric relationship.
  - Valid correspondences are identified by calculating the Euclidean distance between the computed epipolar line in the second image (based on the fundamental matrix) and the actual position of the keypoint as determined by the matching process.
  - If this distance is below a predefined threshold, the correspondence is considered valid (inlier); otherwise, it is considered invalid (outlier).

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- Estimation of the **fundamental matrix** based on the selected sample.
- Calculation of the number of valid correspondences (**inliers**) for the given solution → This indicates the quality of the computed geometric relationship.
- 3 cases:
    - **inliers ≥ minimum number of inliers** → the epipolar matrix is accepted and the algorithm terminates successfully
    - **inliers < minimum number of inliers &**
      number of iterations = maximum number of iterations → algorithm terminates with failure
    - **inliers < minimum number of inliers & number of iterations < maximum number of iterations** → repeat the above steps

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Structure from Motion (SfM)

Overview, prerequisite procedures, SfM methods, incremental SfM workflow

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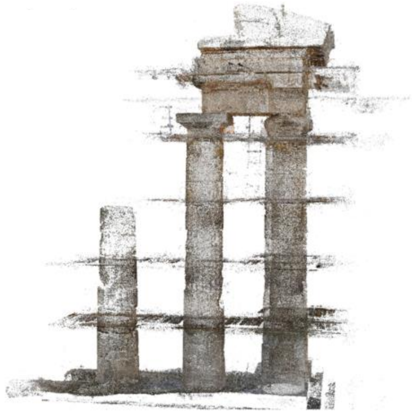
Structure from Motion (SfM)

- Process of
  - estimation of the **position** and **orientation** of the camera at the time each image is taken and
  - reconstructing the 3D geometry of the depicted scene by estimating the 3D coordinates of a **sparse point cloud**

Exterior orientation parameters

Xo, Yo, Zo, omega, phi, kappa

in a local or global reference system



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SfM: Input data

- Images from the same camera or different cameras → Ground, aerial, UAV vertical or oblique images
- Optionally:
  - Interior orientation of images → *Camera constant, principal point coordinates, lens distortion parameters (radial/eccentric)* If they are not input data, they are calculated via self-calibration
  - GPS/INS data → *Approximate exterior orientation parameters* Use for:
    - Georeferencing and/or
    - Detection of pairs of overlapping images
  - Ground control points → Georeferencing

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SfM: Results

- Position and orientation of all images at the time of capture
  → **exterior orientation**

- Sparse 3D point cloud
  → **3D coordinates of tie points** (homologous feature points between images)

- *Interior orientation* (in case of uncalibrated machines)

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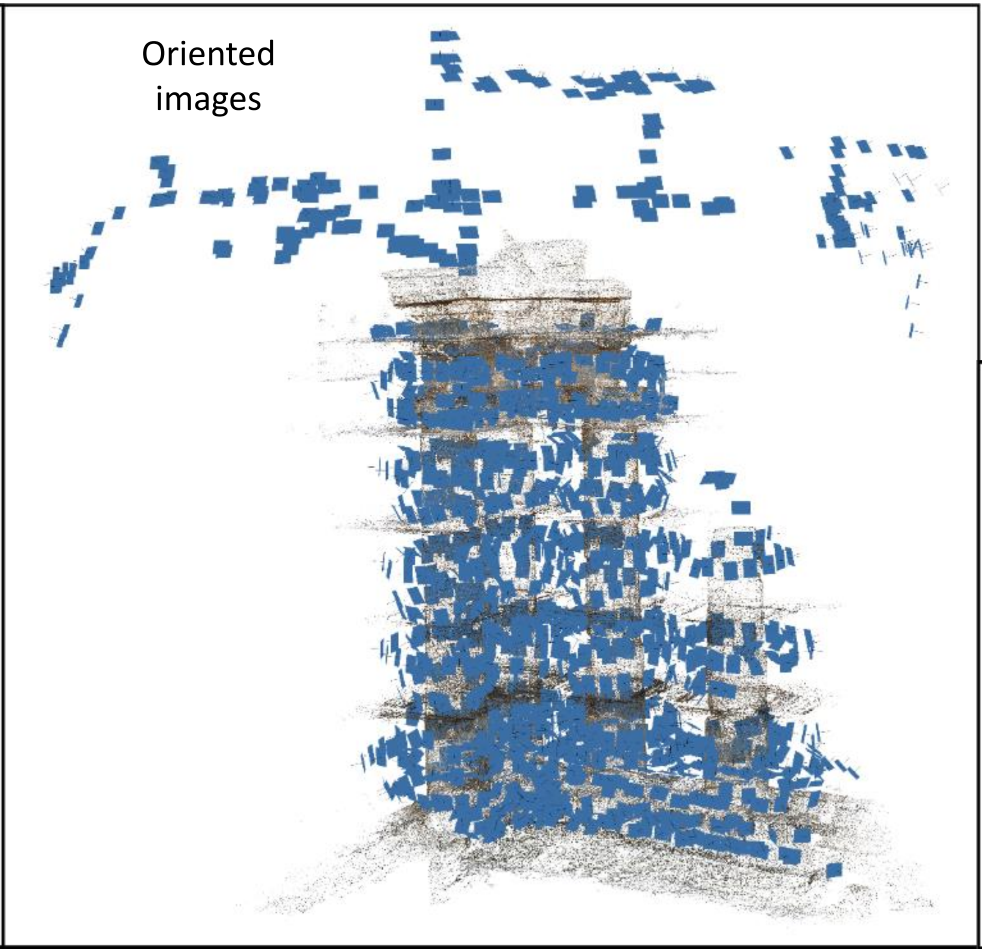
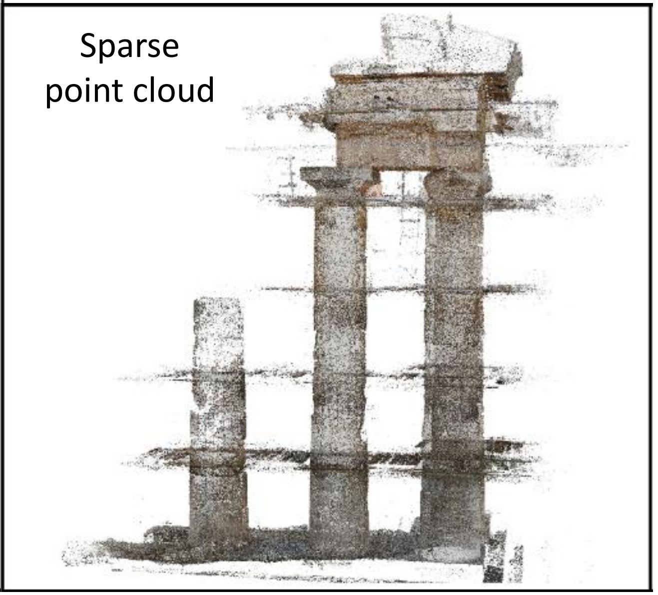
Results – example

UAV images





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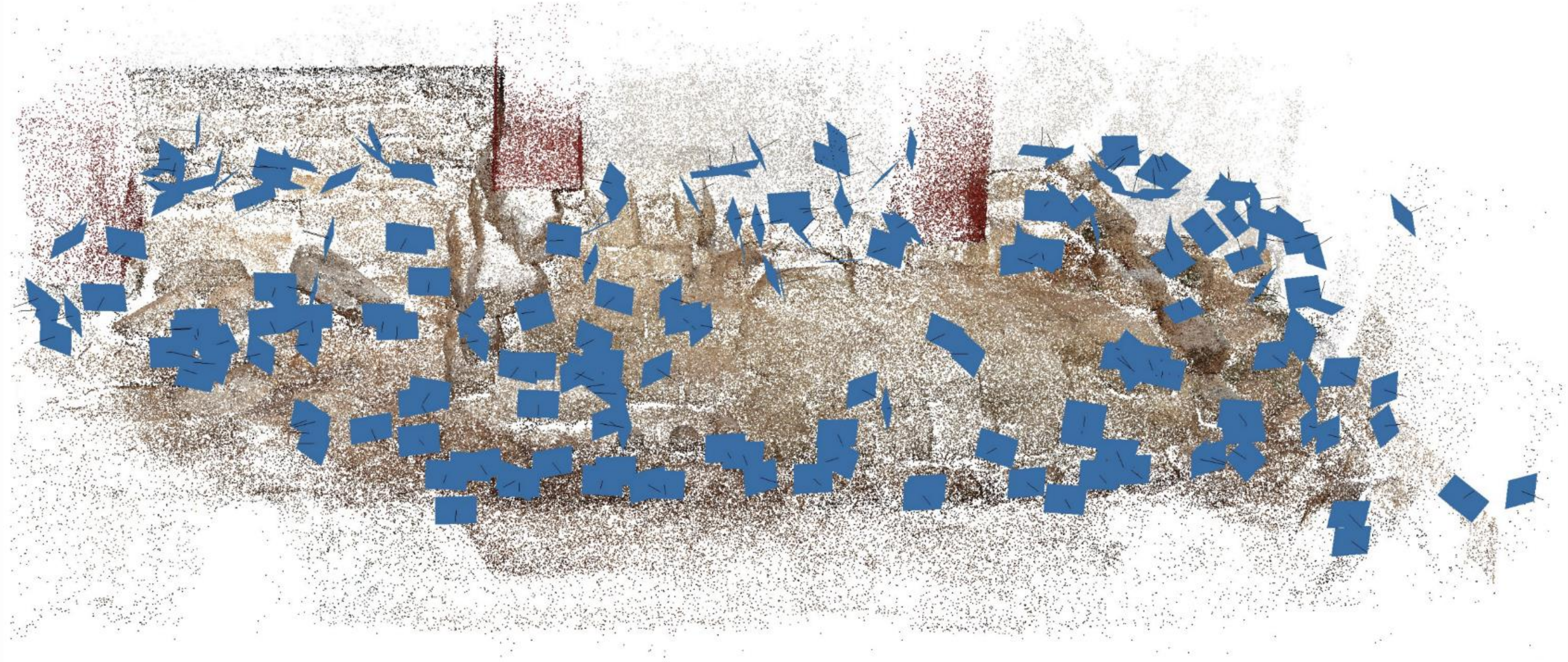
Sparse point cloud and oriented images



Terrestrial images

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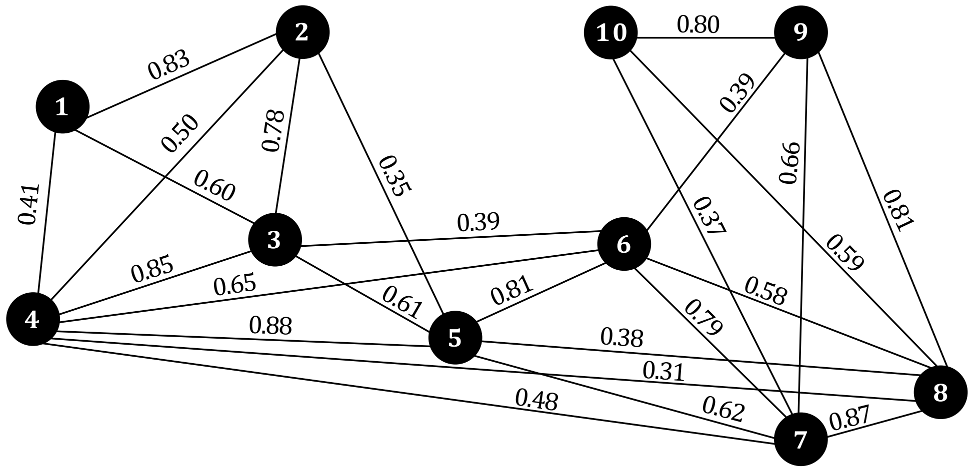
Detection of overlapping images

- Usually before applying an SfM process, overlapping images are identified
  - the subsequent search for homologous points is performed exclusively on overlapping images
  - minimizing computation time of finding homologous points
- Indicative methods:
  - Based on GNSS – INS data
  - Based on image matching of low resolution images

Example of an undirected weighted graph connecting overlapping images



- vertices: images
- edge weight: overlap percentage
- edges: join vertices corresponding to overlapping images

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Image matching

- Typically, **feature-based matching**
- Detection and description of points that are invariant to rotation and scale transformation

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Feature tracking

Usually: use of points for which there are measurements in **at least 3 images**

- Every feature point in space is visible in more than two images → the keypoints must be grouped so that a single 3D point is calculated
- **Organization of pixels by 3D point:** homologous pixels are stored in the "group" (track) corresponding to the 3D point they represent.
  - Example: storing the pixels in a table with the number of rows equal to the number of images and the number of columns equal to the number of points in the 3D space
    - Result: Table with the image coordinates of feature points
      - ✓ One line for each image
      - ✓ One column for each point in space
      - ✓ The array element in row *m* and column *n* represents the image coordinates of the point *n* of the space in image *m*. If point *n* is not visible in image *m* , the array at position (*m* , *n*) contains an empty value (Null)

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Structure from motion methods

- **Incremental SfM methods**
  - Images are introduced gradually into the orientation and sparse reconstruction process, orienting one image at a time during each iteration.
  - These are the most commonly used methods.
- **Global SfM methods**
  - They simultaneously calculate the 3D coordinates of the sparse point cloud and the parameters of the exterior orientation of the images in a single, global solution.
- **Hierarchical SfM methods**
  - They gradually merge small sequences of images or partial reconstructions.

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Incremental SfM methods – indicative methodology

- **1st step** : Selection of an **initial pair of images** (e.g. with a large number of correspondences, central position in the image block, large base-to-height ratio)
- **2nd step** : Calculation of the orientation of this initial pair: Computation of the **projection matrices of the 2 cameras** using the feature point correspondences
  - Data: **epipolar matrix *F*** from the tie points, **essential matrix *E***, with knowledge of the interior orientation parameters (matrices ***K*′** , ***K***): $E = K'^{T} F K$
  - Let us assume:

$$P_1 = K[I_{3\times3}|0] \quad \Leftrightarrow \quad P_1 = K\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & 0\end{bmatrix}$$

$$P_2 = K[R|t]$$

  - Calculation of the **second projection matrix *P* $_2$ based on the essential matrix,** applying singular value decomposition (SVD)

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Incremental SfM methods – indicative methodology

- **3rd step** : Initialization of reconstruction (calculation of the **3D coordinates of the homologous points**)
  - Photogrammetric space intersection
  - Using the projection matrices (P_1 , P_2), feature point correspondences (and interior orientation parameters)
  - Calculation of the 3D coordinates of the homologous points in the SfM system

$$\begin{bmatrix} x_1 \\ y_1 \\ w_1 \end{bmatrix} = P_1 \begin{bmatrix} X \\ Y \\ Z \\ W \end{bmatrix} \qquad \begin{bmatrix} x_2 \\ y_2 \\ w_2 \end{bmatrix} = P_2 \begin{bmatrix} X \\ Y \\ Z \\ W \end{bmatrix}$$

- **4th step** : Selection **of a new image** (e.g. with a large number of feature points, whose 3D coordinates have been calculated)
  - For each image: identification of the number of feature points with determined 3D coords.
  - Based on the table of created during the feature tracking process

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Incremental SfM methods – indicative methodology

- **5th step** : Calculation of the **camera projection matrix of the newly added image**
  - Using the image coordinates of the keypoints whose 3D coordinates have been calculated, and their 3D coordinates

    "The Perspective-n-Point (PnP) Problem"

    E.g. via DLT:

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$x = \frac{p_{11} \cdot X + p_{12} \cdot Y + p_{13} \cdot Z + p_{14}}{p_{31} \cdot X + p_{32} \cdot Y + p_{33} \cdot Z + p_{34}}$$

$$y = \frac{p_{21} \cdot X + p_{22} \cdot Y + p_{23} \cdot Z + p_{24}}{p_{31} \cdot X + p_{32} \cdot Y + p_{33} \cdot Z + p_{34}}$$

- **6th step** : Reconstruction expansion (calculation of the **3D coordinates of the homologous points whose 3D coordinates have not yet been determined**)
  - Photogrammetric intersection
  - Using the keypoints of the new image, their homologous keypoints in an already oriented image, and the computed camera projection matrices (along with the interior orientation)

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Incremental SfM methods – indicative methodology

- **7th step** : **Bundle adjustment**
  - Typically this step is performed after a specified number of images is added
  - Least squares solution – estimation of the best values of exterior orientation parameters and 3D coordinates of homologous points (and interior orientation)
  - Eliminate points based on residual checks
- **8th step** : **Iteration** of steps 4-7 until all images are added
- **9th step** : **Final bundle adjustment**
- **10th step** : **Transformation of the SfM results to the ground reference system**
  - Estimate the 7 parameters (scale, 3 translations & 3 rotations) of a 3D similarity transformation
  - Transform SfM results to the target spatial coord. system
  - Solve using bundle adjustment

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Global SfM

- Frequent intermediate bundle adjustment processes required by incremental SfM methods significantly increase computational time.
- Global SfM methods, however, do not share this disadvantage. They simultaneously compute the 3D coordinates of the sparse point cloud and the parameters defining the external orientation of the images in a single solution, performing bundle adjustment only at the end of the structure-from-motion computation process.
  - Factorization methods
    - Techniques based on matrix decomposition to estimate structure and motion
  - Motion averaging methods (motion averaging methods)
    - Techniques for estimating motion by averaging transformations across multiple views

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Hierarchical SfM methods

Divide the SfM problem into smaller subproblems, which are then combined in a hierarchical manner.

- **Hierarchical organization of images**
- **Generating sparse reconstructions from individual image pairs**
- **Adding images to individual reconstructions**
- **Merging the individual reconstructions**

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Forms of representation of 3D geometry

Depth maps, dense point cloud, 3D model

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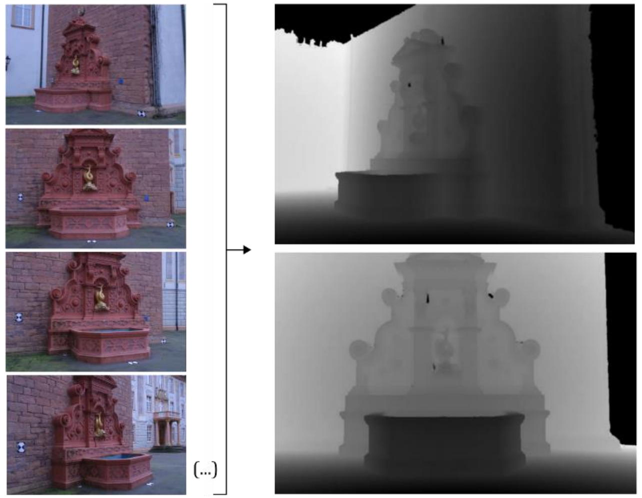
3D geometry representation forms : Depth maps

- Depth map: 2D representation of an image, which includes **for each pixel its depth**, i.e. **the value of its distance from the image capture point**
- A depth map can be visualized as an image **by converting the depth values into intensity values**
- A depth map is created for each image (or for some of the images) using **dense image matching** with overlapping images.
- A depth map (or the set of depth maps) can be used to generate other forms of 3D geometry representation (e.g., point cloud or mesh).



Source of images: https://documents.epfl.ch/groups/c/cv/cvlab-unit/www/data/multiview/denseMVS.html

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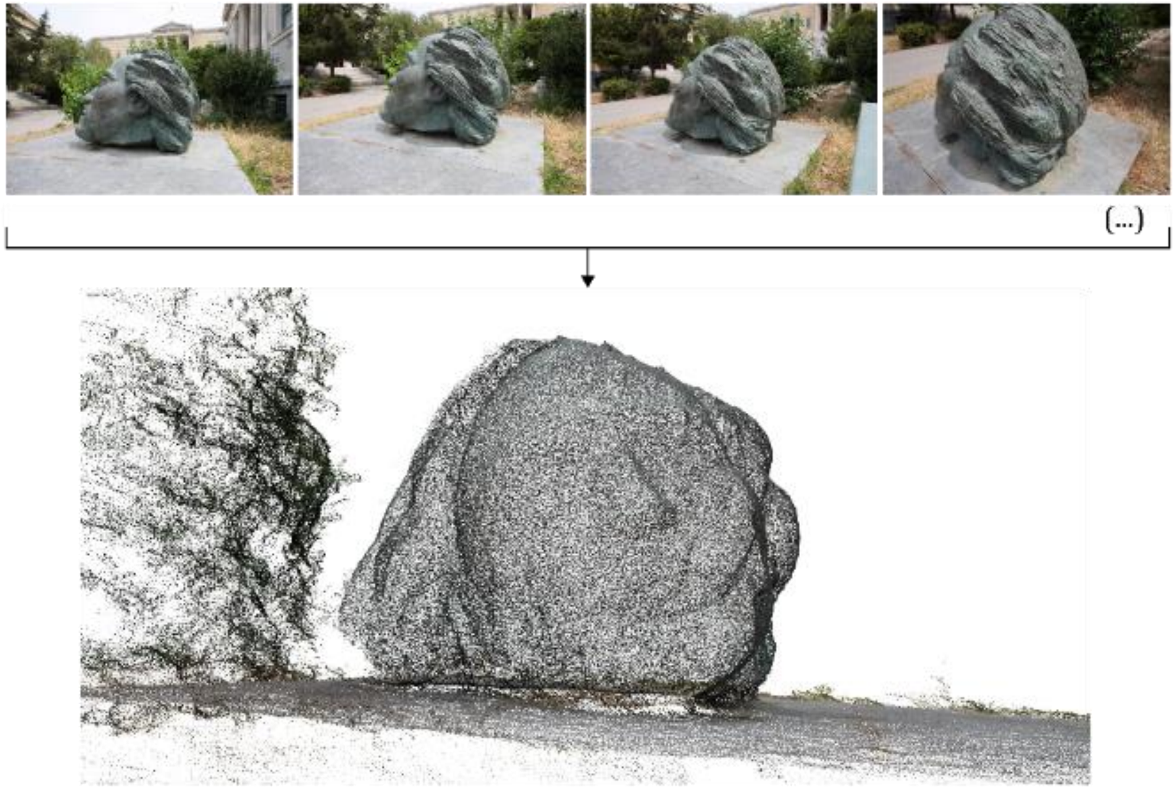
3D geometry representation forms : Dense point cloud

- Set of points in space with known 3D coordinates in a specified reference system
  - From one or more depth maps
  - Through a process of densification of a sparse point cloud
- Usually, each point in the dense cloud is accompanied by color information



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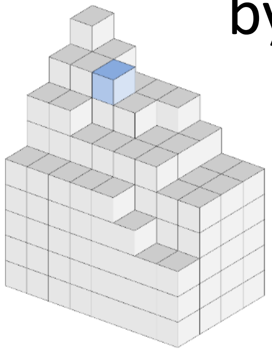
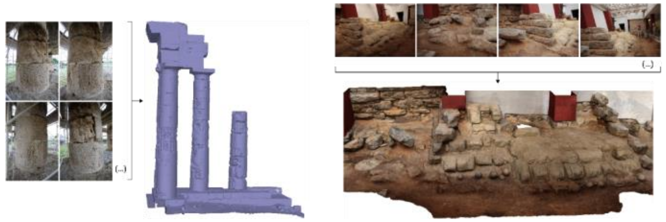
3D geometry representation forms : 3D model

- **Polygon mesh** : 3D model consisting of a set of vertices, edges and faces (usually triangles or quadrilaterals) that describe the 3D surface of the scene
  - It can be derived from the point cloud or from the depth map(s).
  - Texture mapping from images to polygon model
- **Polyhedral mesh** : represents (in addition to the surface) also the volume occupied by the object. Common Volume Representations:
  - Tetrahedral model (in which the elementary polyhedral part is the tetrahedron)
  - Model consisting of parallelepipeds
    - Consisting of parallelepipeds, where the fundamental unit is a voxel, the ”3D equivalent" of a pixel





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Dense point cloud generation

Dense image matching, dense point cloud creation

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Dense image matching

- The process of identifying correspondences for all – if possible – pixels of one image of the pair (reference image) that are visible in the second image of the pair (search image) and not only for characteristic points
- Input: images of known interior and exterior (or relative) orientation
- Output: a disparity map, which visualizes the disparity value (d) for each pixel in the reference image, effectively encoding the third dimension.
  - **Disparity** refers to the horizontal difference in the x-coordinates of corresponding pixels in the stereo pair. It is directly related to the depth of the object in the scene.
- The conversion of the disparity map into **a depth map** is carried out by calculating for each pixel of the disparity map the depth value, i.e. the distance *H* from the camera to the object

$$H = c\frac{B}{d}$$

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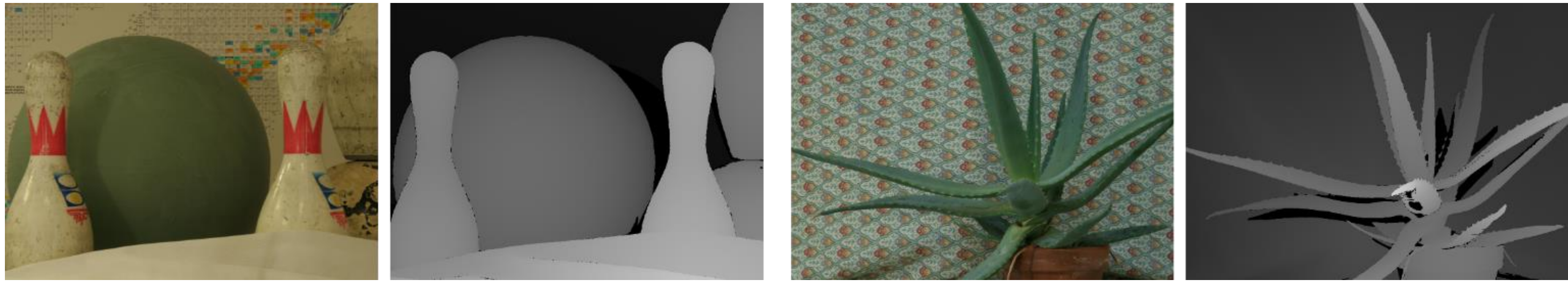
Dense image matching

- To calculate disparity of each pixel in the reference image, its corresponding pixel in the search image must be found
- Commonly applied to epipolar images → drastic reduction of the search area
  - **Epipolar images** are stereo images that have been rectified so that corresponding points lie on the same horizontal line.
- Images are often pre-processed before the dense matching process

Examples of reference images and corresponding disparity maps



Source of images and depth maps: https://vision.middlebury.edu/stereo/data/scenes2006/

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Types of dense image matching methods

- Local matching methods
- Global matching methods

- Semi-global matching methods

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Stages of Dense Image Matching Algorithms

- **Matching Cost Calculation**
  Each pixel in the reference image is assigned a similarity measure for every possible corresponding pixel in the search image (i.e., for each disparity value within the defined range).
- **Cost Aggregation**
  The matching cost for each pixel is aggregated with the costs of its neighboring pixels, supported by a region around the pixel.
- **Disparity Map Generation**
  Homologous pixels are matched, and the optimal disparity value is calculated for each pixel in the reference image.
- **Disparity Map Refinement**
  Performed to reject gross matching errors, fill gaps, and improve the accuracy of dense matching.

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Local matching methods

- The calculation of the disparity of each pixel of the reference image depends solely on the intensity values within a specified window
- For each pixel, the disparity corresponding to the largest or smallest (depending on the selected similarity measure) aggregated matching cost is selected
- Generally, they perform all four distinct stages
- They require significantly less execution time than global methods but are, in general, less accurate

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Global matching methods

- The problem of finding correspondences is related to the minimization of a **global energy function**
  - usually defined for all pixels of the reference image
  - introduces a smoothness constraint for disparity, ensuring continuity in the 3D surface of the scene across the entire image
- Often **skip the cost aggregation stage**
- Usually produce **more accurate disparity maps** compared to local methods.
- Require **longer computation times** than local methods.

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Semi-global matching method

- It aims to **reduce the computational complexity of global methods**
- It offers **a good balance between computational time and accuracy**, especially in edge regions

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Dense cloud generation using disparity maps

Indicative procedures

For all pixels of the disparity map

- Case of producing a dense point cloud from **a single parallax map**
  1. Let $(\underline{x}, \underline{y})$ represent the pixel in the reference image. The corresponding pixel in the second image is calculated as: $(\underline{x}', \underline{y}') = (\underline{x} + d, \underline{y})$
  2. Apply the inverse epipolar rectification transformation to the pixel coordinates $(\underline{x}, \underline{y})$ and $(\underline{x}', \underline{y}')$, o compute their homologous coordinates in the original image systems $(\bar{x}, \bar{y})$ and $(\bar{x}', \bar{y}')$, respectively.
  3. Forward intersection (calculation of 3D point coordinates in the space reference system
- Case: multiple **disparity maps for the same reference image**
  - Corresponding procedure, find all homologous pixels in search images, forward intersection with >2 images
- Case: multiple **disparity maps for different reference images**
  - Gradual incorporation of points from all depth maps; noise removal techniques

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Dense cloud generation by densifying a sparse point cloud

PMVS method (patch-based multi-view stereo) and variations

General workflow

- **Input: Images with known interior and exterior orientation**
- **Matching stage** (Generation of a sparse set of oriented points/patches)
- **Expansion stage** (Expansion of the existing sparse set of oriented points with new patches)
- **Filtering stage** (Removal of erroneous patches)
- **Output: Dense set of oriented points/patches**

A **patch** is a small flat rectangular plane in 3D space that locally approximates the 3D surface. It is defined by its center and a unit vector perpendicular to it, oriented towards the cameras observing it.

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Generation of a 3D mesh model

Surface reconstruction, texture mapping

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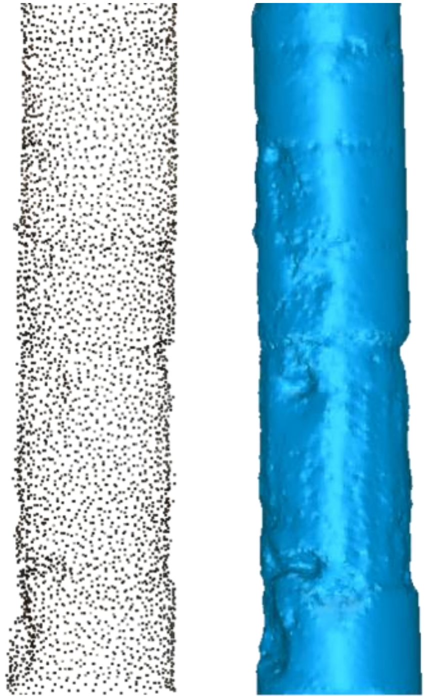
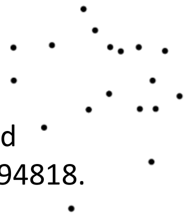
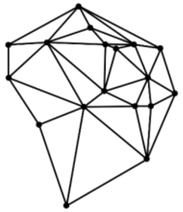
Surface reconstruction methods



Generation of a polygonal (usually triangular) model (mesh)

- Challenges:
  - existence of noise
  - existence of gaps (regions without points)
- Solutions:
  - surface fitting to noisy data
  - filling gaps in areas with missing data
- Methods for producing a 3D surface from a point cloud
  - **Poisson surface reconstruction** method (generates smooth and watertight surfaces, even in the presence of noise)
  - Methods based on **Delaunay** triangulation (constructing a graph that connects neighboring points by forming triangles, ensuring that no point lies inside the circumcircle of any triangle)
  - etc.





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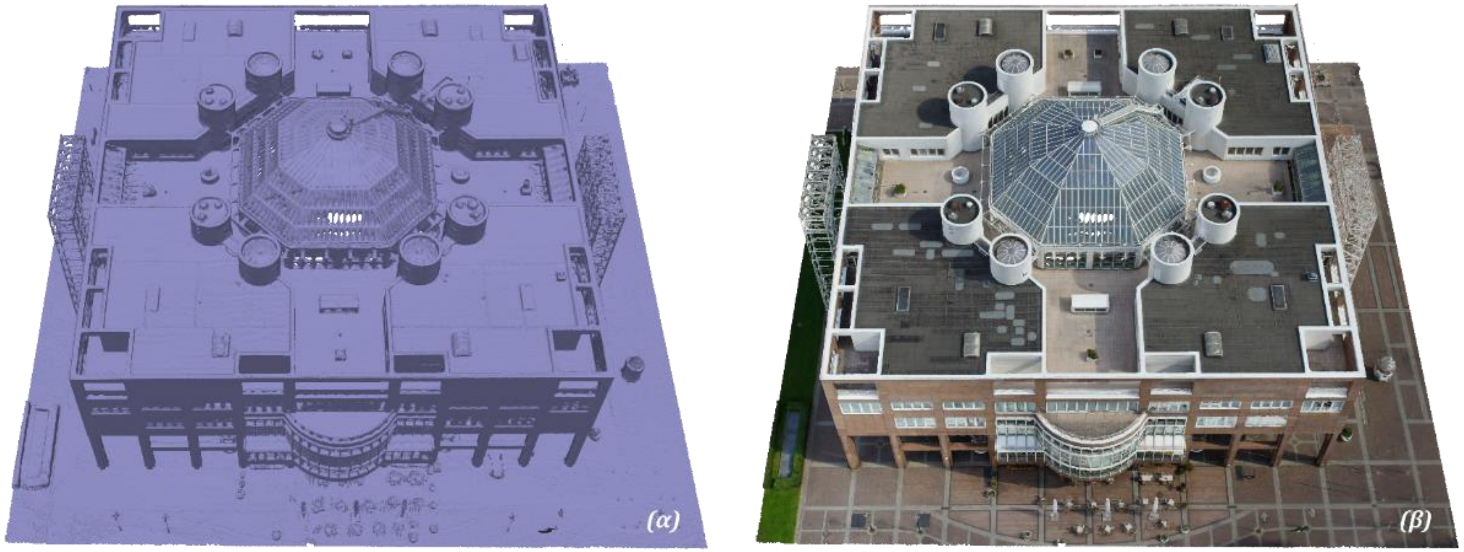
Texture mapping

- The process of applying a 2D image, called a **texture map**, to a 3D polygonal model.
- This is the final stage of the multi-view 3D reconstruction process, where texture is added to the surface of the 3D model using the images (with known internal and external orientation) that were used to create it.



Source of dataset for generating these products: ISPRS/EuroSDR Benchmark for Multi-Platform Photogrammetry

- Nex, F., Gerke, M., Remondino, F., Przybilla, H.-J., Bäumker, M. & Zurhorst, A. (2015). ISPRS Benchmark for Multi-Platform Photogrammetry. *The International Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-3/W4, 135-142. Doi: 10.5194/isprsannals-II-3-W4-135-2015.

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Texture mapping (example)

- **Projection of model faces:** Each face of the 3D model is projected onto one or more images where the face is visible.
- **Selection of optimal images:** The best image(s) for texturing each face are selected based on factors such as:
  - **Occlusions:** Avoiding obstructed areas.
  - **Resolution:** Using images with higher detail.
  - **Viewing Angle:** Favoring direct views.
  - **Consistency with Neighboring Pixels:** Ensuring smooth transitions.
- **Texture map creation:** Gradually store ("copy") connected segments of the same image used to texture the triangles of the model into the texture map.
- **Texture coordinate assignment:**
  Each vertex of every face in the 3D model is assigned texture coordinates from the texture map, corresponding to row and column numbers in the map.

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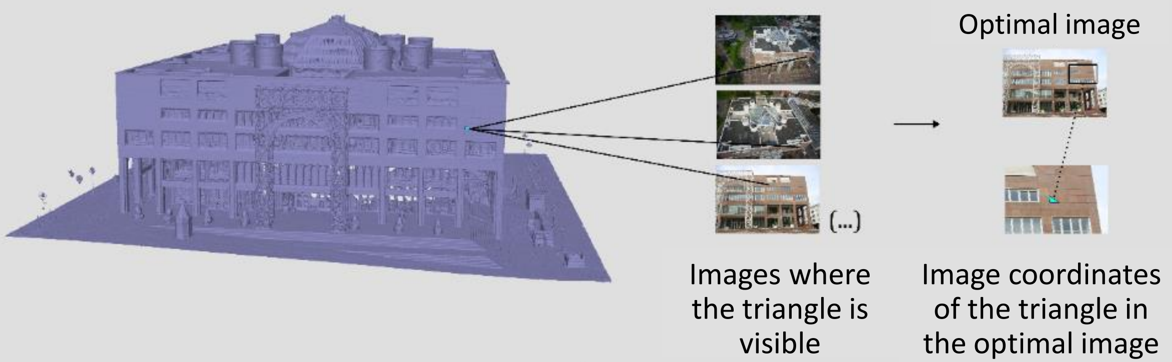
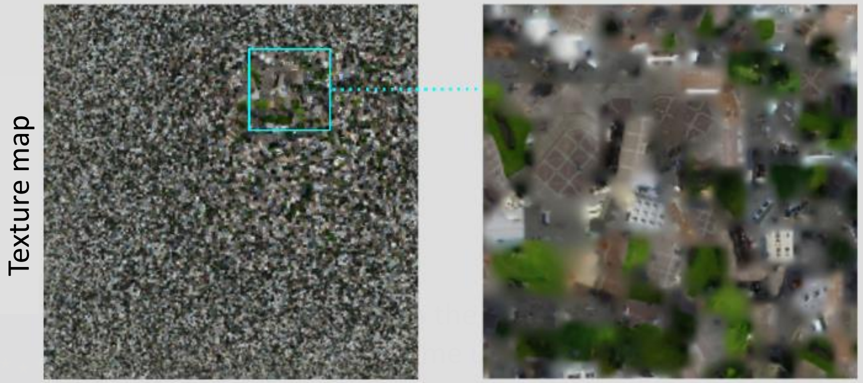
Texture mapping stages

Calculation of the optimal image for each triangle of the 3D model and the image coordinates of the vertices of each triangle in the optimal image



Creation of the texture map and assignment of texture coordinates to the vertices of the triangles in the 3D model



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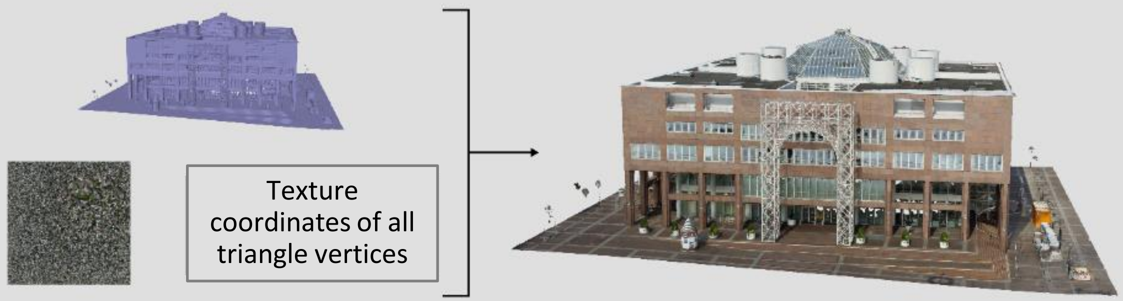
Texture mapping



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Examples – Applications

SfM-MVS results for CH sites and objects

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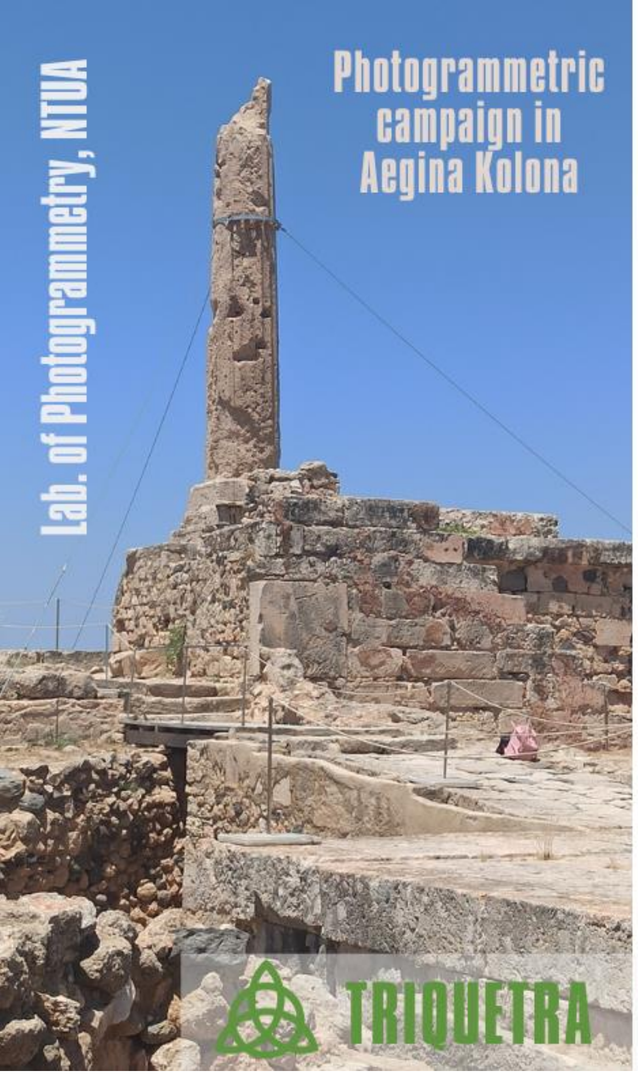

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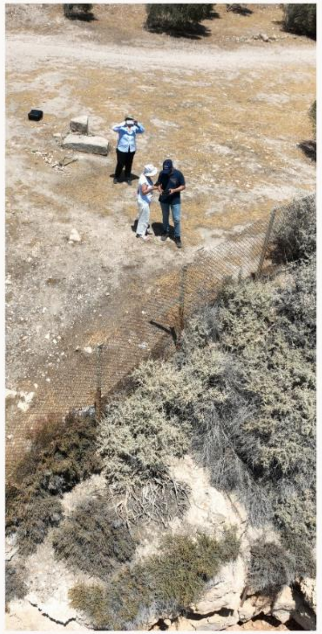
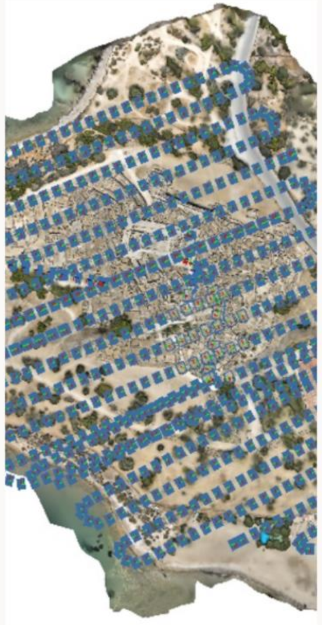
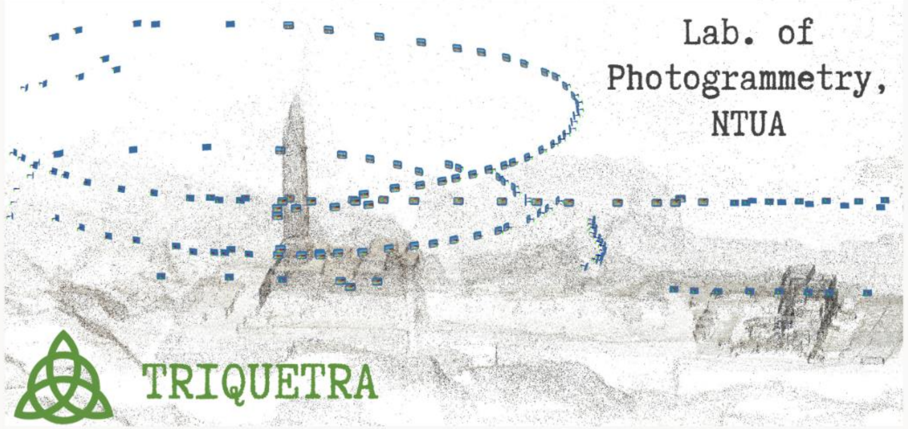




Photogrammetric Campaign in Aegina Kolona



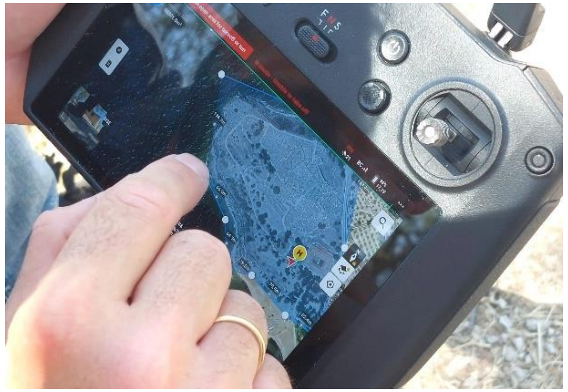
TRIQUETRA

Photogrammetric Campaign in Aegina Kolona, Greece

Lab. of Photogrammetry, NTUA

Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA

- The **DJI Mavic 3 Enterprise** drone was used to capture **945 vertical aerial** images, covering the entire archaeological area. This initial aerial survey provided a broad overview of the site's topography.



Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA




- Furthermore, **4900 oblique aerial images** were captured at lower altitudes to cover in high resolution the slopes and intricate features of the site. Here are representative oblique images showcasing the slopes, walls and other site details.

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

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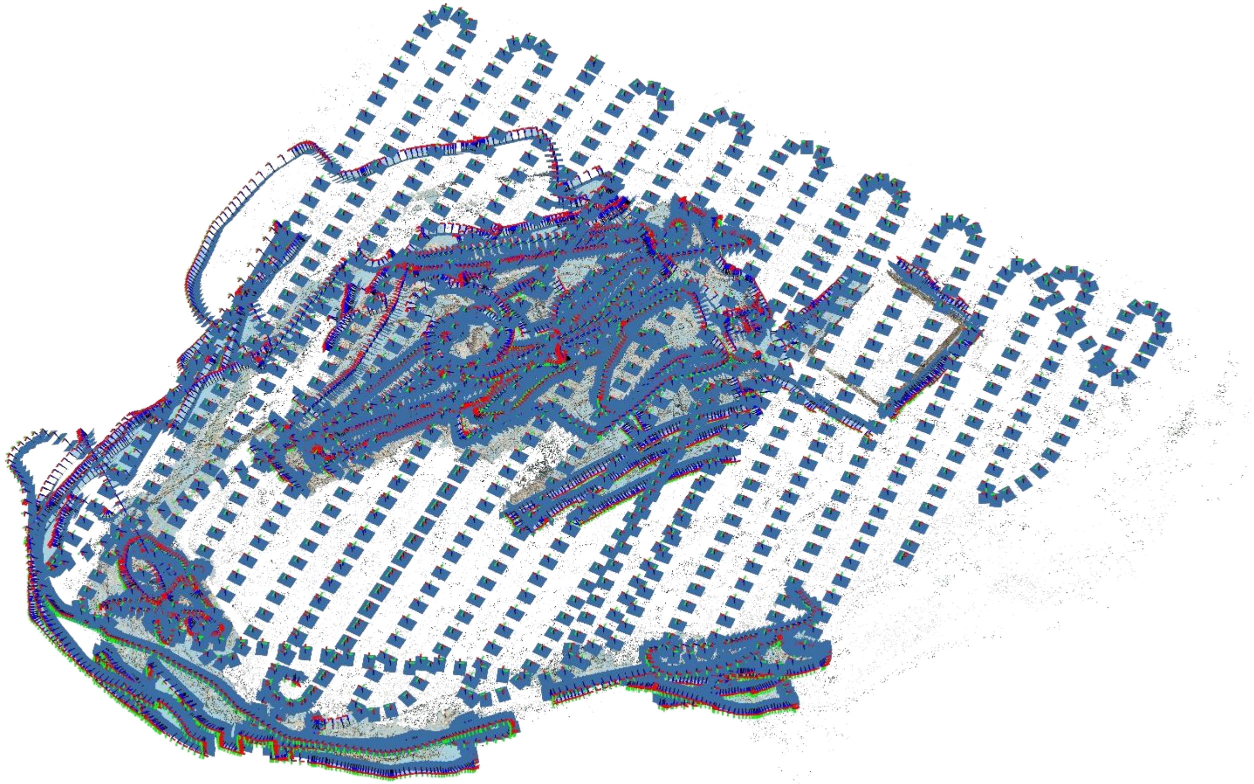


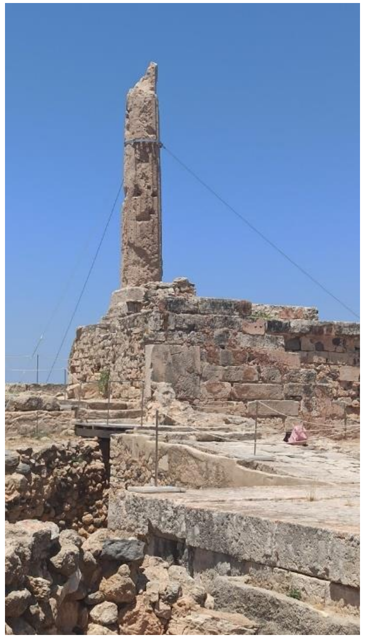
Oriented vertical and oblique aerial images and sparse point cloud

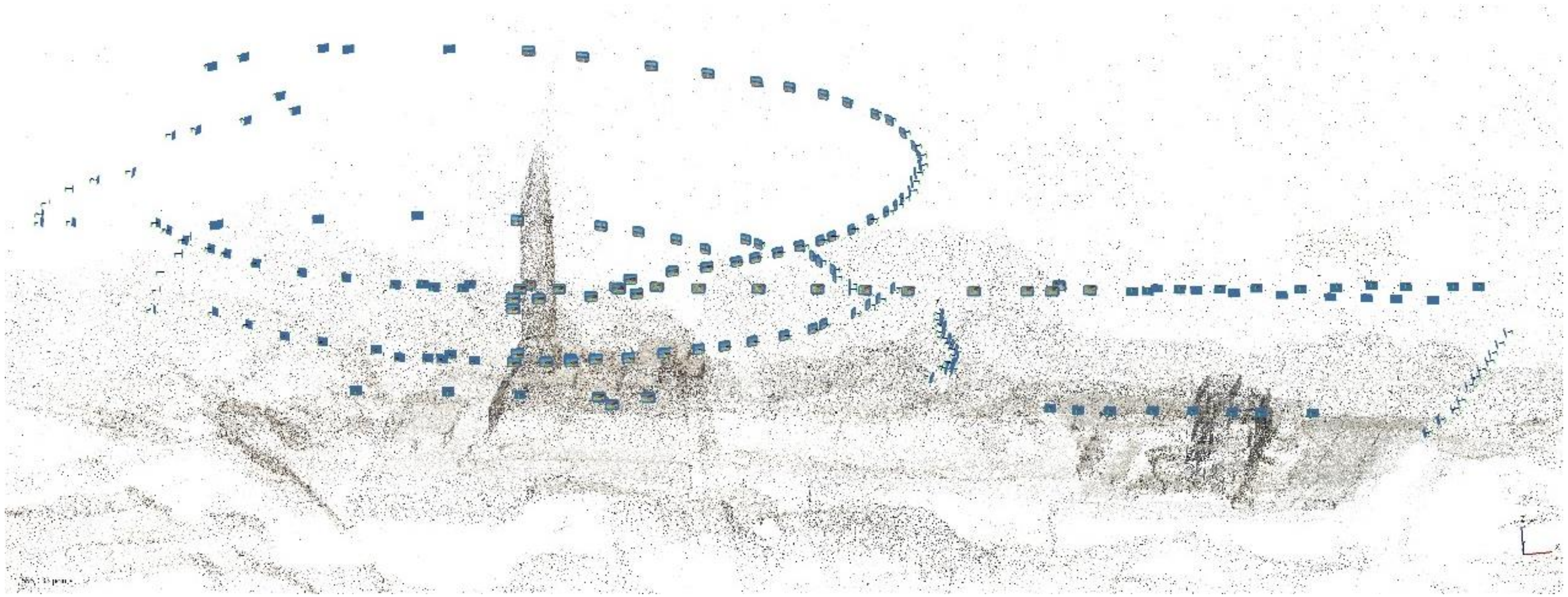
Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA

- In addition, a **DJI Mavic 3 Enterprise** drone was used to capture **930 images** around the Kolonna as well as in areas within the archaeological site and in the museum’s facades.





Project funded from the EU HE research and innovation programme under GA No. 101094818.

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Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA

Ground survey:

- **Fifteen (15) pre-marked ground control points (GCPs)** were strategically placed around the site. The coordinates of these points were determined in the Greek Geodetic Reference System (GGRS '87) using a **Leica 1200 GNSS receiver**. The NTRIP RTK method was employed to receive corrections from the MetricaNet GNSS permanent stations network by Metrica.
- Moreover, **ten (10) characteristic points** within the site were measured for georeferencing the results of the photogrammetric campaign.

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

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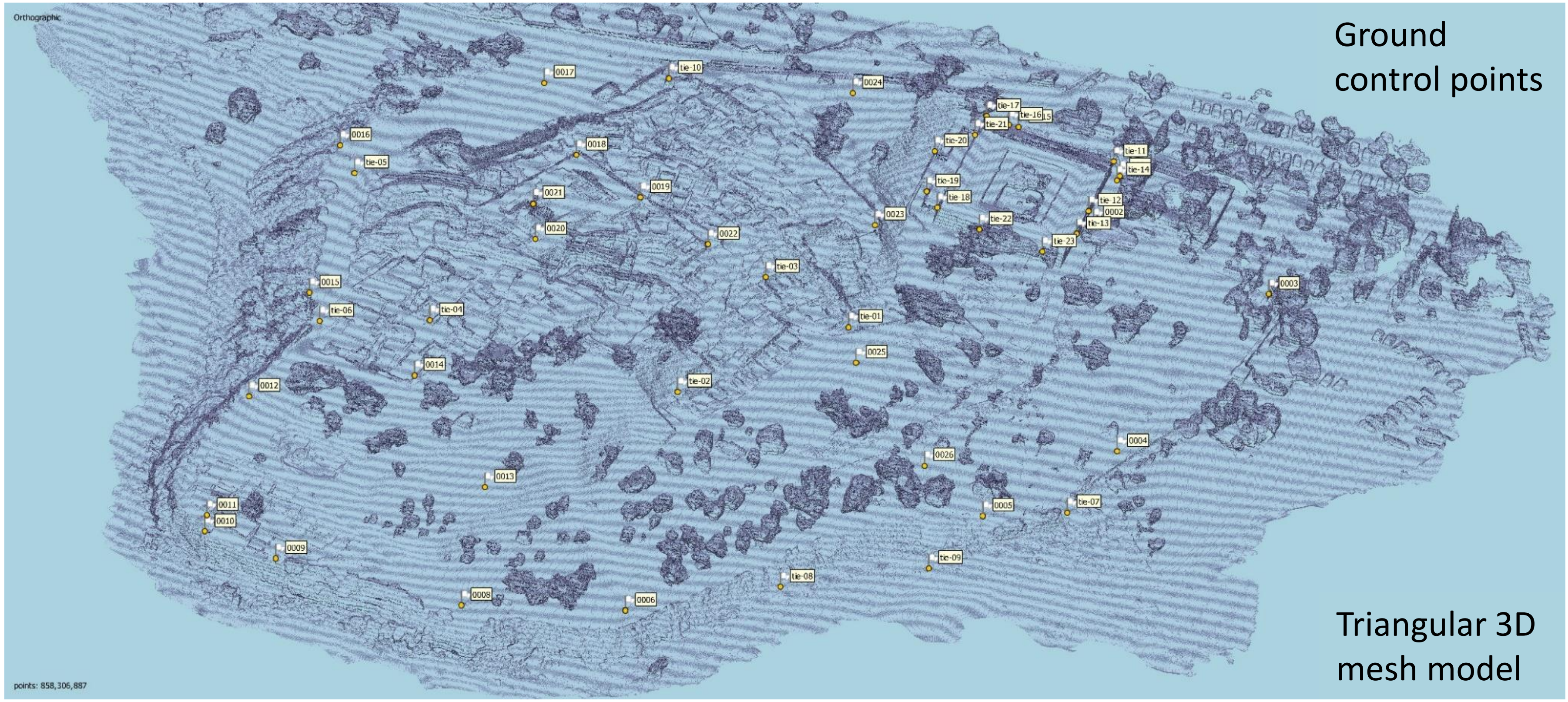

Project funded from the EU HE research and innovation programme under GA No. 101094818.

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Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA

Processing and Outcomes

- **3D Modeling Workflow**:
  - **Sparse Point Cloud Generation**:
    1. Method: Structure from Motion (SfM).
    2. Points: ~2.5M (UAV/terrestrial)
    3. RMS error: 4cm (GCPs), 6cm (check points)
  - **Dense Point Cloud Generation**:
    1. Points: ~61M (UAV/terrestrial)
  - **3D Model Creation**:
    1. Software: Agisoft Metashape & Geomagic Studio
    2. Texturing: Manual image selection for detailed maps
- **Final Outputs**:
  - **High-Resolution 3D Models**: Representing intricate geomorphological features.
  - **Orthoimage:** 2,5cm & 1cm pixel size
  - **DEM**: 1cm resolution

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

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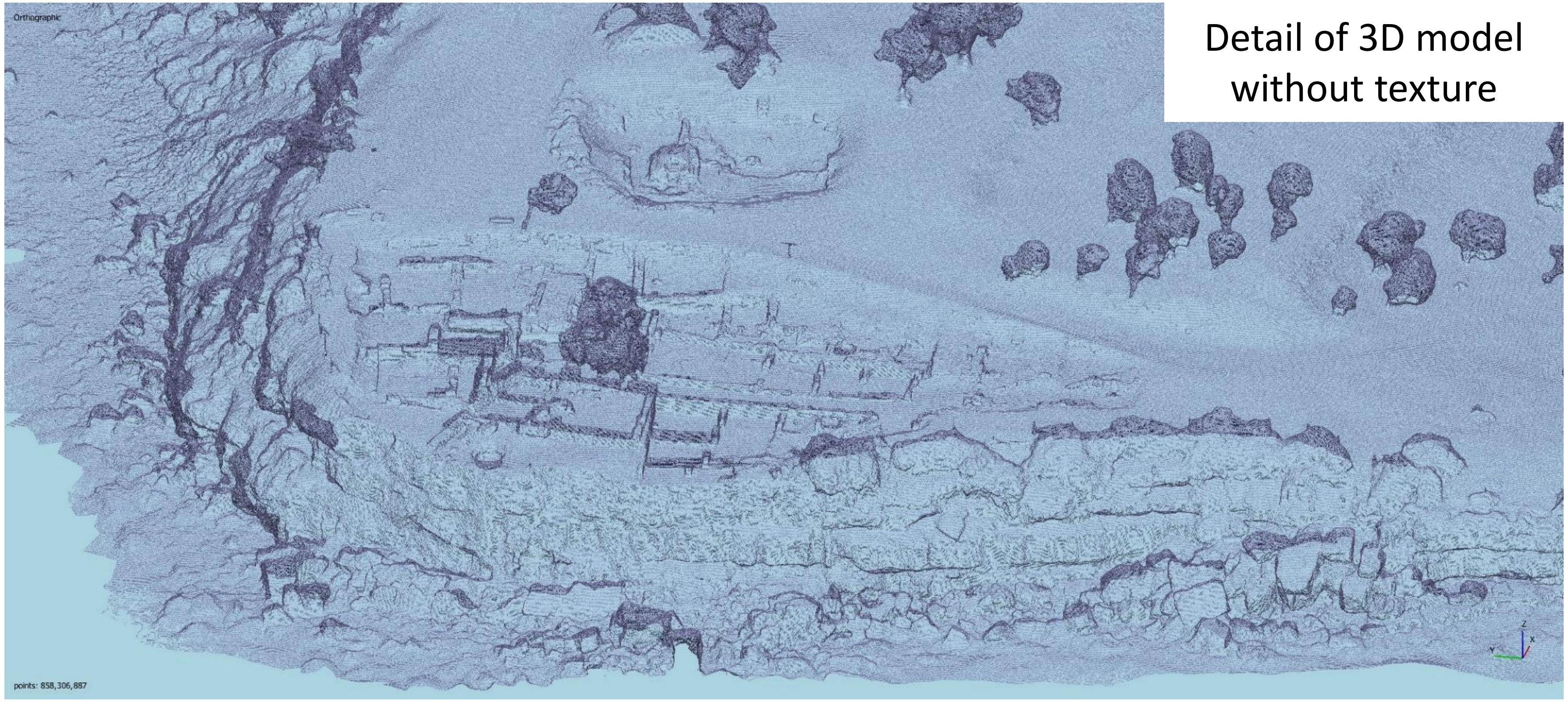


Detail of 3D model without texture

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA

Detail of 3D textured model

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *“3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change.”* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

TRIQUETRA

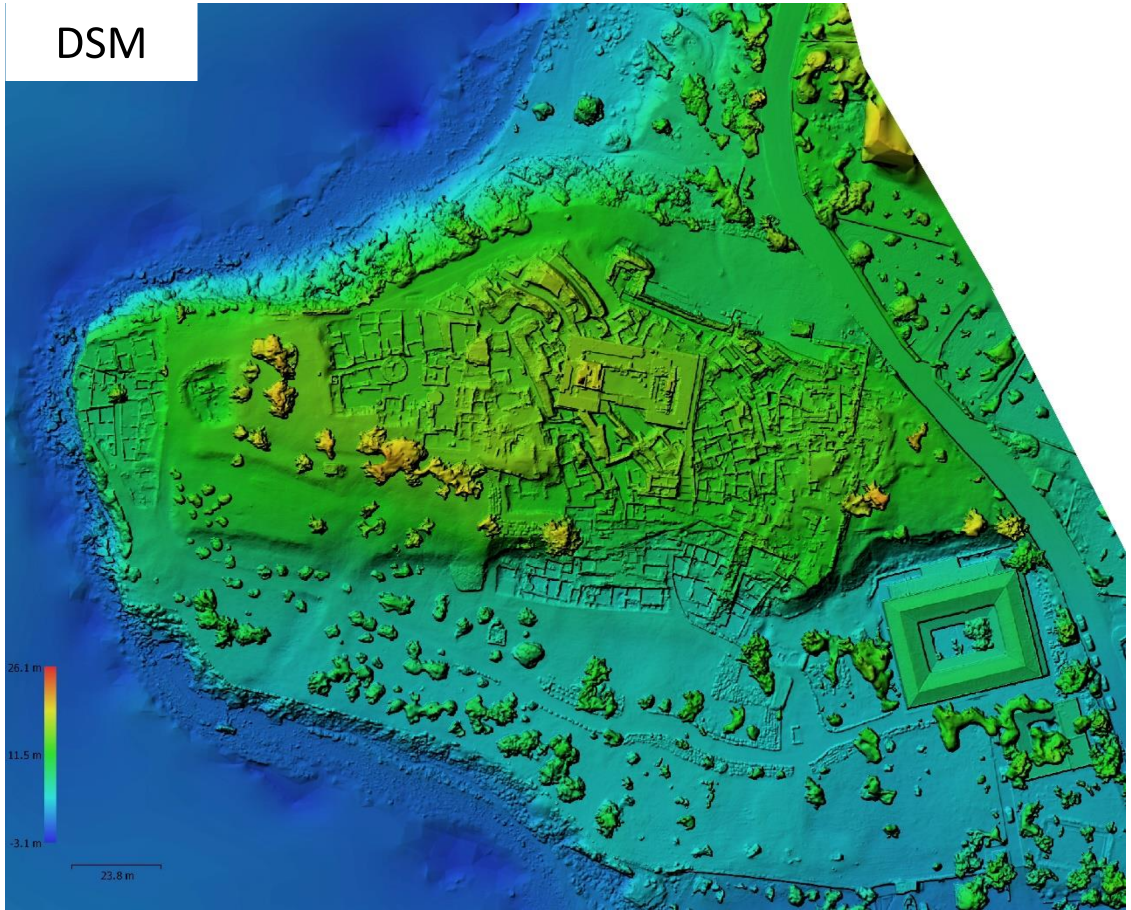
Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA

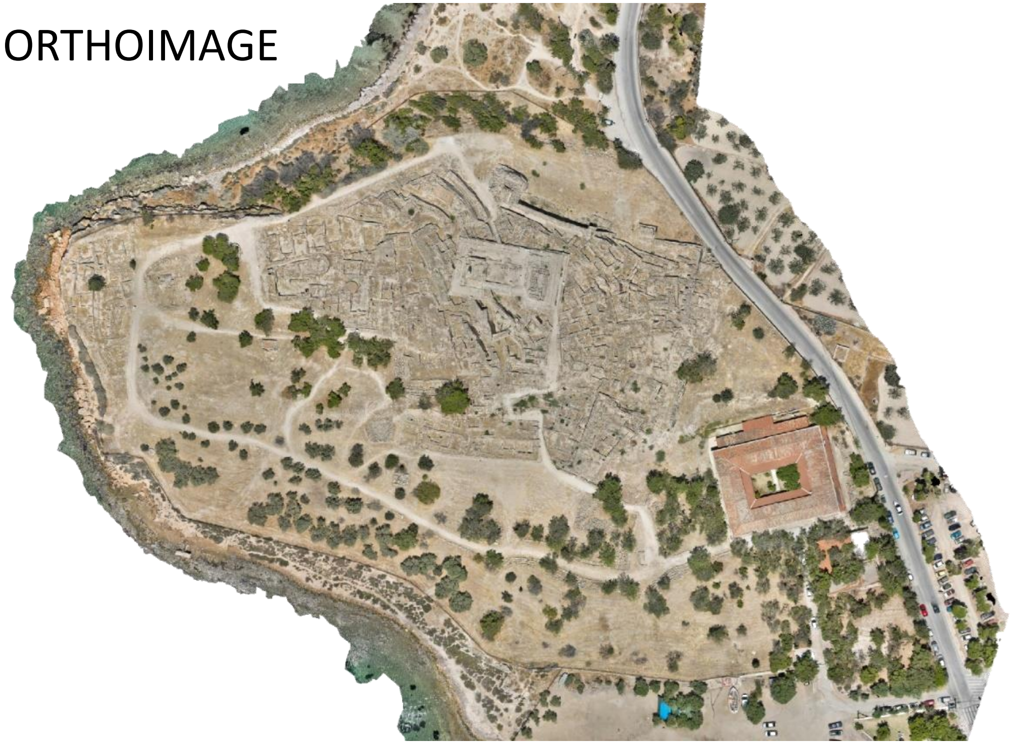
Detail of 3D textured model

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *“3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change.”* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**. CC BY 4.0.

Photogrammetric campaign in Aegina Kolona in the context of the TRIQUETRA project by NTUA





Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**. CC BY 4.0.

3D documentation of Meteora's inaccessible rock formations (Modi & Alyssos)

- **Challenges**: The complex geomorphology, the inaccessibility of the sites, and the need for high-resolution, multi-source data integration posed significant challenges to the documentation process.
- **Data Collection**:
  - **Aerial Images**:
    - Source: Manned aircraft (NIKON D800E).
    - Coverage: 2200 images with 80% overlap; GSD: 5 cm.
  - **UAV Images**:
    - Source: DJI Phantom IV RTK.
    - Coverage: 4000 images; GSD: 3.5–5 mm.
- **Terrestrial Images**:
  - Source: CANON EOS 6D.
  - Use: Captured at the base and top of rocks.
- **LiDAR Data**:
  - High-density point clouds (~80 points/m²).
  - Captured with RIEGL VQ-1560i-DW.
- **Georeferencing**:
  - 40 Ground Control Points (GCPs) collected with RTK GNSS.

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

3D documentation of Meteora’s inaccessible rock formations (Modi & Alyssos)

Processing and Outcomes

- **3D Modeling Workflow**:
  - **Sparse Point Cloud Generation**:
    1. Method: Structure from Motion (SfM).
    2. Points: ~3.4M (aerial) & ~7.4M (UAV/terrestrial).
  - **Dense Point Cloud Generation**:
    1. Points: ~353.1M (aerial) & ~500M (UAV/terrestrial).
  - **3D Model Creation**:
    1. Software: Agisoft Metashape & Geomagic Studio.
    2. Texturing: Manual image selection for detailed maps.
- **Final Outputs**:
  - **High-Resolution 3D Models**: Representing intricate geomorphological features.

Project funded from the EU HE research and innovation programme under GA No. 101094818.

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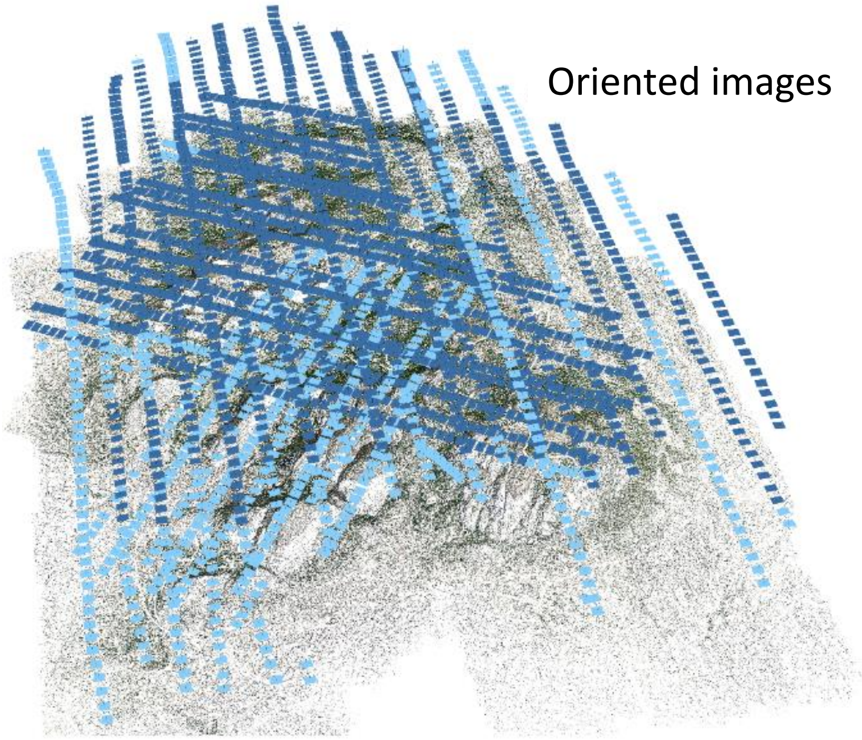
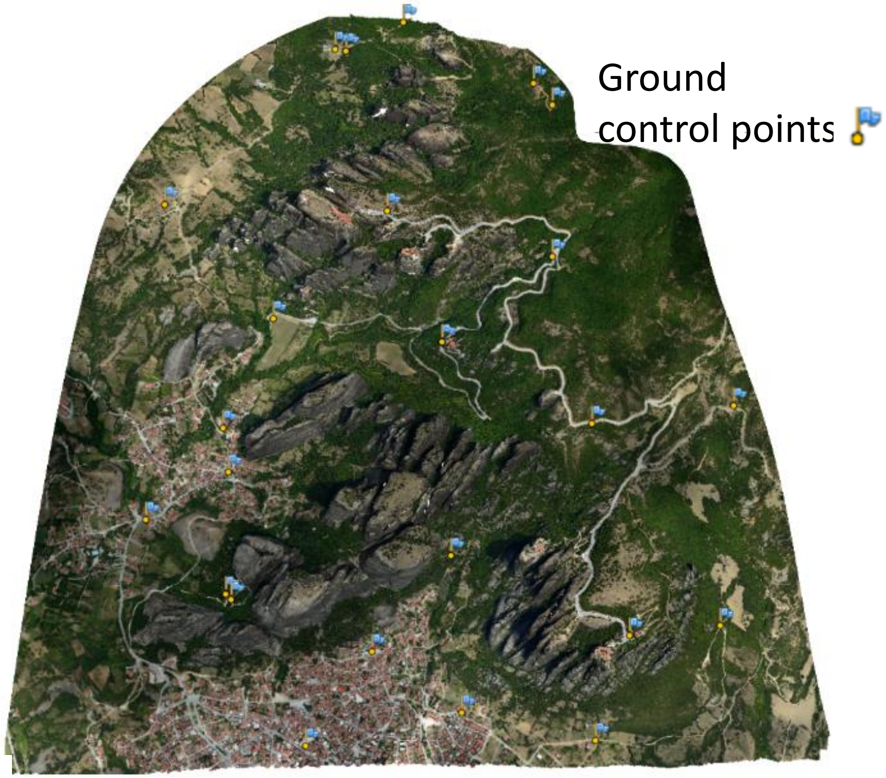
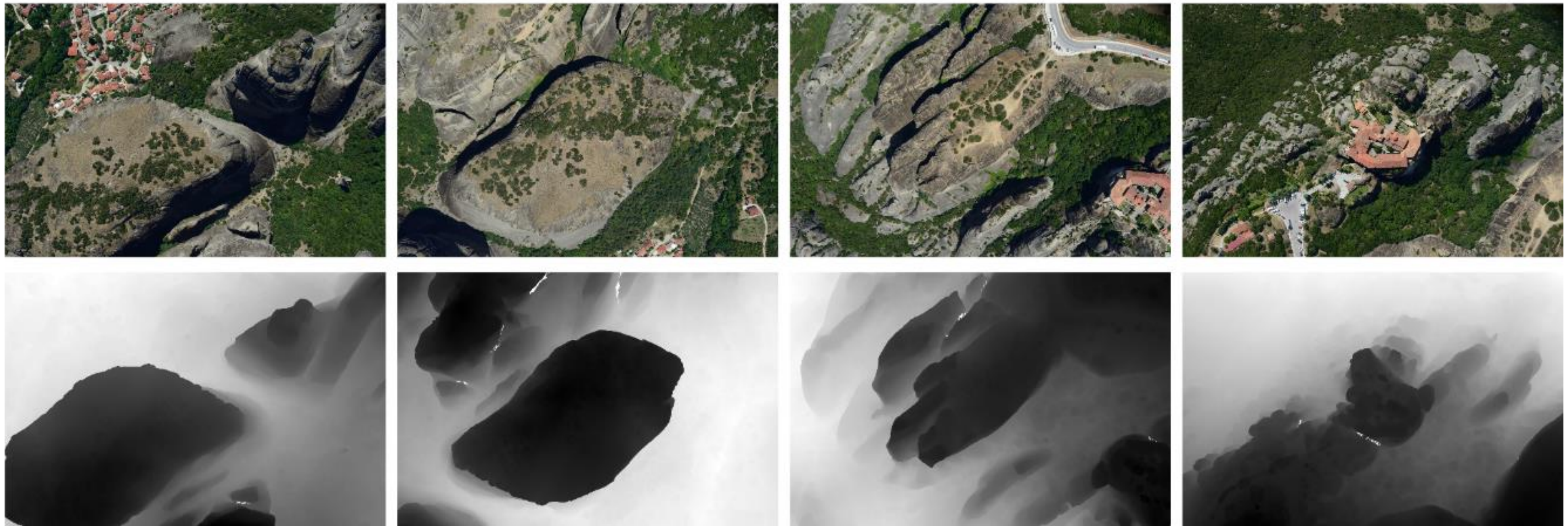




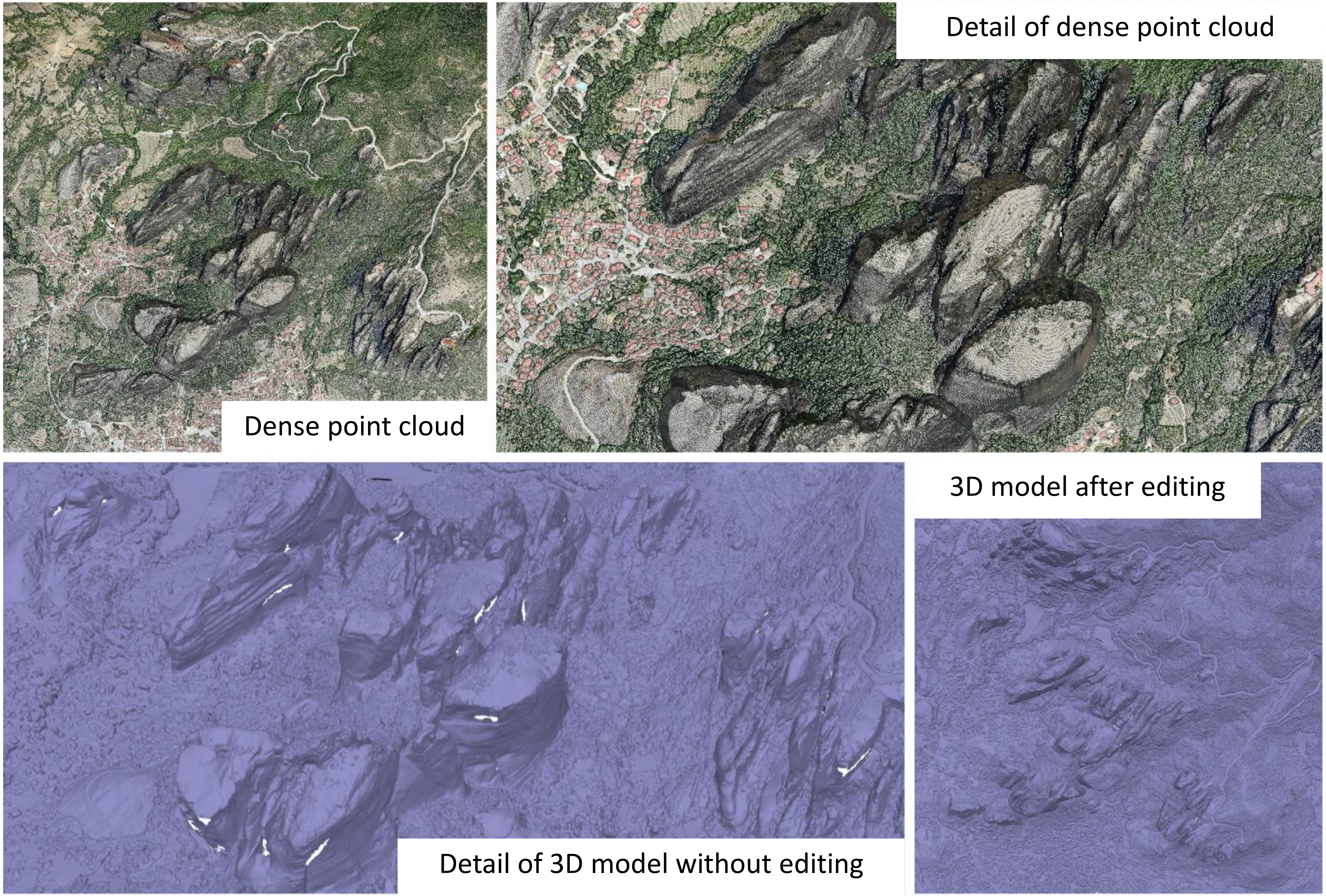
Examples of images and depth maps



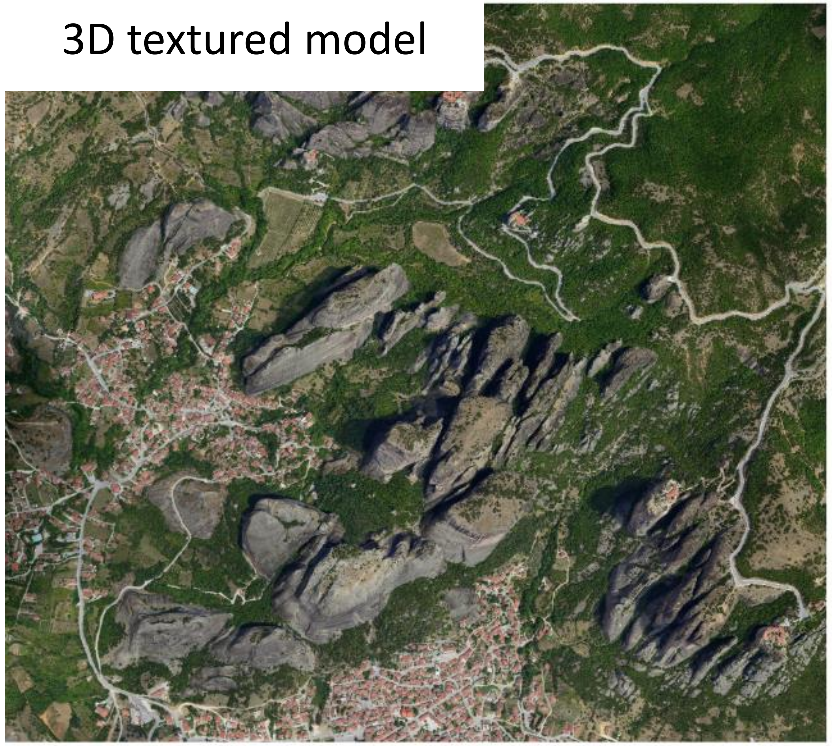
3D documentation of a part of the Archaeological Site of Meteora

Meteora is located near the city of Kalambaka, in the northwestern part of Thessaly, at an altitude of about 600 meters above sea level.

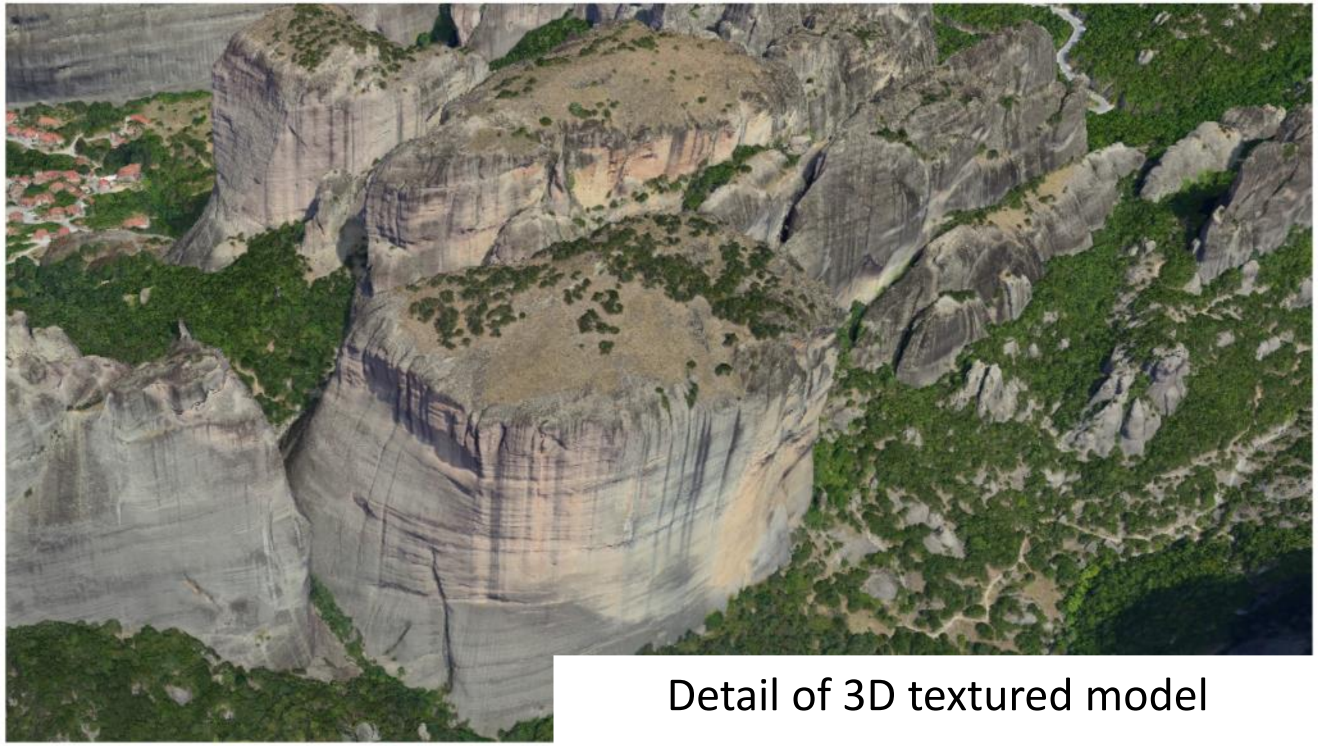
Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.



Archaeological Site of Meteora

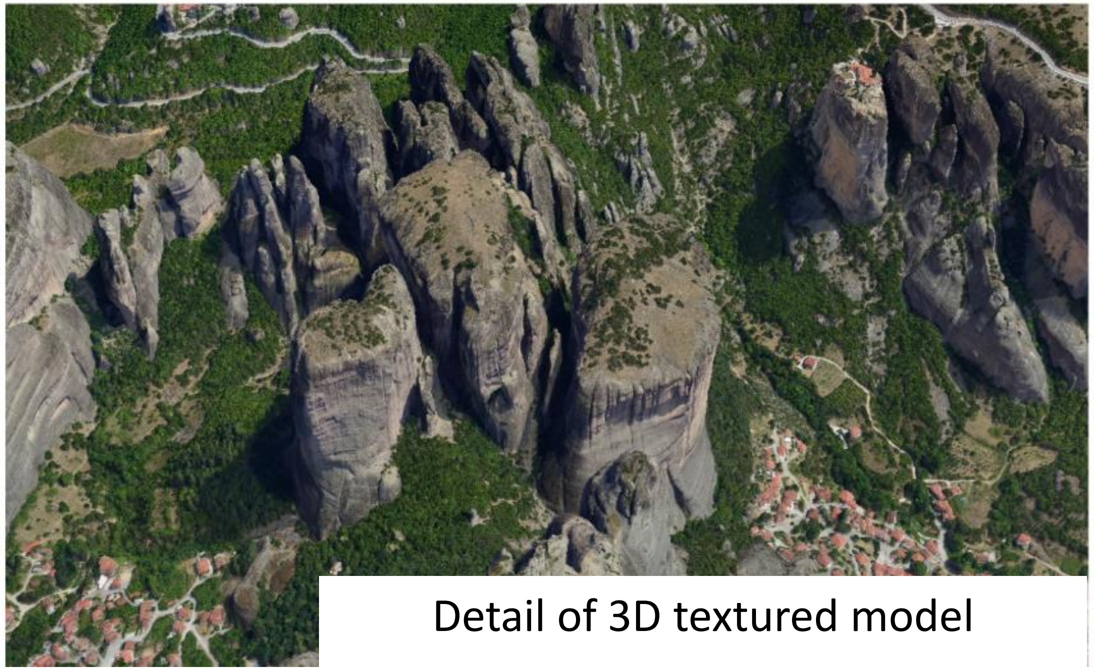


3D textured model



Detail of 3D textured model

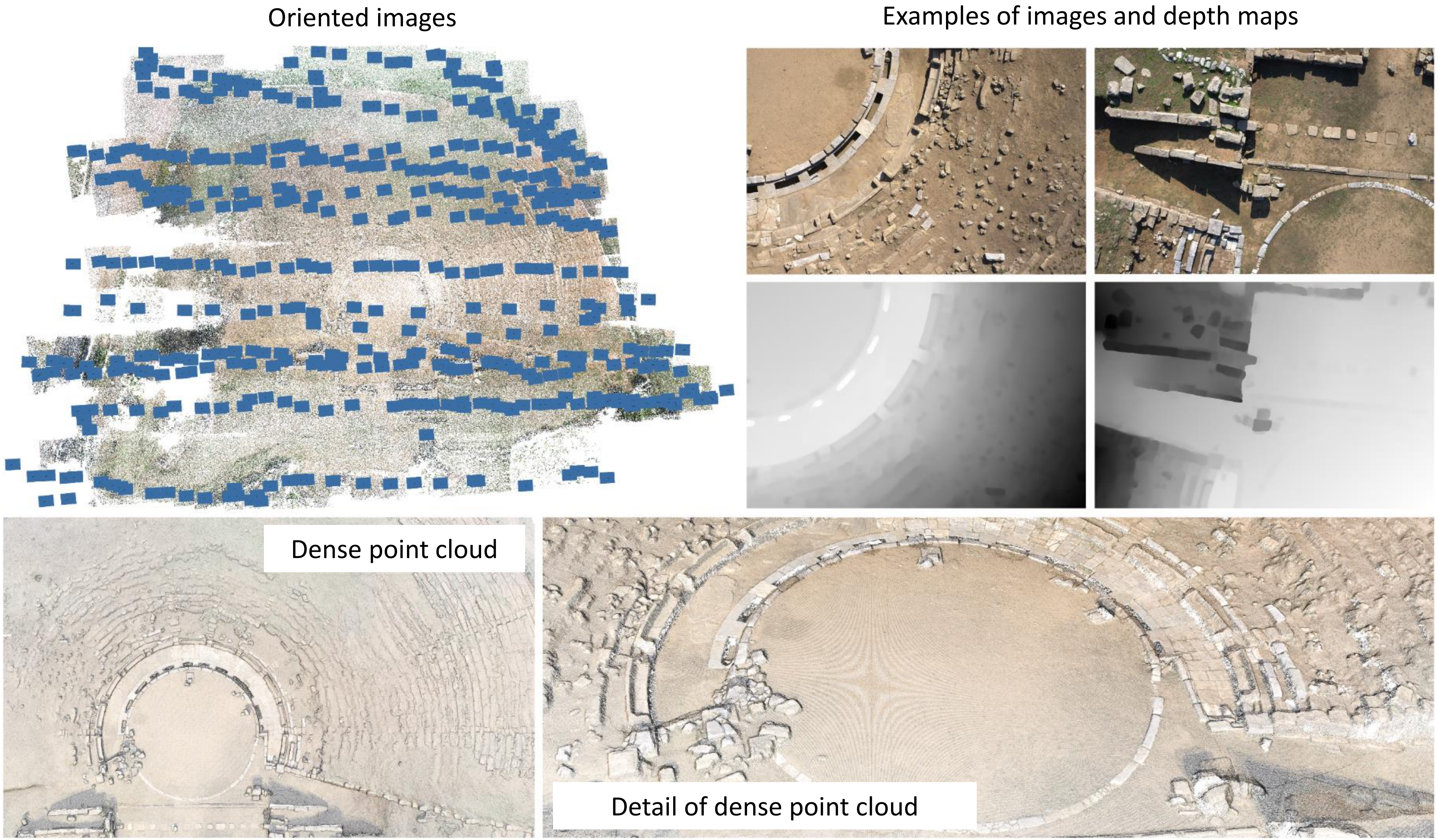
Detail of 3D textured model



Detail of 3D textured model

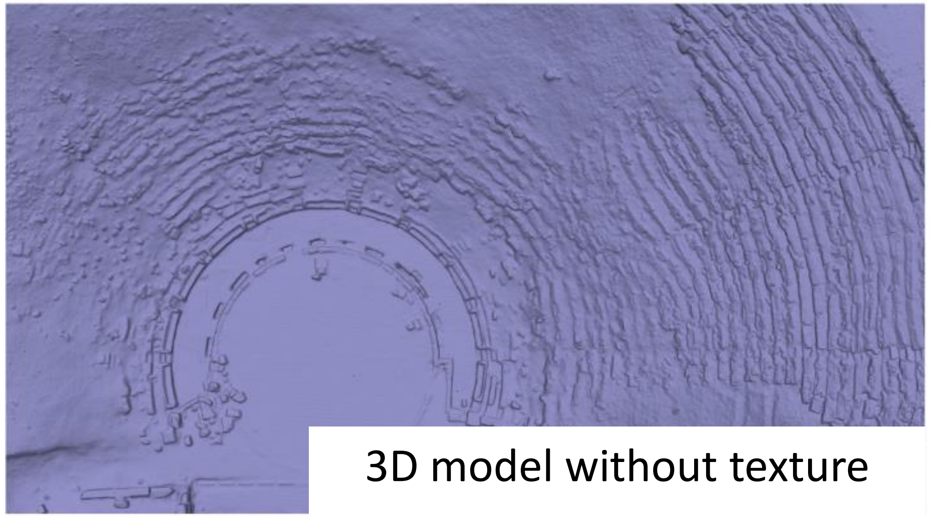
Archaeological Site of Meteora

The main study area consists of two inaccessible rocks: the rock of St. Modestos (“Modi”) and the rock of the Chain of Apostle Peter (“Alyssos").



3D documentation of the Ancient Theatre of Stratos, Agrinio Municipality, Aetoloacarnania, Greece

Ancient Theatre of Stratos

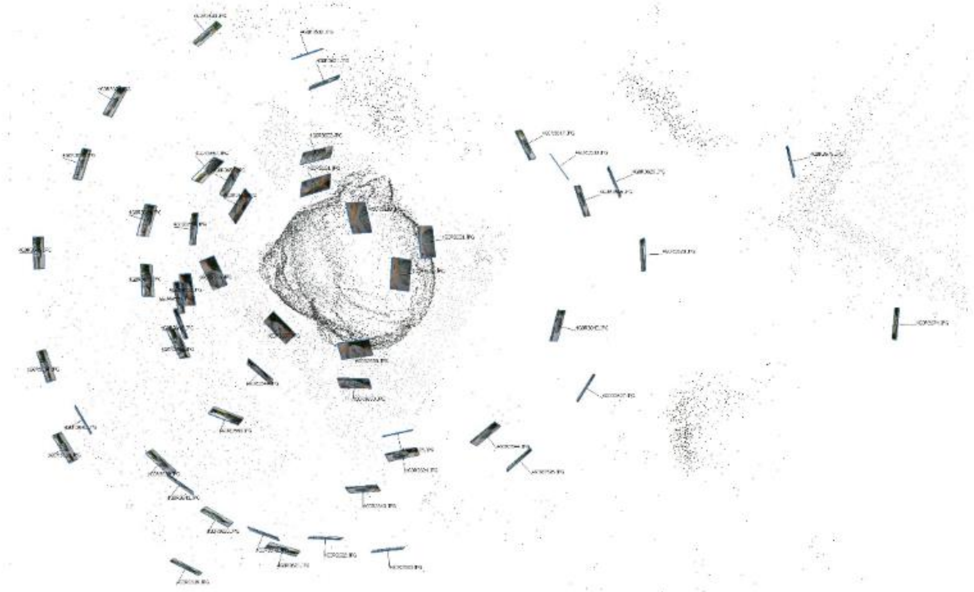


3D model without texture

3D textured model

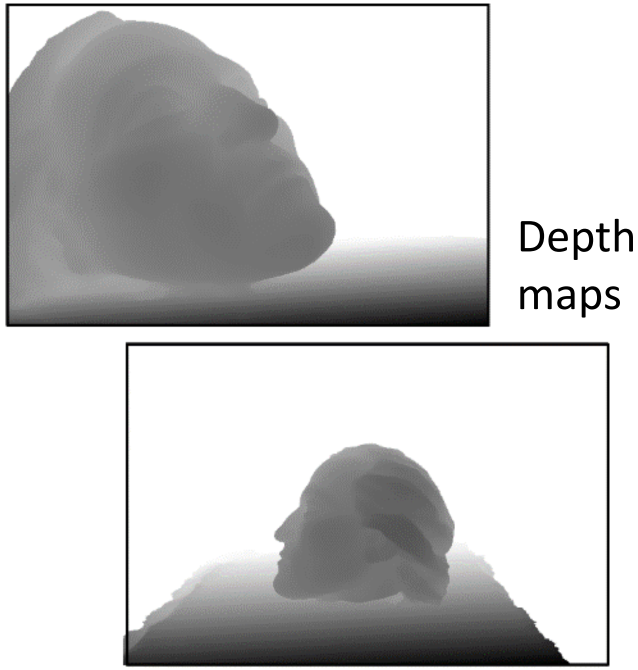
Detail of 3D textured model

Sparse point cloud and oriented images



Dense point cloud

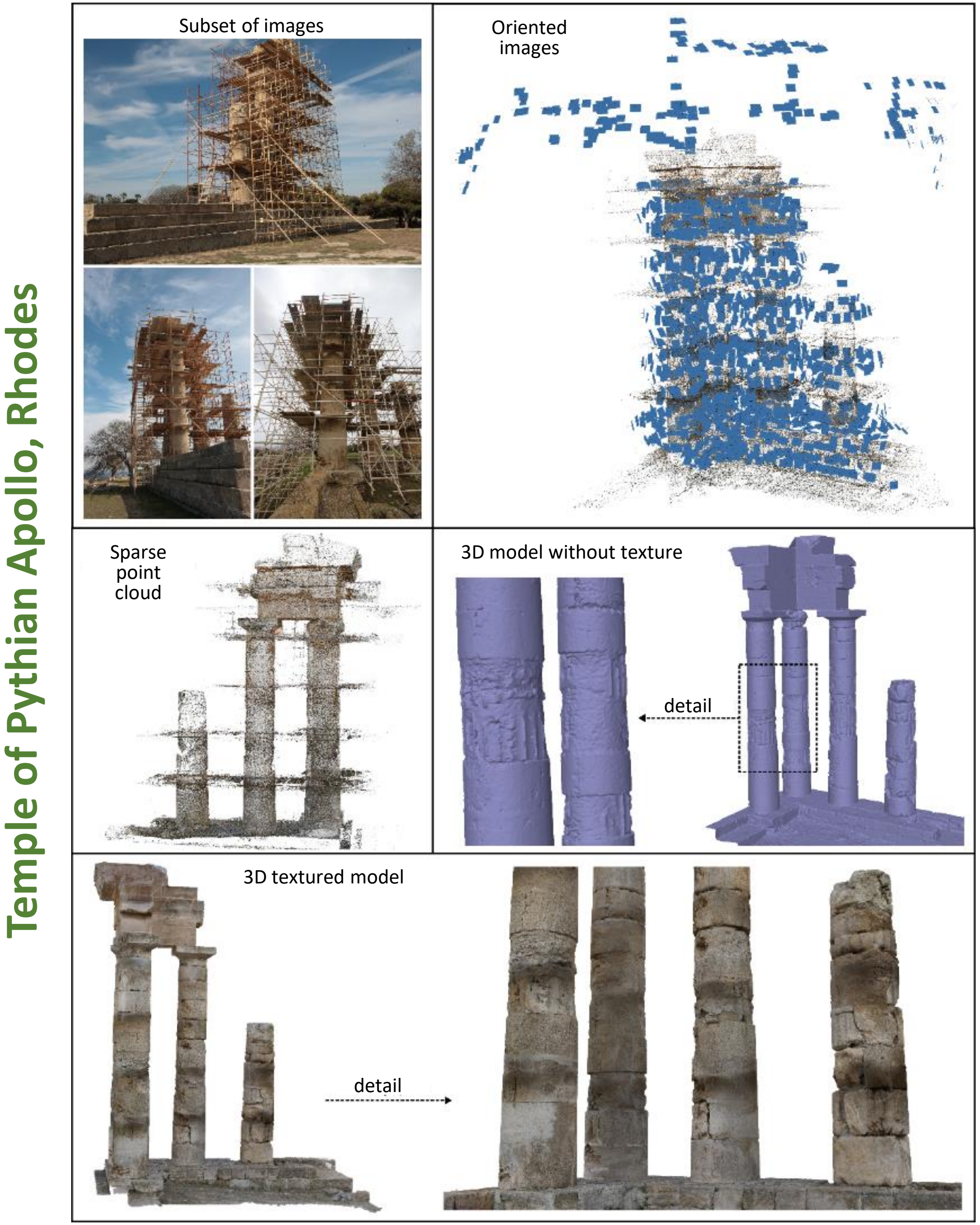
3D model
without
texture

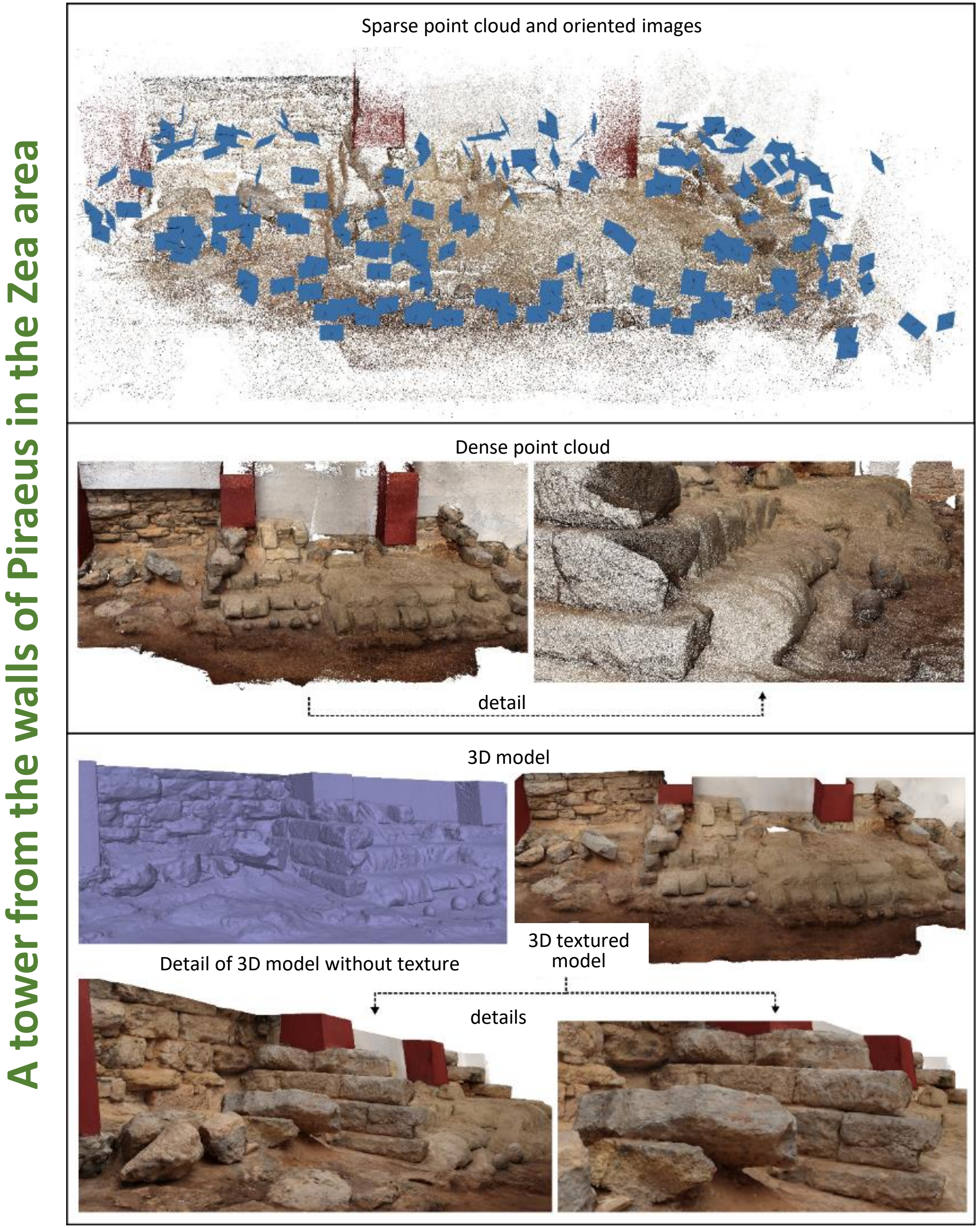


Depth
maps

Textured
3D model

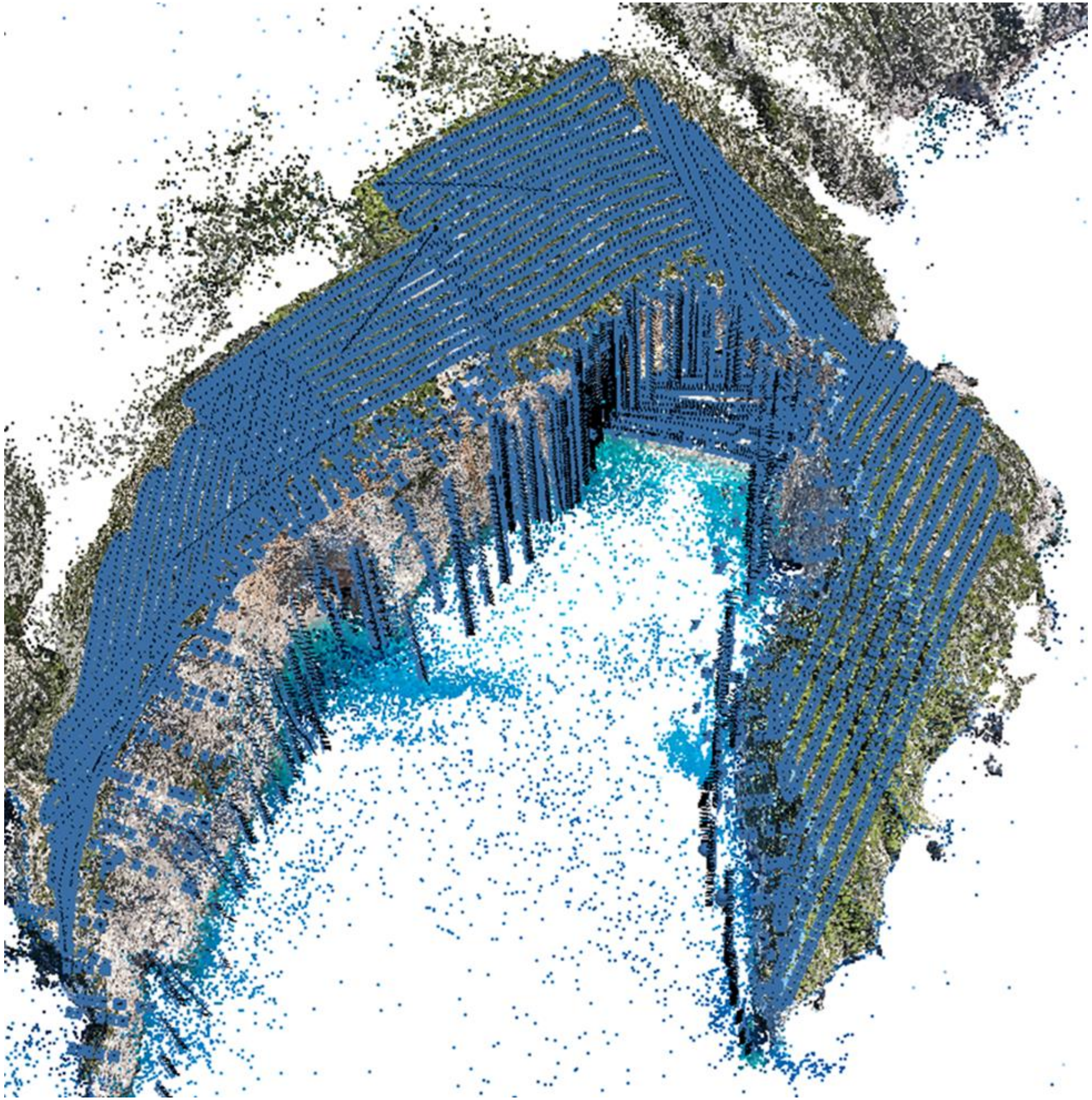
3D modeling of the sculpture of the head outside the NTUA, depicting the historian and professor Nikos Svoronos

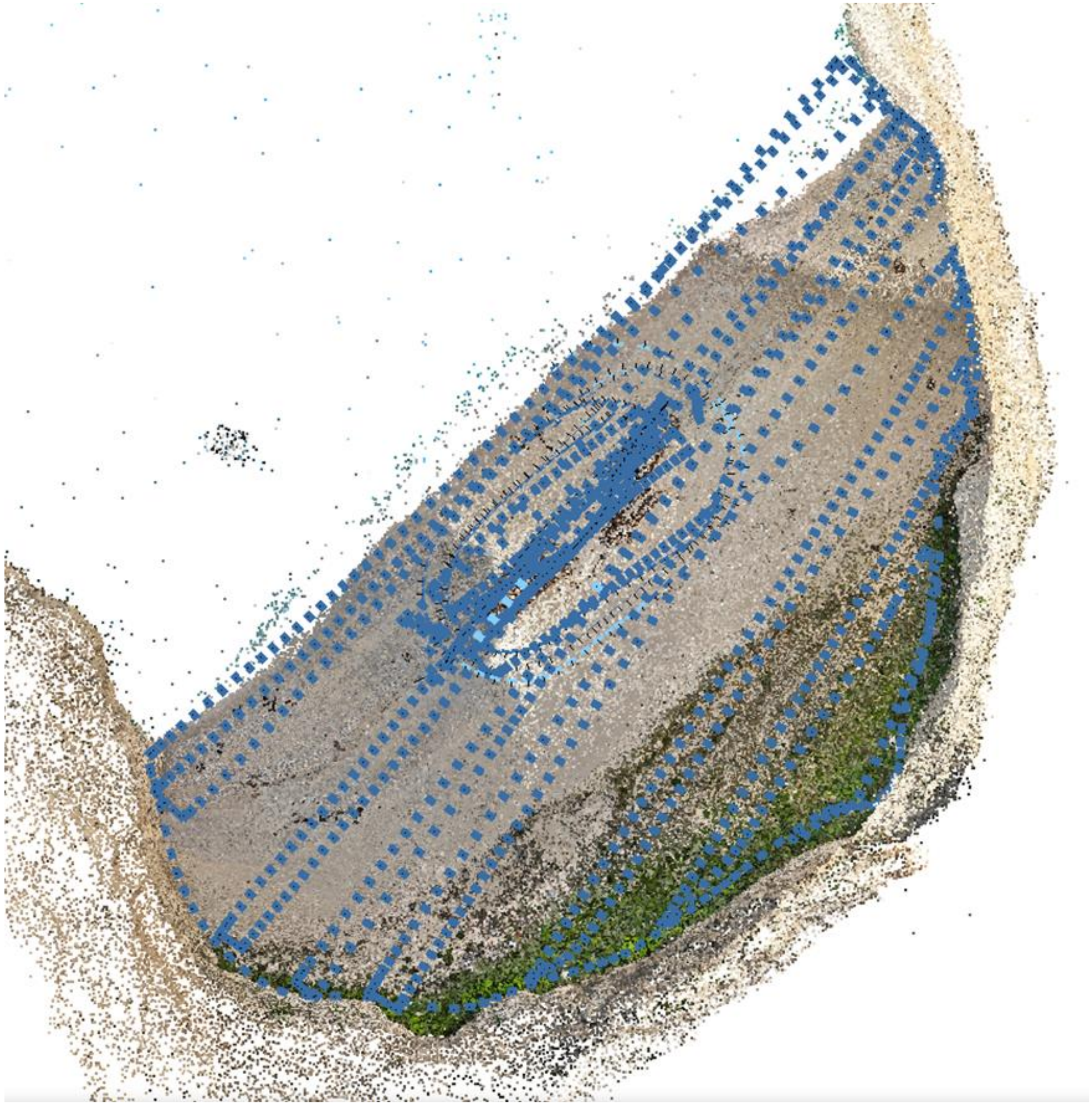

Temple of Pythian Apollo, Rhodes
Subset of images
Oriented images
Sparse point cloud
3D model without texture
detail
3D textured model
detail


A tower from the walls of Piraeus in the Zea area
Sparse point cloud and oriented images
Dense point cloud
detail
3D model
Detail of 3D model without texture
3D textured model
details

Case Study: Shipwreck Beach (Navagio), Zakynthos
The Shipwreck Beach, locally known as “Navagio,” is one of the most iconic heritage sites in Greece, located on the island of Zakynthos. It features a dramatic cove, sheer limestone cliffs and the famous wreck of the ship “Panagiotis,” which stranded there in 1980.

Geometric Documentation: Acquisition of **4550 nadir images** and **4600 oblique images** using drones (UAVs).





Acquisition of **1,550 nadir and oblique images** of the “Navagio” beach and the shipwreck, using an unmanned aerial vehicle.

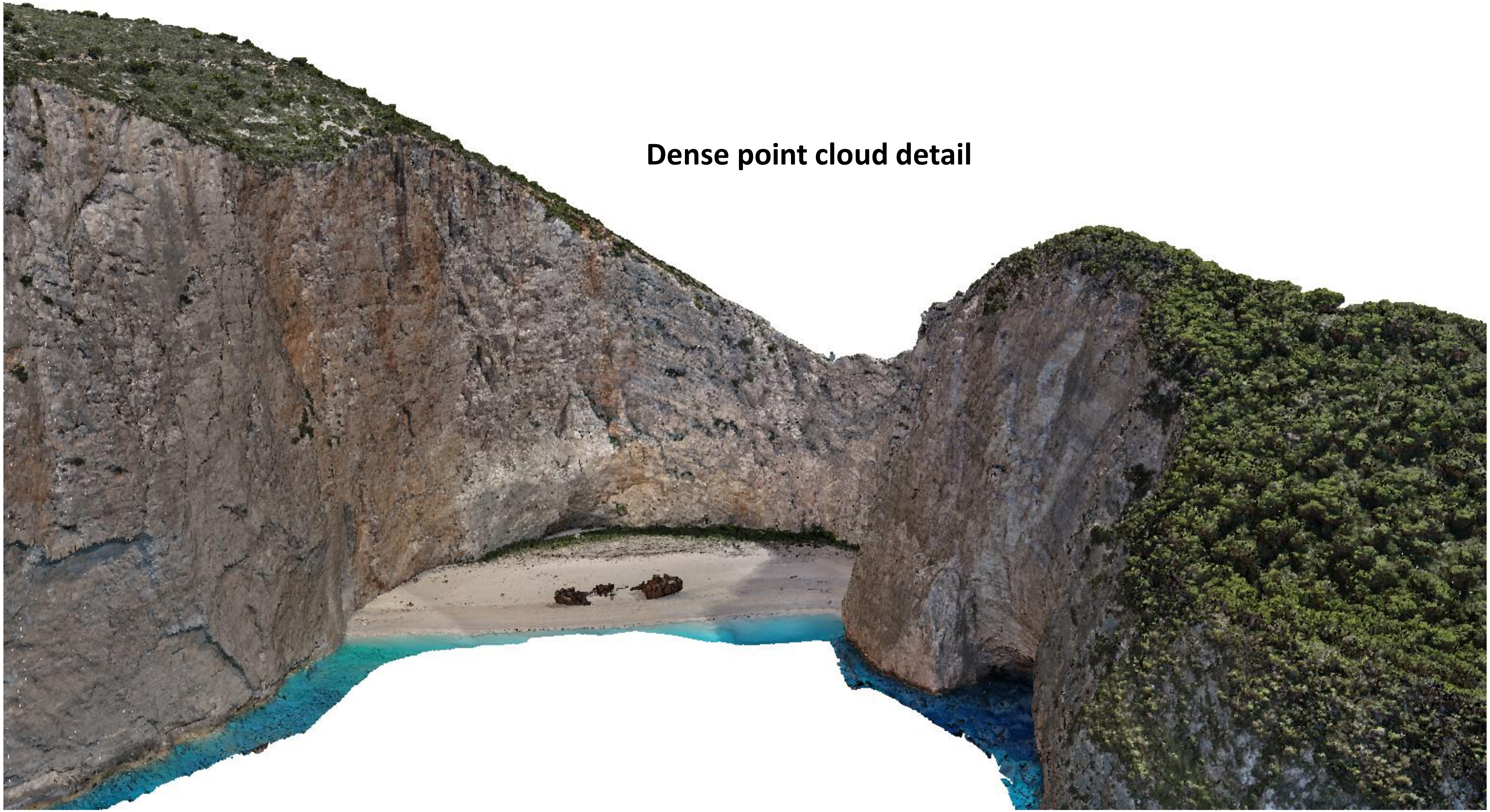
Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *“3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change.”* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

- Measurement of **35 GCPs**, distributed across the terrestrial zone, the beach, the cliffs and the shipwreck.
- **Scanning of the ship's external shell**, using a terrestrial laser scanner.

Dense point cloud: ~98,300,000 points

Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.



Dense point cloud detail

Verykokou, S., Soile, S., Ioannidis C. *“3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change.”* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

3D mesh model
~ 80.000.000 faces

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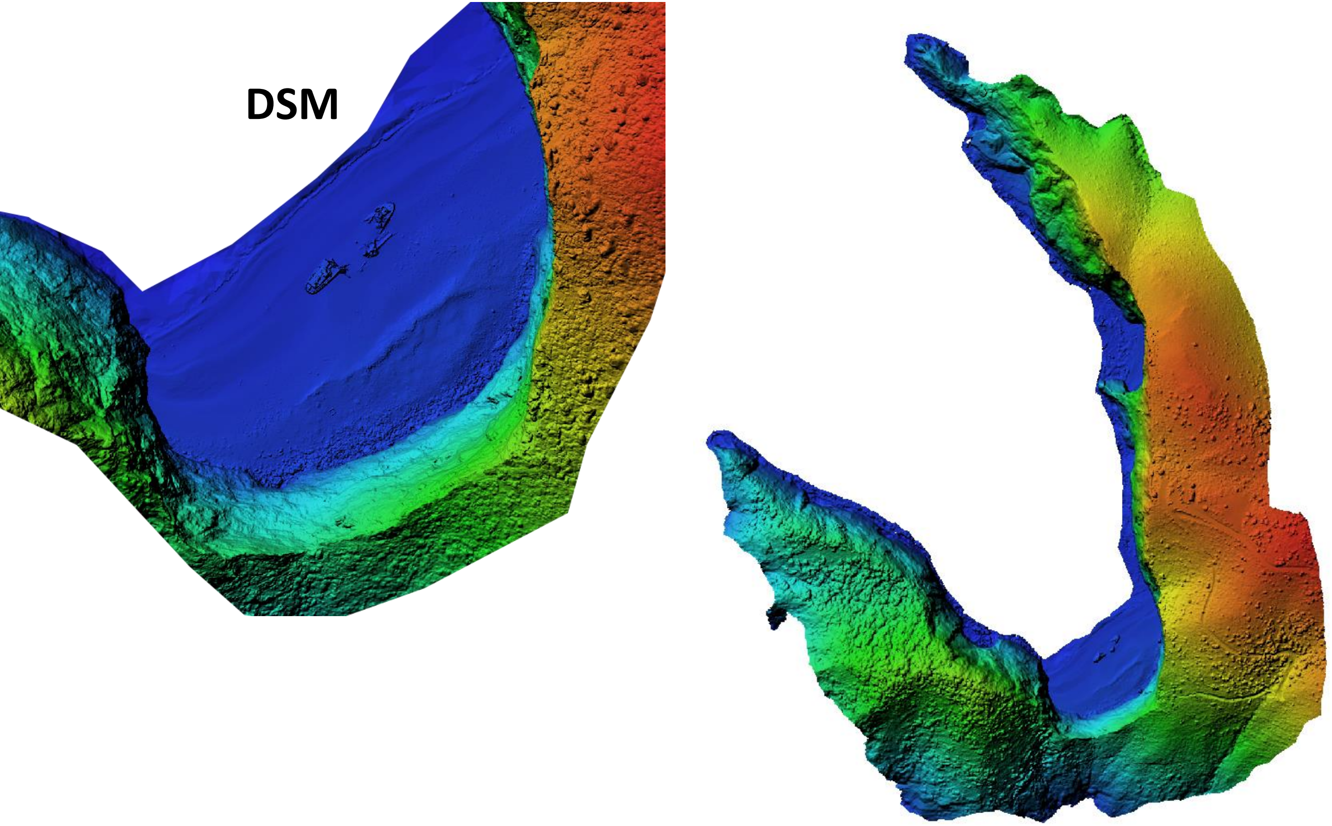


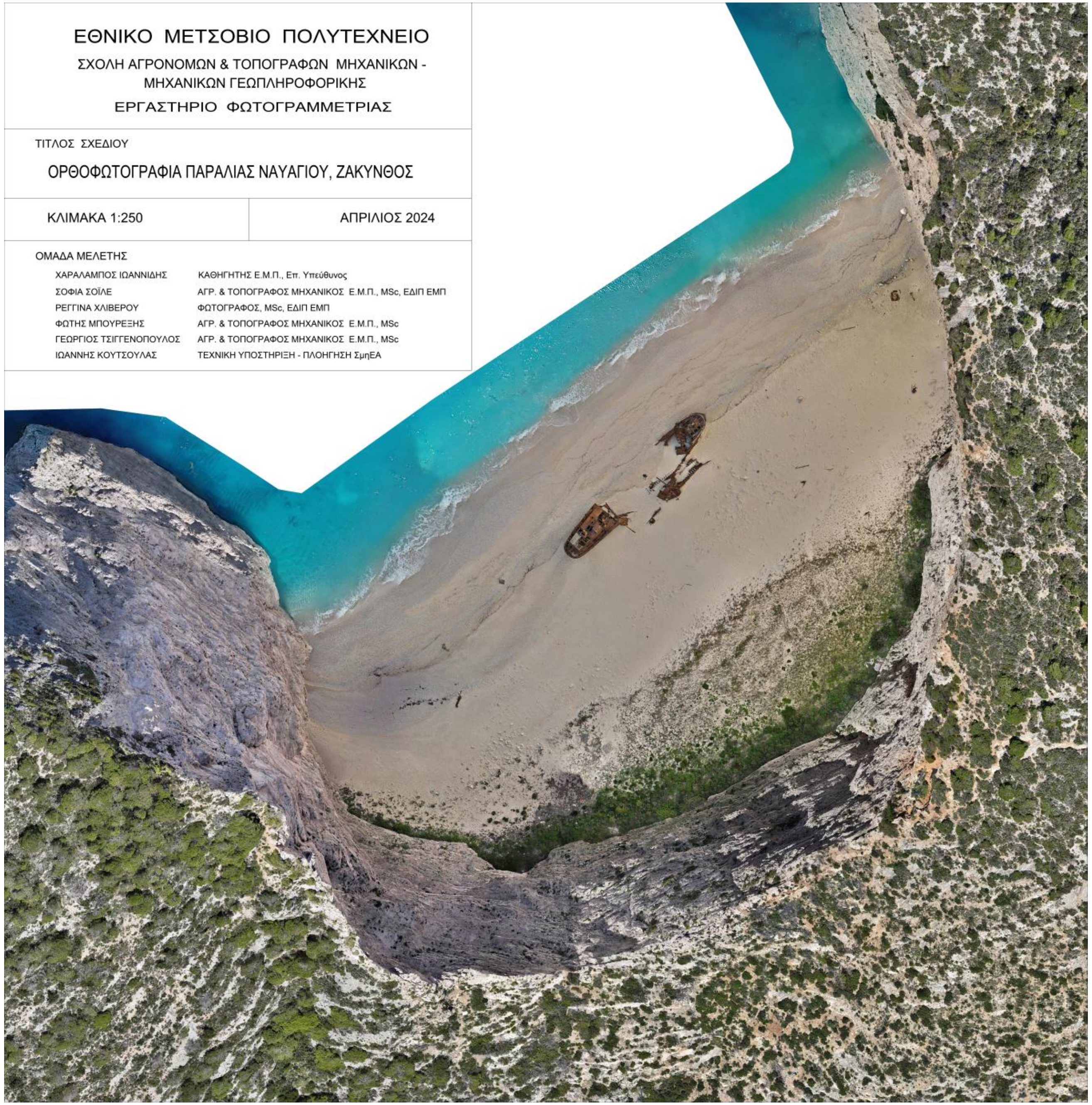
2D products

High-resolution orthophoto of the entire study area

Ground sampling distance (GSD): 3.5 cm

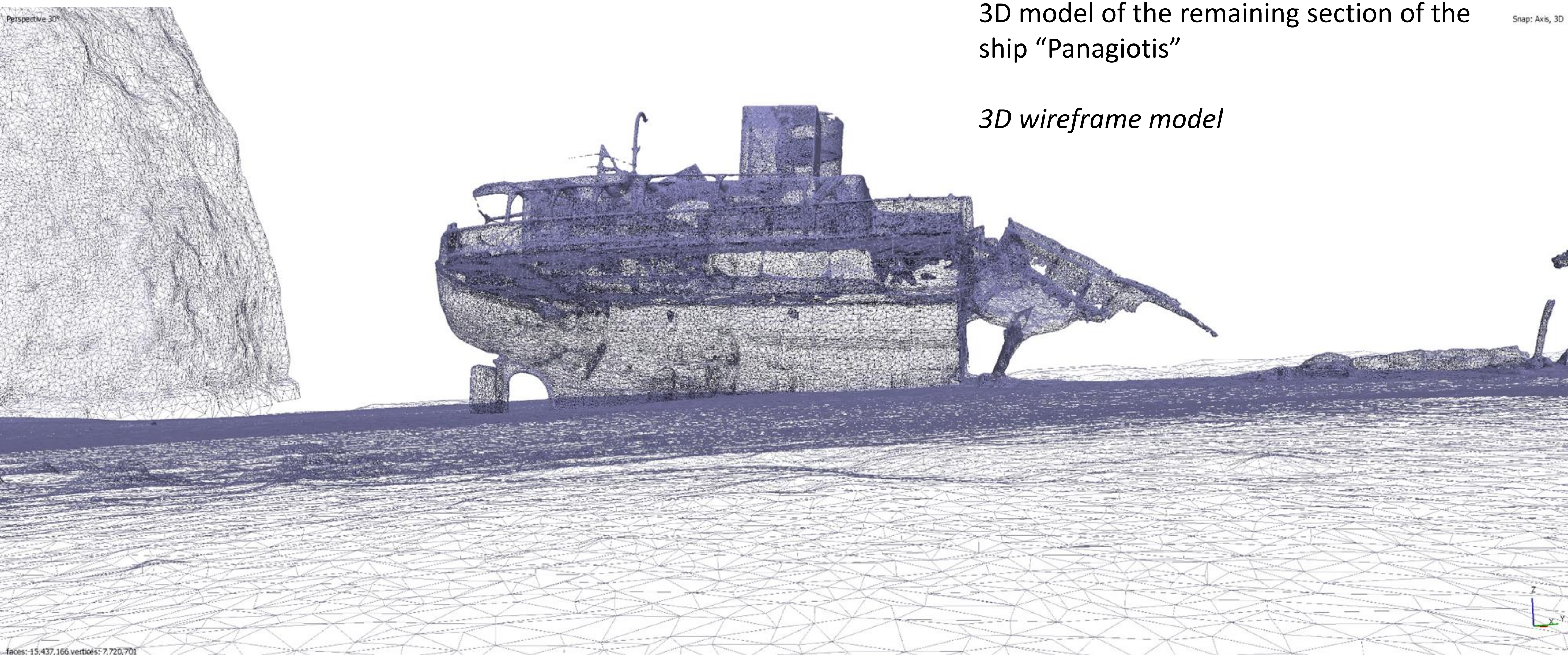
Verykokou, S., Soile, S., Ioannidis C. *"3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change."* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**. CC BY 4.0.

2D products
High-resolution orthophoto of the beach
Ground sampling distance (GSD): 2.5 cm



3D model of the remaining section of the ship “Panagiotis”

3D wireframe model



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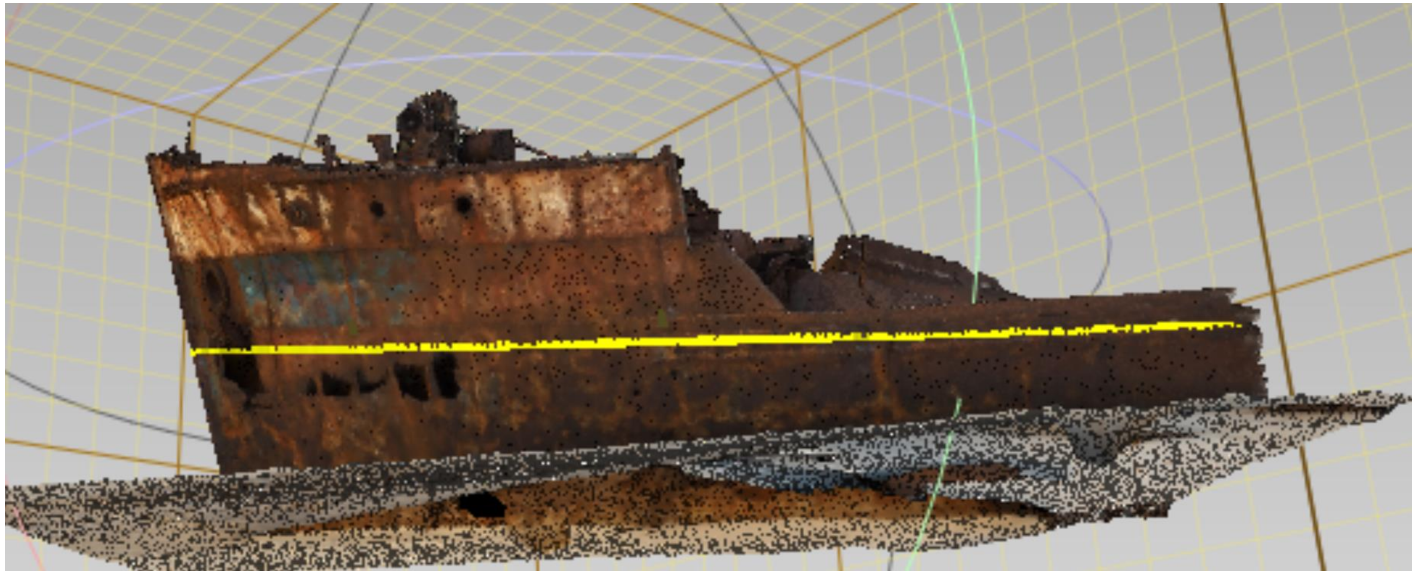
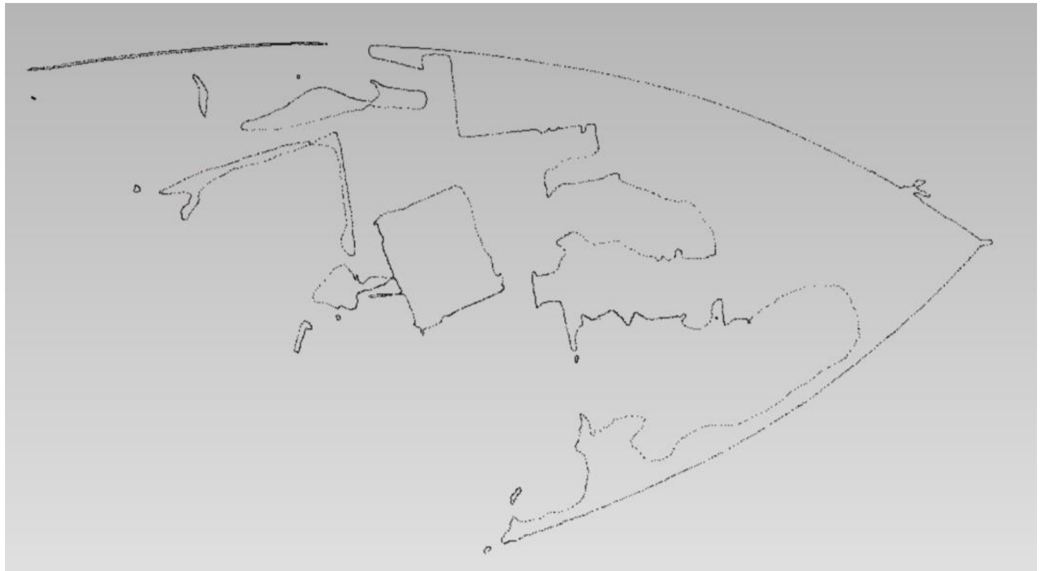
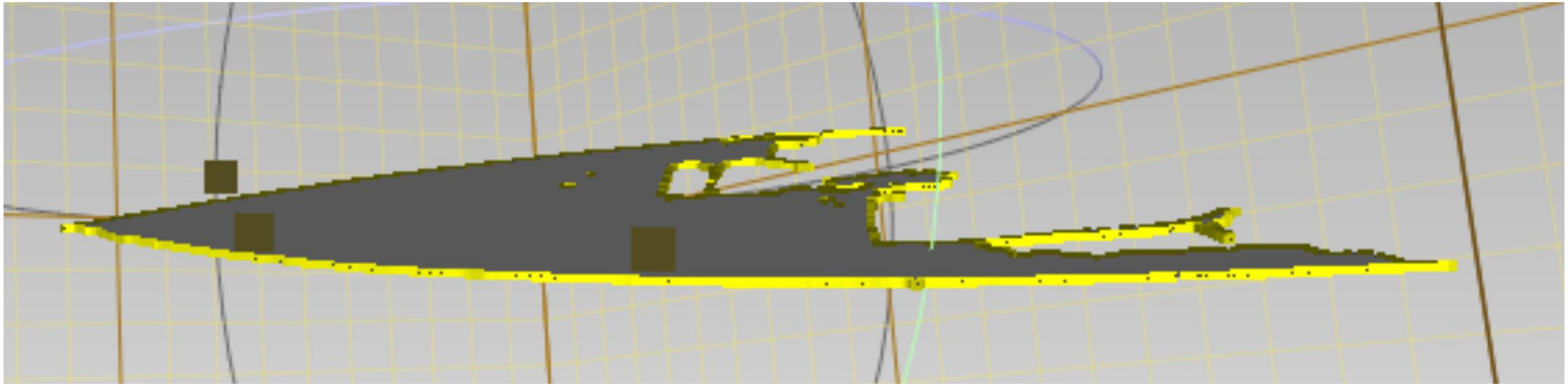
Horizontal and vertical sections







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Software solutions

Open source, commercial

Project funded from the EU HE research and innovation programme under GA No. 101094818.

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SfM-MVS software

Open-source

- **COLMAP** (SfM & MVS)
- **Meshroom** (SfM & MVS)
- **MicMac** (SfM & MVS)
- **OpenMVG** (SfM, can integrate with MVS tools like OpenMVS)
- **Theia** (SfM, requires integration for MVS)
- **Bundler** (SfM)
- **VisualSfM** (SfM, integrates with PMVS/CMVS for MVS)
- **OpenDroneMap** (SfM & MVS)

Commercial

- **Agisoft Metashape** (SfM & MVS)
- **RealityCapture** (SfM & MVS)
- **Pix4Dmapper** (SfM & MVS)
- **ContextCapture** (SfM & MVS)
- **3DF Zephyr** (SfM & MVS)
- **Autodesk ReCap** (SfM, limited MVS capabilities)
- **PhotoModeler** (SfM, limited MVS capabilities)

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3D Meshing software

Open-source

- **MeshLab**
- **Blender**
- **CloudCompare**
- **Open3D**

Commercial

- **Geomagic Wrap**
- **Autodesk ReCap Pro**
- **Rhino + Grasshopper**

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3D Documentation for Monitoring the Impacts of Climate Change

3D Geometric Documentation of CH sites plays a vital role in monitoring the impacts of climate change through detailed, accurate and repeatable data collection and analysis.

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Verykokou, S., Soile, S., Ioannidis C. *“3D Geometric Documentation of Cultural Heritage Sites for Monitoring the Impacts of Climate Change.”* TRIQUETRA Workshop, 2025, Thessaloniki, Greece. DOI: **10.5281/zenodo.14644982**.

Detailed and accurate monitoring

The primary **purpose** of 3D geometric documentation is to **capture a high-resolution 3D record of a cultural heritage (CH) site in its current state**.

- This documentation provides a crucial baseline for **long-term monitoring** of CH sites
- 3D documentation captures not only the **geometry** of a CH site but also **material textures and fine details** that are critical for assessing its condition.
- Tools: SfM-MVS and/or LiDAR

EXAMPLE By documenting erosion patterns on stone carvings, we can observe how weathering progresses and identify areas most at risk.

Project funded from the EU HE research and innovation programme under GA No. 101094818.

Change detection and analysis

3D documentation helps us **identify and quantify changes** of CH sites over time.

- This includes detecting **cracks, erosion and structural deformation**
  - Cracks can be measured to track how they grow over time.
  - Structural deformation (often caused by soil movement or rising groundwater) can be detected and analyzed.
- Tools: change detection software → We can compare point clouds or meshes from different times to detect these changes

EXAMPLE We can study how temple walls deform due to groundwater changes and take action to prevent further damage.

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Climate impact assessment

3D documentation helps us **understand how climate change affects CH sites**.

- By combining 3D models with data like temperature, humidity and wind, we can **map areas impacted by** flooding, storms or other **environmental factors**.
- This helps us understand **which parts of a site are at risk** and **plan for their protection** by prioritizing conservation efforts accordingly.
- Tools: GIS systems can integrate 3D data (e.g., 3D models, point clouds) with environmental data (e.g., temperature, humidity, flood zones) to analyze and visualize how these factors affect CH sites.

EXAMPLE

A **3D model** of a site can be overlaid with **climate layers** (like flood risk zones) to identify areas of the site that are most vulnerable.

Simulations using GIS can show how rising sea levels or higher temperatures may affect a CH site over time.

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Predictive modeling

3D documentation **can help us predict future risks** to CH sites caused by climate change, under different climate change scenarios.

- By simulating conditions like extreme temperatures, floods or heavy rainfall we can see how a site might degrade over time →This allows us to evaluate its stability under future environmental conditions and plan for protection before serious damage occurs.
- Tools: Computational modeling, finite element analysis and scenario-based simulations.

EXAMPLE

We can simulate how rising temperatures might cause thermal stress on historic buildings, leading to cracks or material expansion, and use this information to design strategies for protecting vulnerable areas.

- 3D models help in this, by providing a detailed representation of the structure's geometry and material properties.
- The geometry from a 3D model is used in computational tools.

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Preservation planning

3D models can help us **plan conservation strategies to mitigate risks to CH sites**.

- They allow us to identify areas that need protection.
- By using 3D data in planning software, we can focus resources on the most vulnerable parts of a site.
- Tools: 3D data integrated into conservation planning software

EXAMPLE We can design protective shelters based on predictions of how rain and wind will affect a structure

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Awareness and education

3D models are great tools for **engaging the public and raising awareness** about the effects of climate change on CH sites.

- They can be used to create **interactive experiences**, like virtual or augmented reality tours, which help people explore and understand these sites.
- Tools: AR/VR apps, digital twin technologies.

EXAMPLE Creating a virtual walkthrough of a CH site threatened by rising sea levels → show the risks and importance of preservation efforts

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References

Additional reading material

Project funded from the EU HE research and innovation programme under GA No. 101094818.

References

- Verykokou S, Ioannidis C. Image Matching: A Comprehensive Overview of Conventional and Learning-Based Methods. *Encyclopedia*. 2025; 5(1):4. https://doi.org/10.3390/encyclopedia5010004
- Verykokou S, Ioannidis C. An Overview on Image-Based and Scanner-Based 3D Modeling Technologies. *Sensors*. 2023; 23(2):596. https://doi.org/10.3390/s23020596
- Verykokou, S., Soile, S., Bourexis, F., Tokmakidis, P., Tokmakidis, K., Ioannidis, C. A Comparative Analysis of Different Software Packages for 3D Modelling of Complex Geometries. In: Ioannides, M., Fink, E., Cantoni, L., Champion, E. (eds) *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2020. Lecture Notes in Computer Science*, 2021, vol 12642. Springer, Cham. https://doi.org/10.1007/978-3-030-73043-7_19
- Ioannidis C, Verykokou S, Soile S, Istrati D, Spyrakos C, Sarris A, Akritidis D, Feidas H, Georgoulias AK, Tringa E, et al. Safeguarding Our Heritage—The TRIQUETRA Project Approach. *Heritage*. 2024; 7(2):758-793. https://doi.org/10.3390/heritage7020037

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Thank you!
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