



MULTI-APPROACH STUDY, DIGITIZATION AND DISSEMINATION OF A BRONZE-AGE ENGRAVED CUP FOUND IN FILO BRACCIO, FILICUDI (AEOLIAN ISLANDS, ITALY)

ESTUDIO MULTI-ENFOQUE, DIGITALIZACIÓN Y DIFUSIÓN DE UNA COPA GRABADA DE LA EDAD DE BRONCE ENCONTRADA EN FILO BRACCIO, FILICUDI (ISLAS EOLIAS, ITALIA)

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Highlights:

- A multi-approach methodology was used for a thorough examination of a prehistoric cup decorated with engravings, found at the Bronze Age settlement of Filo Braccio in Filicudi Island (Messina).
- Photogrammetry and near-infrared (NIR) imaging were combined to create a metrically correct digital replica (with switchable texture); 3D and 2D views were exported to study the vessel's morphology and decorations.
- To enrich the visiting experience, the 3D model was integrated into a web-based viewer, and enriched with informative annotation, making it easily accessible through mobile devices and computers.

Abstract:

This paper presents a multidisciplinary study combining photogrammetry, near-infrared (NIR) imaging and archaeological analysis to analyse a 1900-1800 BC engraved cup, found at the Bronze Age site of Filo Braccio in Filicudi, Aeolian Islands, Italy. The artefact is unique within the contemporary 'Capo Graziano' culture, featuring a rare complex figural scene engraved along the exterior walls; the "scene" provides insights into the prehistoric culture of Filicudi and the Aeolian Islands. The study focused on generating an accurate three-dimensional (3D) model to i) support archaeological research on the artefact's engravings and ii) create engaging digital media for remote and on-site visitors. Photogrammetry used high-resolution photographs taken around the object and control points for metric accuracy assessment. This study also utilises NIR and visible light imaging to examine the engraved cup. The photogrammetric workflow provided a realistic 3D model textured with both visible and NIR data: the 3D model enabled to improve the reading of the engraved scene, revealing horizontal registers of figures, while NIR imaging highlighted material inhomogeneity. The resulting 3D model achieved a high level of detail, with 4381407 faces and a root mean square (RMS) reprojection error of approximately 3.9 μm . The NIR imaging revealed additional surface details not visible in the standard photographs. For dissemination, the optimised 3D model was uploaded to Sketchfab with informative annotations, enabling remote study and cultural promotion of the artefact. This multi-approach methodology offers a valuable tool for comprehensive artefact documentation and analysis, providing new insights into the artefact's complex figural scene.

Keywords: digital archaeology; combined methodologies; heritage documentation; 3D reconstruction; near-infrared (NIR) imaging

Resumen:

Este artículo presenta un estudio multidisciplinario que combina la fotogrametría, la imagen en infrarrojo cercano (NIR) y el análisis arqueológico para examinar una taza grabada de 1900-1800 a.C., descubierta en 2009 en el yacimiento de la Edad de Bronce de Filo Braccio en Filicudi, Islas Eolias, Italia. El artefacto es único en el contexto de la contemporánea cultura "Capo Graziano", con una rara escena figurativa compleja grabada a lo largo de las paredes exteriores. La "escena" representada arroja luces sobre la cultura prehistórica de Filicudi y las Islas Eolias. El estudio tuvo como objetivo generar un modelo tridimensional (3D) preciso para respaldar la investigación arqueológica sobre los grabados del artefacto y crear medios digitales atractivos para visitantes remotos y en el lugar. La fotogrametría utilizó fotografías de alta resolución

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tomadas alrededor del objeto y puntos de apoyo para alcanzar precisión métrica. Este estudio también utiliza imágenes en NIR y luz visible para examinar la copa grabada. El flujo de trabajo fotogramétrico proporcionó un modelo 3D realista texturizado con datos de luz visible e infrarroja: el modelo 3D permitió mejorar la lectura de la escena grabada, revelando registros horizontales de figuras; la imagen NIR resaltó la inhomogeneidad del material. El modelo 3D resultante logró un alto nivel de detalle, con 4381407 caras y un error medio cuadrático (RMS) de reproyección de aproximadamente 3.9 µm. Las imágenes NIR revelaron detalles adicionales de la superficie que no eran visibles en las fotografías estándar. Para su difusión, el modelo 3D optimizado se cargó en Sketchfab con anotaciones informativas, lo que permite el estudio remoto y la promoción cultural del artefacto. Esta metodología de enfoque múltiple ofrece una herramienta valiosa para la documentación y el análisis integral de artefactos, proporcionando nuevos conocimientos sobre la compleja escena figurativa del artefacto.

Palabras clave: arqueología digital; metodologías combinadas; documentación del patrimonio; reconstrucción 3D; imagen en infrarrojo cercano (NIR)

1. Introduction

1.1. Background and goals

Prehistoric cultural heritage artefacts offer invaluable insights into ancient societies and their ways of life. However, uncovering the full significance of these objects often requires advanced analytical techniques beyond traditional archaeological methods.

In recent years, the integration of spectroscopic and metrological techniques has revolutionised the study of museum's archaeological artefacts, enabling researchers to capture high-resolution data, reveal hidden details, and create interactive digital representations for further analysis and dissemination. This led to a more comprehensive understanding of artefacts itself and their cultural context. On the one hand, techniques as photogrammetry and 3D laser scanning have been widely used to document and analyse pottery and other artworks, providing accurate geometric data and enabling virtual reconstruction. On the other hand, near-infrared (NIR) imaging has proven valuable in revealing surface details, material composition, and hidden features not visible to the naked eye. Nevertheless, the dissemination of these digital datasets to a wider audience, including researchers and the public, remains a challenge.

Since 2018, the Museum of Lipari has been experimenting with the creation of mobile laboratories to study artifacts using advanced spectroscopic techniques such as X-Ray Fluorescence (XRF) and Raman spectroscopy to investigate material composition and manufacturing process in combination with digitisation techniques, such as 3D laser scanning and photogrammetry (Giuffrida et al., 2019, 2021; Armetta et al., 2023a; Armetta et al., 2023b).

In this context, we present a multi-approach study one of the most fascinating and enigmatic findings of the entire Aeolian Bronze Age: the engraved cup discovered in 2009 during the excavation of the prehistoric settlement of Filo Braccio in Filicudi (Aeolian Islands, Messina, Italy) currently displayed inside the "Minor Islands" section of the Aeolian Regional Museum of Lipari.

The investigations integrate colour (Red-Gree-Blue, RGB) 3D photogrammetry and NIR imaging to create a high-resolution digital replica of the cup, analyse its engravings, and disseminate the results through a web-based application enriching both on-site and remote visitor experiences.

This multi-approach methodology seeks to demonstrate the potential of combining advanced imaging techniques for comprehensive artefact documentation and analysis, contributing to the broader field of archaeological research and heritage preservation. This study also aims to bridge the gap between scientific analysis and public engagement by making the digital dataset accessible to a wider audience, promoting the cultural understanding, significance and access to this unique prehistoric artefact.

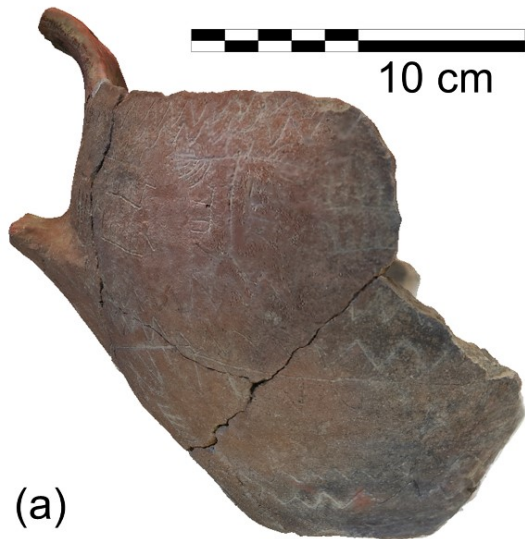
1.2. The prehistoric engraved cup

The object investigated, dating back to the Capo Graziano archaeological culture (1900-1800 BC), is a convex-profiled single-handled cup, measuring 12.5 cm in height and 16 cm in length (Figs. 1). Along its exterior walls, a complex figural scene is deeply engraved to form one of the oldest narrative scenes known all over the Italian protohistory. It consists of a collection of undulating and zigzag lines, symbolising the typical representation of the sea's wave motion in common iconography, boats featuring delineated sterns, bows, and rowers. Additionally, a stylised anthropomorphic figure is portrayed in the praying position, drawing comparisons to numerous examples of rock art.

For shape and decoration, the specimen is a *unicum* against the backdrop of the pottery styles characterising the contemporary Capo Graziano *facies* (Levi et al., 2020; Martinelli & Giordano, 2017). In fact, while several pottery findings from the same period feature depictions of stylised elements, these representations do not appear to be arranged in a cohesive "scene" or "narrative" as in the case of the Filo Braccio cup. One of the most recent hypotheses (Martinelli, 2018) interprets the 'scene' as the memorial of a significant historical event, connected to the relationship between mankind and the sea within the island setting, or as an episode of the myth. However, the interpretation of the 'scene' still remains a conundrum among scholars.

1.3. Archaeological context

A brief mention of the discovery location is worthwhile for a better understanding of the artefact. The locality called Filo Braccio, known for the presence of the ruins of a prehistoric settlement occupied during the Early and Middle Bronze Ages I-II (Martinelli, 2015) is situated in the southeastern part of Filicudi, at a land isthmus near Filo Lorani (Fig. 2).



(a)



(b)



(c)

Figure 1: The engraved cup found in Filo Braccio, Filicudi: (a) side with human figure; (b) side with handle; (c) side with “boats”.

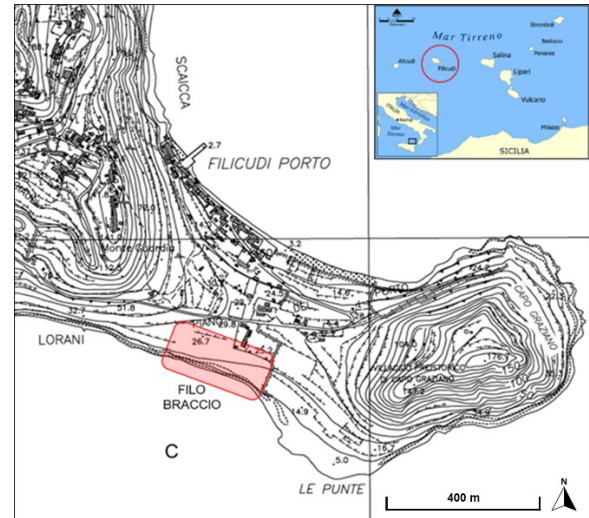


Figure 2: The red area evidences the Bronze Age settlement of Filo Braccio, in the Island of Filicudi | The basemap utilized is the Sicilian “Carta Tecnica Regionale”, n. 580030, Filicudi.



Figure 3: The prehistoric village of Filo Braccio, located along a coastal terrace, in the southern part of the Filicudi isthmus. The Hut F is located on the western borders of the excavation area, characterised by the ruins of ovoidal huts | Image produced using a Google Earth Pro satellite 08/2019 basemap.

In contrast to the most renowned Capo Graziano village, perched on a terrace at 174 m above mean sea level with defensive purpose, Filo Braccio is nestled in a coastal area, topographically characterised by a series of small terraces that gently slopes down towards the shoreline (Fig. 3). The settlement underwent its initial excavation campaign in 1959 (Bernabò Brea & Cavalier, 1991), when a dozen oval-shaped huts, made of a rudimentary masonry technique using rubble, sea cobble and big round blocks from the local hard layer, were found (Hut C with spaces A and B, Huts D and E). In 2009 and 2013, further investigations were conducted by the Service for Archaeological Heritage of the Superintendence of Messina (Martinelli *et al.*, 2010), revealing additional enclosed and open structures used as living spaces, work areas, food storage, and shelters for domestic animals. These included farms that, alternating with agricultural spaces, occupied the entire Piana del Porto on the high eastern coast. Alongside pottery fragments and food remains (as sheep, goat, pig, cattle, fish, and mollusks) the settlement have preserved several archaeobotanical samples: the implementation of 21 radiocarbon dating

analyses has allowed the reconstruction of the precise timeline for the occupation of the settlement, ranging from 2200 to 1700 BC.

During these recent excavations, inside the Hut F (Fig. 4), which was one of the structures closest to the sea, the engraved cup was also discovered (Martinelli & Speciale, 2017). Specifically, it was found scattered in 13 fragmentary pieces, within the collapsed layers relating to the last phase of occupation of the hut, just before its abandonment (Fig. 5). The carbon dating analysis conducted on relevant archaeological samples provided a calibrated C14 chronology indicating a timeframe of 1900-1800 BC (Martinelli, 2018; Martinelli, 2020).



Figure 4: The remains of the Hut F visible today in Filo Braccio locality. Photo taken on 24 Aug. 2019.

One of the unresolved questions is related to whether the vase was intentionally destroyed, since the big gap in the centre of the vessel might be compatible with an ancient fracture caused by a fall or an intentional hit. The rite of crushing is in fact a practice that finds many parallels in other contemporary contexts, as remarked in literature (Castaldi, 1965).

At the same time, the same site of Filo Braccio lacks elaborates decorative elements in its complex pottery decorations. However, there are occasional depictions related to the sea, zigzags, and boats. In contrast, the other sites in the Aeolian archipelago present comparable decorative motifs, which align with the dominant style observed in the final stage, when the villages settled on high peaks. Upon resuming the investigation in the village, it became evident that Filicudi Island was the first landing place for the Capo Graziano people. Despite considering other settlements in the archipelago and the distinct changes in characteristics across islands, no other settlement similar to Filo Braccio has been discovered. The coastal location, extended occupation period (from 2200 to 1700 BC), absence of decoration in the typical pottery style, and the distribution of huts within the site all contribute to its uniqueness as a distinct settlement. Notably, Hut F, spanning approximately 150 years in its internal chronology, serves as a significant case study.

Moreover, as remarked by Martinelli, the representation of the boat finds comparisons within the synchronous Aeolian context (Martinelli & Levi, 2021), even outside. The depictions of ships generally testify to processions and ritual practices because the sea is seen as the connection to the underworld where the souls of the dead are. As regards the human figure. The position of the arms is very important to understand the meaning of the posture: in this case it is correlated with a praying figure.

The breakage of the cup supposedly occurred towards the end of the hut F existence can be symbolically considered as an event mark for the conclusion of a likely peaceful period and the relocation of the settlement to the site of Montagnola.

Finally, it is worth noting the overall condition of the site: currently, intense erosion caused by atmospheric and marine agents is wearing away the remains of the huts and reducing the coastal bay.

2. Methodologies

2.1. Close-range photogrammetry

The geometric survey of the engraved cup was conducted using digital close-range photogrammetry, an image-based technique very common in the field of cultural heritage survey (England, 2017). The technique involves capturing a set of photographs from different angles and positions, ensuring that each part of the object is visible in at least two images. By identifying and matching homologous points across these overlapping images, photogrammetry software can calculate the shape, size, and position of the object within the scene. This information is then used to generate a 3D model that is not only visually realistic but also metrically precise, meaning that measurements taken from the digital model accurately represent the dimensions of the real-world object. The resulting 3D model serves as a valuable tool for documentation, analysis, and preservation of cultural heritage artefacts. Di Angelo et al., 2022 provides a complete review for computer-based methods for classifying and reconstructing high-density 3D scans of archaeological pottery fragments and vessels.

It should be noted that photogrammetry is different from laser scanning, as it reconstructs the point cloud using reverse engineering algorithms known as structure from motion, rather than using direct range-based measurements (Gonizzi et al., 2012). Photogrammetry has always been considered as a low-cost method, as is feasible to perform using any type of photographic equipment and frequently with freely available software solutions (such as MeshLab developed by CNR ISTI), which have become highly automated.

The photogrammetric block of the prehistoric cup consists of 131 pictures, captured using a Canon EOS M3 camera, mounting a Canon Lens EF-S 18-135 mm f/3.5-5.6 (shooting parameters: 50 mm, f/5 1/40 s). 15 printed control points were strategically placed around the vase to ensure the accuracy of spatial orientation and scale. The camera has a resolution of 6000 x 4000 pixels and a pixel size of 3.72 x 3.72 μm . During acquisitions, the object has been kept in a fixed position while rotating the camera around it at approximately 30 cm, according to a converging axes scheme (Fig. 5). This operation was performed with care to cover the entire internal and external surface of the vessel, maintaining a regular offset, an overlap of approximately 80% and sidelap around 60%.

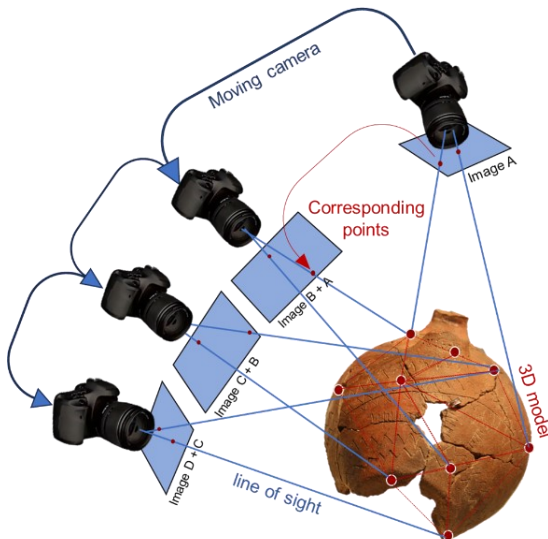


Figure 5: Scheme of photogrammetry acquisition.

The completed 3D model will provide a detailed basis for measuring and describing the shape and size of the vessel (Di Angelo *et al.*, 2023).

The photographs were processed using Agisoft Metashape Professional v. 1.8.4, a photogrammetry software that employs advanced algorithms to align the images, generate a dense point cloud, and create a textured 3D mesh. The software parameters were optimised to achieve the highest possible resolution and level of detail while minimising noise and artefacts.

The first step of the workflow involved camera calibration, with Agisoft Lens plug-in to determine the internal camera parameters. This step provided the calibration coefficients and their respective errors, which are essential for ensuring the accuracy of the photogrammetric reconstruction. The focal length (F), principal points (C_x , C_y), distortion coefficients (K_1 , K_2 , K_3), and tangential distortion coefficients (P_1 , P_2) were calculated during the calibration process. The calculated reprojection error is around 1.1 pix, where the pixel size is $3.72 \times 3.72 \mu\text{m}$.

During image alignment (with accuracy set to 'high'), the software matched the multiple images to find common points (148187 tie-points), which are essentials to estimate the relative orientation parameters of the photogrammetric block. The use of control points also allowed the correct scaling and positioning of the point cloud. The calculated accuracy of the control points is within $\pm 0.4 \text{ mm}$. The average error in object space is estimated to be 0.75 mm.

After alignment, the software generated a dense point cloud for the model. Each point in this cloud has XYZ coordinates that denote its position in 3D space (as defined by the control points), and RGB colorimetric values that capture the colour information from the photographs. The dense point cloud, generated from 131 depth maps, consists of 21,2 million points.

In the following step, a Triangulated Irregular Network (TIN) model was created using the dense cloud. This process involves connecting the points in the dense cloud with triangles (by using the Delaunay algorithm), which creates a surface model of the object. The final model

consisted of 4.4 million faces and 2.2 million vertices, indicating a high level of detail and complexity.

Once the TIN model was created, textures were applied to it. This involves mapping the colour information from the original photographs onto the 3D surface, resulting in a realistic and detailed representation of the object's appearance. Texture size $9,029 \times 9,029$ (4 bands, uint8) denoted a high-resolution image applied to a 3D model, enhancing detail and visual quality significantly.

To assess the accuracy of the 3D model, ground truth data was collected by manually measuring three distinct dimensions of the cup using a calliper. The comparison between the 3D model and direct measurements (ground truth) of the vase revealed a deviation of 0.75 mm on average across various dimensions of the vase, which corroborated the high precision of the reconstruction.

The final step was exporting the generated models and data. The software can output various file formats that are suitable for different applications, such as GIS analysis, cultural heritage documentation, or further 3D modelling work.

In consideration of the latter point, we remark that the model exported for Sketchfab visualisation has been decimated in the mesh and optimised for smartphones and tablets. Conversely, the high-resolution model was provided to the museum and is accessible to scholars upon request.

2.2. NIR imaging

In addition, a dataset of NIR images were acquired on the cup to generate a parallel photogrammetric model with different texture and to identify areas of inhomogeneity. Recent studies, such as those by Rahrig *et al.* (2023), have explored multispectral imaging methodologies. Our approach aligns with these studies in the use of NIR and visible spectra but differs in the specific application to Bronze Age artefacts. Multispectral imaging is a non-invasive and image-based technique utilised extensively in the field of cultural heritage. Through this technique, images of an object are captured while it is illuminated using ultraviolet, visible, and/or infrared light, which enables the identification of features that are imperceptible to the naked eye (Jones *et al.*, 2020). Multispectral imaging has gained popularity in cultural heritage circles for examining manuscripts, documents, and artwork, although various approaches and methods are adopted in its use. The technology is particularly suited for heritage diagnostics and preservation (Es Sebar *et al.*, 2023) due to its non-destructive nature and versatility, merging imaging and spectroscopy to analyse objects (Del Pozo, 2017). It is increasingly common to employ imaging systems like multispectral cameras and 3D scanners in the cultural heritage sphere (Barszcz *et al.*, 2023, Miłosz *et al.*, 2022). These systems, although often used independently, gather complementary information—spectral vs spatial—which is pivotal for the study, archiving, and visualisation of cultural heritage artefacts (Condorelli & Bonetto, 2022, Chane, 2013). Under infrared reflectography or NIR imaging, users might see underdrawings, artist's alterations, or previous restorations (Bloisi, Califano, Falcone, Pagano, & Vicari, 2008).

While these methods fall under the broader category of multispectral imaging, it is important to note that UV imaging was not employed in this investigation.

NIR acquisitions were performed using: a Samsung NX3300 camera 20.3 MP, equipped with a manual UV-IR lens with 20-50mm focal length and aperture ranging from f/3.5 to f/5.6; a 950 nm long pass filter, used to capture images primarily in the near-infrared range between 950 nm and 1100 nm; an halogen light was used for targeting the paintings. The images (Fig. 6) were acquired by following the same sequence of frames of the RGB photo-scanning and processed using Agisoft Metashape.



Figure 6: Example of NIR imaging of the engraved cup, highlighting material inhomogeneities and details obscured in visible light.

2.3. Integration of imaging data

The visible light imaging captured the general morphology and colouration of the cup, while NIR imaging was particularly useful in highlighting underlying material compositions and previous restorations not visible to the naked eye. Together, these imaging techniques provide a comprehensive view that is critical for accurate archaeological interpretation.

The integration of NIR and visible imaging was meticulously conducted using Agisoft Metashape. This integration is crucial for combining data collected from different spectral bands to create a comprehensive and detailed digital representation of the archaeological artefact. Initially, both NIR and visible images were aligned, ensuring that all images, despite being from different spectral bands, were correctly positioned relative to each other, thus maintaining the geometric accuracy of the 3D model. Once aligned, the images were layered in a composite model within Metashape. This involved adjusting the opacity and blending modes to allow for optimal visibility of details that are unique to each spectral range. Data fusion techniques were applied to merge NIR and visible spectra, enhancing the texture details and enabling a more detailed analysis of material properties and surface conditions of the cup.

Following the data fusion, texture mapping was applied to the 3D model. This involves projecting the combined

image data onto the 3D surface, creating a realistic and highly detailed texture that reflects both visible and NIR imaging insights.

Texture enhancement techniques were utilised to sharpen the image details and improve contrast, making finer details like minute engravings more discernible.

2.4. Unwrapping

Unwrapping painted vessel surfaces to flattened projections is a valuable technique for studying ancient pottery, enabling examination of the complete decorative scene without photographic distortions or segmentation (Giuffrida et al., 2019; Karl et al., 2022). This allows archaeologists to examine the complete pictorial composition and glean insights about artistic style, dating, and symbolic meaning. Traditionally done by hand tracing, this is laborious and prone to errors, with contact risks to fragile surfaces. Recent advances utilize 3D scans and computational methods to generate minimised-distortion unrollings revealing coherent views of painted motifs (Bechtold et al., 2010, Preiner et al., 2018, Houska et al., 2021). Bechtold et al. (2010) developed unrollings from 3D meshes by approximating sections as developable surfaces like cones and cylinders. Preiner et al. (2018) improved this by globally minimizing distortions through physically-based simulation of a mass-spring system. Houska et al. (2021) extended the technique to photographs only, assuming rotational symmetry.

For this engraved cup, digital unwrapping provided clearer observation of the horizontal banding and interrelationships of the elaborate exterior scene. Further work could uncover additional perspectives and insights on this unique artifact's complex figural composition.

3. Results and discussions

Figure 7 showcases four key outputs from the photogrammetry workflow:

- Tie point model (a): it is the sparse 3D point cloud, which represents the initial stage of the reconstruction process.
- Dense cloud model (b): it shows a significantly more detailed 3D point cloud compared to the tie point model. This increased point density is achieved through advanced image matching algorithms, resulting in a more comprehensive representation of the object's geometry.
- TIN model (c) generated by connecting the points in the dense cloud to form a network of triangles.
- Uncoloured solid mesh model (d), generated as the result of further processing the TIN model. It represents the object's 3D geometry as a solid, watertight mesh, without any colour information. This model provides a clear view of the object's shape and structure.
- RGB solid model (e - h): 3D mesh with RGB colour information applied to one side.
- NIR model (f - g): 3D mesh with NIR imaging data.

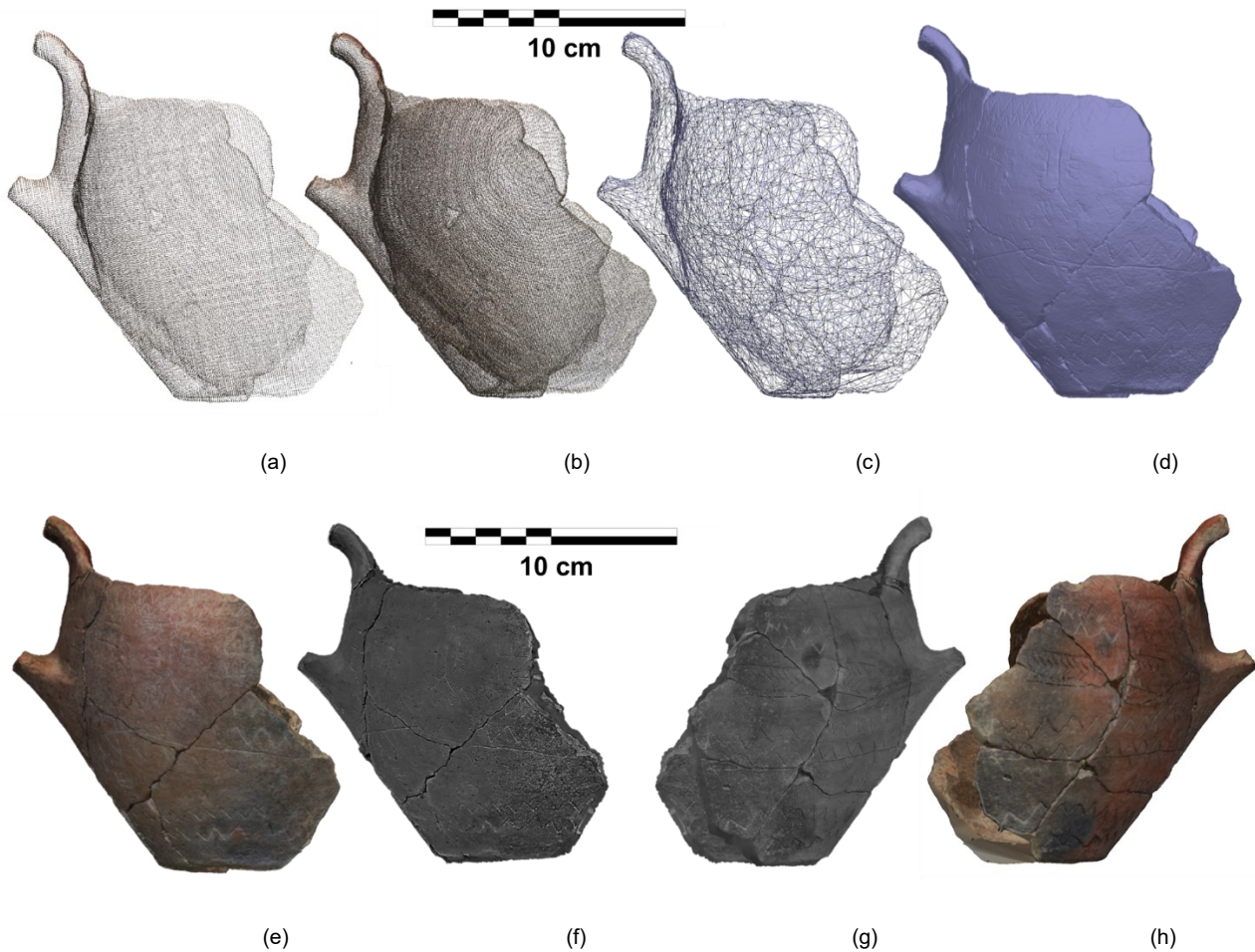


Figure 7: Photogrammetry workflow outputs: a) tie point model; b) dense cloud model; c) triangular irregular network model; d) uncoloured solid mesh model; e) RGB solid model (side A); f) model textured with NIR images (side A); g) NIR model (side B); h) RGB solid model model (side B).

These outputs illustrate the progression from the initial sparse point cloud to the final uncoloured 3D mesh, highlighting the increasing level of detail and refinement at each stage of the photogrammetry workflow. The tie point model, dense cloud model, TIN model, and uncoloured solid mesh model served as the foundation for further processing, such as texture mapping and colour application, to create the final coloured and textured 3D models of the object.

The created hybrid 3D photogrammetric models (visit <http://wwgis.ipcf.cnr.it/modelli3D/tazza-filicudi>) provide an invaluable research resource for ongoing analysis of this singular masterwork. The digital replica allows intimate examination of details related to material, technology, and artistic technique not feasible by direct observation of the fragmentary object within its museum display. The 3D visualisation enables taking measurements and investigating the find with a proximity approximating direct physical access, minus risks of handling the fragile original.

The provided quantitative data emphasises the remarkable accuracy achieved in the photogrammetric reconstruction process. In the final point-cloud model, the calculated RMS reprojection error is 0.2 in terms of the normalised image coordinates (1.1 pixels). The reprojection error is a measure of the difference between the projected 3D point and its corresponding 2D point in

the image plane, expressed in pixels. To calculate the RMS reprojection error in microns, we multiplied the error in pixels by the size of each pixel, resulting 3.9 μm . This indicates the level of precision in the photogrammetric process, highlighting the average discrepancy between the projected and observed point locations.

This showcases an exceptional level of precision in mapping the 3D points back to their original positions within the images, highlighting the meticulousness of the reconstruction. This level of precision is particularly significant for small-scale objects, where even minor inaccuracies can distort the understanding of fine details. Furthermore, the maximum reprojection error still falls within an acceptable range for photogrammetric reconstructions, indicating that the largest discrepancies between the reconstructed model and the original images are minor.

The error margin is especially compelling given the context of reconstructing small objects, such as a prehistoric vase, where preserving and accurately rendering every detail is crucial. The relatively low magnitude of these errors demonstrates the efficacy of the photogrammetry process in creating highly detailed and accurate 3D models. It underscores the technology's potential in applications demanding high fidelity, such as cultural heritage preservation, where capturing the minutiae of artefacts is essential.

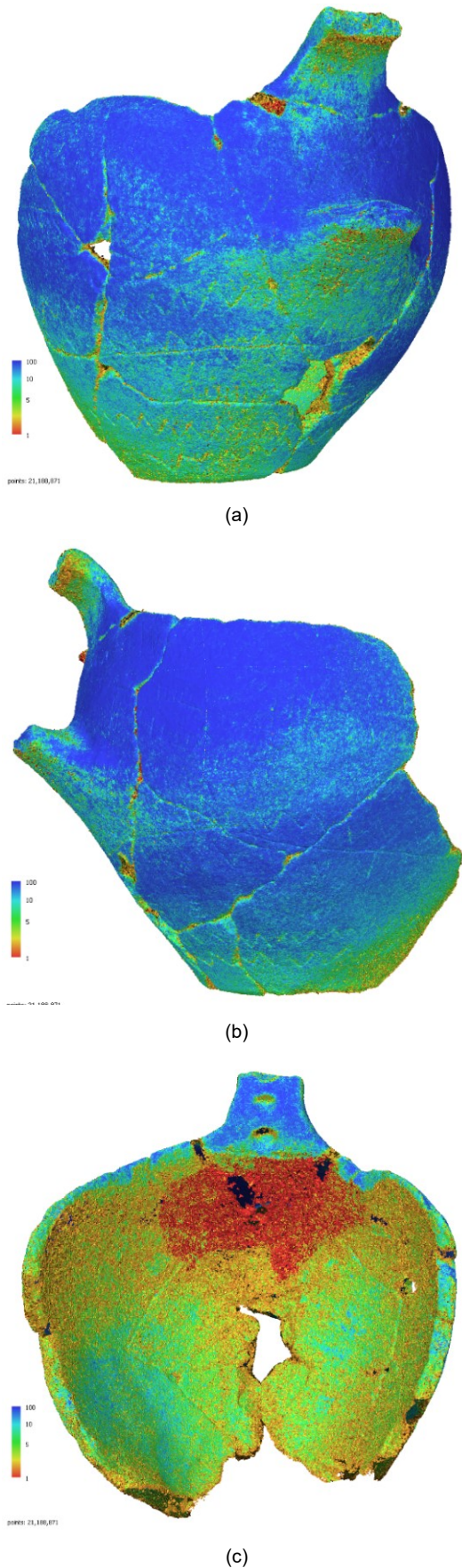


Figure 8: Confidence maps in the photogrammetric reconstruction (RGB data) with a scalebar displaying the levels of confidence.

A confidence model was also calculated using Agisoft Metashape. In photogrammetry, a confidence model visually represents the quality of data obtained from photographs used for 3D reconstruction. The confidence map typically displays the level of confidence in the measurement of each point in the 3D point cloud or reconstructed model.

Points with high confidence are typically coloured blue or green. These points are considered reliable and are likely derived from images with good overlap and clear features. Points of medium confidence might be coloured yellow, indicating that there is some uncertainty in the measurements, possibly due to less optimal image overlap or less distinct features. Low confidence points are often shown in red or orange. These are areas where the software had difficulty matching points between images, which could be due to poor texture, motion blur, reflections, or other factors that interfere with feature matching.

In Fig. 8a, the model shows a predominance of blue, which suggests that most of the data points have high confidence. The fractures and edges are well defined, but there are also scattered patches of green and a few spots of yellow and red. Fig. 8b is similar to the first one, showing primarily blue with some green areas and scattered points of yellow and red. Again, the blue dominance indicates a generally high level of confidence across most of the model, while the other colours indicate areas that might benefit from further analysis or additional data collection. The confidence model in Fig. 8c displays a significant amount of red and orange in the central region, indicating a large area of low confidence, which is particularly concerning if this is a critical part of the model. The surrounding areas are green and blue, which suggests better data quality. The reasons for the low confidence area is due to occlusions and shadows provided by the support of the vase.

In summary, the confidence levels across the three models suggest that while most of the data points are reliable, there are areas that need additional attention to ensure the accuracy of the final 3D model.

Finally, the digital replica has been used as a basis for further exports such as orthogonal, isometric, and sectional views (Fig. 9).

The 3D model created through photogrammetry was loaded into the free, web-based 3D model viewer Sketchfab in order to enable accessibility for both general public users and specialist researchers (Fig. 10).

The Sketchfab platform allows supplementary information to be added through interactive annotations layered onto the 3D model itself. For this artefact, annotations were utilised to provide explanatory details about the engraved decorative motifs and share key information on the object's archaeological background and significance to site visitors accessing the model online. The annotations currently include the following points of interests:

- Schematic anthropomorphic figure of a character in the orant position.
- Boats seen from the side and above. Schematic drawing of a ship with an angular hull, high bow and stern forming a right angle with the keel, and rowers simplified as oars indicated by vertical rods.

- Two rectangle-metopes filled with wavy lines that belong to symbols representing water in general.
- Horizontal line that could suggest the horizon.
- Decoration with wavy lines indicating the wavy motion of the sea.
- 16 dots impressed on the lower attachment of the handle.
- Circular impressions on the handle.

The combination of an accurate 3D visualisation with integrated content creates an engaging and pedagogical resource for the digital diffusion of cultural heritage.

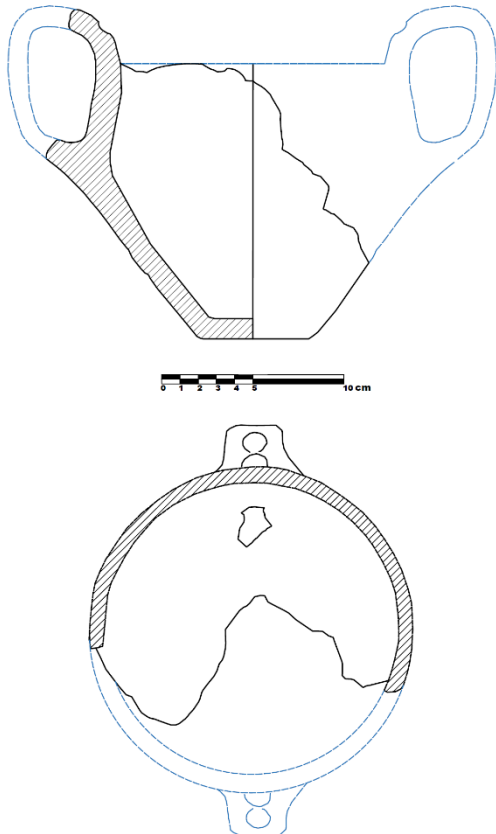


Figure 9: Drawings of the engraved cup from Filo Braccio, Filicudi. The top image shows the vessel's profiles, while the bottom image is an orthogonal projection from top. Both drawings show a blue line indicating the reconstruction of missing parts.

Sketchfab

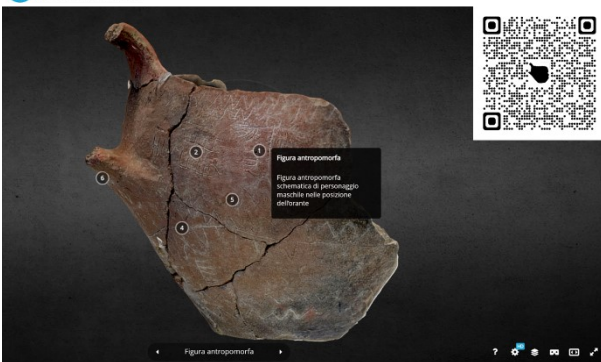


Figure 10: 3D model visualisation in the Sketchfab web-application (visit <https://skfb.ly/oD6Hu>): The model is supplemented by interactive and informative annotations.

The NIR imaging reconstruction brought out a colour contrast shift from red to black in areas of the vase visible in the RGB image. This likely stems from a heterogeneous material composition, with an enhanced infrared sensitivity to certain pottery minerals. The observed variation in grayscale likely stems from the heterogeneous composition of the material, revealing an elevated sensitivity to NIR wavelengths within specific pottery minerals. This grayscale variation suggests differential absorption of NIR light by the pottery, a phenomenon influenced by the coordination environment of iron (II) within an octahedral symmetry. NIR imaging has pinpointed an absorption band around 1000 nm, associated with hexa-coordinated Fe(II), with coordination intricately linked to the firing temperature. Notably, increased absorption correlates with lower temperatures or reduced mineral phase evolution (Bruni, 2022).

Moreover, the slight darkness in the grey area may indicate the absence of carbon, a characteristic feature of pottery produced by firing clay in a reducing atmosphere in the presence of organic materials. These organic materials, naturally present in the clay or more likely intentionally added by the potter in the kiln, contribute to the formation of carbonaceous residues and generate a stronger absorption in the NIR range.

Observations on the NIR imaging compared to the RGB of the prehistoric cup highlight the capability of this imaging technique to reveal different materials and conditions of the artefact that are not discernible in visible light alone. Figure 11a shows the presence of inhomogeneities given from differential firing on the ceramic body. In the NIR image, the areas of lesser firing appear darker due to their different absorption characteristics. This suggests variability in the kiln conditions or the thickness of the ceramic during firing. In Figure 11b, the dark area under the handle appears transparent in infrared, indicating that it is likely a superficial layer, possibly of dirt or organic deposits, rather than a feature intrinsic to the ceramic material itself. The red streaks in the RGB image, which show up slightly darker in the NIR, may be indicative of a material applied to the cup's surface that absorbs more infrared light. Finally, Fig. 11c illustrates how NIR imaging can differentiate between areas of discoloration due to variations in firing (which remain darker in infrared) and those due to patinas (which do not show increased absorption in the NIR). This can help in understanding the cup's manufacture and post-depositional changes.

These insights from NIR imaging could provide valuable information for archaeological analysis, including the cup's manufacturing process, use, and post-depositional alterations. It may also help in planning conservation treatments by identifying the types of materials and conditions present on the cup's surface.

Moreover, the NIR data helps the understanding of the production process but did not significantly improve the readability of the engraved decorations themselves. The lack of detectable material contrast between the motifs and underlying base clay, even in the NIR, suggests the engraved lines were not filled with pigments or other substances (Falcone *et al.*, 2008; Bracci *et al.*, 2015). Thus, while the NIR data provided insights into material variability, conventional RGB visualisation proved most effective for examining the intricate details of the carved

scene based on surface shading and relief. Further spectroscopic analyses by project partners may reveal more about the chemical makeup of this ancient ceramic.

The digital unwrapping and analysis of the exterior engraved motifs enabled critical new observations relating to the artefact's complex figural scene. Due to the irregular shape of the cup, flattening the surface inevitably introduced some distortion.

As a first test, two different unwrapping approaches were utilised - one prioritising the upper registration of figures and another focused on the lower decorative bands. Multiple unwrapped visualisations of the vase's engraved motifs were generated, which enabled a better study of the arrangement and relationships between the figural elements. This first projection proposal (initially requested as such by the museum manager) was finally rejected. A second projection was therefore requested to enhance the three figurative registers in a horizontal vision (Figs. 12 and 13).

Further experimentation with projection methods could uncover additional perspectives on this complex artefact. Since the model is very irregular and asymmetrical, the lower two thirds of the basin have a different inclination from the part located between the two attachments of the handles, the graphic projection has an inevitable distortion in one or the other part. Despite this limit, the unwrapping and flattening of the 3D model surface enabled clearer observation of the organisation of the "scene", which seems to be characterised by a horizontal development on three divided superimposed registers.

This unwrapping facilitated clearer discernment of the "scene" progression and interrelationships between the engraved figures. The upper register depicts the undulating lines representing the sea along with small boats outlined in careful detail. Two larger boats with accentuated prows at the apex may indicate particular importance. The stylised anthropomorphic figure in a praying posture occupies the central register. This enigmatic element has sparked much scholarly debate regarding its meaning within the broader maritime context. The lower register features additional small craft clustered near the base.

Our unwrapped analysis aligns with the interpretation of these horizontal divides separating the thematic zones. While debate continues regarding specifics of the narrative, it is likely commemorating an historical event or mythic episode of great significance to the seafaring culture that created it. The technical fluency of the engraving suggests masterful skill reflecting refined development of an artistic tradition. Comparative iconography reveals shared maritime symbols, yet compositionally this appears unique in known corpuses.

Though missing a lower portion, the cup's remaining height of 12.5 cm indicates a vessel size and elaboration beyond everyday utility. It may have served ceremonial purposes associated with feasting, ritual, or commemoration. The social role of such a cup remains conjectural, but the artistic sophistication implies elite patronage. Authentic ancient repairs visible on the handles signify it was a valued object prior to burial. While retrieval in fragmented state precludes certainty regarding causes of breakage, the missing segment does not appear simply accidental.

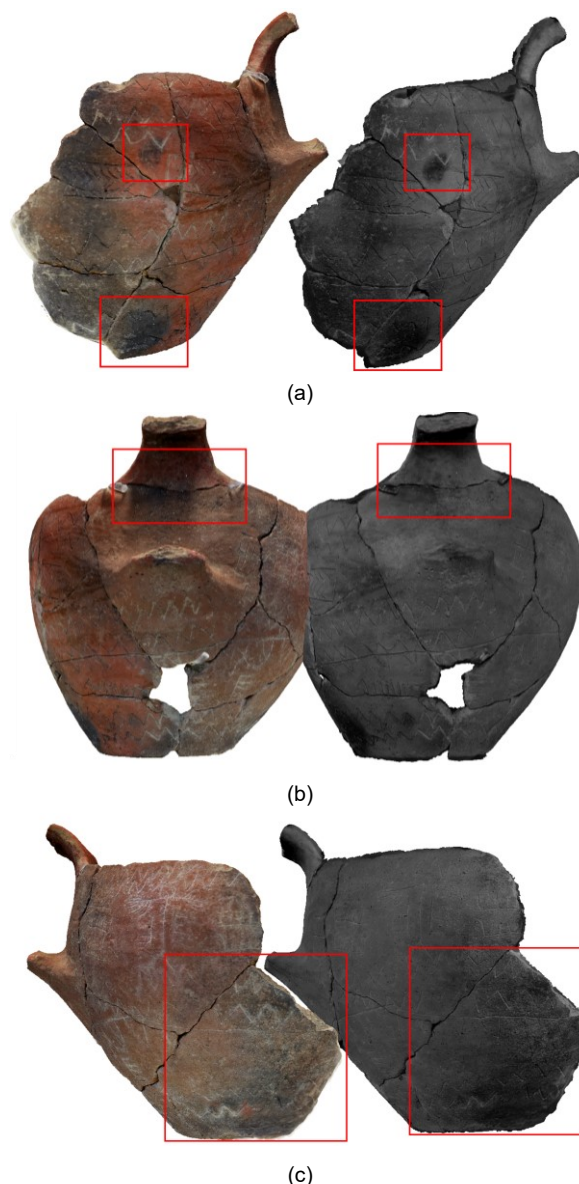


Figure 11: Observations on the RGB acquisition compared to the NIR imaging.

The work therefore made it possible to obtain a graphic apparatus that goes beyond the mere representation of the artefact, but which itself is an analysis tool aimed at improving the understanding of the find and generating new knowledge. Without going into the interpretative hypotheses, already exposed in [Martinelli, 2018.](#), the strong symbolic value of the object should be underlined. For example, the wavy line decoration for example highlights the importance of navigation and the sea for this island community. Regardless of whether the represented character is a praying man or a deity, or whether the boats are departing or arriving, it is important to underline that this is the only example of a complex representation from this period. This can be compared to the simple lines of decoration that are found in the ceramics of the final phase of Capo Graziano. All this leads us to hypothesise that we are dealing with symbols represented to hand down a real event or a very ancient myth belonging to this community of migrants of the second millennium BC.



Figure 12: Projection onto a plan of the vessel surface with digitisation of the engravings.

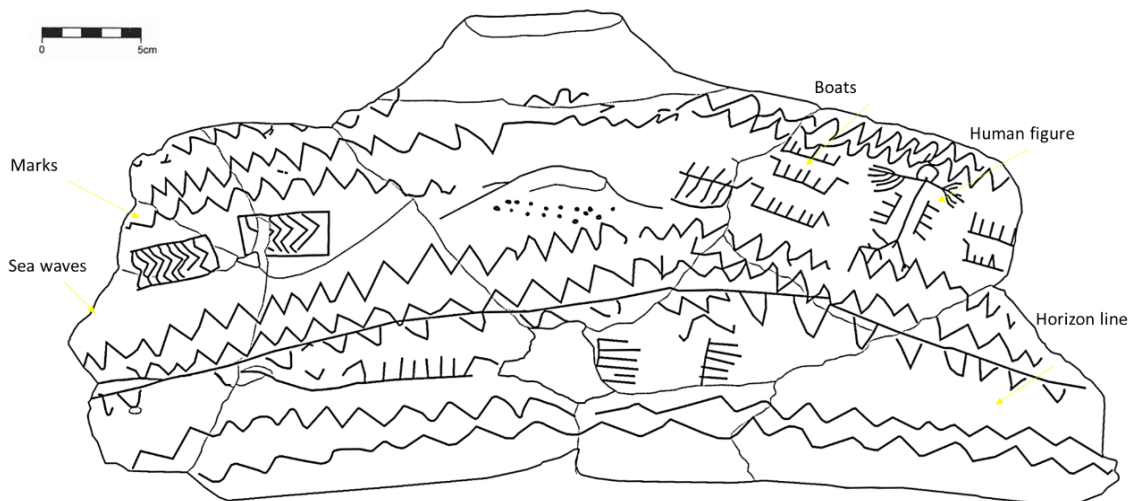


Figure 13: The "scene" depicted on the vase after digitisation.

Additional comparative research and technical analysis may further illuminate both the content and historical context behind the cup's incised designs. Above all, this object testifies to the advanced aesthetic and technical capabilities of island artisans over three millennia past.

Our study contributes to the field of Aeolian heritage documentation and dissemination in several novel ways. Firstly, we have created a high-definition (HD) digital model of the engraved cup from Filo Braccio, which provides an unprecedented level of detail and accessibility for scholars and researchers. This digital model allows for in-depth examination and analysis of the artefact's surface, engravings, and overall structure, without the need for physical access to the object. Furthermore, the high-definition digital model serves as a valuable tool for preservation and conservation efforts. By capturing the current state of the artefact in

great detail, future comparisons can be made to monitor any changes or deterioration over time.

Secondly, an innovative fruition model has been developed, tailored specifically for Aeolian heritage. This model is aimed at enhancing the visitor experience through an engaging and interactive approach. The HD digital model has been leveraged, and multimedia elements such as storytelling, historical information, and interactive features have been incorporated to create a unique and immersive experience that transcends the limitations of traditional museum displays. This novel fruition model has the potential to captivate a broader audience, including younger generations and tourists who are increasingly drawn to digital experiences and interactive learning opportunities.

4. Conclusion

The examined engraved cup occupies a seminal place in the Italian protohistoric iconographic record as one of the most ancient complex figural scenes known.

The value of 3D digitisation for cultural heritage cannot be overstated, as it serves countless purposes including conservation, preservation, reproduction, research, education, exploration, and creative or tourism-related reuses. For at-risk tangible heritage, 3D digitisation is invaluable for preservation and restoration efforts. It also enables virtual access to artefacts otherwise inaccessible due to fragility, remoteness, or obscurity. 3D models can be tactilely explored through printing, increasing accessibility. By facilitating non-invasive study, 3D models also reduce handling risks to irreplaceable originals.

However, it is important to acknowledge the limitations of 3D digitisation. While it offers numerous advantages, it does not eliminate the risks to cultural heritage. It should not be viewed as a substitute for physical preservation efforts, as the preservation of the physical artefacts remains crucial. Furthermore, the quality and accuracy of 3D models depend on various factors, such as the scanning technology used, the skill of the operator, and the complexity of the object being digitized. Certain materials, textures, or intricate details may pose challenges for accurate digitisation. It is essential to recognise that 3D models are representations of the original objects and may not capture every nuance or imperfection. In addition, it is essential to recognize that 3D digitisation does not guarantee long-term digital preservation. Additional measures and strategies are required to ensure the enduring preservation of digital assets. This can include proper data management, migration to new formats, and continued maintenance of digital repositories. Institutions utilising 3D digitisation must plan for the long-term custodianship of the resulting data.

This project contributed to 3D digitisation research, using multimodal techniques to reconstruct and interpret a seminal Bronze Age relic. The engraved cup is a supremely fascinating and important representation of Aeolian Island culture. Our 3D model and imaging analyses revealed new insights while expanding access and protection.

The photogrammetric model offers an invaluable research resource, enabling intimate examination otherwise impossible with the fragmented original. At full resolution, surface details related to material, technology,

and artistic technique become appreciable. The 3D visualization facilitates measurement and virtual handling without endangering this rare survivor. Proposals for hypothetical physical restoration can be developed and tested digitally.

Beyond assisting interpretation, this well-preserved replica provides a springboard for educational applications and digital diffusion to new audiences worldwide. Annotated online 3D models create an immersive, interactive experience that superbly conveys cultural heritage virtually. As a compelling showcase example of emerging methods, this project models pathways for digitally empowering scholarship.

Looking ahead, we will aggregate all 3D, imaging, analytical, and contextual data related to this cup into a centralised open-source repository, constituting a "virtual museum" for researchers and the public. Findings too delicate or obscure for physical display can achieve broader access through such virtual curation. This collective digital archaeology resource will facilitate connections across disciplines, technologies, and materials necessary for holistic understanding.

Most rewarding are the glimpses this collaborative digital investigation provides into a remote cultural consciousness over 3,000 years extinct, yet vibrantly preserved through ancient artefacts. New analytical techniques allow us to pose questions unimaginable to the engraved cup's original creators. As technology progresses, so too will revelations from our shared human heritage. But enduring resonance stems from artefacts' tangible testament as the work of hands and minds not unlike our own, though separated by millennia.

Like this cup, seemingly mundane objects may transcend their original time and purpose, persisting as milestones marking the long road travelled by humanity through history. Their lasting significance is continually rediscovered by new generations granted temporary custodianship of these relics. How will our digital custodianship empower those who come after us? By bridging physical and virtual, we ensure ancient voices echo on.

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MULTI-APPROACH STUDY, DIGITIZATION AND DISSEMINATION OF A BRONZE-AGE ENGRAVED CUP FOUND IN FILO BRACCIO, FILICUDI (AEOLIAN ISLANDS, ITALY)

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