Journal of
Electronic Imaging

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Integrated three-dimensional models for noninvasive monitoring and valorization of the Morgantina silver treasure (Sicily)

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Abstract. The Morgantina silver treasure belonging to the Archaeological Museum of Aidone (Sicily) was involved in a three-dimensional (3-D) survey and diagnostics campaign for monitoring the collection over time in anticipation of their temporary transfer to the Metropolitan Museum of Art in New York for a period of 4 years. Using a multidisciplinary approach, a scientific and methodological protocol based on noninvasive techniques to achieve a complete and integrated knowledge of the precious items and their conservation state, as well as to increase their valorization, has been developed. All acquired data, i.e., 3-D models, ultraviolet fluorescence, x-ray images, and chemical information, will be made available, in an integrated way, within a web-oriented platform, which will present an in-progress tool to deepen existing archaeological knowledge and production technologies and to obtain referenced information of the conservation state before and after moving of the collection from its exposure site. [DOI: 10.1117/1.JEI.26.1.011015]

Keywords: three-dimensional scanning; reverse modeling; noninvasive diagnostics; semantic annotations; web-oriented platform.

Paper 16551SS received Jun. 30, 2016; accepted for publication Nov. 17, 2016; published online Dec. 19, 2016.

1 Introduction

The silver treasure of Morgantina, one of the most valuable collections of the Museum of Aidone (Sicily), consists of 16 pieces of worked silver that were returned to Italy in 2010 following an agreement among the Ministero dei Beni e le Attività Culturali, the Regione Siciliana, and the Metropolitan Museum of Art of New York (Fig. 1).

Through police inquiry and data derived from direct archaeological excavation in a specific area of the ancient city of Morgantina, the origin of the collection was determined to be the so-called House of Eupòlemos, where the valuables were hidden probably during the Second Punic War.[1–3]

Since the agreement signed in 2006 provides for the alternating temporary exhibition of the silver treasure for 4 years at the Museum of Aidone and then 4 years at the Metropolitan Museum, a careful campaign of noninvasive analysis was prepared to document the conservation status and previous treatments of the collection.

The stability of optimal conservation conditions is crucial for the life of a work of art. The archaeological silver artifacts are rare. At first sight, some are in very good condition, and it is easy to forget that they are very fragile and brittle, and their state of conservation depends on their history and the burial time. Often they can have some bodies damaged by microfissures, tiny-cracks, burial accretions, corrosion, and missing parts. The conservation of these artifacts should depend on a detailed understanding of the state of conservation, especially the kind of decay and embrittlement. The noninvasive investigations, carried out on the silver artifacts from Morgantina, provide a first overall picture of the conservation of the 16 silver items.

With the aim to realize a new tool to increase the existing archaeological knowledge and to obtain referenced information of the conservation state, before and after moving of the collection from their exposure site during the next scheduled temporary exhibition, three-dimensional (3-D) models and diagnostic data have been acquired and organized for the first time, in an integrated way, within a web-oriented platform.

The noninvasive methods have provided complementary results for a more comprehensive evaluation of the state of conservation and of the execution technique. In particular, the diagnostic study was directed to

i. distinguish the original material from degradation and/or restoration materials;
ii. obtain a deeper knowledge of the production technique;
iii. assess the current state of conservation and acquire useful data for scheduled monitoring.

Finally, one of the main purposes was to produce significant scientific material for an innovative and interactive display to offer to visitors even during the period of absence

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Fig. 1 The silver hoard from the Eupolemos's House—Archaeological Museum of Aidone (Sicily).

of the silvers through a virtual model available in the museum or in a dedicated website, which can provide customized visits of the Morgantina treasure.

2 Material and Methods

The set of studied archaeological silver, known as the Morgantina silver treasure, consists of several vessels plus an *arula*, a *phiale*, and two *pyxides*, which were used probably for ritual libations related to the Greek symposium, and two horns, which presumably were originally part of a parade helmet. Most of the silver bears dotted and engraved inscriptions with names, monograms, or indications of weight. The technique of engraving on the cups and the technique of embossing on the medallion with Scylla, on the two *pyxides,* and on the *arula* can be counted among the masterpieces of silver work in the Hellenistic period.

Stylistic analysis, gilding technique, and excavation data place the Morgantina silver group in the third century B.C. On the *phiale*, on one of the two little plates and, in simplified form on the *arula*, is a Macedonian star, a symbol well-known already in the Archaic period that became very popular during the Hellenistic period. However, there are no significant typological parallels between the Morgantina coordinated set and the Macedonian metal vessels. There are many typological parallels, on the other hand, with ceramics produced in Sicily. Even the convivial crown that appears on cup NI 6 is found at Morgantina in one of the mosaics of the House of Ganymede. It is the preference even for decoration of a symbolic character that indicates a common background of tastes and interests.[4]

Unfortunately, very limited scientific literature is available for other silver treasure comparable to the set from Morgantina, and we do not know much about the techniques for working metals in the Hellenistic period. It would be important to know something more about the silver set from Paternò (Sicily), which is now in Berlin. This find has been considered to be of Tarantine origin, and it has been dated to a period shortly before the Morgantina group. The Paternò *pyxis* presents strong similarities with the two *pyxides* from Morgantina.[4]

We can only speculate about the location of the laboratory that produced the wonderful silver vessels from the House of Eupolemos. From the excavation at Morgantina come several examples of jewelry from both sanctuaries and houses: rings, a tiara, several engraved gems, and jewelry in glass paste.[5]

Fig. 2 Fragments of hammer, anvil, and cuttlefish bone from Serra Orlando's area.

The existence of one or more craft areas at Morgantina, where one can assume that the silver and gold work took place, is documented by the presence of excavated finds, such as a jeweler's anvil, a cuttlefish bone with four holes and traces of burning, a bronze hacksaw, different types of tools in bronze, and the end of a bronze object that could be identified as part of a hammer from a silversmith (Fig. 2).

Importantly, all of these objects, with the exception of the hammer, came from the immediate area around the House of Eupòlemos; the cuttlefish bone, the hacksaw, and several small pointed tools all came from the House of Eupòlemos itself. Also, came glass paste and a miniature ivory figurine depicting a draped figure came from this house.

The exceptional artistic value of the silver group is typical of a workshop in a large city, such as Syracuse or Taranto, but the typological analysis of some of the objects would seem to favor Sicily. We can conclude that the silver objects were in that particular area of Morgantina perhaps because they were waiting to be restored or modified, perhaps even for the inclusion of the medallion in the center of the hemispherical cup or the incision the latest inscriptions bearing the name of Eupòlemos. These matters, however, must remain speculation as the silver objects were not recovered through regular, scientific excavation, and therefore we lack data that would allow us to understand both the original context and processes of production, as well as the origin and movement the workshops' final products.

In the context of these few and unconfirmed hypotheses about the findings, the realization of 3-D models and the acquisition of scientific information useful for monitoring the conservation state and offering new approaches for an innovative fruition in the archaeological field is considered essential.

Indeed, among the new technologies currently proposed for the application to cultural heritage, the potentialities of the 3-D scanning technique represent a significant example of how originally far apart fields, such as those of conservation, research, and advanced industry, can find a common interest. Noninvasive experimental use of methodologies and innovative tools has been developed for analytical procedures of geometric dimensional data, restoration, and monitoring.

In our case study, the innovative applied technologies had the purpose of creating a 3-D collection of data to assist the restoration and conservation of the Morgantina treasure.

Now, after the transfer of the collection, the 3-D digitalization is bringing to restorers and archeologists a documentation of the process of investigations and presenting it to the public.

The geometric survey helps us to evaluate the state of material preservation of the external and internal portions of the object and permits the registration of anomalies and stresses to which the object has been subjected each time the collection is moved to a new location through a systematic program of monitoring (Fig. 3).

The process started on physical models is defined as reverse modeling, and the digital resolution up to 0.1 mm for each object was realized using a 3-D portable scanning system with a structured light flash bulb (Artec 3D Scanner_Spider), permitting highly detailed digital models to be produced.

The choice of this technology was greatly determined by the physical characteristics of the 16 objects of collection to be scanned, including the size of pieces, the complexity of their outer surfaces, the light-reflecting properties of the surfaces of the metal object, and the constraints on access/manipulation.

The size of the pieces varied greatly, ranging from the large piece of *kyathos* (diameter 26 cm and height 20 cm) to pieces of average size such as the concave cups (diameter 22 cm) to smaller pieces such as the *Émblema* with Scylla shown (diameter 8.3 cm and height 5.5 cm).

The selection of the specific instrument is also influenced by the characteristics of the 3-D model required, in terms of accuracy and resolution, which depend on the intended use for the digital model.[6] In the case of the Morgantina treasure, the process with a high surface detail can also be managed to ensure enjoyment to various categories of users: cataloging, restoration work, promotion, consumption, and diffusion.

Fig. 3 Acquisition phases via 3-D scanning of two pieces of the collection.

The campaign of indirect detection was carried out by the team in 20 working days, under the supervision of museum staff. The acquisition structured light system is based on the capture of the points that make up the surface of a physical object returning a digital 3-D model with a high degree of geometric correspondence to the real object.

The extremely versatile system scans at 7.5 frames per second; frames are automatically aligned in real-time. (It does not require any special markers to be placed on the object being scanned). The process is functional, rapid, and capable of acquiring almost 1.000.000 points/s and turned out to be particularly suitable for the geometric-dimensional characteristics of the objects. The used tool captures images also (texture resolution 1.3 Mp and image color 24 bpp).

The structured light system works with a light source projecting a series of light patterns on the object to be scanned (blue LED). The reflected image is captured by cameras, and from the analysis of the distortion of the pattern, the position is evaluated on each point of the surface to be scanned.

For every object in the collection, the greatest difficulties were encountered in the alignment and registration phases of the front side and the back side since their thicknesses were really tiny. It was necessary to set up some processing strategies to cope with specific problems of the objects. During the acquisition phase, it was necessary to apply specific markers and small colored pellets modeling paste to the surface, after a careful evaluation with restorers (Fig. 4).

To obtain a complete 3-D model, it is sufficient to move around the object and film it from various angles (angular field of view, $H \times W$, 30×21 deg). Considering the complex forms of scanning objects of the collection, the geometry + texture tracker was employed. It allows the registration algorithm to track and align scans using both texture and geometrical features of the object that is being scanned; using a geometry + texture tracker ensures the best possible results. During the acquisition phase, the optimum working distance is from 0.17 to 0.35 m. If it gets out of distance range or the movement is too abrupt, the management software loses traceability and goes into error.

Although the technical characteristics report alleged irrelevance of the camera angle, it is easy to observe how rays, which are perpendicularly incident and/or not tangent, assure a greater final accuracy.

The related proprietary software (Artec Studio, software for professional 3-D scanning and data processing) automatically joins all the acquired frames in a single mesh. The algorithm, in fact, recognizes the geometry of the object (points clouds processing) and allows the correct alignment of the various captured 3-D frames to visualize them in a single model (therefore conserving the reference system), eliminating as much as possible the presence of holes and shadows due to back drafts (Fig. 5).

We acquired from a minimum of 5 to a maximum of 20 scans for each piece of the collection. According to the complexity of the scanning object and the surface detail, the number of scans varies. A total of 180 scans were shot, and 12 GB of raw data were collected.

Fig. 4 Data acquisition phase. Employed markers to georeference the captured frames.

After the scanning and data registration process (the workflow includes the following stages: revising and editing the data, alignment of scans, global data registration, fusion of data into a single 3-D model, final editing of the 3-D model, and texture mapping), the procedural phases of post-processing and polygon mesh tessellation were performed through the *Leios*, mesh editing, and reverse engineering software. This software directly integrates with the Artec Spider 3-D scanner with dedicated tools that allow a rapid optimization of point clouds and meshes and full support for textures and huge raw datasets. The software was developed by an Italian company, EGS.

Semiautomatic algorithms, which are able to take into account the surface geometry (curvature, adjacency edges, and density of the polygonal mesh), remove artifacts scans.

The texture mapping phase added to the 3-D geometric information; the 2-D ones contained in the frames were recorded by the instrument (Fig. 6).

The method is the UV mapping that correlates the spatial coordinates of the polygon model (related to the points and mesh vertices) to texture coordinates; in particular, the Artec Studio software uses the atlas texture method (image size: 2048×2048).

An atlas texture is a large image containing a collection, or "atlas," of subimages, each of which is a texture for some part of a 3-D object (Fig. 7). This method cuts the surface into chunks, unfolds, and nests them flat, and fits them into the image of a specified size. The processing takes a long time in relation to the surface detail and the size of the scanning object, but the texture obtained is convenient for manual editing (e.g., for the kyathos, diameter 26 cm; height 20 cm, the process required 4 h with an image size: 2048×2048).

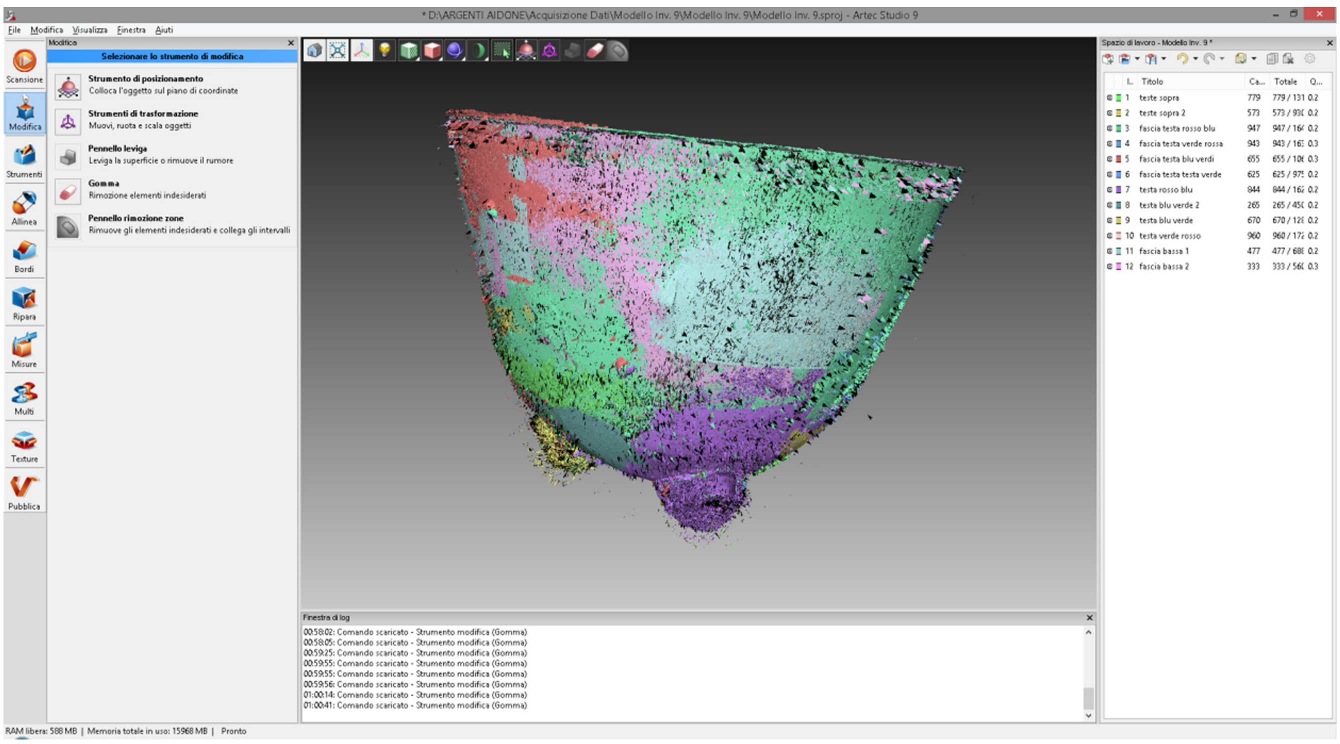


Fig. 5 Data processing: scanning frames alignment, registration, and merging point clouds.

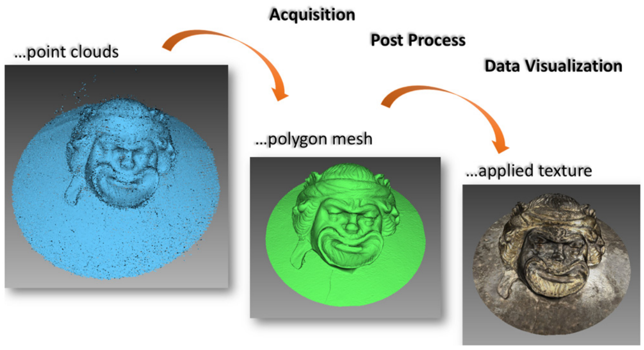


Fig. 6 Pipeline describing the 3-D scanning and data registration processing steps.

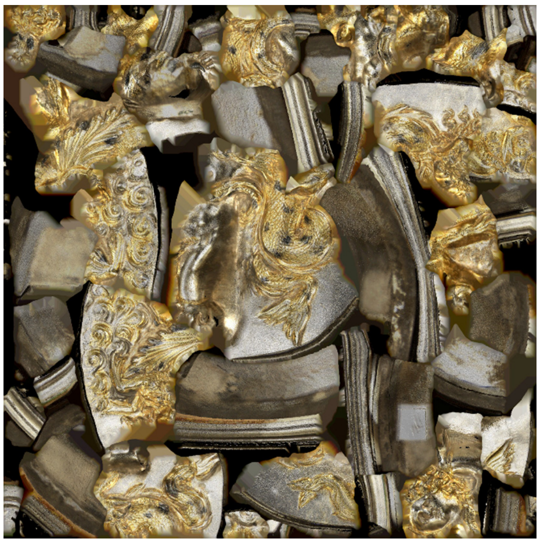


Fig. 7 The atlas texture of the locket with *Émblema* with Scylla shown.

For each of the 3-D models made, the points or areas affected by the analyses have been referenced and linked to the conservation status considerations as well as to diagnostic information obtained from spectrometric and imaging investigations.

In this context, UV fluorescence data, x-ray fluorescence (XRF) analysis, and digital x radiographs of all the silver objects were carried out directly *in situ* using portable instrumentation.[7–9]

Usually, diagnostic imaging investigations supply a large amount of information useful for a preliminary analysis of the conservation status and the mapping of different materials present on surfaces to be examined. In particular, UV-induced visible fluorescence (UV-IF) imaging can be used for localizing and delimiting the specific areas, i.e., residuals of materials damaged and not visible to the naked eyes, where further deepening spectroscopic and structural analyses is performed.

Moreover, the UV-IF technique is aimed at identifying the presence of original and extraneous materials, such as deposits of degradation and/or restoration products. In some cases, it can clearly distinguish the presence of materials that appear similar in the visible range but are different in chemical–physical nature.

The UV-IF acquisitions of the silver surface samples have been carried out by using a photo-camera CHROMA C4-DSP (C250ME, DTA srl) mounting a 6-Mpx CCD air cooling, sensor KAF8300ME, and eight interferential filters for selecting eight different spectral bands. The fluorescence was acquired by two Wood's lamps (UV, 365 nm)—160 W Sylvania, air fluxed—filtered by HeBO HU 01, placed with a fixed geometry (distance of 1 m from the center of the investigated object and at 45 deg with respect to the acquisition CCD camera), which homogeneously illuminated the entire surface for each acquisition frame.

Energy dispersive XRF (ED-XRF) analysis is a noninvasive chemical technique that allows, through the identification of chemical elements, identification of the constituting materials employed for the realization of the different investigated layers/surface (or different typology of works of art).

After a preliminary macroscopic observation, both under visible and ultraviolet illumination (to avoid restoration areas, i.e., zones involved by previous interventions), the measurement points were localized for XRF analysis. The results allow characterization of the chemical composition and, consequently, provide information on the dating and attribution of the studied work of art.

The planned investigation is to be considered qualitative; XRF analysis does not, indeed, directly provide quantitative data. They could be obtained only by comparison with results on reference standards and exact knowledge of the stratigraphic sequence of the investigated thickness.

The analytical evidence obtained by the XRF identification of materials allows data to verify the execution period and the compatibility with the hypothesized period, supporting the scientific results by the related available scientific literature.

The portable instrument consists of a miniature x-ray system, which includes the x-ray tube (max voltage of 40 kV, max current of 0.2 mA, target Rh, and collimator 1 or 2 mm), the power supply, the control electronics, and the USB communication to the laptop; a silicon drift detector (SDD) with a 125 to 140 eV FWHM @ 5.9 keV resolution, 1 to 40 keV detection range of energy, max rate of counts to 5.6×10^5 cps, a software for acquiring and processing the XRF data to provide the qualitative or quantitative evaluation of the detected chemical elements.

The indirect digital-type radiographic system allows the noninvasive analysis of the internal structures of objects through the study of the material discontinuities based on their different radiopacity value, the possible detection of remakes, or superposition. The analysis provides information on the conservation status of the entire investigated thickness and on the presence of gaps, cracks, and defects, giving indications about production technique.

The information coming from the x-radiography depends on absorption and scattering of the x-rays by the crossed volume and material type. They can vary from point to point, in relation to the composition and inhomogeneity thickness. The radiation emitted by the analyzed surface, if properly detected, provides an image in shades of gray at different intensities. The areas of lesser thickness or less radiopaque density appear darker, while the thicker or more absorbent ones are made clearer. The x-ray is used for the analysis of many types of artworks to generally identify the structural features of the whole volume of the specimen. The method is

Table 1 Instrumental and acquisition parameters used for noninvasive diagnostic investigations.

Noninvasive technique	Instrumental characteristics	Acquisition parameters
UV-IF	Photo-camera CHROMA C4-DSP (C250ME—DTA srl); 6 Mpx CCD air cooling; KAF8300ME sensor; 8 interferential filter. Wood's lamps (UV, 365 nm)—160 W Sylvania, air fluxed- filtered by HeBO HU 01	450, 540, 600 nm interferential filter; 15 min exposition time (for each filter)
Digital x radiography	X-ray tube (Poskom X +, mod. PXP-100 CA, maximum voltage 110 kV)	70 kV voltage and 50 mA current
ED-XRF	X-ray tube (max voltage of 40 kV, max current of 0.2 mA, target Rh, collimator 1 or 2 mm); SDD with a 125–140 eV FWHM @ 5.9 keV Resolution; 1 keV to 40 keV Detection range of energy	35 kV voltage, 80 μA current, 70 se acquisition time, 0.8 cm working distance

Fig. 8 Details with complex geometric features of the collection.

completely nondestructive, both of the material and the information contained in it.

In this case study, a portable x-ray tube (Poskom X +, mod. PXP-100 CA, maximum voltage 110 kV) was used to acquire radiographic images. The *in situ* collected data were subsequently processed using a propriety software with application of reconstruction algorithms (hardening and softening of the image) to highlight the different structures and enhance the density differences (in terms of photon absorption) of the components (structural intact, degraded, and different composition materials) of all examined finds.

Table 1 summarizes the main instrumental features and the acquisition parameters employed for each noninvasive technique, optimized for the typology of analyzed object and for diagnostic information achieved.

(a)

(b)

Fig. 9 3-D digital models: (a) the Émblema with Scylla shown and (b) one of the two pyxides.

3 Results and Discussion

3.1 *Three-Dimensional Digital Models*

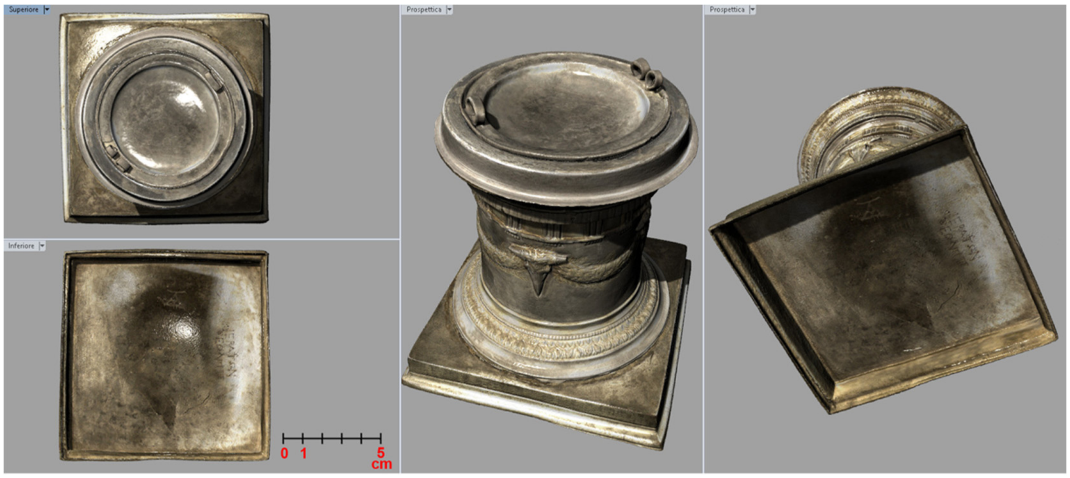
The high-quality 3-D digital models are responsive to the complexity of the geometric-form of the analyzed objects, and the digital collection reproduces the decorations in organic form really well (Figs. 8–10). The collected data so far are a great start for deepening the existing knowledge from the archeometric to the conservative point of view.[10,11]

The workflow we followed allowed us to build a "master model" that retains the geometric complexity of each object of the collection. Starting from this typology of model, we created other derivative models with a lower detail of the mesh optimized for web-based viewing.[12]

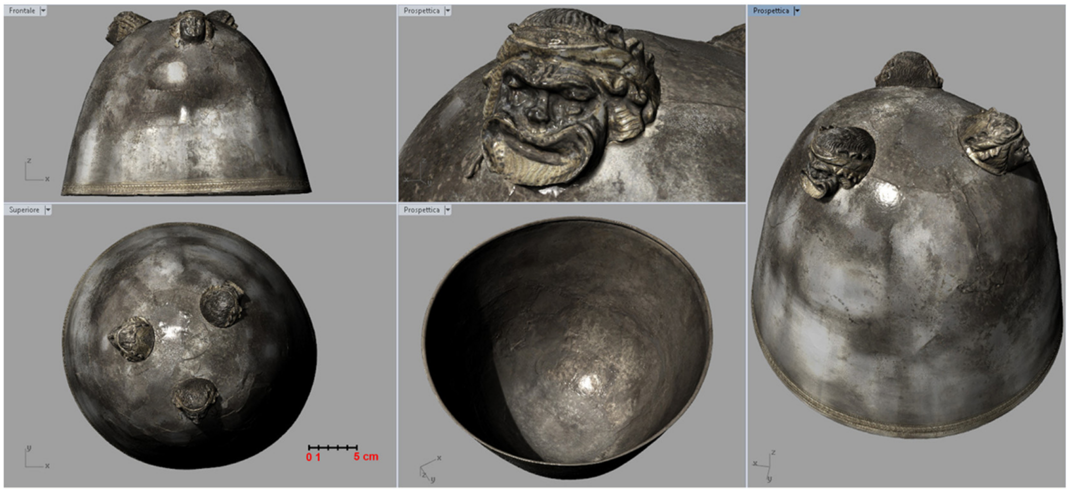
Further on, we describe the framework able to implement a friendly interface for immediate access to cultural information by researchers, archeologists, conservators, or the general public (the 3-D models can currently be viewed in the video in Ref. 13).

3.2 *Diagnostic Noninvasive Investigation*

The diagnostic acquisitions carried out on the 16 silver objects have produced 110 XRF spectra for the analysis of silver and gilded surfaces and of the area affected by corrosion phenomena, i.e., the formation of silver and/or copper degradation products; 40 h of UV fluorescence (450, 540, and 600 nm) acquisition for the identification of materials present on the surface, i.e., integration, adhesives, and protective materials; and 27 x-ray exposures (two projections for each object obtained placing more finds in the same plate in



(a)



(b)

Fig. 10 Orthogonal and perspective projections: (a) the arula and (b) one of the kyathos.

order optimize the number of acquisition) for structural analysis.

The x-ray imaging has allowed documention of details related to the execution of embossing (Fig. 11) and the technology of assembly (Fig. 12).

The radiographic data, which analyze the internal structure of the object by comparing the varied absorption of x-rays, have provided information on the presence of fractures, which for the most part were subject to previous restoration (Fig. 13), also highlighted by observations under Wood's light.

Simultaneous observation of the UV fluorescence image shows the presence of organic material (adhesive) along the discontinuities that was applied during prior restoration work carried out to solve fractures visible on x-ray. This deformation allows to supposes that the fractures occurred at the time of the clandestine excavation.

For most of the analyzed finds, UV fluorescence in the visible range acquisition has allowed us to map materials present on the surface, which were used for protection or integration during the past restorations. This technique highlights the use of different types of adhesives present in fractures already evident in the x-ray images.

In the case of the *Eirene* and *Ploutos* pyxide (NI. 11), the RX acquired in the lateral projection showed the presence of a fracture along the external edge (Fig. 14). The representation appears in radiography and is characterized by very variable thicknesses, with thinning gradually affecting the more relief surfaces (note the drapery of the female figure). These minimum thicknesses make the surface very resistant to mechanical stress. In some areas of junction between the surfaces in relief and those flat, mostly stressed in the execution process, real *lacunae* are evident.

For the study of the silver medallion with Scylla hurling a rock (NI 4), two radiographic views (superior-inferior, and lateral projections), which showed the presence of fractures due to minimum thicknesses of silver foil, in the border between the flat and the relief surfaces were acquired (Fig. 15).

Such mapping has not always been done in documenting previous conservation efforts. Finally, the analysis of the x-ray fluorescence has enabled us to identify chemical elements, which provide information on both the silver alloy and the application of gold leaf decoration, as well restoration material localized by x ray (Fig. 16) and UV fluorescence imaging.

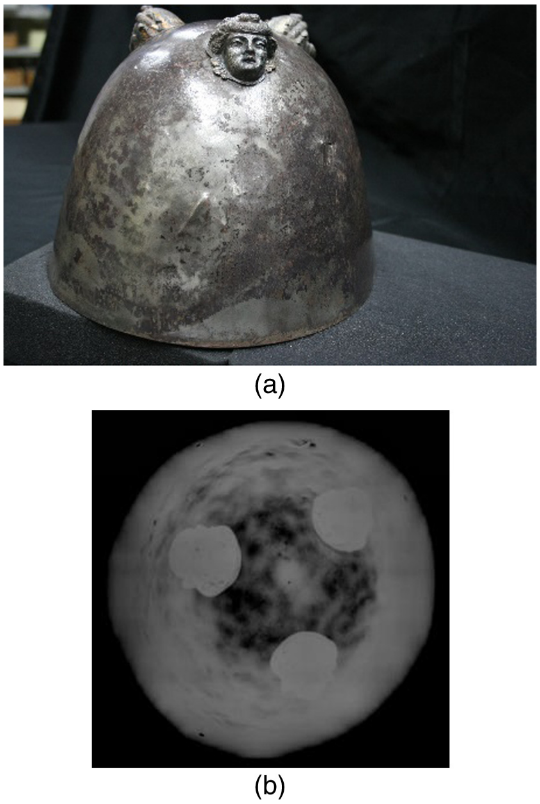


Fig. 11 X-ray acquisition on (a) Mastòs (NI 9) and (b) upper-lower projection.

Among the constituent materials of precious finds, in addition to gold and silver in the silver matrix, copper was also found, but in a variable ratio with respect to the silver content. Starting from this analytical evidence, the ratios between the intensities of the characteristic XRF signals of copper and silver were calculated. These characteristic values, constant within the metal matrix analyzed for each of the findings, have obtained a significant distribution of the whole chemical data set. Indeed, on the basis of Cu/Ag ratio, three split clusters corresponding to the proposal by archeologists based on stylistic criteria[3] were obtained (Fig. 17).

The copper content was probably added voluntarily into the alloy to modify properties rheological and mechanical properties of the melt, since the copper (above 3%) increases the resistance of the silver and lowers the melting point.

In correspondence with the gilded surfaces, the presence of mercury was not found, which is attributable to the technique of gilding with amalgam. Consequently, the gold leaf likely was applied to the silver surface by thermal treatment.

Microscopic examinations have revealed a small, convex protuberance in the center of the cup NI 3 (Fig. 18). This feature has the same size as the garnets present in the other two similar cups (Inv. 1 and 2), and it probably indicates that a stone, presumably another garnet, was once at the center of the Inv. 3 cup.

The loss of this garnet may have prompted the later substitution of the medallion with Scylla, whose shape and dimensions coincide with the circular outline present on the bottom of the cup. It was not unusual for precious emblemata worked separately to be inserted into cups or bowls in silver. Cicero (In Verrem II,4,24) reports the news that the infamous Roman governor Verres employed a group of silversmiths that were tasked with the recovery of valuable silver emblemata from ancient cups, which were then reinserted into newer vessels. It appears possible, also, that these ancient emblemata also originated in the Hellenistic period and that the full list of famous silversmiths reported by Pliny the Elder (N.H., 33, 156-157) may refer mostly to artists of a couple of centuries earlier, whose works were still in circulation during the early Roman Empire.

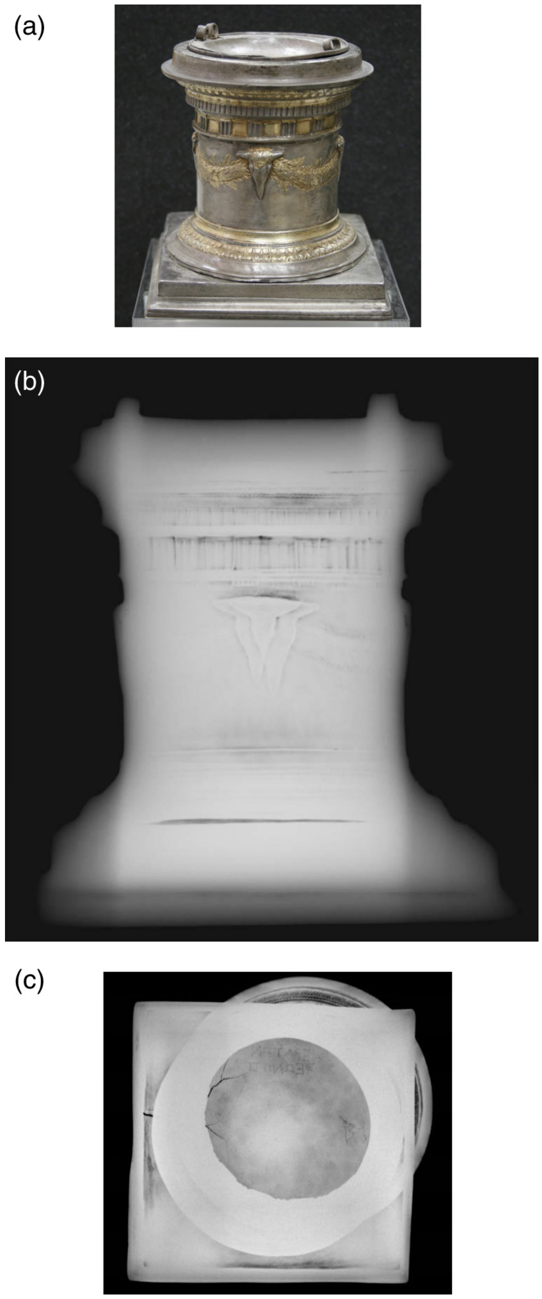


Fig. 12 X-ray acquisition on (a) Bomiskos (NI 12), (b) lateral projection, and (c) upper-lower projection.

Finally, a useful chemical marker was also identified for the evaluation of conservation state and, in particular, the monitoring of the blackened areas due to the formation of silver or copper sulfides, as shown for find NI 7 in Fig. 19, bromide, or chloride.

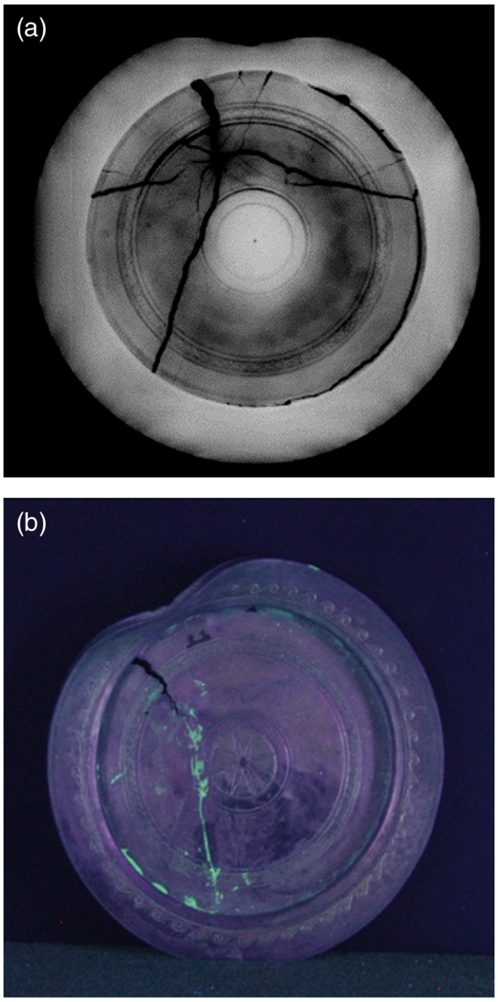


Fig. 13 (a) X-ray and (b) UV fluorescence acquisition on find NI 16a.

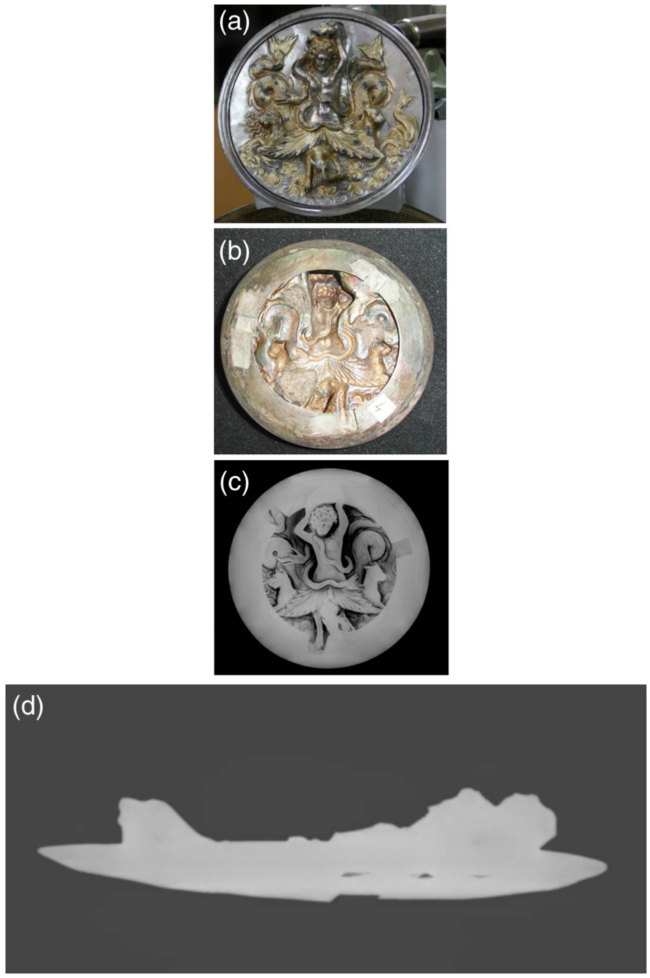


Fig. 15 X-ray acquisition on (a, b) medallion with Scylla (NI 4), (c) upper-lower projection, and (d) lateral projection.

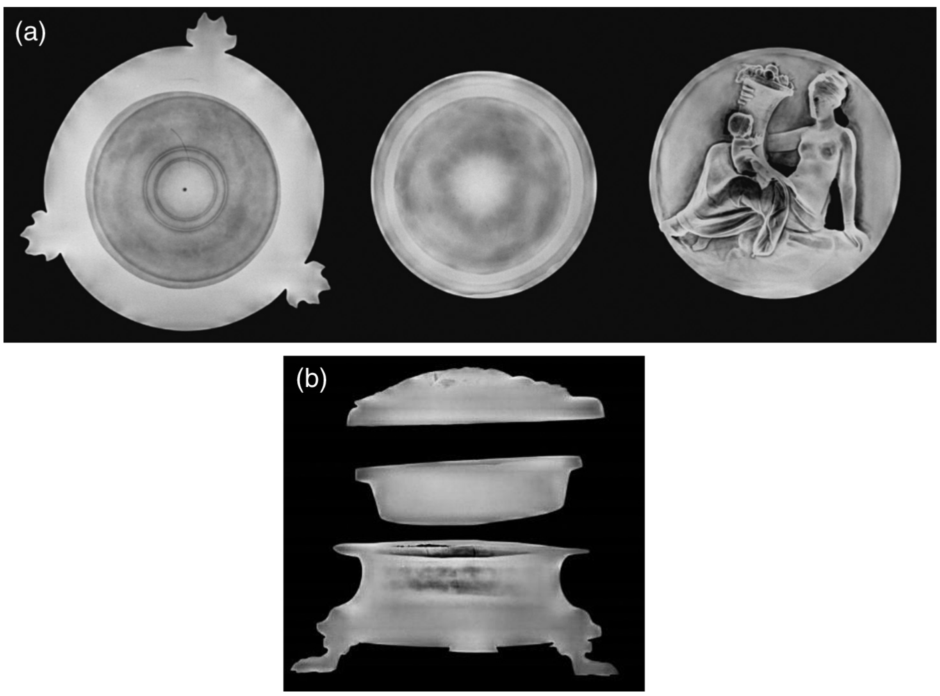


Fig. 14 X-ray acquisition on pyxis (NI 11): (a) upper-lower projection and (b) lateral projection.

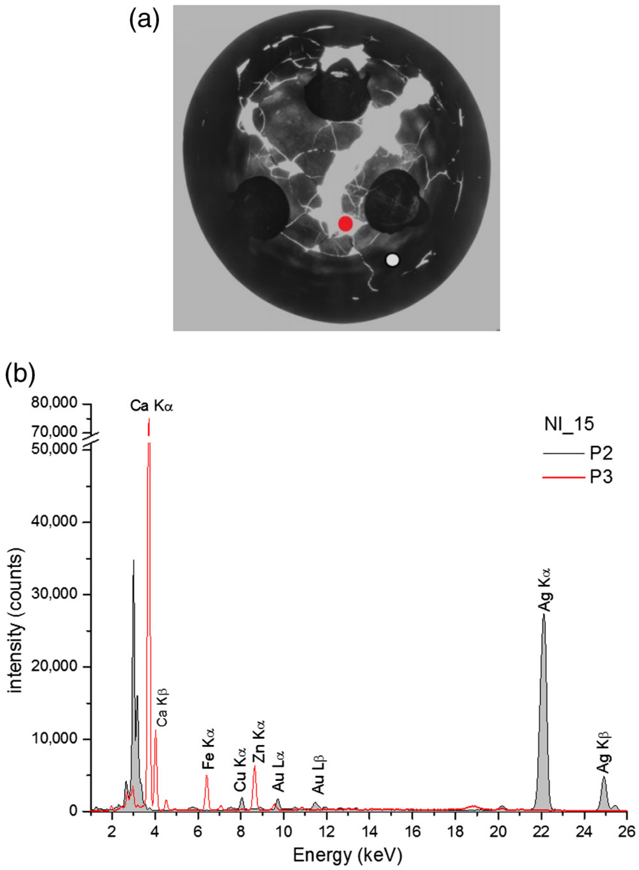


Fig. 16 (a) X-ray image on Mastòs (NI 15): inverted gray levels of the upper-lower projection; (b) XRF spectra acquired on the original surface (P2, gray) and on the integration (P3, red) shown in RX.

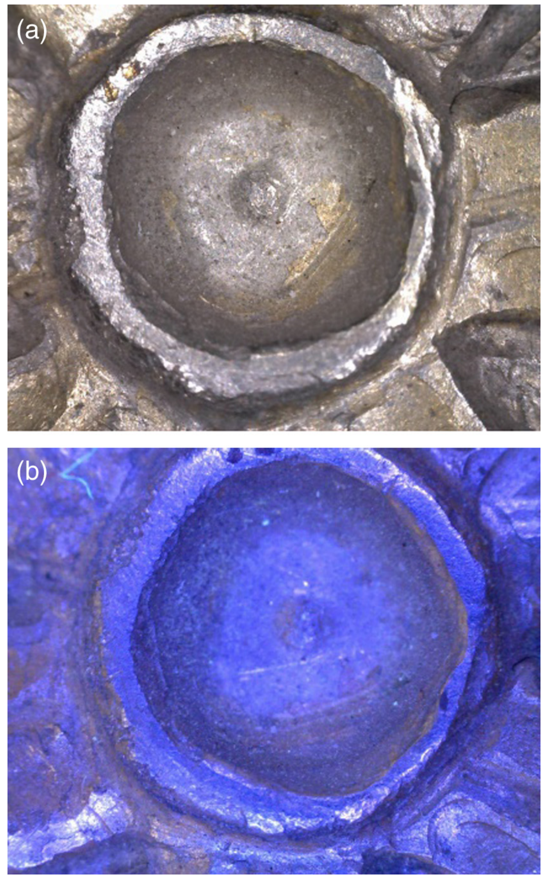


Fig. 18 Observation to the digital optical microscope (50×) of the central area of the emblem cup (NI 3), acquired both in the (a) visible and in (b) ultraviolet light.

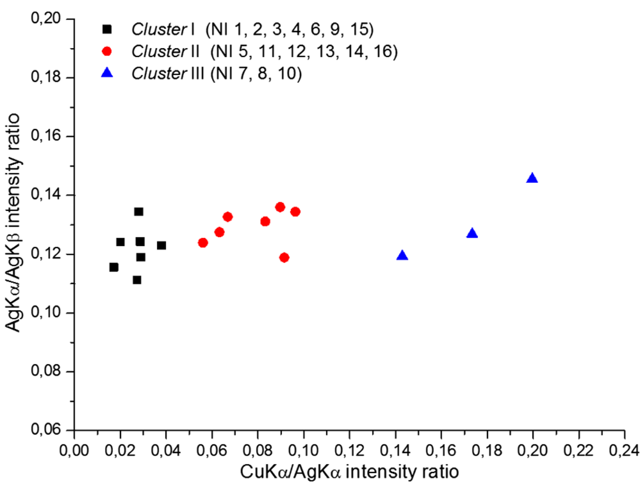


Fig. 17 Biplot of the whole set of silver (NI 1-16) based on the XRF data relating to characteristic emission lines of copper ($K\alpha$) and silver ($K\alpha$ e $K\beta$). Different color highlights the three groups obtained on the basis of the Cu/Ag ratio.

Each of these objects has a different technical history, as shown by the diagnostic results of analyses. Consequently its behavior with the environment can change as a function of the chemical composition or technological processing.[14–17] The black tarnish of the silver, such as in the Scylla medallion (Fig. 20), can be caused by the presence of sulfide in the air, especially in unfavorable environmental conditions in which the relative humidity is over 40%.

It is more important to monitor the environment and to recognize the causes of this decay as the pollution of the materials that constituted the collection show. The presence of the chloride salts in some silver items evinces a corrosion process that could be dangerous for the conservation of Morgantina treasure.

3.3 *Web-Oriented Interface Framework*

To make the 3-D models and the archeometric data effectively available in a user friendly and integrated way, a web-oriented interface framework has been developed. Its main functionalities are the cataloguing of new 3-D scans and the management of additional metadata that can be implemented during the monitoring activities.

Through 3-D scanning technologies employed by Cultural Heritage field,[18–22] the Morgantina silver gilt treasure collection has been acquired to obtain 3-D digital models, as described in the previous sections. In this work, our intent also provides a user-friendly digital system to allow fruition and scientific analysis of the treasure pieces. In addition, we will make available the results of aforementioned spectral analyses for research purpose. To this aim, we have developed a software for two kinds of platforms: a web application developed by Unity 5.0 and a mobile Java application for Android. Although several 3-D viewers

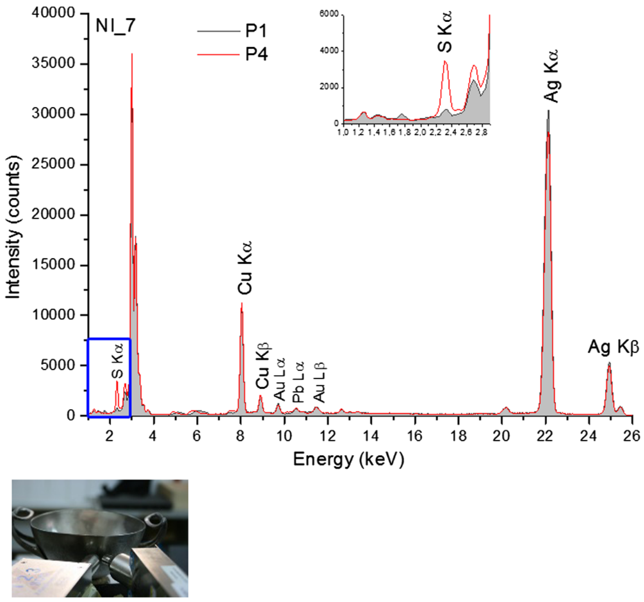


Fig. 19 Silver Skyphos (NI7): spectra acquired at the surface in good preservation state (P1) and the one affected by blackening (P4). From the zoom reported, highlighted in blue, the high signal counts of sulfur peak is evident.

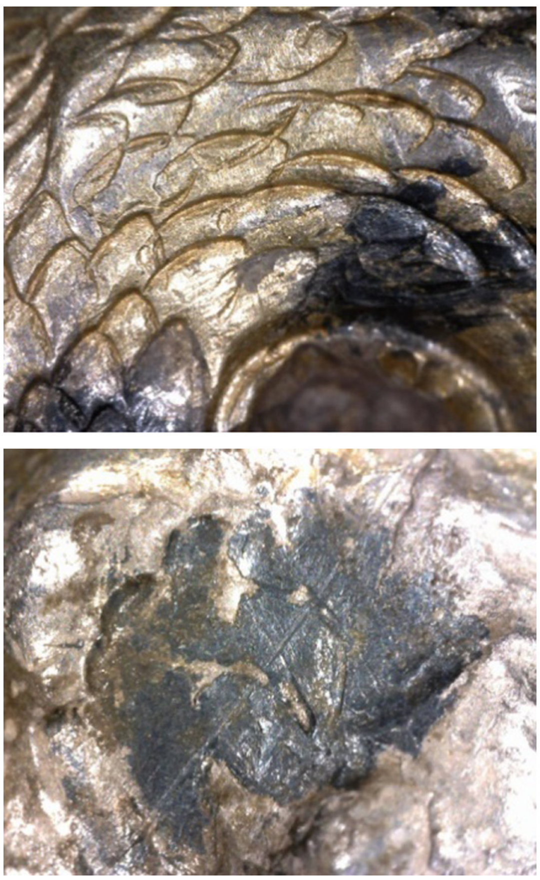


Fig. 20 Optical microscope visible observation (50×): details of black tarnish of the gilt silver on Scylla medallion (NI. 4).

already exist,[23,24] we aim to realize a customized software that includes functionalities specifically designed for cultural heritage scholars. Currently, the platforms described in this paper implement elementary functionalities since they are

Fig. 21 Shaded version of a 3-D model in Android platform. Red spheres are used as markers.

prototypes thought to test the feasibility of a more long-term project.

Its main specs are the cataloging of already existing or totally new 3-D scans and the management of additional metadata. The digital version of the artifacts is augmented with semantic annotations about the history, measurements data, expert comments, and so on. The meaning of term "semantic annotation" is the action and results of describing (part of) an electronic resource through metadata.[25,26] First, a comprehensive description of software specification is given. Please note that this description focuses on the system functionalities, which are independent from the platforms employed (web or Android). Second, a brief discussion about the technical details and the exclusive properties of the two platforms is reported.

Opening graphical user interface gives a list of the available 3-D models that are selectable for the investigation. Each of the 3-D models is placed in a different 3-D environment, which offers conventional navigation functionalities such as rotating and zooming. Hence, the surface and the finest details of each treasure artifact can be examined from any point of view. Users are able to navigate around the 3-D meshes through mouse, touchscreen, or using the proper buttons on the GUI (it depends on the available input peripheral device). To properly analyze the mesh surface, two visualization modalities are offered by the system: shaded mode and textured mode. Shaded mode is designed to permit an accurate geometric examination because general shape and surface particulars look well marked with no texture data. This kind of surface analysis visually detects alterations in the original form of the artifacts (e.g., deformation and missing parts). Texture mode shows material and color information of the 3-D models, which are very valuable to check the conservation state of the external surface. Chemical reactions (e.g., oxidation) or pigment scratches easily emerge if a texture analysis can be performed. Figures 21 and 22 show shade and texture for the Android platform, respectively, while Figs. 23 and 24 show shade and texture modes for the Unity platform, respectively.

In the future version, texture information could be also used as an input for a computer vision algorithm to automatically detect and classify decorative patterns.[27]

However, the main feature of the proposed system is the semantic annotation that enriches the original 3-D model

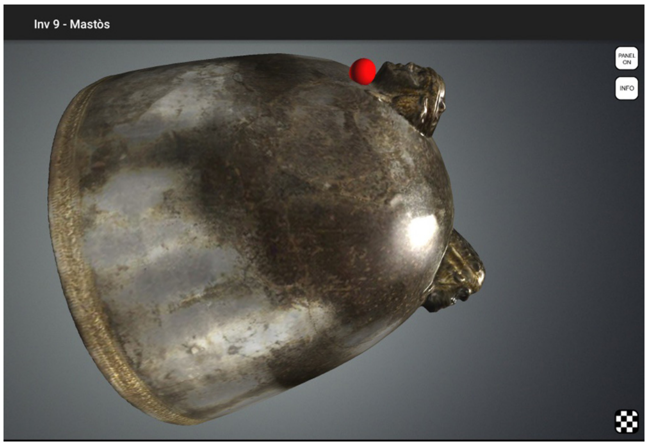


Fig. 22 Textured version of a 3-D model in Android platform. Red spheres are used as markers.

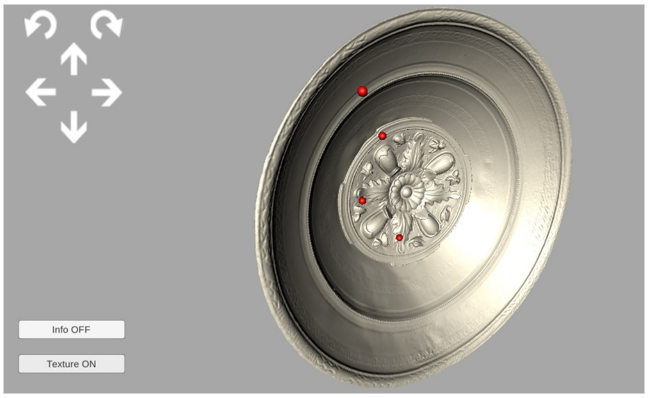


Fig. 23 Shaded version of a 3-D model in Unity platform. Red spheres are used as markers.

Fig. 24 Textured version of a 3-D model in Unity platform. Red spheres are used as markers.

with textual and visual data. Textual information gives a detailed description about some significant area of the artifact, while visual data (e.g., images and graphs) are useful for reporting analytic results and for the comparison of the same artifacts at different times. Interactive parts of the meshes are highlighted with well-noticeable markers, and when users select them, a tooltip appears or a sided info-box shows the related info.

The proposed Unity web system is mainly intended to assist experts to explore 3-D models and consult analytical reports. The system is able to work by using a simple internet browser with no other specific client application. Moreover, the system can be accessible through the internet to make the 3-D artifacts available to researcher from all over the world. The prototype has been developed by using Unity engine, version 5.0. It is an environment with an integrated game engine, provided by Unity Technologies, that is typically employed to produce digital games for different platform, such as PC, consoles, mobile devices, and websites. It handles 3-D models and other kinds of assets, such as material, light, image, and video. Unity 5.0 encodes the algorithms in two different program languages: C# and JavaScript. In this work, we employed C# and the Unity IDE called Mono Develop to implement the entire system. Although Unity is often used for digital game development, it can be employed for generic applications related to 3-D modeling. The main advantage of Unity is the simplicity in managing multimedia resources and the user-friendly development GUI, as well as the multiplatform builder. To give the possibility to test our system, we provide a demo version available at Ref. 28.

The main aim of a mobile application (Android platform) is to follow user mobility. This leads us to develop a fruition system of Morgantina treasure to enrich users experience during museum visits, which is especially useful when the original artifacts are lent to other institutions. Nevertheless, we decide to keep the semantic annotation feature to give the users historical information, as well as a further platform for research purpose.

The app has been developed using Android Studio IDE and the build system Gradle, a plugin to assist project generation and maintenance. Java and the eXtensible Markup Language (XML) have been employed to encode the algorithms and the GUI of the proposed system. Specifically, Java was used to develop the function for handling 3-D models, the user input, and the interactions. On the other hand, XML provides a natty and standard tag scheme to define data structure of the GUI. The 3-D scene is drawn exploiting OpenGL ES (Open GL Embedded System), a subset of the standard OpenGL functions intended for embedded systems, such as smartphones, tablets, and so on. Java interface for Open GL rendering calls is provided by Rajawali, a free library available under Apache License 2.0. Finally, to manage semantic annotation and related markers, we decide to use SQLite, the free database management system) adopted by Android. The developed application can be found as a demo version in Ref. 28. To test it, we used a low-mid end device that mounts a CPU Intel Atom Z2520 Dual-core 1.2 GHz, a memory of 1 GB, a GPU PowerVR SGX544, and the OS Android 5.0. Currently, despite the good application portability, we cannot ensure the correct functioning of all the devices and Android OS version; a main requirement is an OS Android version 5.0 or higher.

4 Conclusion

In this paper, we presented the results of a campaign of noninvasive diagnostic analysis (x-ray, UV, and XRF) and a 3-D survey on the Morgantina silver treasure to collect useful data for a twofold aim: monitoring the conservation state over time (to check after 4 years) and guaranteeing the virtual visit of the collection during its absence.

In particular, x-ray analysis has been exploited to detect the cracks of some objects that could be the result of external crushing forces combined with an adverse environment. The UV images show the presence of previous restorations materials such as adhesive, coating materials (resins or waxes), and stuccos. Lastly, the XRF analysis of the stucco has shown that the objects seem to be made using pigment and gypsum that it is not suitable for conservation of silver artifacts, despite the modern conservation approach which prefers the reversible remedial measures that respect the artifacts integrity.

The acquired 3-D models and diagnostic data have been organized for the first time, in an integrated way, within a web-oriented platform and an Android application to increase the existing archaeological knowledge and to obtain referenced information of the conservation state. They were also used for the development of holograms now on display at the Museum of Aidone, while the archeometric analyses have made important contributions to the investigation of their composition and the processing techniques utilized in their creation.

The ongoing web-oriented platform and the Android app consist of an active tool for managing metadata; it will gradually be implemented through knowledge acquired by specialists and at the same time contribute to the valorization of these archaeological findings to the public. All the findings of the archeometric analyses have been included in these digital platforms to enable scholars to access a lot of information in a fast and practical way. Furthermore, the software contributes greatly to the valorization of the Morgantina cultural heritage by allowing users access to a digital version of the collection, especially during its absence.

For future works, we plan to conduct further analysis on the pieces of the Morgantina treasure and to improve the functionalities of both the proposed platforms. From the technical perspective, the additional ongoing functions include the labeling of semantic annotation with one or more tags. For instance, all additional notes concerning corroded regions would be labeled with the tag "alteration." This feature will be useful for implementing a query system that is able to filter annotations by selecting just a specific tag.

We are also considering including new tools for mesh analysis., One tool will subdivide an object into subparts (e.g., the handles of an amphora) and independently analyze them. Another tool we will provide a measurement group of functionalities to digitally measure distances between mesh parts or computed surface areas.

Finally, we are considering implementing an editing system for run-time adding of new 3-D models and new semantic annotations. In this way, users could exploit the system to archive and annotate their own artifact 3-D models. Although the proposed system is currently designed for two platforms (Web and Android), in the future release, we will take into account new platforms. We are also exploring different kinds of 3-D engines and a software library to provide a more efficient and responsive system.

Acknowledgments

The authors would like to express their gratitude to Assessorato Beni Culturali e dell'Identità siciliana of the Regione Siciliana, for funding for the project, for authorization granted to carry out *in situ* investigation, and for their cooperation. The authors would like also to thank Mr. Salvatore Velardita and Mrs. Linda Scordato for the technical support during the data acquisition phase at the Archaeological Museum of Aidone. Finally, we extend an important thanks to Dr. Laura Damiani for her cooperation in the radiographic image processing and interpretation.

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