



# Digital Modelling in Museum and Private Collections: A Case Study on Early Italic Armour

RESEARCH ARTICLE

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## ABSTRACT

Public, and particularly museum-based, collections provide invaluable opportunities for analysis. The objects in these collections typically offer relatively complete examples which often become reference points for newly excavated material or analyses. However, aside from issues of provenance and occasionally authenticity, one of the biggest challenges with the analysis of objects in museum collections is, perhaps ironically, their public and collection-based context. Objects on display are often only directly analysed immediately following their initial discovery and are then increasingly restricted for direct analysis (e.g. placed behind glass, displayed in such a way that their removal is difficult, etc.). Although visible to millions, once in a collection the level of analysis possible is often limited and superficial. In this paper we discuss the analysis of three collections of ancient Italian armour now housed in collections, both public and private. We examine some of the ethical considerations when looking at such collections. We also discuss the issues faced when analysing and making digital models of objects, which are used to explore the nature and importance of military equipment in Italy during the first millennium BCE. In addition, we argue that, although famous, many of the pieces held in collections are currently being underutilized in studies of the ancient world. We suggest digitization, even when conducted quickly, can help to unlock more information from previously excavated and analysed items and we highlight the pros and cons of various techniques when working in museum-based contexts.

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KEYWORDS:

Etruscan; 3D modelling; Photogrammetry; LiDAR; Museum collections; Private Collections

TO CITE THIS ARTICLE:

Emmitt, JJ, Mackrell, T and Armstrong, J. 2021. Digital Modelling in Museum and Private Collections: A Case Study on Early Italic Armour. *Journal of Computer Applications in Archaeology*, 4(1), pp. 63–78. DOI: <https://doi.org/10.5334/jcaa.63>

## 1. INTRODUCTION

Examination of ancient military equipment has typically focussed on broad stylistic categories. For Italian equipment, this has included both basic classification (e.g. Egg 1986; Bottini et al. 1988; Paddock 1993) and attempts to quantify stylistic change, typically within a wider discussion of either ‘Hellenization’ or ‘Romanization’ (e.g. Quesada-Sanz 1997; Lendon 2005). Apart from some efforts to explore the practical use of various types of equipment (e.g. Zhmodikov 2000; Taylor 2014; Armstrong 2017), there is little consideration of artefacts as objects themselves (q.v. Born 1989) and what information they can provide about wider Italian society (Bishop and Coulston 2006). When equipment finds have been used, they are typically deployed in support of literary evidence, which retains its primacy of place. Further, our knowledge of the practicalities involved in the production, market, and maintenance of military equipment is extremely limited. The available sources on the topic (primarily literary) provide little direct evidence for the nature of this industry, and modern scholarship has largely viewed what evidence there is in an isolated and disconnected manner (e.g. McKechnie 1994; van Daele 1999; Croom 2000).

The project “Blood and Money: The ‘Military Industrial Complex’ of Archaic Central Italy”, aims to address some of these issues by increasing our understanding of nature, development, manufacture, supply, and maintenance of bronze military equipment in Central Italy, from c. 900 to 300 BCE. Through identifying different production techniques and methods, and exploring how these changed over time and across regions, the project seeks to reconnect the items with the individuals/groups which made them (and not simply with their final, depositional context) and recontextualize them within the wider productive landscape of ancient Italy and the Mediterranean basin. This involves an integrated study of the ancient literature, archaeological evidence, and experimental archaeology. As part of the project, pieces of bronze military equipment from a range of Italian provenances, in both public and private collections, were analysed with a number of analytical techniques, including portable x-ray fluorescence (pXRF) and 3D analysis. The primary function of the models produced through 3D analysis was to use them to identify artefacts of manufacture, as well as decoration, inscriptions, and damage that could inform about their pre-depositional use-lives. Most notably, the project sought to identify discrete techniques connected with production and/or repair, which could be associated with specific types of items, locations, or time periods – these results will be discussed in subsequent articles. Another purpose of the 3D models was to use them for visualisation purposes and as reference points for future analyses, both as part

of this project and by future scholars. Many of the items had been excavated or acquired many decades, and even centuries, prior, and have since only been subjected to superficial visual examination – often in the context of *objets d’art* and from behind the glass of the display case, or indeed from photographs alone (e.g. Egg 1986; Bottini et al. 1988). Our actual knowledge of these objects both as ancient artefacts and restored pieces in modern collections is surprisingly limited. With the ever-growing corpus of material being unearthed in Italy, and pressure on the limited space available for physical displays of items in museums, digital records and exhibits are increasingly important as a way of making objects available to researchers and the public (Agus et al. 2018; Bagnall and Heath 2018).

## 2. CONSIDERATIONS OF CURRENT PROVENANCE

Traditionally, and still in general, Roman military equipment studies have included (generally unprovenanced) items from private collections in their data sets without discussion (e.g. Egg, 1986; Bottini et al. 1988; Paddock 1993; Flower, 1998; Burns 2005; Bishop and Coulston 2006; Fabregat 2012; etc.). This situation is problematic and the inclusion of items with dubious histories alongside artefacts from officially sanctioned excavations risks legitimizing both their acquisition and current location in a private collection (cf. Elia 1993 and Renfrew 1993). Engagement with items in private collections also blurs some boundaries which usually exist around academic research in the public realm and as a ‘public good’, as academic work does not exist in a vacuum and can directly impact private wealth and reputations, both positively and negatively. However, it is also not practical or ethical to pretend that these items in private collections do not exist. Items from private collections have long formed part of the wider dataset used by ancient military historians (Burns 2005). At present, this material exists as an ambiguous category of ‘grey evidence’: vaguely known, sometimes considered, not universally accepted, and almost never studied in detail.

It is clear that a compromise must be reached, although, as with any compromise, it is unlikely to please all parties. There is no doubt that looting is a significant problem (Campbell 2013; Barker 2018) and the private antiquities trade, as it currently exists, limits the kinds of questions we can ask and answer about the ancient world (Miles 2014). With regards to looting, this study firmly supports the ethical guidelines of the Archaeological Institute of America (AIA), following the United Nations Educational, Scientific and Cultural Organization (UNESCO 1970) Convention of 1970, on the

authentication, acquisition, publication, or exhibition of undocumented antiquities. ‘Undocumented antiquities’ are:

‘those that are not documented as belonging to a public or private collection before December 30, 1970, when the AIA Council endorsed the UNESCO Convention on the Means of Prohibiting and Preventing the Illicit Import, Export, and Transfer of Ownership of Cultural Property’ *AIA Code of Ethics*, initially adopted 1990 and amended in 1997.

However, it must be noted that even the 1970 date is not set in stone and was later amended to the end of 1973 (AIA 1973). This was still further amended in 2020 (AIA 2020), with the use of the ‘[non-prov]’ designation for all work which did not meet the 1973 cut-off.

The system, as it presently exists, actively discourages publication of items in private collections (as most lack a clear documentary trail before 1970/1973). While this has kept academic consciences clean, it has also largely avoided the issue, has resulted in a known gap in our knowledge, and the private antiquities trade has continued to grow, albeit without any academic oversight or involvement (Mödlinger 2020). We suggest that the system, at present, is not sustainable and this is likely one reason why the AIA regulations have been regularly amended (and all too often ignored). However, digitizing items in private collections may represent a way in which many of these items can be fully integrated into modern, academic work. The ability to both permanently move items into the public sphere, with their full past illuminated, and also to accurately describe and define the piece in absolute terms changes the situation, and its implications should be explored.

Within this project we did not set out to analyse any items which appeared to have entered the private market after 1973, although, given the nature of the antiquities trade and its approach to ‘documentation’, this was difficult to prove conclusively as most of the ‘documentation’ amounted to little more than signed statements and oral histories. Our goal here, and following the AJA statement of 2004 (Norman 2004), is therefore to ‘keep the checkered past of an object out in the open and part of the continuing scholarly discussion of that piece’. Our use of these items by no means exonerates how the items were initially acquired, and there is always a certain spectre of doubt and suspicion which hangs around these items (as, indeed, is the case with many items now located in museums, e.g. Watson and Todeschini 2006, Mödlinger 2020). With regards to the private antiquities trade, we have striven for increased public awareness and transparency in our work and only examined items where permission was given to publish

all relevant findings – even where they lowered the value of the artefact or cast its official provenance or history into doubt. Indeed, a primary goal of the analysis is to permanently move these items into the public sphere and raise public awareness of them (and others like them). In this way, it falls within the wider trend in ancient studies to use digital methods (including 3D data) and archives as a way to both preserve and disseminate physical resources (Bagnall and Heath 2018).

### 3. 3D DATA

Three-dimensional (3D) data acquisition is now commonplace in archaeology and cultural heritage studies. In excavation contexts this has taken the form of photogrammetry and LiDAR scanning to record objects, deposits, and features, or arbitrary points during the excavation (Roosevelt et al. 2015; Porter, Roussel & Soressi 2016). Museum collections are digitized and models of objects made available to researchers and the public either through self-hosted platforms, in conjunction with commercial online platforms such as Sketchfab, or through ‘Virtual Museums’ (Means 2015; Pescarin 2014; Biedermann 2017). It must be recognized that the digitization process is a creative process and the relationship between a digital object and the physical object it was derived from is by no means clear cut, and neither are issues of ownership, interpretation, and usage which vary depending on national copyright laws (Meehan 2020). As noted above, the goal of the present project is to make the objects more accessible for researchers, and to increase the amount of available information for them by more accurately measuring their physical properties. The methods adopted for the 3D model creation were guided by this purpose.

#### 3.1 LIDAR SCANS

A FARO Laser Line Probe (LLP HD) on a FARO-ARM Edge (2.7 m, 7 axis) was used for creating LiDAR models of objects. The models constructed from the LiDAR material provided relatively high levels of precision for examination of details on objects such as manufacture marks. While the results of laser scanning and photogrammetry are complementary and often produce similar results (Tadeusz, Karol & Chorazy 2018), in our case the models generated were generally of higher quality (i.e. had a larger point and face count) than the meshes generated from the photogrammetry using the set-up we describe below. In most cases the exterior and interior surfaces of objects were scanned. Objects were situated on a tripod or stand depending on their form, and rotated as necessary (*Figure 1*).

Multiple, overlapping scans of the same object were taken. This was done in part to mitigate issues with



**Figure 1** Laser scanning setup with the Faro-ARM Edge and tripod for holding a helmet during scanning.

processing time. Ideally a high performance computer is required with data acquisition, as each scan can be composed of tens of millions of points. However, in the interests of a mobile analysis setup, a relatively high-powered laptop was used, which was fit for purpose but still lagged slightly when recording data. Scans were collected and aligned with Geomagic Wrap 2017. These were first processed as ordered points which were then meshed together. Size and resolution of the exported mesh are related, with higher resolution meshes with more faces being of a larger size than smaller lower quality meshes. Large meshes can easily be giga-bites in size and unmanageable for seamless viewing on most computers, but are also unnecessary in most cases. High resolution sections of particular elements can be generated, but for most general views a decimated mesh is sufficient.

### 3.2 PHOTOGRAMMETRY

In comparison to LiDAR scanners, photogrammetry provides a more affordable system for the construction of 3D models. Data for models can be acquired relatively quickly depending on the resolution required, but processing can also take some time (Magnani, Douglass & Porter 2016). The main consideration was the expedient capture of data while in the museums. The setup for the photogrammetry consisted of a light tent surrounded by five LED lights on tripods, a bluetooth controlled turntable with a custom foam stand placed over it, and photogrammetry targets printed from Agisoft Metashape 1.5.3 (Figure 2). A Canon EOS 7D with a Canon EF 50m f/2.5 Macro lens was used, and between 125 and



**Figure 2** Example of the photogrammetry set-up.

250 images were taken for models of helmets depending on their complexity (i.e. less photos for a helmet with no decoration, whereas more were required for those with attachments).

As one of the main outputs of the models was the colour texture for the model, it was necessary to take particular care with lighting the object and colour correction. This was primarily to control the white balance and the exposure of the images. Colour correction was done with an X-Rite Colour Checker Photo Passport 2, which has been shown to provide satisfactory results with colour corrections (Vitorino et al. 2015; Marziali and Dionisio 2017). Colour correction also allows for consistency between interior and exterior textures on a single object. The colour checker was photographed at the start of each set-up. Raw photographs were processed as digital negatives (DNG) in ColorChecker Passport and Adobe Lightroom Classic CC with the ColorChecker Passport plugin. The colour corrected photographs were exported as JPG files for photogrammetry.

For the construction of the 3D models, Agisoft Metashape 1.5.3 (Agisoft 2019) was used. Blank images of the workspace were used to create masks of the objects and stand. Once the objects were aligned the tie points were edited. The same editing parameters were used for every model (Reprojection Error: 0.2 px; Reconstruction uncertainty: 15 px; Image count: 2; Projection accuracy: 2.5 px), these were set based on a result which offered the lowest error in the final model while still creating a complete representation. The bounding box was limited to the object and a dense cloud was constructed on the highest resolution. Editing of the dense cloud was done manually with some automation based on colour where possible. A mesh was generated over the object and a texture created. Where required a reflexive method of deleting stray points on the dense cloud and re-generating the mesh and texture was conducted. White backgrounds were used for all images, which in some cases resulted in colour distortion, particularly around the edges of objects. When this could not be removed through the manipulation of the dense cloud, the final texture was edited in Adobe Photoshop CC to blend the areas with residual background to that of the object.

### 3.3 LIDAR MODELS AND PHOTOGRAMMETRY TEXTURES

The models generated from the LiDAR scanning were of a higher quality in terms of point and face counts than those obtained from the photogrammetry. In particular, the edges of objects on the LiDAR models were clearer than those from photogrammetry. Despite this, the photogrammetry models provided satisfactory results for an overview of the models, low-polygon versions of which can be used for outreach purposes where specific detail is not required. This is desirable because displaying

and manipulating models of higher resolution can take more processing power than is typically available on a standard computer, so the creation of smaller resolution models makes them more accessible to a range of audiences. Merging the models from the LiDAR scanner and the textures from the photogrammetry models provided the best results for visualisation and utility. The software packages Blender 2.8 (2019) and MeshLab 2016.12 (2016) are used to merge the texture from the photogrammetry model with that of the laser scan, which we discuss further below. We applied this method to over 30 objects, four of which we discuss here.

## 4. THE OBJECTS

The collections utilized in this study were the Doug Gold Collection (both privately held and on display in the Teece Museum of Classical Antiquities at the University of Canterbury), the collection of the Museo Nazionale Etrusco di Villa Giulia (National Etruscan Museum of Villa Giulia), and the collection of the Museo Archeologico Nazionale di Paestum (National Archaeological Museum of Paestum). While some of the privately held items were able to be acquired on loan for several months, the museum collections were each studied in a single visit which lasted up to seven working days. Objects were selected based on the level of their reconstruction, usefulness for the aims of the study, and logistical concerns. For the purposes of this paper, we have selected a helmet from each collection as a sample of the material examined and are outlined in [Table 1](#).

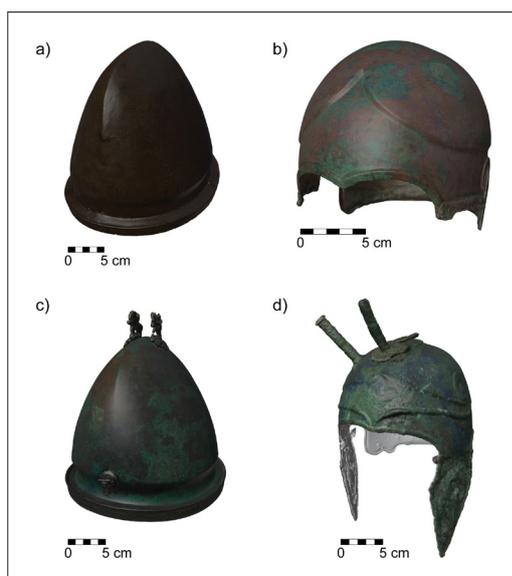
## 5. RESULTS

Two separate models were constructed of each object through photogrammetry and LiDAR scanning. The laser scan models represent the entire 3D volume of each helmet. The models of each helmet were decimated partially to around 5 – 10 million faces. The majority of the photogrammetry models represent only the exterior of the object, as the interior could not be captured. The two models were combined to create a visualisation of each object which represents the most accurate surface data with texturing ([Figure 4](#)). Areas which could not be textured on the combined model were left grey.

Alignment of the photogrammetry and laser scan models is not a simple one-to-one fit. The photogrammetry models required alignment to the laser scan models, and in some cases manipulation of the size of the helmet to fit. This was carried out in Blender v2.8 and involved scaling the photogrammetry model along the x, y, or z axis relative to the laser scan generated model which created a better fit between the

OBJECT NAME	DESCRIPTION	TENTATIVE DATE	PROVENANCE
<i>Negau Helmet, Doug Gold Collection</i>	A Negau-style helmet with a high-domed crown and a carinated area above the rim ( <b>Figure 3a</b> ). The rim is flanged and decorated with egg-and-dart motifs. The area above the carination is decorated with palmette decoration. Two perforations along the rim indicate where chin strap was attached. Two inverted teardrop-shaped appliques. Golden colour (unknown source), and with retrograde Etruscan inscription above the palmette band towards the rear of the helmet.	c. 400 BCE	Ex-private South Carolina collection; ex-Liebert & Lenkert Ausgrabungen collection, Krefeld, Germany; ex-private Aberdeen, South Dakota collection. Most recently purchased from Artemis Gallery in 2017. Privately held by Doug Gold. Should be considered [non-prov] and bear the disclaimer that it was acquired after December 30, 1973.
<i>Samno-Attic Helmet, Doug Gold Collection</i>	Samno-Attic in style, it features a pronounced carinated edge, bifurcated at the centre of the forehead and at the back ( <b>Figure 3b</b> ). The edge of the neck-guard is flared and the cheek-pieces are connected to the helmet with a modern riveted hook (original connection unknown).	c. 300 BCE	Ex-private collection, 1970s; ex-Richard Ivy Smith III, Virginia, 1982; ex-Boris Mussienko, Maryland, 1999; ex-private collection, New York. Most recently purchased from Christie's, New York in 2013 by Doug Gold. On display in the Teece Museum. Should be considered [non-prov] and bear the disclaimer that it was acquired after December 30, 1973.
<i>Negau Helmet, Museo Nazionale Etrusco di Villa Giulia</i>	Part of a rich 'warrior burial' (Vulci, Necropoli dell'Osteria. Tomba 47), which featured greaves, spears, and a large aspis (circular shield) as well as a range of bronze vessels and pottery. Elaborate example of the Neagu type with high-domed crown and a deeply carinated area above the rim ( <b>Figure 3c</b> ). The rim is flanged and decorated with linear and egg-and-dart motifs. There are decorative, cast figures applied to the front, back, and top. The front and back are bearded figures – possibly satyrs. The top is a set of winged horses being led by grooms separated by a gap for a crest. See Riccardi 2000.	530–510 BCE (Amorelli 1989)	Excavated from Vulci by Mengarelli in excavations in the late 1920s (Amorelli 1989).
<i>Samno-Attic Helmet, Museo Archeologico Nazionale di Paestum</i>	Part of a 'warrior burial' (Gaudio Tomba 164) from the Gaudio necropolis at Paestum which also featured a triple-disc cuirass, greaves, bronze belt, iron spear, and various other finds. Samno-Attic in style, and featuring two (of an original three) attachments for feathers on the top ( <b>Figure 3d</b> ). Decorated cheek pieces attached by hinges, and stylized brow.	380–370 BCE (Cipriani and Longo 1996)	Excavated in the Gaudio Necropolis at Paestum in 1990 (Viscione 1996, Cipriani 2000). Inventory number: 104106.

**Table 1** Descriptions of the objects examined here with tentative dates and provenance histories.



**Figure 3** Images of the final models of combined laser scan and photogrammetry of the a) Negau Helmet (Emmitt, Mackrell & Armstrong 2021a), b) Samno-Attic Helmet (Emmitt, Mackrell & Armstrong 2021b), c) Negau Helmet (Emmitt, Mackrell & Armstrong 2021c), d) Samno-Attic Helmet (Emmitt, Mackrell & Armstrong 2021d). These models are also available in the published dataset Emmitt, Mackrell & Armstrong 2021e.

two models. The laser scan models were considered the most accurate in terms of measurements. Additionally, as the meshes often included the interior of the objects, they were more complete. It is suspected that despite attempts to control reflectance on the surface of some objects and the curvature of them, as well as the thin nature of the materials, that these factors compounded to create the discrepancy in the photogrammetry model.

The combined models, including both photogrammetry and laser scan data, therefore offered the most complete datasets and reconstructions for each item, allowing them to be utilized in a range of different ways. It is likely that, for most users and most items, the photogrammetry model alone would prove the most accessible and practical (Meehan 2020), with the laser scan data likely being reserved for detailed, scholarly analysis alone. However, even in cases where the photogrammetry model represents the main outcome, the presence of the laser scan data was useful in confirming its accuracy and providing data for areas, generally interiors, where photography was not-possible.

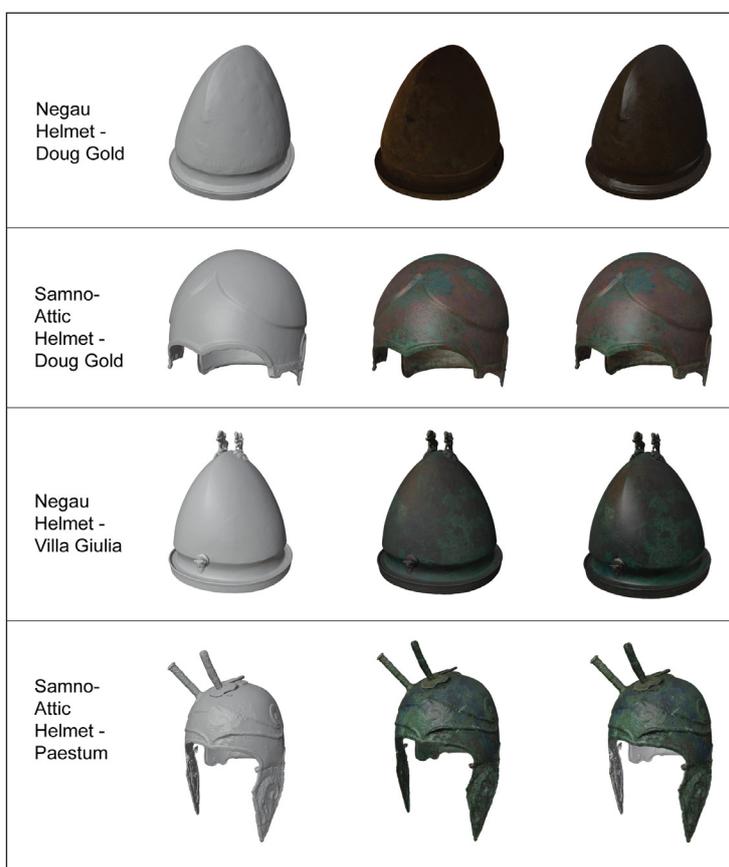
For each model the Hausdorff measure (Cignoni, Claudio & Scopigno 1998) was calculated in Meshlab

2016.12 to assess the difference between the photogrammetry and laser scan models. The Hausdorff distance samples a number of points across two meshes to calculate the maximum deviation between them and thus provides a measure of accuracy between them. Full equations for and discussion of the calculation of this measure are available in Cignoni, Claudio, and Scopigno (1998). The results of the Hausdorff measure for each model is presented in [Table 2](#) and demonstrate that while some points on each model intersected, others had some variation. The means of the measure suggest a relatively good fit between the two forms of model creation, despite what could be seen as relatively larger levels of error ([Table 2](#)). A lower error level may have been achievable with closer and more images of the helmets, but this would have resulted in a longer acquisition time than was available to us, which we discuss below. The

variations of the Hausdorff measures for each helmet are presented in [Figure 5](#) and highlight where some of the thinner, reflective, and curved areas caused discrepancies between the different methods of model creation. It is worth noting that the Negau Helmet from the Villa Giulia and the Samno-Attic Helmet from Paestum had the lowest errors, and that these were also the helmets with the most decoration which likely acted as additional features in the photogrammetry reconstruction.

### 5.1 IDENTIFIED MARKS ON THE OBJECTS

The different methods of data acquisition were successful, to varying degrees, in highlighting specific detail on some of the objects that were otherwise identified through visual inspection. The expediency at which data was collected in some cases resulted in some compromise of resolution. Here we discuss some representative



**Figure 4** Comparison of the laser scan, photogrammetry, and final combined models.

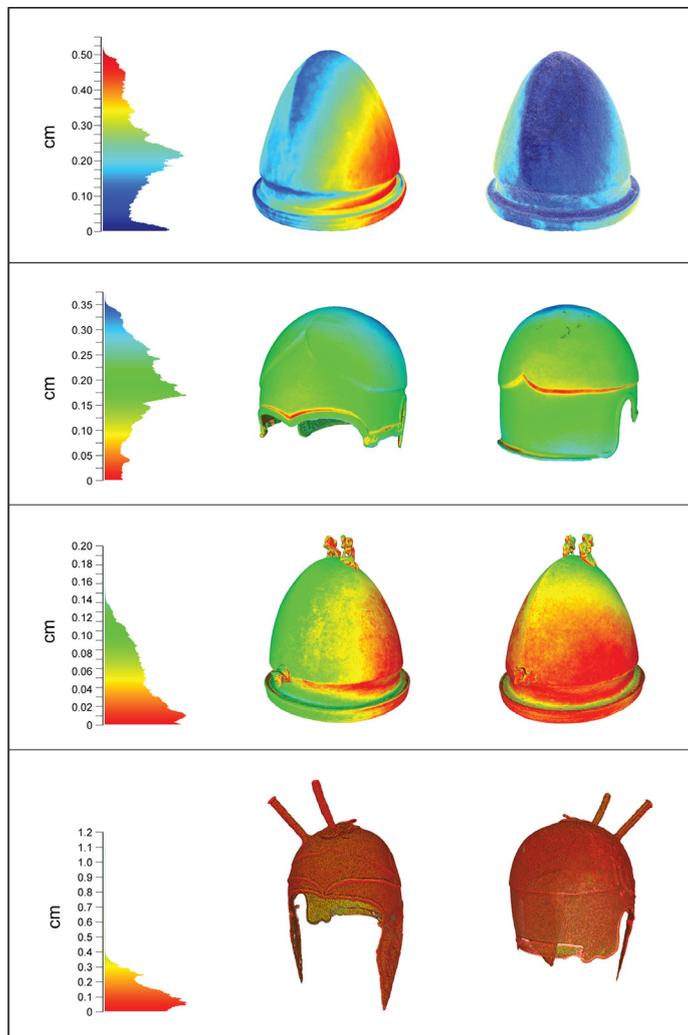
	NEGAU HELMET – DOUG GOLD	SAMNO-ATTIC HELMET – DOUG GOLD	NEGAU HELMET – VILLA GIULIA	SAMNO-ATTIC HELMET – PAESTUM
Sampled pts. (n.)	2926811	2670524	1502877	1918993
Min. (cm)	0.0000	0.0000	0.0000	0.0000
Max. (cm)	0.5380	0.3749	0.1976	0.4880
Mean. (cm)	0.2159	0.1811	0.0568	0.0482
RMS (cm)	0.2493	0.1975	0.0621	0.0567

**Table 2** Hausdorff measure for each model, comparing the photogrammetry model to the laser scan model. RMS = Root mean square.

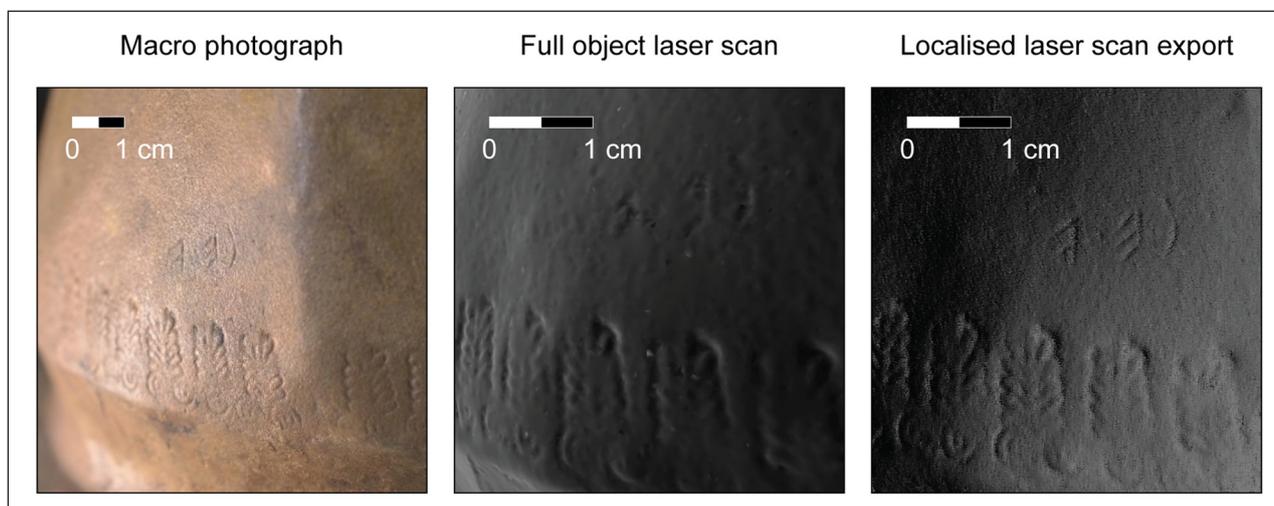
examples where details are visible at different resolutions and via data capture methods.

A faint retrograde inscription on the left rear quadrant of the Negau helmet from the Doug Gold collection was identified on visual inspection of the object. This

inscription was captured well with macro photography under raking light (*Figure 6*) but was otherwise not identifiable on photogrammetry models. The laser scan of the full object used to visualise the helmet shows the inscription at a coarse resolution, but is better



**Figure 5** Coloured point-clouds and histograms displaying the results of the Hausdorff measure on each helmet.



**Figure 6** Comparison of macro photograph and image from whole object and high-resolution localised export LiDAR scan of inscription on the Negau helmet from the Doug Gold Collection.

represented by a localised export of the laser scan data at a higher resolution, as was the stamped decoration that circles the helmet below the inscription (*Figure 6*).

Both of these features were visible, upon detailed inspection, by both the naked eye and through more traditional forms of photography. However, the inscription is faint enough that it would be difficult to see in a museum display context, meaning that researchers accessing the item in that manner are likely to miss it. Indeed, when working on a separate helmet from the Villa Giulia collection (the helmet from Tomba LV from the Necropoli dell'Osteria at Vulci, not pictured here), we uncovered a previously unknown inscription from the inside rear of the artefact, despite the item having been discovered almost a century prior in the Mengarelli excavations at Vulci in 1929 (Amorelli 1989) and on display in the Villa Giulia since 2010. Additionally, more detailed and quantitative analysis of the design elements is enabled than traditional visual analysis has typically allowed. For instance, Paddock 1993 attempted to organize the various palmette designs found on Italian Negau helmets based on style, with the goal of assigning 'workshop groupings'. However, this categorization, based on perceived similarities in the comparison of basic

design elements was limited to style, while the high-resolution, digital capture of these elements would allow direct comparison of scaled models and indeed their overlay, offering the possibility of identification of single, unique stamps used on multiple items.

Small statuary detail on the Negau helmet from the Villa Giulia provides another example. Detail of twin grooms leading horses is most clearly visible from photography and laser scan data, which show finer details than the photogrammetry model (*Figure 7*). These statuettes are at a scale which would merit their own models with photogrammetry to capture the detail at a required resolution. In this case the photogrammetry data was captured with the rest of the helmet and so does not provide a resolution that may otherwise be possible with closer images. Macro photography of these objects provides a good representation of them, but the glare from the surface hinders the interpretation of the finer details, which is where the laser scan data can aid in their interpretation.

With production marks, similar rules held true with regards to the efficacy of different techniques in capturing detail. For instance production marks on the inside of the Negau helmet from the Doug Gold Collection, likely from



**Figure 7** Comparison of detail of decoration (right groom/horse) between macro photography, photogrammetry, and LiDAR scan from Negau Helmet, Museo Nazionale Etrusco di Villa Giulia.

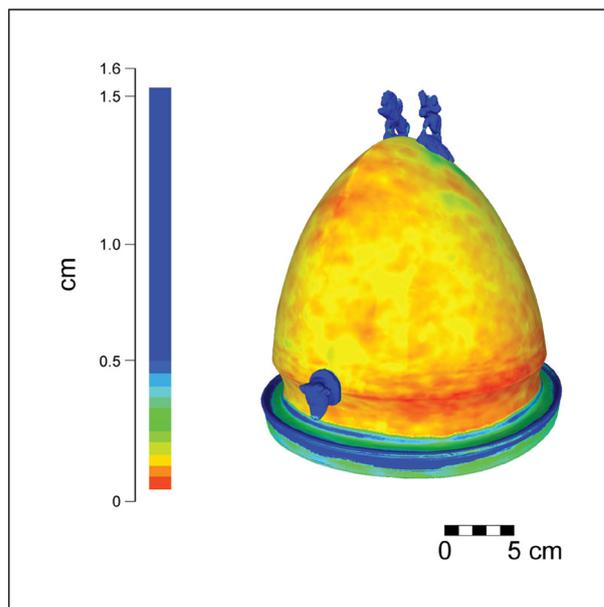
either a hammer or anvil, were clearly visible through a macro lens, but were inaccessible (due to position) for photogrammetry (Figure 8). Where the macro photography is subject to specific lighting conditions to capture such detail, the laser scan data captures the surface of the object irrespective of the lighting conditions when captured. Lighting intensity and angle can be changed on the final scan output to enhance subtle surface variations. Representation of the marks from surface data provides a reliable measure of their presence on the surface of the helmet in a way that is not contingent on lighting conditions.

The 3D model produced from the LiDAR scan was particularly useful when exploring production marks, as it was able to reveal in the relative thickness of the Negau helmet from the Villa Giulia indications of more hammer strikes. These followed the same pattern seen on the inside of the Doug Gold Negau helmet, but higher up the bowl of the helmet and invisible to the naked eye, macro photography, and photogrammetry (Figure 9). This sort of work mirrors some of the work done with x-rays on bronze military equipment in the 1980s and 1990s (e.g. Born 1989), which showed variations in thickness. The potential of this type of digital capture in this area is clear, and is an area where LiDAR has a marked advantage.

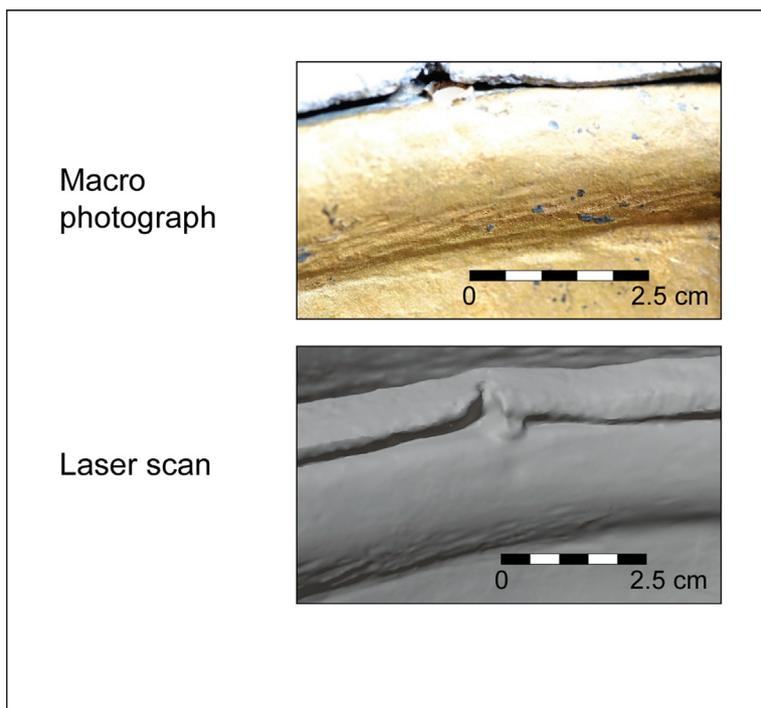
### 5.2 DIGITAL RECONSTRUCTION OF OBJECTS

The meshes captured also provide a medium by which to digitally reconstruct the objects to how they likely looked prior to damage and degradation. In doing this careful consideration of what is being reconstructed

is required, and that it is informed by the object and supplementary data. One such example is seen on the Paestum Samno-Attic Helmet (Figure 3d). The helmet would have had three prongs extending from the top, only two of which remain. The solder point for the third prong, in line with the other two, is clearly visible on the helmet and examples of this are seen in similar helmets from the period (e.g. Egg 1986; Bottini et al. 1988). Using Blender v.2.8 the remaining outside prong was mirrored



**Figure 9** Negau helmet from the Villa Giulia rendered with respect to the thickness of the material. Thickness of the mesh was calculated using the Shape Diameter Function (Shapira, Shamir & Cohen-Or 2008).



**Figure 8** Production marks from the inside of the carination, near the left hole for the chin strap on the Negau helmet from the Doug Gold Collection.

to provide a reconstruction of how the helmet may have looked had all three prongs remained (Figure 10). A more straightforward example of reconstruction is from the Samno-Attic Helmet from the Doug Gold collection (Figure 3b). While only the main helmet is depicted above, included in the collection are two detached cheek flaps. The helmet and the cheek flaps were analysed separately. However, these flaps were then aligned to the helmet in Blender v2.8 to provide a more complete representation of the helmet (Figure 11). Solder marks were also visible on this helmet, but as the shape and form of the prongs that may have extended from it were unknown, these were not reconstructed.

These digital reconstructions are useful in several ways. First, they allow both conservators and scholars to reconstruct and display items, which may have been found in a damaged or fragmentary state, without physically (and typically permanently) altering them through the use of adhesives and other reconstructive elements. Pieces can be digitally captured, reconstructed, and displayed in a digital medium to achieve a similar result to that typically achieved through physical reconstruction. This allows the ‘digital artefact’, ideally alongside the excavated pieces themselves, to possibly take the place of the ‘reconstructed artefact’ which is typically displayed in museums. Second, albeit in a related point, this sort of digital reconstruction demonstrates the potential (at least theoretically) for scholars to possibly *deconstruct* and then reconstruct artefacts in



**Figure 10** Suggested representation of the reconstructed Paestum Samno-Attic Helmet (Emmitt, Mackrell & Armstrong 2021f).



**Figure 11** Suggested representation of the reconstructed Doug Gold Samno-Attic Helmet with both cheek flaps (Emmitt, Mackrell & Armstrong 2021g).

slightly different ways, and most notably those which have been the subject of reconstruction/conservation previously. Although it is never possible to undo what has been done to an artefact, and indeed there are issues around this sort of approach and challenges it poses to the legitimacy of a reconstructed artefact as it currently exists in its modern context, the possibility of these reconstructions – like other digital models – opens the door for a range of interpretations which may cater to different purposes (see Meehan 2020 for more complete discussion of the issues highlighted above). Third, this type of reconstruction offers scholars the opportunity to more accurately test hypotheses around the placement and use of attachments and missing pieces without needing to access the original. Indeed, one could also foresee this sort of technique being useful in determining whether various pieces, either found or currently located separately, ultimately belonged together.

## 6. CONSIDERATIONS

### 6.1 ISSUES WITH OBJECTS

In the majority of cases, the interior or reverse of objects could not be modelled with photogrammetry. In some cases, and in particular with helmets, situating them stably in a position with consistent lighting, either in a fixed position or a turntable, was not logistically possible in the museum contexts. When it was possible, the resulting interior textures and meshes were of either poor quality or mismatching colouring compared to the exterior colours,

even with colour correction. Consequently, the exterior colours were the made the priority for photogrammetry, while the interiors of objects were prioritized for the LiDAR scans – which was able to access them more easily. If an area of interest was identified on the interior of an object it was photographed separately for reference.

In some cases the final meshes of objects' small details, such as perforations, often required manual editing as they were automatically covered during mesh creation. This was the case for the Doug Gold Negau helmet, where there is a perforation on either side, likely for the attachment of some form of strap. This was done either in the mesh creation software, or in Blender v2.8. Such details were also photographed separately for reference.

## 6.2 LOCATION, EXPEDIENCY, AND EFFICIENCY

Due to the nature of the work and the limitations on access associated with the requirements of the museum with time constraints and temporary workstations, there was the requirement for expediency in data capture. To this end an operator was left to capture photos for photogrammetry of each object, averaging three to four objects per day. As a result, the photos of each object were individually adjusted and calibrated, but broadly consistent; shot from the same distance and of the entire object. As discussed above, this resulted in a lack of detail in some places, whereas closer higher-resolution photos would have enabled for a higher definition of features – such as the attached figures from the Negau helmet from Museo Nazionale Etrusco di Villa Giulia (*Figures 3c, 6*).

Having enough space in the museums was also an issue. We were fortunate that each museum had enough lab space, or was able to close sections of the museum during the research visits. The photogrammetry setup was required to be large, because the objects were large. The light tent was a cube of 1.5 m with the lights on the exterior to the sides and rear, then room for the tripod at the front (*Figure 2*). The LiDAR scanner required a radius of 1.5 m around the object (usually on a tripod), with the scanner taking another 1 m<sup>2</sup> to the side of this (*Figure 1*), and also a table for the laptop (the screen of which needed to be visible while scanning). A clear space was required in each of these setups, for the photogrammetry this was to prevent the accidental movement of the camera tripod or lights, and for the LiDAR scanner it was to allow sufficient space for the operator and arm to move. Another consideration is power, data cables, and tripod legs, create potential trip hazards which are undesirable around the objects. It was found that having the two stations for these processes away from other analysis activities was best, either by their placement in another room or cordoning off the relevant areas. In addition, positioning the LiDAR scanner away from areas of high movement was also desirable as

vibrations in the floors of rooms had adverse effects on the quality of scans.

## 6.3 MUSEUM DISPLAYS

Regarding the acquisition of data, the mountings of many objects presented some issues. Some objects were permanently attached to the stands they were presented on, while in other cases the stands presented the most stable way to analyse them. Stands, where required, were recorded with the objects and, where possible, were edited out in post-processing. This was less of an issue for LiDAR scanning, but more of an issue with photogrammetry, as the stands would often obscure the surface of the object. Stands made of metal presented the least amount of disturbance in that when an object could not be removed or shifted on the stand the obscured area was obvious on the resulting texture.

A more difficult medium, and one which is common in museum collections, was transparent Perspex. It was found during LiDAR scanning that, at some angles, the laser would not reflect off the Perspex and would measure the surface of the object, while at other angles the laser would reflect off the Perspex. However, it was not possible to isolate these conditions consistently enough to use them. Where an object surface rested on the Perspex it was not possible to differentiate between the surfaces as the combination of variable scan results, the curvatures and roughness of object surfaces, and differential distances from Perspex to object could not be controlled. In cases where Perspex affected analysis and the object could not be removed from the stand, that part of the object was omitted.

In the case of photogrammetry, Perspex produced similar issues, particularly when part of the object was seen through the medium. In addition, the material caused issues for texture generation, where Perspex would cause discolouration of the obscured parts of the object, even when those areas were masked during processing. While there has been some success in mitigating the interference of acrylic materials to photogrammetry (Miyazaki, Hara & Ikeuchi 2010), such techniques were not possible to implement, and in cases where it was an issue the influenced areas were omitted.

## 7. DISCUSSION AND CONCLUSIONS

From provisional analyses, it is clear that 3D models of artefacts can significantly increase the amount of useable data available from military equipment finds. 3D models, created using current technology with both photogrammetry and LiDAR, are useful for the broad stylistic analysis (which has hitherto formed the basis of their study) and, more importantly, quantification. They provide accurate measurements and good levels of detail for larger design elements. Further, these models

offer ‘snapshots’ at the point of analysis, and offer the ability to assess degradation over time and to aid in their reconstruction (e.g. Frischer 2014; Dell’Unto et al. 2016). They are also useful for identifying aspects of an item’s specific geometry (incl. damage and/or repair) which may not be visible to either the naked eye or traditional photography. This being noted, traditional and macro photography retain their functionality— particularly for decoration, discrete production marks, and inscriptions.

3D models also allow more detailed inspection than typically allowed in museum collections, as well as manipulation of light/shadow in a digital environment. The ability to publish these models also ensures the presence of this data in the public domain and grants access to a much wider audience, allowing multiple interpretations of the same data. This is a significant benefit, particularly for items located in private collections. Digitizing these items may represent a way to bring them permanently into the public sphere with their full and often ‘checkered’ histories. This acts not only as a resource in its own right, but also as a growing collection of quantitative data against which new pieces of evidence – both from excavations and private sales – can be compared. Items held in museum collections are sometimes only slightly more accessible than those in private collections and, as we have demonstrated here, come with their own challenges. It is our hope here that by making the data for these models available, that it will encourage others to do so.

The inaccessibility of physical items in collections, both public and private, is one of many reasons why many museums are increasingly creating 3D models, most notably for outreach. In some cases these provide interactive models of objects that are usually in a fixed position while on display. However, such scans often are not of the quality that is required by researchers and not suited towards all research questions. There are also the issues which arise when an object is fixed or positioned in such a way that it cannot be removed from display for analysis. Additionally, as noted above, areas of fine detail on the items, including inscriptions, fine decoration, and production marks, can be either invisible or indistinct in 3D models created using existing technology. These aspects are still best supplemented using targeted, macro photography which requires direct access to the items.

The traditional approach to many ancient artefacts, and particularly pieces of ancient military equipment, as *objets d’art* has unlocked only a tiny facet of their potential. The creation of 3D models of these items allows not only their study in a range of new contexts, but also enhances their presentation. Perhaps paradoxically, digital models offer a more durable, accessible, and functional means of accessing these fragile items. Aside from this, the creation of 3D data related to these objects opens a new avenue of replicable and quantifiable study that has previously been

limited or unachievable. Such studies can be used to test prior assumptions about the past and create bold new narratives. They allow items to be rediscovered and re-investigated again and again.

## DATA ACCESSIBILITY STATEMENTS

The models presented in this paper are available at: Emmitt, J., Mackrell, T., and Armstrong, J. 2021. Early Italian helmet models published in “Digital modelling in museum and private collections: A case study on early Italic armour”. *Zenodo* DOI: [10.5281/zenodo.4278038](https://doi.org/10.5281/zenodo.4278038).

## ACKNOWLEDGEMENTS

This study was funded by the Royal Society of New Zealand Marsden Fund project ‘Blood and Money: The ‘Military Industrial Complex’ of Archaic Central Italy’ (17-UOA-136) awarded to Jeremy Armstrong. Thanks is due to the directors and curators from the Teece Museum, Museo Nazionale Etrusco di Villa Giulia and Museo Archeologico Nazionale di Paestum for facilitating access to their collections, permitting publication of the resultant models and data, and allocating staff, space, and time to help us during our visit. In particular we would like to thank Giulia Bison, Valentino Nizzo, and Gabriel Zuchtriegel for their help. Thanks is also given to Doug Gold for providing access to his collection for study and for permission to publish the results. The work would also have been impossible without Jono Grose and Nic Harrison of Redoubt Forge, who operated the photogrammetry workstation and assisted with the macro photography.

## COMPETING INTERESTS

The authors have no competing interests to declare.

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TO CITE THIS ARTICLE:

Emmitt, JJ, Mackrell, T and Armstrong, J. 2021. Digital Modelling in Museum and Private Collections: A Case Study on Early Italic Armour. *Journal of Computer Applications in Archaeology*, 4(1), pp. 63–78. DOI: <https://doi.org/10.5334/jcaa.63>

Submitted: 26 August 2020

Accepted: 16 February 2021

Published: 23 March 2021

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