A fragmented past: (re)constructing antiquity through 3D artefact modelling and customised structured light scanning at Athienou-*Malloura*, Cyprus

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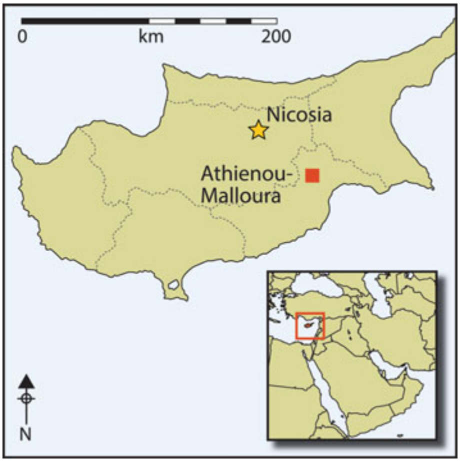

*Many archaeological objects are recovered as fragments, and 3D modelling offers enormous potential for the analysis and reconstruction of large assemblages. In particular, structured light scanning provides an accurate record of individual artefacts and can facilitate the identification of joins through details of breakage surfaces and overall morphology. The creation of 3D digital models has the further advantage of enabling the records to be accessed and manipulated remotely, obviating the need for prolonged access to the original materials in museums or repositories. Here, the authors detail the use of structured light scanning to produce a corpus of 3D models based on a sample from a large assemblage of terracotta and limestone sculptural fragments from the Cypro-Archaic period (c. 750–475 BC) at Athienou-*Malloura*, Cyprus.*

Keywords: Cyprus, Iron Age, 3D artefact modelling, structured light scanning, terracotta figurine, limestone sculpture

Introduction

The continuing development of 3D-scanning technologies has allowed an increased range of applications in archaeological contexts, from the visualisation of specific features and landscapes to the detailed analysis of artefacts (Frischer & Dakouri-Hild 2008; Javidi 2014;

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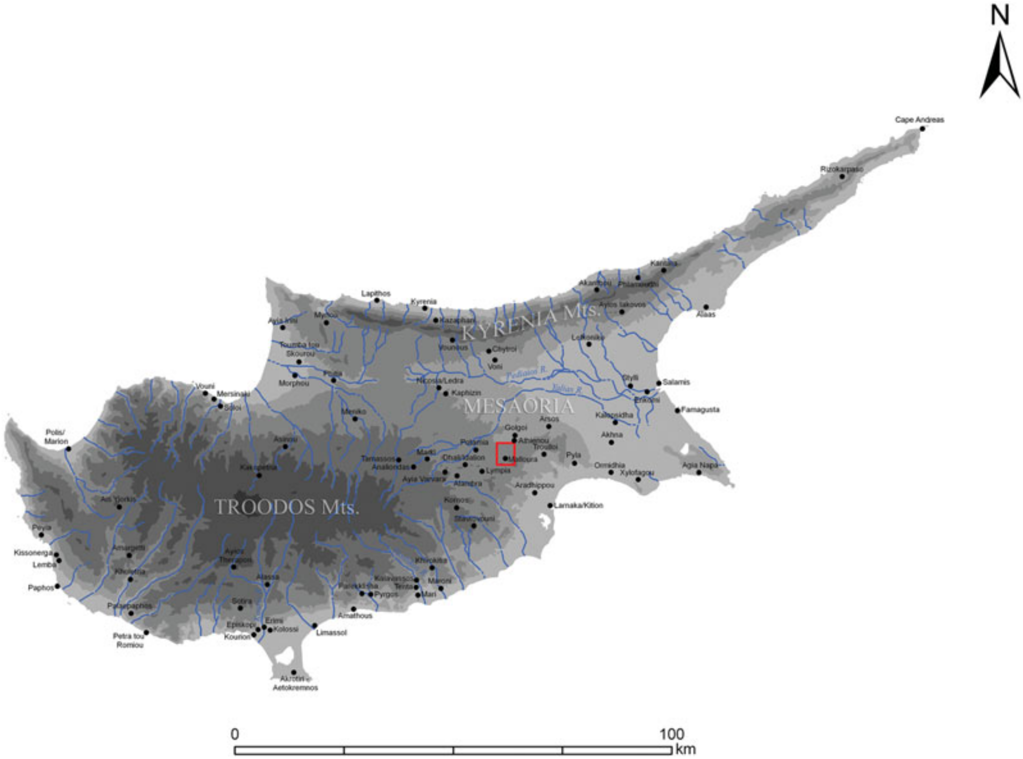

Figure 1. Map of ancient Cyprus with major sites; AAP project area indicated by rectangle (map by David Massey).

Remondino & Campana 2014; Olson & Caraher 2015). Creating 3D models is becoming increasingly common in archaeology, although so far most projects have focused on a small selection of significant objects or isolated 'museum-quality' pieces, generating 3D models for archival purposes, public outreach and education (e.g. Akca *et al.* 2006; Bevan *et al.* 2014). The pilot season of a multi-phase 3D initiative by the Athienou Archaeological Project (AAP) has employed a customised structured light scanner to produce 3D models of artefacts recovered from a rural sanctuary at the site of Athienou-*Malloura* on Cyprus. The creation of a 3D corpus is intended to document artefacts and, ultimately, to address specific research questions regarding the assemblage of votive offerings from the Malloura sanctuary. This article outlines our methodological considerations, reviews the equipment used and technical aspects of the process, contextualises the project within the broader archaeological use of 3D models and discusses the benefits and drawbacks of this technology in the context of the material from Athienou-*Malloura.*

The AAP has been investigating long-term cultural change at Athienou-*Malloura* and the surrounding region since 1990 through systematic excavation and pedestrian survey (Figure 1). These investigations have unearthed domestic, religious and funerary contexts, with an impressive assemblage of material remains associated with a 3000-year occupation beginning in the early first millennium BC (Toumazou *et al.* 2011, 2015). The focus of

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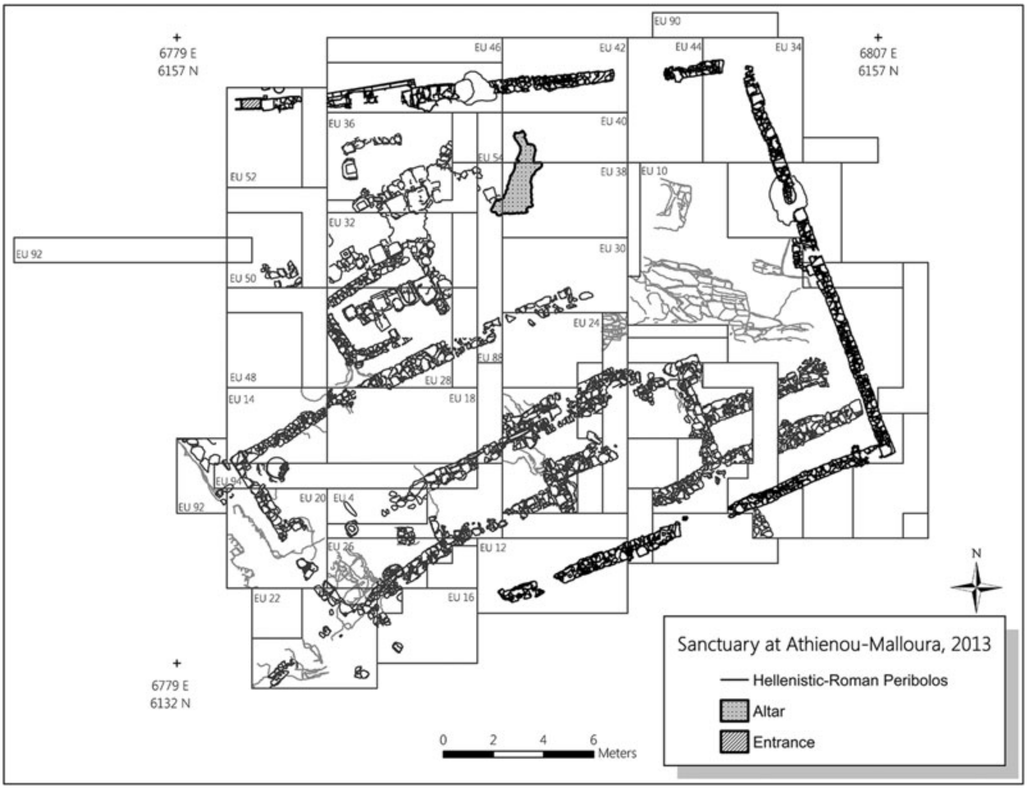

*Figure 2. Plan of the sanctuary of Athienou-*Malloura*, Cyprus, 2013 (plan by Remko Breuker, updated by Kevin Garstki).*

excavations for over a decade has been a large rural sanctuary, which has revealed an extensive history of use from the eighth century BC to the fourth century AD (Toumazou & Counts 2011) (Figure 2). The artefact assemblage from the sanctuary includes ceramic vessels, coins, animal bones and other cult objects. Excavations have also recovered over 3000 fragments of votive terracotta figurines and limestone sculptures, which are the focus of our new 3D-imaging project. These include approximately 800 terracotta figurines, most of which are handmade and date to the Cypro-Archaic period (*c.* 750–475 BC). The figurine fragments depict predominantly male subjects (warriors, chariot groups, horse-and-riders, votaries or worshippers and so on) (Averett 2011). Additionally, over 2500 fragments from limestone dedications, dating from the Cypro-Archaic to Roman periods (*c.* sixth century BC to first/second century AD) depict predominantly male votaries and divine types (including male divine iconography commonly found in Cypriot sanctuaries, e.g. ‘Cypriot Herakles’, Zeus Ammon, Apollo and Pan types), ranging in scale from statuettes to statues larger than life size (Counts 1998, 2011). The site of Athienou-*Malloura* represents one of the few inland rural sites in Cyprus (distinct from the larger urban centres on the coast) to have been subject to detailed modern excavation. Moreover, the terracotta and limestone sculptures recovered from the sanctuary constitute one of the largest and best-recorded assemblages of Iron Age figural art ever excavated in Cyprus.

The state of preservation of the *Malloura* sculptural dedications is a direct reflection of the sanctuary's long use. Over time, older and broken statues and figurines were gathered up and buried or repurposed as floor packing or wall stones during subsequent renovations of the sanctuary. More recently, looting has removed caches of broken sculptural fragments completely from their original context, leaving them in a state of disarray in modern pits. The large quantity of excavated sculptural remains, their fragmentary nature and the project's limited access to the materials, which are stored remotely in the Larnaka District Archaeological Museum in Cyprus, made a 3D digital repository an ideal platform for post-excavation study. Such a database is particularly helpful in dealing with challenges such as the identification of connecting joins among fragmented artefacts. Although we have successfully discovered many matching joins using photographs, illustrations and visual memory, the creation of a 3D image archive for the *Malloura* artefacts counteracts two significant obstacles to their study: first, the sheer number of fragments, which makes individual observation time-consuming, and identifying matching joins exceedingly difficult; and second, that the objects housed within the Larnaka Museum are only available to researchers in small numbers and for very limited periods.

Developing a means of capturing accurate digital models became paramount for addressing several important research goals:

a) To develop and test a cost-effective 3D scanner with which to produce models that accurately pinpoint surface geometry (dimensions of the x, y and z planes) and texture.

b) To create computer-aided, hypothetical reconstructions of fragmentary sculptures based on established typologies.

c) To explore surface treatments (paint, fingerprints, carving marks) so as to understand technological aspects of production better and consider wider implications with regard to identifying regional styles, evidence of exchange and the influence of different artistic schools.

d) To identify and match unique joins (i.e. broken fragments that can be pieced back together) in order to help reconstitute limestone and terracotta statues.

These data, when integrated with other related information (e.g. typology, find-location, date, material type), have the potential to inform a more complete understanding of the sculptural assemblage with regard to types and attributes. Reducing the total number of fragments by piecing joins back together also allows for greater insight into the use of the sanctuary prior to the breakage of these artefacts.

Methods and equipment

In consultation with the University of Kentucky's Center for Visualization and Virtual Environments (VisCenter), we determined that structured light scanning was the most appropriate method for attaining our research goals. This method produces geometrically accurate models that capture metric measurements with realistic textures. Precision was crucial as we intended to use the models to identify connecting fragments, while capturing texture was necessary for the analysis of surface treatments such as paint, tool marks and fingerprints. This positioning of 3D visualisation for data collection and subsequent in-depth interpretative analysis distinguishes our project from those whose primary concern is artistic facsimile. The portability of the equipment meant that it could be built at the VisCenter and transported to Cyprus. Finally, a customised structured light scanner, utilising affordable components, allowed a relatively low production cost to be maintained.

In addition to reflectance transformation imaging (RTI), laser scanning and photogrammetry, structured light scanning is one of several 3D scanning technologies to have been used by archaeologists in recent years (Bretzke & Conard 2012; Gilboa *et al.* 2013; Olson *et al.* 2013; Wittur 2013; Javidi 2014; Miles *et al.* 2014; Remondino & Campana 2014; Olson & Caraher 2015; Olson & Placchetti 2015). Structured light scanning technology involves the projection of a series of parallel stripes of light onto an object; based on the displacement of the stripes, as viewed through the camera, the system can identify and retrieve the 3D coordinates on the surface of any object in view. Techniques such as RTI and digital photogrammetry present some benefits for the digital recording of archaeological objects, including their low cost. There is, however, a distinct increase in the accuracy of the digital model when using either laser scanning or a structured light system. The difference in metric accuracy is largely due to the way that each system gathers spatial information: while photogrammetry or structure-from-motion relies on the digital comparison of pixels within and between images to create geometry, range-based modelling techniques rely on the distance between the scanner and the object, leading to higher levels of precision and often a more accurate model. Using a method that created the most accurate 3D models with high resolution, detailed surface geometry and colour photograph texture was advantageous because of the ultimate goal of our project: to identify artefact joins.

The pilot project took place between 11 June and 17 July 2014 at the Larnaka District Archaeological Museum and at the Athienou Kallinikeio Municipal Museum, which exhibits a small selection of artefacts from the excavation. Before the season began we developed four selection criteria for objects to scan in order to optimise efficiency and test the results of our system: 1) museum-quality artefacts; 2) objects of different scales ranging from a few centimetres to approximately 30cm; 3) objects known to conjoin; and 4) objects with visible surface treatments such as paint, fingerprints or tool marks. Additionally, a few artefacts of different materials (metal, ceramic, bone and opaque glass) were scanned to test the full potential of the equipment for future stages of the project, acknowledging the inherent limitations of the structured light scanning (e.g. with reflective or clear materials/ surfaces).

Our structured light system consisted of a BenQ W1080ST 1080p 3D short throw DLP projector (US$949) to generate the light patterns that were projected onto the objects, and a Flea3 8.8MP colour camera (US$895) to capture the 3D coordinates and photograph texture of the object (Figure 3). The Flea3 camera was chosen because it is a professional vision camera that comes with a full software development kit for computer control. A Dell XPS 8700, Windows 8.1 (64-bit) desktop PC (US$739) was used to run programs for calibration, scanning and reconstructing. The projector and camera were mounted on a framework made from aluminium rails and orientated towards a turntable, on which the objects were placed for scanning. A black cloth backdrop was used to reduce glare. After the initial setup, customised software ('SLScaner2' written by Bo Fu, University of Kentucky)

Figure 3. The set-up of the pilot project structured light system in the Larnaka District Museum study room.

together with a checker-patterned board and axis rod were used to calibrate the camera to ensure that it correctly identified points in three dimensions. It was necessary to recalibrate every time the equipment was re-positioned or altered. Following this, the SLScaner2 software was used in combination with the projector and camera to project structured light patterns onto an object and scan it. The scan process was repeated with every 45° rotation and on the 'top' and 'bottom' of each object for a total of 10 scans per object. For each of the 10 scans a point cloud was produced that was used to create a triangular mesh of the object (Figure 4).

After scanning each object, significant processing was necessary using the 'Structured Light Merge Tool' program (written by Qing Zhang, University of Kentucky), operated in conjunction with MeshLab (http://meshlab.sourceforge.net/), an open-source application used for processing and editing 3D meshes. These programs 'cleaned-up' background noise and then merged the 10 scans. MeshLab was used for the manual alignment of the cleaned files, while the Structured Light Merge Tool refined this manual alignment (Figure 5). The last step was adding texture to the reconstructed model. A final mesh of the scans was produced for each artefact, complete with photograph texture (Figures 6 & 7).

Results and discussion

By the end of our pilot season we were able to scan 78 artefacts from Athienou-*Malloura*, 61 of which were fully reconstructed with accurate surface geometry and texture. Even though we were largely successful in our goals, we did encounter several issues that we plan to address in the future. While not unexpected, the transfer of the system from the controlled environment of the VisCenter's laboratory (specifically designed for 3D imaging) to an *ad hoc* workspace in Cyprus presented some challenges. Although the scanner was designed for use in any setting, the study space provided by the Larnaka Museum required us to make a number of procedural adjustments. For example, after initial attempts to calibrate failed, we realised that the glare from the work surface was affecting how the camera recorded images; covering the table and the nearby wall with a dark cloth alleviated the noise created

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by the glare. A more difficult issue arose with the ability of the system to adjust easily for differences of scale. Medium-sized objects (ranging from 25–30cm) required placement of the turntable further from the projector and camera in order to capture the entire object when rotating. In turn, objects smaller than 25cm were positioned closer to the equipment for higher resolution scans. Each adjustment required recalibration and repositioning. As a result, our workflow was determined more by the size of an object than any of the other selection criteria.

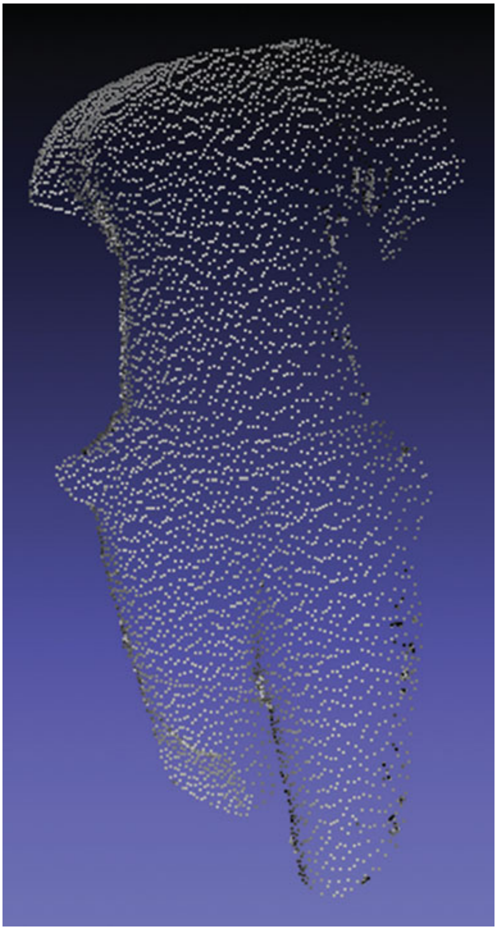

Figure 4. Image of the point cloud generated by the structured light scanning.

Despite these setbacks, we were able to fine-tune the scanning process. The 3D artefact models produced from this pilot season provide significant data with which to answer our initial research questions. Of the 78 artefacts scanned, the 42 limestone statue fragments produced the best results. These range in size from 10–35cm in length, which we determined to be the ideal scale for our scanner (Figure 6). In addition, the surface features of the limestone objects are not overly detailed, and therefore their reconstruction was not constrained by the resolution of the scanner. In contrast, certain terracotta figures were difficult to scan due to their detailed composition and complex surfaces (Figure 7). Each model contains metadata including information on the object's surface geometry accurate to 0.5mm. This provides us with the capability not only to view the objects outside Cyprus, but also to analyse, measure and document these artefacts remotely. In some cases, the resolution of the surface allowed us to see imperfections in the stone and human-made tool marks, as well as to begin to experiment with digitally joining 3D models of broken fragments from the same sculpture.

Moving forward, we plan to build a more robust customised structured light system that will, in conjunction with the associated software, improve our original system by: a) capturing higher resolution models of small scale objects (*c.* 5–20cm) with a new optic engine; b) decreasing the risk of human error through further automating and expediting the scanning process; and c) streamlining and refining the meshing and reconstruction of scans. The improved system will include two DLP® LightCrafter™ 4500 modules for projecting structured light patterning and two Point Grey® high-speed cameras to capture points more efficiently and accurately than our previous one-camera set-up. This system

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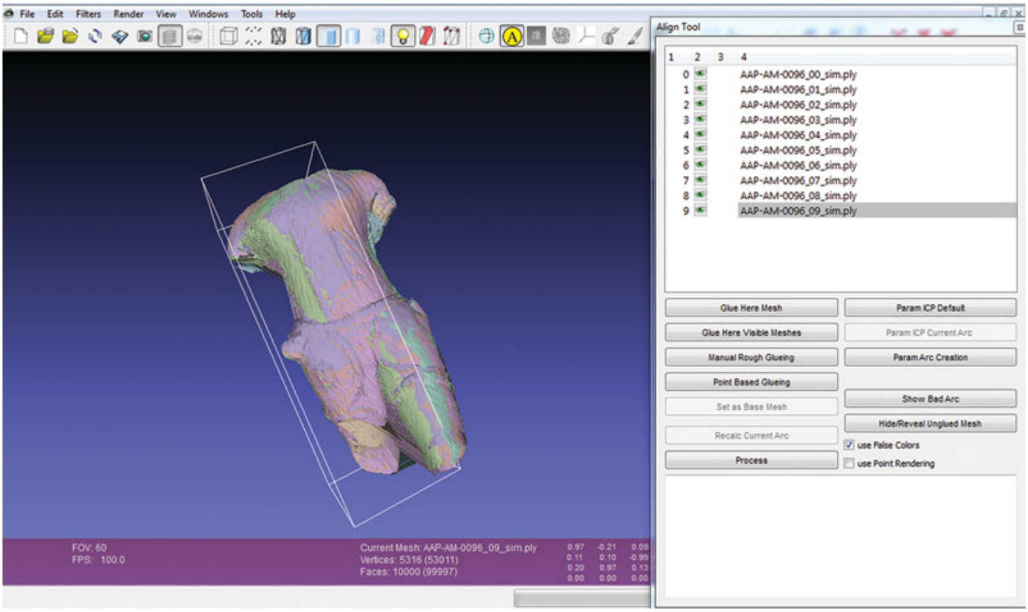

Figure 5. Screen shot of programs merging using MeshLab.

will allow scanning at 75 micron resolution (0.075mm) as opposed to the 0.5mm scanning potential of our current equipment. Adjustments to the scanning protocol and set-up will resolve minor issues noted during the pilot season. For example, the creation of a higher quality calibration board will expedite this process, and professional lighting and backdrops will allow greater control over the final product. A computerised turntable will be used to automate the scanning process, which requires scans from multiple angles, and will significantly accelerate the scan time.

A custom-built system is not only more cost efficient than comparable commercial scanners (US$40 000+), but allows for increased adaptability (adjustable for artefact scale, materials and so on), as well as continual upgrade as emerging technologies become available (e.g. higher quality parts can be added to the system and software can be re-written). Modifications and upgrades to our system will allow for higher resolution models that capture more accurate metric data and more detailed surface texture for analysis. Eventually, we hope to disseminate a structured light scanning 'kit', although the main drawback of the system discussed here is the relatively high level of technical knowledge required to run the software. We hope to mitigate this by publishing detailed user guides and specifications that will include a list of components and assembly instructions. We also wish to make the programming software available as open source via a version control system, such as GitHub, so that archaeological or cultural heritage management projects with limited resources can recreate our set-up. In our case, close collaboration with the VisCenter has created an active dialogue between technology, process and product, which we believe will ultimately lead to a more successful application of 3D visualisation in archaeological investigation.

Figure 6. Reconstructed model of a limestone head of Herakles wearing a lion-skin headdress (inv. no. AAP-AM-851, Larnaka District Museum).

Our long-term plan is to develop this pilot project into a truly innovative contribution to the use of 3D models for research purposes that builds on several key projects. In partnership with the VisCenter, we will experiment with predictive matching algorithms that will consider geometric dimensions, surface texture and break patterns to propose potential joins from the full collection of 3D object scans. The increased use of range- and image-based modelling systems in archaeology has supported attempts to address the widespread problem of reassembling fragmented artefacts using automated computational methods. Each breakage surface will be given a unique ID that includes the surface geometry metadata. The algorithm will use inverse geometry, combined with information on the artefact's material and stratigraphic data, to match breakage surfaces amongst artefacts. Using MeshLab, we have already successfully completed a digital reconstitution of two known fragmentary joins from a life-sized limestone statue base with sandalled feet (Figure 8).

Computer-aided reconstruction algorithms are an active area of research in computer science, and have already been developed for archaeological and cultural heritage applications. Although some projects have experimented with geometric shape-matching algorithms, this technology has not been fully developed for 3D objects exhibiting breakages on multiple surfaces, often with worn breaks. One of the first projects to experiment with developing a computer-aided reconstruction algorithm to find joins among incised fragments was the Stanford Digital Forma Urbis Romae Project. In order to find matches amongst the hundreds of stone fragments from the Severan Marble Plan of Rome, the project experimented with several different types of matching algorithms, including boundary incision matching, wall feature matching, multivariate clustering and edge fracture geometry matching (Koller & Levoy 2006; Koller *et al.* 2006; Koller 2008). Ultimately, their attempt to match edges based on preserved geometry was not successful and they ended up relying upon matching the plan incisions. A later project led by Q.-X. Huang was successful in applying a geometric matching algorithm to sculptural fragments from single objects, including the Severan Marble Plan (Huang *et al.* 2006).

A Spanish project has made significant strides using a segmentation algorithm to reconstruct the so-called Aeneas Group of Roman sculptures found in pieces at Mérida, Spain. They developed an algorithm that enabled them to identify the sides of the 3D models belonging to both original and fractured surfaces (Merchán *et al.* 2011). In this case,

Figure 7. Reconstructed model of a terracotta votary figurine (inv. no. AAP-AM-4653, Larnaka District Museum).

the algorithm was only applied to models from a single statue group. The Thera Fresco Project, meanwhile, has set a precedent for the large volume of data acquisition on a scale necessary for our proposed research. They were able to use a 3D matching algorithm to recover potential refit candidates amongst hundreds of fragments of wall frescoes from the Akrotiri excavations (Brown *et al.* 2008; Toler-Franklin *et al.* 2010).

Our proposed project differs from previous applications of matching algorithms in the sheer number of fragments, from hundreds of different votives, and in attempting to use an algorithm to match complex breaks from often heavily fragmented or damaged pieces. In the future, we also plan to experiment with virtual reality (VR) technology to the matching algorithms process. It would be possible to use a VR system to test the joins predicted by the algorithms, 'manually' piecing two fragments together in a digital platform. VR technology is ideal for this application because it is fast-developing, portable and adds a human dimension to the automated joining process.

While the potential of computational predictive algorithms has already been tested with some 3D datasets, a fully automated 3D matching algorithm applied to a large and complex (with regard to scale and material, states of preservation) collection remains extremely challenging. The addition of a human element has the potential to optimise the process and thus increase our success rate significantly. Therefore, to supplement the geometric matching process, we aim to build an interactive VR system that will allow the user to manipulate 3D models to explore potential fits identified by the algorithm, or to find fits that are otherwise unidentified. This system will use a VR head-mount (e.g. Oculus Rift) for immersive display, and a low-cost, hand-tracking device (e.g. LeapMotion) that will allow virtual interaction with models using gesture recognition. The hand gestures will be detected automatically so that virtual 3D pieces can be picked up, turned and manually tested for refit. In cases where the user is able to find and complete matches more reliably than the optimisation algorithm, the VR interface will still allow user-discovered joins to be established and committed to the archive.

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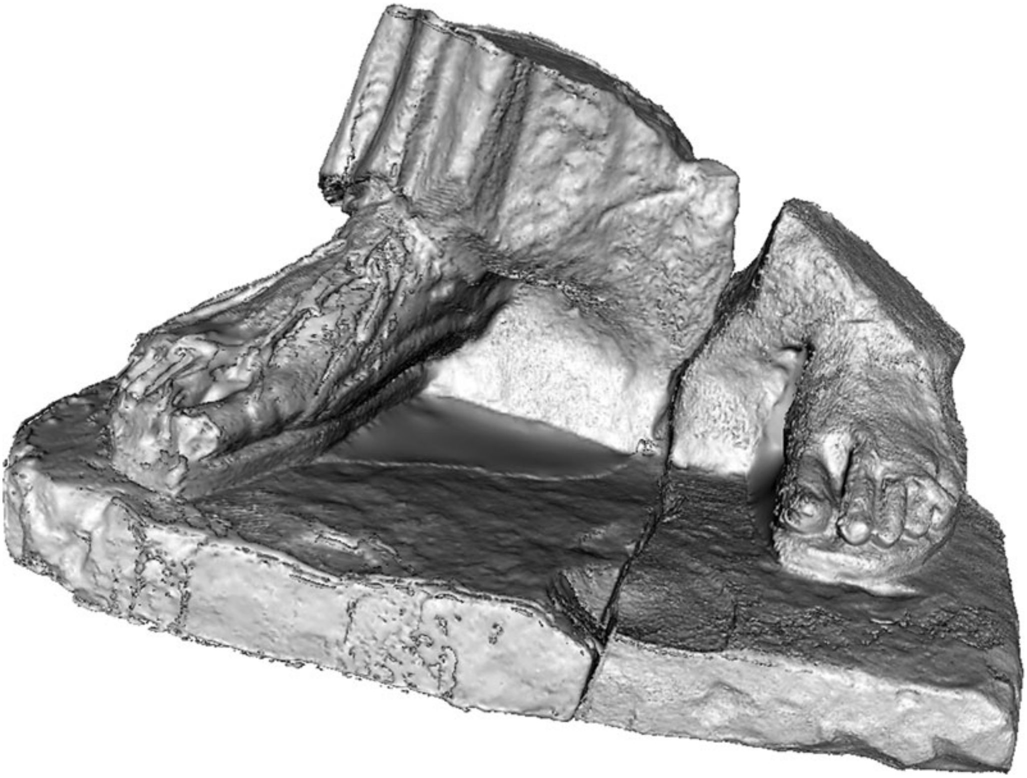

Figure 8. Two joining pieces from a pair of life-sized limestone sandalled feet with base; scanned separately and virtually reconstructed (inv. no. AAP-AM-3900, Larnaka District Museum).

Conclusion

The dynamic alliance between 3D visualisation, archaeology and material analyses has emerged as one of the most successful and promising areas for interdisciplinary collaboration, dramatically changing the way we collect, archive, interpret and disseminate information about the past. AAP's 3D pilot in 2014 featured a useful and cost-effective tool for creating 3D models of a specific subset of the artefacts recovered from the Malloura Valley. This project demonstrated that structured light technology provides both accurate models for detailed artefact analysis and photorealistic images that can be used for creating a digital corpus of artefacts. From a research perspective, the emphasis on 3D imaging as a tool rather than just for demonstration and display, has already granted access to a more robust data set, and can help develop more complete object biographies. These, in turn, may lead to a better understanding of the ritual use of the Athienou-*Malloura* sanctuary. The results of our work advance current dialogues on the role of 3D technologies in archaeological recording and interpretation. Beyond addressing the specific research goals of our own work, we hope that the exploration of innovative methodological practices for acquiring, archiving and analysing 3D datasets will allow our project to demonstrate the potential that 3D visualisation techniques offer for researchers in both archaeology and other disciplines.

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Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.15184/aqy.2015.181

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