Assembling Çatalhöyük

Edited by Ian Hodder and Arkadiusz Marciniak

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ISBN: 978-1-910-52600-2
e-ISBN: 978-1-910-52601-9
ISSN: 2056-6174
e-ISSN: 2057-1011

Cover image(s): *Left*: Ochre hand prints on the north wall of Building 77; *Middle*: Bucrania and horned bench associated with the northeast platform of Building 77 (both taken from Taylor pp. 127–50, this volume); *Right*: The incised panel above burial 327 in TP Area (taken from Marciniak et al., pp. 151–66, this volume).

Published for the European Association of Archaeologists by Maney Publishing, Suite 1C, Joseph's Well, Hanover Walk, Leeds LS3 1AB, UK

Maney Publishing is the trading name of W. S. Maney & Son Ltd.

Printed and bound by Charlesworth Press, Wakefield, UK

Maney
Publishing

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MAURIZIO FORTE, NICOLO' DELL'UNTO, KRISTINA JONSSON AND NICOLA LERCARI

INTRODUCTION

The 3D-Digging Project started at Çatalhöyük in 2009 with the intent to digitally record and display in 3D all the archaeological stratigraphy: the case study is Building 89 (B.89), a Neolithic house (Forte et al., 2012; Forte, 2014). A house is an ideal case study because of the consistency of all the elements interrelated with domestic and ritual activities: in other words, it is the perfect dataset representing the complexity of a social unit. In addition, the experiment is able to demonstrate the relevance of 3D information in a sealed and distinct environment, the house, where diachronic, depositional, and post-depositional activities involve several problems of interpretation, relative chronology sequences, and micro-data analysis (Forte, in press). From the archaeological point of view, this approach forces the interpretation to be more focused on models (by 3D recording), rather than maps, metadata, or two-dimensional documentation. A stratigraphy represented and elaborated in models is a new challenge for archaeological interpretation and reconstruction. In fact, models include more information and stimulate a different understanding of the archaeological excavation.

In over 6 years of fieldwork and digital post-processing, the research team processed terabytes of information, tested different protocols and technologies. This collaborative effort was aimed mainly at the full standardization of different categories of data for different software platforms. As of the beginning of 2015, an integrated and fully operative system of visualization is not yet ready, but it is still under development on the basis of this methodological approach. At the current stage of the project, it is possible to include all the 3D models and spatial georeferenced data in ArcGIS-ArcScene and all the stratigraphy of B.89 in a new software called Dig@IT (developed at Duke University). The models are also implemented for different visualization environments: fully immersive (DiVE), desktop stereoscopic (Z-space), and immersive with head and positional tracking (Oculus Rift). In other terms, for 3D archaeology, 'assembling' means interaction, standardization, management, and implementation of different kinds of data for multiple platforms and simulation environments. The combination of different categories of 3D data—although completely integrated—involves different research perspectives, never explored before. We can call them 'big data', a technical term designing huge datasets (structured or unstructured) collected for a potential public accessibility. Archaeology did not face these issues before, at least before the revolution generated by the adoption of digital technologies and 3D data capture, and visualization.

THE 3D-DIGGING PROJECT

The initial strategy of the 3D-Digging Project was to make comparative testing involving optical, time-of-flight scanners, phase comparison scanners, and computer vision technologies (camera-based), in order to understand the performance and accuracy of the devices in relation to archaeological research questions. More specifically, for archaeological stratigraphy the following laser scanners were used: Minolta Vivid 910 (optical), Trimble GX (time-of-flight), Trimble FX (phase-comparison), and FARO Focus^{3D} (phase comparison). In 2010, the first experiment involved a Minolta Vivid 910 for recording all the excavation layers in a 'midden', a term used for rubbish areas. The focus on the midden was motivated by the micro-stratigraphy characterizing this kind of deposit and very difficult to interpret using an autoptic approach (Shillito et al., 2011). The Minolta Vivid 910 has accuracy in the range of microns and it fits this of kind of investigation. Nevertheless, in terms of general usability, this scanner presents several issues in outdoor surveying because of the hyper-sensibility to direct sunlight and the limited field of view (1 × 1 m). These limitations determine very slow data-capturing sessions and subsequently long post-processing activity due to a large number of point clouds and diffuse data occlusion. In short, so high level of accuracy is not justifiable in terms of technological performance and excavation strategy. In addition, this kind of data (sets of unprocessed mesh) requires a lot of post-processing so that the data cannot be deeply discussed during the excavation.

In 2011, the strategy was completely different and a new system was adopted in order to allow a very quick and daily 3D data recording of all the excavation phases (Forte et al., 2012). Timing is an important factor in relation to excavation strategies and data interpretation. Therefore, two different digital data recording systems were used simultaneously: (i) a new phase comparison scanner (Trimble FX); (ii) a combination of uncalibrated DSLR cameras and image-based 3D modelling techniques based on Structure From Motion (SFM) and Multi-view reconstruction (MVR) software (Photoscan Pro and Stereoscan). In this way, all the layers/units were recorded in the sequence of excavation using both TLS and IBM (Figure 1). The instruments, of course, record all the stratigraphic units of interest but the models have to be split manually in order to visualize correctly the sequence and the relationship with metadata and database. Typically, every session of data capturing lasts less than 10 minutes and produces a dataset of digital images to be processed (on site) afterwards. The generation of the 3D scene is strictly related to the computational capacities of the machine used to process the set of pictures. Laser scanning sessions involve longer post-processing time but produce higher precision data and metric measurements. Image-based 3D modelling returns 3D data almost in real-time but it generates 3D models with a slighter geometrical precision and accuracy than laser scanners. The standardization and speed of this approach involves daily on-site discussions on the interpretation of the archaeological stratigraphy and the 3D spatial relationships between layers, structures, and phases of excavation. The outcome of this digital process is a 3D-multilayered model of stratigraphy related to the depositional and post-depositional phases of the Neolithic building. The B.89 is a quite large house, well preserved and with a well-designed decoration: 3D recording and reconstruction can generate and validate multiple interpretations. In methodological terms, for this building, 3D data recording has followed the procedure of single context excavation: every 3D model was generated in relation to the identification and prioritization of stratigraphic units. Finally, all the 3D models of B.89 were aligned and georeferenced in MeshLab and ArcGIS.

The 2012 fieldwork season diversified the data recording in the following way: artefacts by optical scanner (micron accuracy); stratigraphic units by image-based 3D modelling (accuracy: 0.5–1 cm); buildings and features by time-of-flight and phase comparison laser scanning (accuracy: 3–5 mm); large-scale models (South and North Areas) by phase-comparison laser scanners (0.5 cm). The team of osteologists achieved outstanding results in the use of image-based 3D modelling techniques. In fact, thanks to the systematic use of 3D data recording, the osteologists were able to identify complex sequences of multiple burials and skull retrieval pits (Haddow et al., 2013). 3D models can show hidden connections among skeletons, pit edges, infill, and stratigraphy, not otherwise recognizable. In 2012, 21 burials were recorded and classified with this method and re-analysed in post-processing. Moreover, the interpretation process of human remains at Çatalhöyük has been expanded to a first attempt to employ 3D physical replicas using 3D printing technologies. In 2013, Nicola Lercari digitized via image-based 3D modelling a female mandible (x-find 19829.X2) found in a retrieval pit in B.89 in 2012. He then optimized the mandible's 3D model for 3D printing in Pre-Form software and then printed it (1:1 scale) using a Form 1 printer (Figure 11), a high-precision machine that uses stereolithography to solidify polymer resin into plastic objects. During the field season 2014, the 3D print of the mandible was used to foster on-site discussion between the human remains team and the 3D-Digging project team.

In the case of human remains documentation at Çatalhöyük, the digital workflow involves computer vision

Figure 1. *Data capturing sessions via laser scanning and image-based 3D modelling.*
Courtesy of the 3D-Digging at Çatalhöyük project team.

for data recording (3D models by camera motion, Photoscan Pro); drawing of the burials in CAD and implementation of the models in ArcGIS as digital maps (raster-vector) and 3D models. In this way, all the burials are correctly georeferenced with the general geodatabase of excavation. For example, in the Space 77, Feature 3686 (sk.20430, Haddow et al., 2013), the human remains team was able to reconstruct and interpret a very complicated set of burial sequences (Figure 2). More specifically, a headless primary burial (sk.20430) was identified by the virtual removal of overlying layers of disarticulated bones. In many cases at Çatalhöyük, skull removals, burial events, and human depositions are only identifiable in a 3D sequence, given the difficulties to properly document all the stratigraphy in single pits. The digital simulation (for example in GIS or MeshLab) creates new insights for the interpretation of these platforms/burials placed under the house floors. The adoption of the 3D approach for all the burials at Çatalhöyük opens new research perspectives for human remains improving the ability to interpret data in situ and in the correct depositional sequence.

Methodologies and strategies at Çatalhöyük involve the use of image-based 3D modelling techniques at intra-site/micro-scale level for data recording of buildings, layers, units, features, and burials; laser scanning surveys are used for large-scale documentations (South, North, TPC, and GDA Areas as well as the entire East mound landscape). The laser scanning of large portions of the site is a viable solution for monitoring the state of conservation of buildings and architectural elements, given the serious problem of decay of raw brick architecture. This multiscale approach offers new insights in the interpretation of the site starting from single stratigraphic unit up to the entire areas of excavation. In particular, 3D point clouds include details and accuracy, not achievable once the models are meshed and simplified by interpolation.

Finally, it is important to highlight that excavators at Çatalhöyük, who operate simultaneously in several areas (North and South areas) along with the 3D-Digging Project, were progressively trained to the new digital documentation methods: image-based 3D modelling, 3D polygonal mesh editing, tablet drawing (Berggren et al., 2015; Forte et al., 2012). The first experiments with tablet PCs started in the excavation of B.89 in 2012 and became a standard in 2014, whereas all the trenches adopted the same system using digital field drawing in ArcGIS or QGIS. The 3D approach was extended in 2014 to most part of the site; this was not done in a systematic way, like in the B.89, and not for all the stratigraphy. However, the standardization and the effectiveness of the method fostered all the teams to include 3D models on daily-basis documentation. The increase of the numbers of workstations in the digital lab on site was able to produce 3D models of all the excavation areas by the end of the work hours.

STRUCTURE FROM MOTION AND MULTI-VIEW RECONSTRUCTION

Recent developments in the fields of computer vision and photogrammetry gave archaeologists the opportunity to utilize field acquisition techniques based on digital imagery to generate accurate 3D models. Specifically, SFM-based packages have recently been largely employed to obtain a (semi-automated) processing workflow for the generation of resolute 3D archaeological models (Verhoeven et al., 2012b). The development of this technique represents an important opportunity for archaeological documentation. Using this approach in the field, archaeologists can generate accurate georeferenced virtual replicas of the different data retrieved during the excavation (Callieri et al., 2011; Forte et al., 2012; Dellepiane, 2013; Dell'Unto, 2014; De Reu et al., 2013; De Reu et al., 2014).

Since 2011, this technique has been systematically employed at Çatalhöyük to generate accurate 3D digital replicas of the sequence of contexts detected during the field activities. Specifically, the commercial package Agisoft Photoscan Pro 1.0 was used. This software combines algorithms of Structure from Motion (SFM) and Multi-view Stereo reconstruction

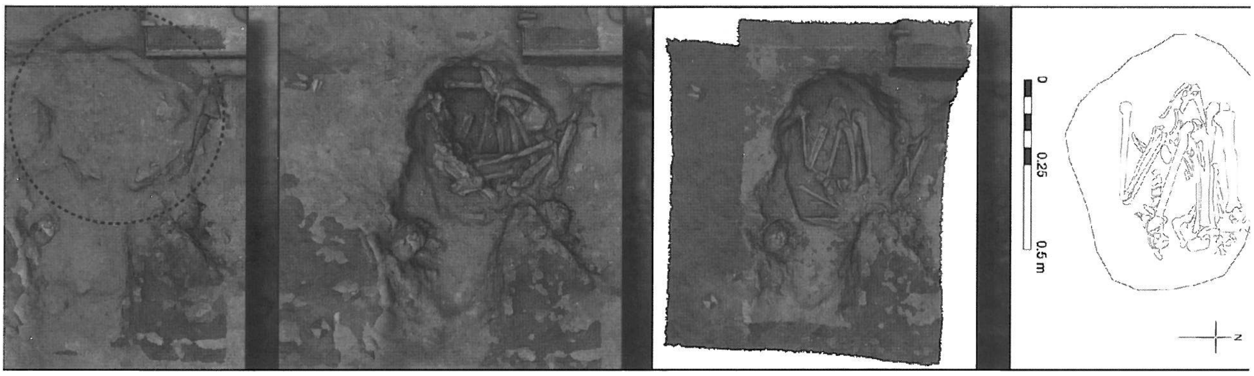

Figure 2. *Virtual excavation of Space 77, Feature 3686 (sk.20430).*

(MVS), to generate a 3D scene starting from a series of unordered images. At first, the software estimates the inner parameters of the camera, detecting and matching common features between each pair of images (SFM). This operation allows computing the locations of those points of interests by visualizing them as sparse 3D point clouds (Verhoeven et al., 2012a).

Subsequently, using the pre-estimated camera parameters, multi-view stereo algorithms are applied to the sparse 3D point cloud in order to create a detailed model of the scene (Verhoeven, 2011; Verhoeven et al., 2012b; De Reu et al., 2013). The use of such technique allowed to generate daily a number of textured 3D models of the contexts detected on site; this capability makes 3D data already available during the excavation campaign. In order to georeference the different contexts retrieved on site, ground control points (GCPs) have been placed on the scene. GCPs were then measured by total station and then used as geometrical and topographical reference for the models. The 3D data generated as result of this process have been used: (i) to create 2D orthoimages to use as geometrical reference for the field documentation; (ii) to implement the 3D GIS developed on site (Figure 3); (iii) to create 3D real-time visualization in Unity 3D suitable for virtual reality systems.

The possibility to employ 3D models in support of the field investigation activities, opened new important scenarios in archaeology. The introduction of this technique entailed the development of new workflows for intra-site digital documentation, which implied the use of 3D models as main geometrical reference. Despite its incredible efficiency and versatility, it is very important to consider that the results obtained using this technique are strongly affected (i) by the camera positions and settings chosen by the photographer (in this case the archaeologists), and (ii) by the light conditions that characterize the scene at the moment of the acquisition. These aspects make this type of documentation more dependent on the skills of the operator, which perform the photographic campaign in comparison with laser scanning. For such reason, before implementing this new technique in the 3D documentation workflow, we defined a robust acquisition strategy that could have been efficiently employed during the entire documentation process, and eventually extended in the future to the entire site.

Currently, one hundred and two georeferenced 3D surface models of B.89 have been generated using this technique. Each 3D object represents an accurate replica of every contexts detected on site. Those data allow us today (i) to reconstruct and review all the steps that have characterized so far the field investigation activity of the Building 89 and (ii) to simulate in three dimensions the stratigraphic relations that characterize the building.

LASER SCANNING

As described in the previous sections, the multimodal digital documentation process employed at Çatalhöyük relies on the integration of an array of cutting-edge survey technologies such as Terrestrial Laser Scanning (TLS), Ground Penetrating Radar (GPR), and image-based 3D modelling.

Terrestrial laser scanning underpins the digital recording process of Çatalhöyük East Mound, both at macro-scale and micro-scale levels. Although laser scanning was previously employed on site (Lees, 2003; Forte, 2010), it was only in 2011 that laser scanners units such as Trimble FX (phase comparison) and FARO Focus ^{3D}S120 (phase comparison) proved successful in the documentation of every stratigraphic layer of a building, specifically B.89, as well as were employed systematically to conduct area-wide surveys of North, South, TPC, and Mellaart's III-0 areas for conservation purposes. In addition, in the field seasons 2010, 2011, and 2012 laser scanners were also used to digitize a number of Çatalhöyük artefacts. This task was mainly performed using a Next Engine optical scanner. Digitization of artefacts by laser scanner has been limited to finds such as figurines, pottery, stone, bone tools and, more in general, small objects.

Starting in the excavation season 2012, a more accurate and precise laser scanning survey has been performed at Çatalhöyük using a FARO Focus ^{3D}S120 phase comparison laser scanner, a powerful, portable, and accurate non-touch measurement device suitable for outdoor survey. The maximum precision of this scanner is 2 mm on 80 m distance. This equipment is capable of 2 mm precision on a 1–25 m distance with a recording time lasting about 15 to 20 minutes per scan and producing coloured point cloud of forty–fifty million points (3D dataset made of points characterized by X, Y, Z coordinates and RGB colours). A built-in camera that features an automatic 70 megapixels parallax-free colour overlay generates the colours that are applied to the point clouds during post-processing.

Given the large number of stratigraphic layers to be recorded in B.89 as well as the vast areas to be surveyed in the East Mound, a scan quality of ⅛ and a resolution of ¼ were employed to generate accurate, RGB coloured, point clouds with a resolution of about 5500 × 4000 pixels and about eleven million points per scan. At this resolution, each scan takes less than 5 minutes so that each TLS survey of a layer excavated and recorded in B.89 takes approximately 15 to 20 minutes, employing an average of two or three scans. Moreover, the built-in camera of the FARO Focus^{3D} is able to add adequate colour information to the point clouds merging brightness and colour automatically in the post-processing phase.

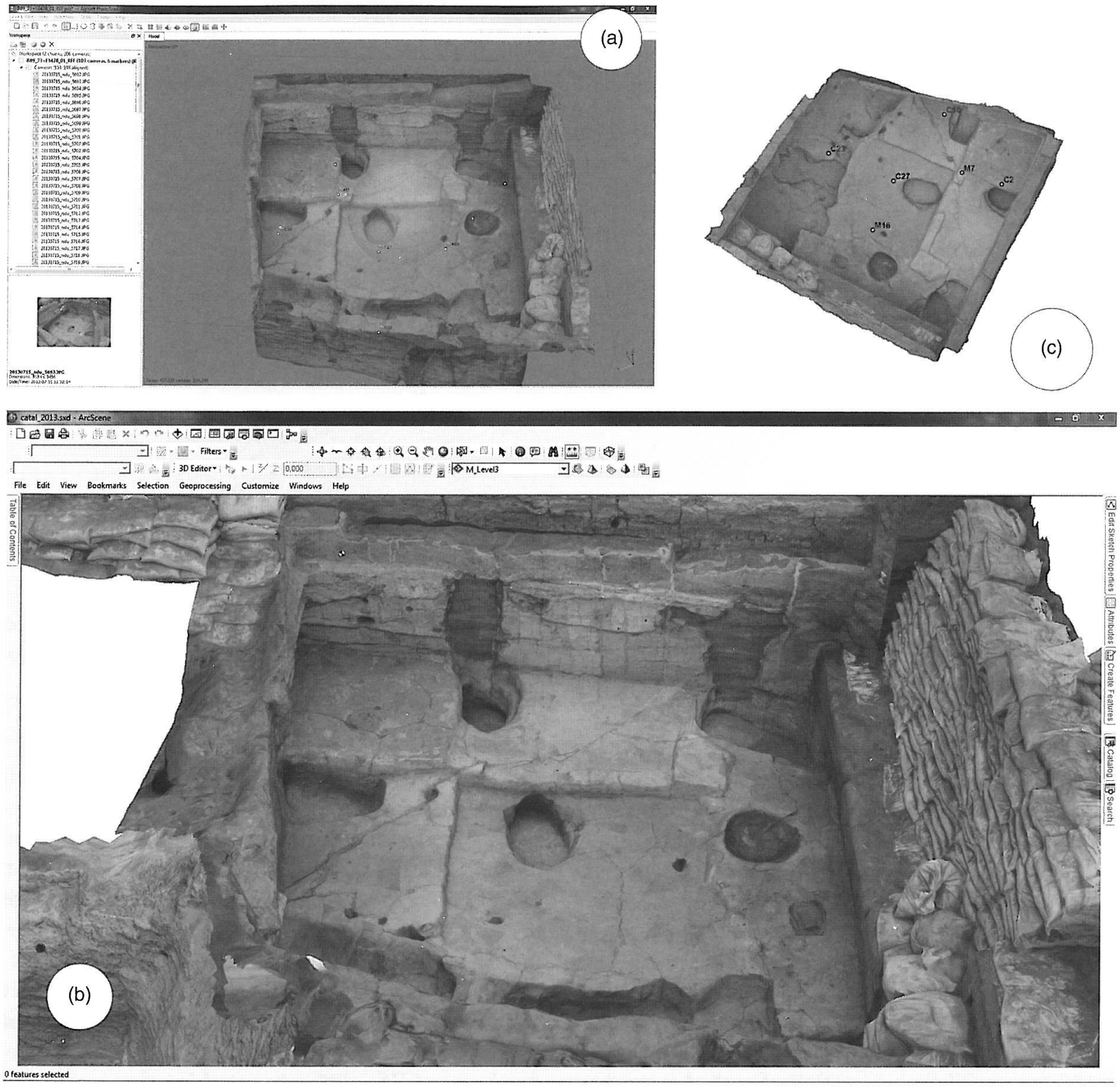

Figure 3. *3D surface model of B.89 generated in Agisoft Photoscan (a) and implemented in the 3D GIS (b) using GCPs (c) to georeference the model.*

Every stratigraphic unit of B.89 has been scanned several times from different positions to allow a homogenous and dense point cloud to be generated. In addition, each scan has been automatically aligned using the FARO Scene 5.1 software, and later georeferenced using measurements provided by the total station survey team. The automatic alignment of 3D scans has been possible by manual or automatic recognition of white sphere targets that were placed around the perimeter of B.89 along with other paper checkerboard target taped to the perimetral walls of the South Shelter. A high-resolution (18 Megapixel) DSLR camera has also been employed to take higher quality photographs of each layer of B.89 with the aim to add to the point clouds more precise and vivid texture colours (RGB information). These photos were eventually added to the registered end-edited point clouds using texture parameterization tools in the open source software MeshLab or in the commercial tool 3D Reshaper.

In 2012, the TLS survey techniques used for intra-site documentation of B.89 were employed at a macro-scale (area-wide) for producing valuable data for the conservation of Çatalhöyük as a UNESCO World Heritage site. Thus, laser scanning became instrumental for the documentation of all the excavated, or currently exposed, buildings of the East Mound. Areas such as South Area and North Area have been surveyed yearly between 2012 and 2014; TPC and Mellaart's III-0 areas were respectively documented by laser scanner in 2013–2014 and 2014 only. Area-wide scanning relies on the same FARO Focus 3D X120 unit

Table 1 *Terrestrial laser scanning workflow at Çatalhöyük*

Workflow	2010	2011	2012	2013	2014
Intra-site survey	X	X	X	X	X
Area-wide survey North Area			X	X	X
Area-wide survey South Area			X	X	X
Area-wide survey TPC Area				X	X
Area-wide survey GDA Area					X
Landscape survey			X		X
Sphere targets		X	X	X	X
Ground control points			X	X	X
Textures recorded by operator	X	X	X	X	X
Textures recorded by scanner			X	X	X
Next Engine	X	X	X		
Minolta Vivid 910	X				
Trimble GX	X				
Trimble FX		X			
FARO Focus ^{3D}S120			X	X	X
Trimble VX					X

used in B.89 as well as on the same sphere and checkerboard targets for precise alignment and georeferencing of the point clouds.

TLS survey at Çatalhöyük is akin to other digital documentation techniques employed on-site and requires the post-processing of as many data as possible on a daily basis. However, given the great deal of data produced by the area-wide survey and the limited processing power available at the Dig House, an extensive visualization of the point clouds via animation videos or interactive sessions can only be achieved after the excavation season. In fact, the limit of TLS in relation to IBM techniques is the amount of time and computational resources required to post-process the large dataset produced by the FARO Focus ^{3D}S120 (e.g. a TLS survey of the South Area generates point clouds of seven hundred million points per seasonal survey). Laser scanning implies faster acquisition time for larger areas and produces higher precision data than image-based 3D modelling while it is less dependent on the personal skills of the operator and the light conditions of the site. TLS involves, though, longer post-processing time to align, georeference, clean, and finally generate triangular mesh surfaces from the point clouds. Image-based 3D modelling returns coloured 3D models of the documented surfaces in real-time but it generates 3D models with a slighter geometrical precision and accuracy than laser scanners.

In 2012 and 2014, TLS was also employed to document the morphology of small quadrants of the East Mound landscape located south and north of the North Area. More precisely, data from the 2012 landscape survey experiment were compared with magnetometry and GPR prospections elaborated by the University of Siena and the University of Southampton. Experiments of remeshing and segmentation of area-wide point clouds were still ongoing in 2014.

3D GIS IMPLEMENTATION

The results previously described, highlighted the importance of finding new visual platforms for merging the 3D data into the current digital documentation system in use on site.

The increasing diffusion and use of 3D models in different disciplines has encouraged the private sector to propose new solutions. Companies, such as ESRI (http://www.esri.com/), have recently invested in developing GIS platforms capable of managing and visualizing 3D information in spatial relation with the current documentation usually managed in the more traditional GIS systems.

After a brief investigation to develop an efficient workflow for the implementation of textured 3D geometries, we started a systematic import of the models into the 3D system.

The visualization of the dataset was performed using ArcScene, which is a 3D platform developed by ESRI that allows displaying GIS data in three dimensions. The high-resolution models, previously georeferenced in Photoscan, were imported and visualized in spatial relation with the shape files created during the excavation. This operation was performed in the field and allowed combining, in the same virtual space, data coming from different analysis (Figure 4).

An important advantage in merging 3D models into a 3D GIS platform stands in the possibility to connect each 3D entity with an attribute table, through which it is possible to link the models with

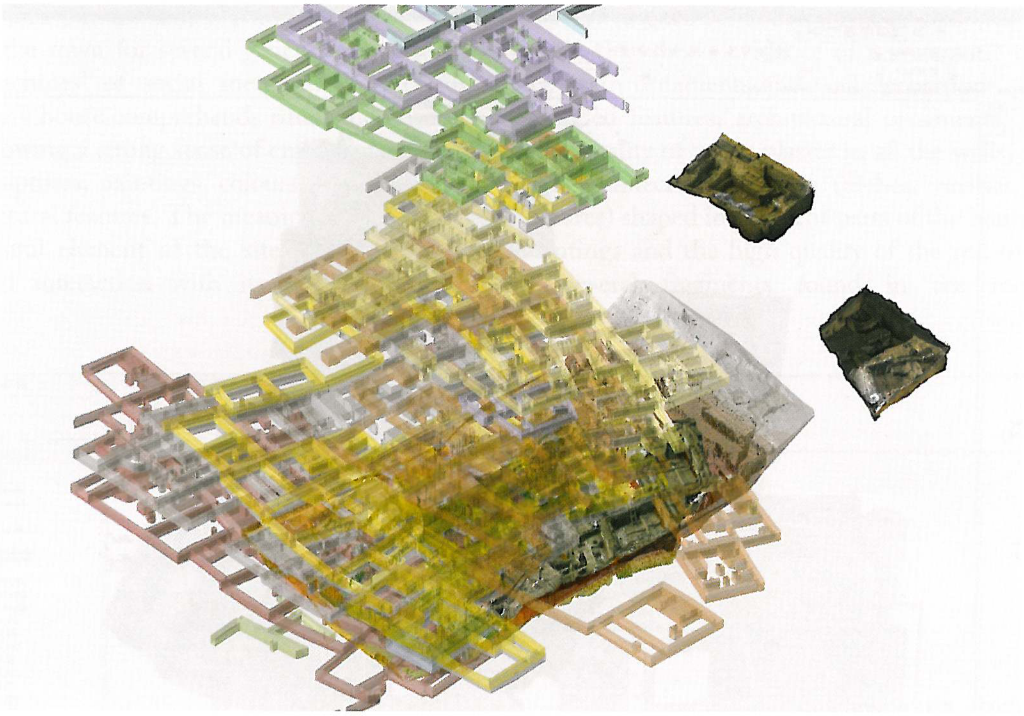

Figure 4. *3D GIS visualization of Mellaart phases superimposed to the models generated by IBM by the 3D-Digging Project.*

different meta-data (Dell'Unto et al., 2015). This allows selecting and displaying, in real time and in the frame of the excavation campaign, different 3D scenarios as result of specific queries. The 3D GIS proved to be the most flexible platform to employ during the investigation campaign, the possibility of the system to be implemented and used by multiple scholars and to host, combine and analyse different typologies of data, makes this tool a powerful instrument of 3D visualization, and certainly one of the most efficient platforms where visualizing the 3D models generated as a result of a documentation campaign.

Further analyses in 3D GIS will involve the reconstruction of the diachronic Mellaart sequence of buildings in the South shelter area (Figure 5) in relation to the buildings recently excavated by Hodder and other research teams (2011–2014).

DIG@IT A SOFTWARE FOR VIRTUAL DIGGING

Interaction and use of 3D models are crucial for data interpretation on site, but also during the simulation process in a laboratory session. During the excavation, all the data have been processed and visualized in MeshLab (Cignoni et al., 2008): in fact, this software includes many tools for data processing, meshing, merging, and layers visualization. However, a higher level of 3D processing was needed in order to better study the 3D connections of models and layers. All the models made by image-based 3D modelling have been optimized and implemented for the DiVE (Duke Immersive Visualization Environment) (Figure 6), a powerful CAVE (Cave Automatic Virtual Environment) visualization environment available at Duke University. The DiVE is a 3 × 3 × 3 m stereoscopic retro-projected room with head and hand tracking powered by a cluster of computers that render interactive 3D scenes in real time. All six surfaces of the DiVE—the four walls, the ceiling, and the floor—are used as screens onto which computer graphics imagery is displayed. In the DiVE, the immersive simulation improves the embodiment and sense of presence of the user in the virtual domain, allowing identification of affordances and 3D connections, otherwise non-visible in the real world. This virtual reality system is powered by a cluster of seven computers that run Unity 3D as a visualization engine and Middle VR Pro for managing the virtual reality scripts that connect the tracking system with 12 Full HD stereo projectors and the scene manager.

The entire B.89 was virtually reconstructed in the immersive system including all the stratigraphic layers excavated in seasons 2011 and 2012 (Figure 4). The handheld controller (wand) allows users to browse the layers and to interact with the models and artefacts in 3D, using an in-context menu. The tracking system connected with stereo glasses allows the system to display the correct point of view related to the true head position of the user. In this way, the virtual exploration augments the sense of presence in the virtual environment.

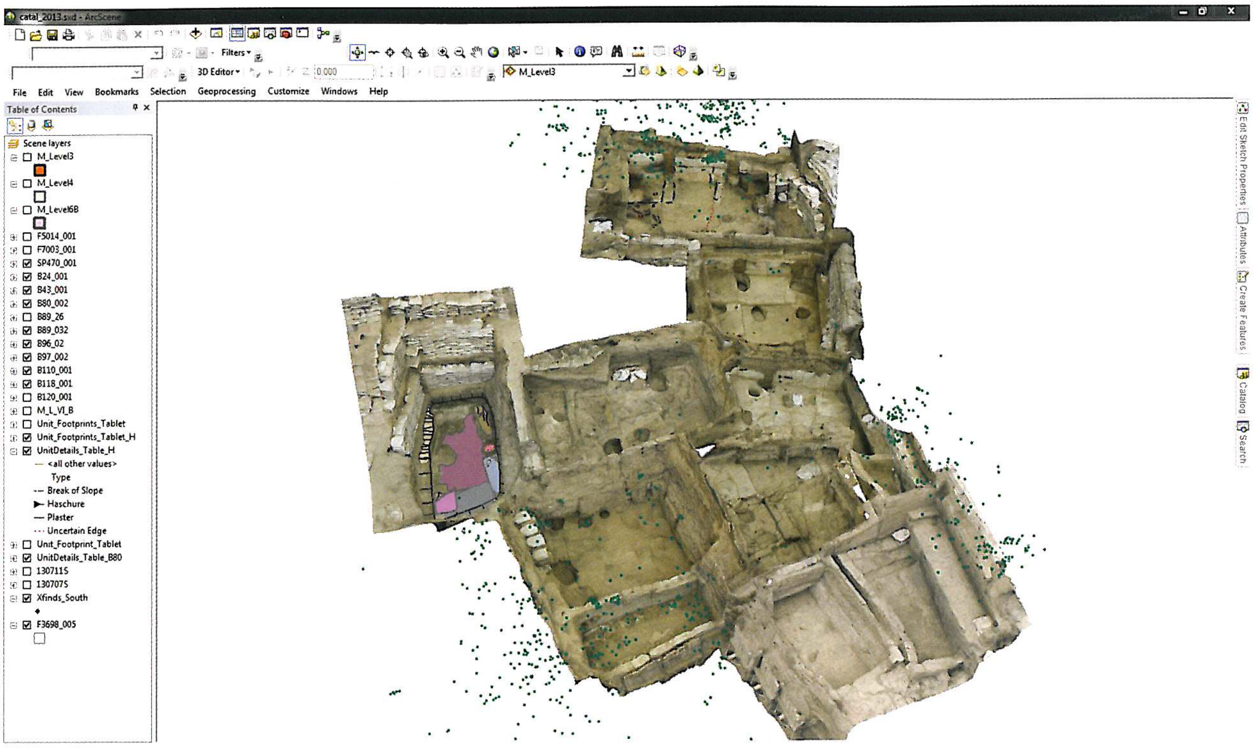

Figure 5. *Diverse datasets—acquired in different field campaigns—were implemented and visualized into the 3D GIS platform (ArcScene) during season 2013. The 3D points (green dots) represent the spatial location of the finds. The polygons and polylines overlapping in B.118 and B.80 were documented by tablet PCs. The 3D models of the buildings were generated in Photoscan.*

Testing visualization and interaction of the Neolithic house B.89 at the DiVE has been quite successful: the 6-sided CAVE rescales the virtual building in a very realistic way, giving the users a very immersive sense of space and the feeling to be in the trench. The interaction with different layers and stratigraphy 'from inside' creates a specific 'archaeological' embodiment, where the users can discuss and see data/models in transparency. Thus, the immersive visualization at DiVE enhances the interpretation of the phases related to the life and abandonment of B.89 allowing users to visualize and interact with 1:1 scale high-resolution 3D models representing each excavated stratigraphic unit of the building. Our work with Dig@IT seeks to clarify whether the interpretation of B.89 is enhanced by the possibility to employ cyber archaeological tools in the simulation of the excavation (Lercari et al., 2013).

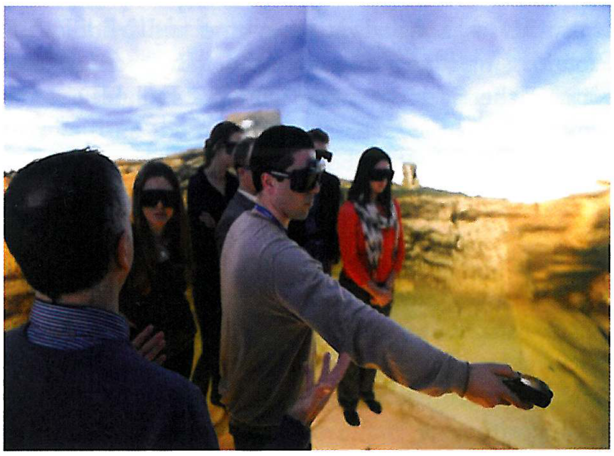

Figure 6. *Immersive simulation of B.89 in the DiVE.*

Specifically, the simulation of B.89 at the DiVE benefits of the following features: clipping planes that cut through layers and emphasize cross-sections not visible in reality, in-context menus to toggle different layers, volumetric visualization of each unit, graphics shaders that enhance the visualization of texture, composition, and colour of the layers, finally a virtual tablet that allows users to access, directly within the simulated 3D scenario, metadata related to the units and features stored in the Çatalhöyük SQL database. The significance of Dig@IT relies on the possibility to enable archaeologists to perceive and analyse the depositional and post-depositional phases of B.89 using a cyber-approach that integrates a plurality of data in a single simulation environment that is not limited by reality constraints (Lercari et al., 2014).

BUILDING 89

Social organization at Çatalhöyük shows a very consistent use of 'patterns' in the form of spatial organization, decorative art, ritual activities, construction techniques, and burials. These patterns constitute the identity of the town for several generations, a sort of 'survival machines' of social memories and cultural models. Every house comprehends ritual and domestic activities showing a strong sense of embodiment developed by sculptures, paintings, colours, motifs, objects, and architectural features. The meaning of every object or architectural element of the site is defined by its relation and interaction with its environment and context (Figure 7). B.89 is a large and well-preserved house that shows evidence of a systematic removal of the main ornaments and wall decorations (sculptures, moulded features, architectural ornaments, etc.). The high quality of white plaster in all the walls, the 'negative' architectural features (niches, cavities, moulded features) shaped in different parts of the house, the wall paintings and the high quality of the red components in several fragments found in the room infill,

Figure 7. Ortho view (a) and perspective view (b) of B.89 in the 3D GIS of the South Area.

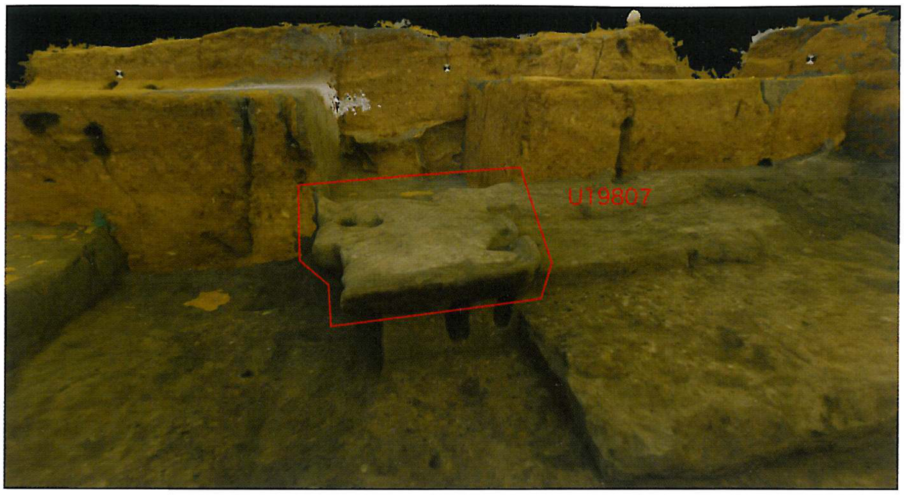

Figure 8. Observable data of unit19807.

demonstrate the remarkable architectural 'rank' of the house in the Çatalhöyük context. The size of the house is also remarkable, around 51 square meters, one of the largest in the South Area.

The 3D systematic digital recording of all the stratigraphy of Building 89 has meaningfully refocused the archaeological interpretation to the multiple relationships among different kinds of units (positive and negative), activities (living phases of the house or post-depositional), and architectural elements. For example, in the case of the Unit 19807, a moulded architectural element (Figure 8), the simulation of the stratigraphic context in transparency (Figure 9) shows very clearly the relations between this unit, the house walls, and the rest of the room infill.

3D simulation is also helping the excavation team to study more in detail the sequence of floors and in general the microstratigraphy associated with this kind of layers.

The preliminary microscopic analyses performed by Aroa García-Suárez on the floors stratigraphy (University of Reading, oral communication on site) are able to recognize up to 22 floors in only 14 cm of stratigraphic thickness. This helps to estimate the existence of over 50 floors for the house in a life span of 55–60 years (as usual in many buildings at Çatalhöyük).

Going back to the above-mentioned embodiment, the house can be seen as a social unit ruled by a virtual trigger, able to transform a domestic unit in a ritual space and vice versa. The core of this process is in the role of the affordances that is the potential relationships generated by ornaments, sculptures, architectural features, burials, wall paintings, textures, and colours. It is a very complex taxonomy and it is based on the role of the embodiment able to connect the social mind to the potential activities running within the building in different spaces/time. In other words, the affordances

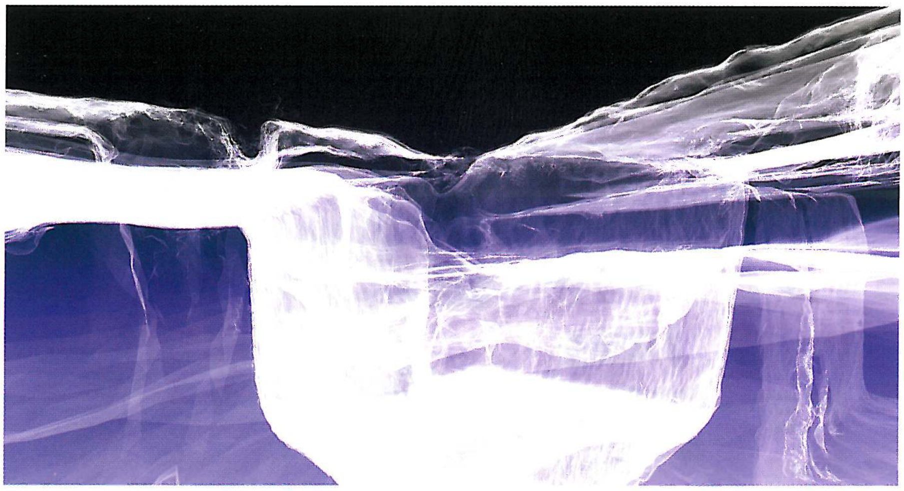

Figure 9. X-ray shader applied to the 3D model of unit19807.

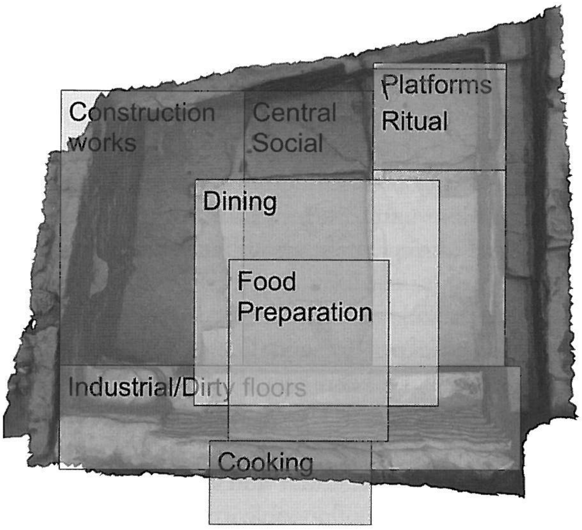

Figure 10. *Main activities and affordances in the spatial domain of B.89.*

guide the performing roles of the different items of the house: decorative, ritual, functional, aesthetic, productive, domestic, collective, social, and so on. We have therefore to imagine an embodied mind able to imagine all these performing objects as activities, whether or not they are really executed. This visual and multi-sensorial spatial pattern stimulates the embodied mind to recall the affordances. The repetitiveness of the patterns across generations and in different buildings indicates the pressing need of an entire community to elaborate a high-fidelity cultural and social transmission.

Figure 10 shows the spatial reconstruction of potential activities within the Neolithic house B.89. This perfectly explains the role of affordances/activities performed inside the house in different spaces/time. The overlapping of different functions displays how different areas of the house recall diverse activities: domestic, social, ritual, industrial, and so on. These relations are not easily representable in traditional archaeological maps and in single stratigraphic units, but they can be visualized in a 3D simulation and in immersive virtual environments.

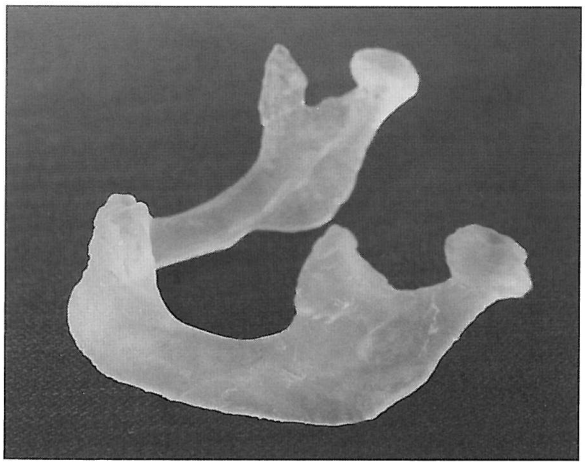

Figure 11. *3D print of human mandible 19829.X2 retrieved in B.89 in 2012.*

In the season 2012, a human mandible with plaster and red painting was found in a retrieval pit and documented in 3D (see paragraph on *3D-Digging Project*) (Figure 11). When the soil was carefully removed from the bone, red pigment (probably ochre) was clearly visible on the body and rami of the mandible. In addition, a thick band of plaster covers the anterior dentition. It is possible that this mandible was originally attached to a similarly modified cranium.

SYSTEM EVALUATIONS

Image-based 3D modelling has, to some extent, also been tested and used by the other diggers at Çatalhöyük who are not part of the 3D-Digging Project. Nevertheless, the 3D data capture has not been implemented yet in the daily routine of standard documentation on site. In season 2012, a test was made to replace the paper-based 'daily sketch' documentation in Building 97 (B.97) with an interactive 3D model codified in 3D Portable Document Format (3D PDF). Daily sketches have been part of the documentation process at Çatalhöyük for years. This type of documentation is normally based on a digital photo of the excavation area, which is first printed on the paper onto which excavators write comments and draw annotations on a daily basis. The comments are intended to reflect the ongoing interpretation of features and structures, rather than the archaeological progress. Upon completion, a daily sketch is scanned and subsequently stored in the Diary database, with references to the units/features it describes. In the test that was performed in B.97 in 2012, markers and annotations were added directly in a digital format to a 3D model using Acrobat Pro. The model was created using Agisoft Photoscan and MeshLab, and then it was exported as a 3D PDF file.

The advantage that a 3D-daily sketch has over its paper version, is related to the higher amount of information it stores and displays regardless of the written comments; to have a daily model showing every nook and cranny of the building under excavation is of course an incomparable source of documentation that was even enhanced by metadata and annotation. 3D-daily sketches not only make it possible to go back and see how features exactly looked like at earlier stages of the excavation (at least, what they looked like at the end of a specific day), but present georeferenced data. This option allows archaeologists to verify post-ex the extent, orientation, and spatial relationships of

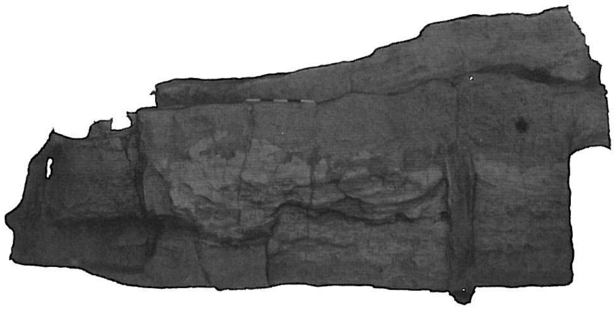

Figure 12. Orthophoto of B.97 south wall section generated using image-based 3D modelling.

excavated features. In B.97, the 3D models were also used when working with section drawing of walls. Instead of struggling with manual drawing of an uneven surface, sections were produced using scaled orthophotos as templates (Figure 12).

In season 2014, tablet PCs were eventually adopted as the official means for drawing archaeological plans. Digital drawings and annotations were made in ArcGIS—instead of on drawing film—on top of georeferenced photos. Initially, archaeologists who were documenting large structures such as walls in B.97 struggled with tablet PCs because the built-in camera lens of the tablet is not exactly suitable for capturing big areas. In this regard, image-based 3D modelling was a great help to support the digital documentation process. Instead of generating poor imagery with the tablet, 2D georeferenced orthophotos were generated using 3D models produced with the image-based 3D modelling techniques described in the previous sections. The orthophotos not only were able to display the entire building, but also had a much higher accuracy than single photos of the same area taken with a tablet. Using orthophotos allows us to solve the problem with skewed perspectives and faulty scaling that you can get when rectifying and georeferencing one single photo taken with a tablet.

Archaeological documentation is rapidly becoming more and more digital in the field. This is, in many cases, a welcome development; although the accuracy, precision, and effectiveness of the digital documentation continuously need to be assessed and reassessed regarding choice of methods, equipment, and implementation. For instance, the use of a total station or RTK GPS for documentation instead of manual drawing is commonplace in many countries today, but it has its disadvantages since you cannot achieve the same detailed accuracy for small or complex features. For example, in Sweden, image-based 3D modelling and the rendering of georeferenced orthophotos are now gradually replacing digital measuring, since it makes the documentation process less time-consuming and more accurate. Digital plans can still be produced if needed, but at the desk instead of under the open sky. As pointed out above, 3D models of layers and contexts make extraordinary supplementary records of the archaeological features as well as tools for interpretation, even if they cannot stand completely for themselves. 3D documentation is also a great medium for illustration and dissemination of what the site looked like during excavation, and, at large, these methods may be used for further visualization of past environments and landscapes in larger scale models.

Hence, the experiences at Çatalhöyük—where the 3D methods have been tested and refined through several years by the 3D-Digging project—should be taken into account by other archaeological projects worldwide, in both research and contract archaeology initiatives. The range of possible implementation will of course depend on available resources, time, and funding; in fact, it is important to bear in mind that what may seem an expensive investments in technical equipment and specialized expertise is actually a way of saving time otherwise spent on manual documentation and processing. Time is money, and since the end products are mainly digital today, the earlier on in the process we go digital the more time we save. By cutting out the intermediary manual conversion of analogue data to digital, the end product will be even better and have a great potential for further elaboration.

It is also important to remark that a large mass of digital data are produced in a very short time, but they are easily managed by different software keeping the same spatial information. This growing amount of digital information characterizes the new trends of fieldwork archaeology and fosters the research teams to create new open and online repositories able to host and update large datasets in three dimensions.

CONCLUSIONS AND FUTURE WORK

The use of 3D models has a broad impact in managing, visualizing, and querying archaeological data. This impact will be also bigger once all the 3D data will be available in an open access Web 3D repository. In addition, the project creates fully scalable data: from GIS platform to virtual immersive systems to game engines. In our case, thanks to the Middle VR plugin for Unity 3D, all the data are compatible with many visualization devices and virtual reality systems.

The digital workflow we used in the fieldwork is somehow revolutionary in comparison with the 'traditional' methodologies of documentation and data processing in archaeology (Forte, in press). The drawback of this new inferential activity is the generation of very large datasets even in one season of fieldwork

(Berggren et al., 2015). This approach generates the need to manage terabytes of data in few weeks as well as the necessity to archive them for future digital access (online and offline). It is quite clear that these advancements can change the way archaeologists interpret, share and communicate data, and deal with the idea of 'reconstructed past'. It would be more correct to discuss about simulated pasts, rather than reconstructed ones. In fact, the new digital methodologies force our interpretation to be focused on the performance and simulation of models and on the involvement of different variables. Therefore, the interaction becomes the starting point of the interpretation process: it opens new research perspectives.

3D archaeology, as new domain, introduces different and more advanced inferential methods of interpretation, which do not necessarily pursue the achievement of better results, but they enrich the meta-interpretation: how we learn to learn. 'Thinking' in 3D is something different: new perceptions, awareness, connections, and affordances are involved. The migration of 3D worlds in immersive systems, such as 'CAVEs', haptic systems, and holographic projections generates a different kind of embodiment and spatial relationship between the body and the environment. The embodied archaeologist is immersed and surrounded by interactive and performing data and models: the interpretation comes from a simulation process. An interesting example is the use of Oculus Rift, a new and portable head-mounted display. This system uses accelerometer and gyroscope sensors and allows a very accurate perception of the scale and spatial presence in the virtual environment. This augmented embodiment is able to stimulate additional affordances and a deeper sense of tangibility of digital objects.

The 3D digital reconstruction of an archaeological excavation with the above-mentioned methods is very accurate, but it is still far away from a reproduction of what is in situ: in short, it is an incomplete representation. What is missing, indeed? Volumes and stratigraphic context, for instance. Laser scanners and digital cameras record the surface of stratigraphy and deposits but they do not go through the interface (Figure 13). We still do not see what is invisible for the naked eye; this is still a relevant constraint. In the future, we should be able to combine geophysical prospections with photogrammetric methods: in that way it should be possible to integrate the geometrical information of stratigraphic units with their volumetric content (this is not really possible with the current remote sensing technologies). Another missing target is the identification and classification of units, usually validated just by autoptic and empirical analysis of the diggers and not on a more 'objective' control by digital instruments. In this regard, it would be interesting to experiment multispectral cameras for the recognition of specific depositional or post-depositional features in the excavation. Definition and recognition of 'unit' is still based on very subjective criteria: the soil conditions, the experience of the archaeologist, the research questions during the fieldwork and so on.

The 3D simulation of spatial data (GIS, remote sensing, architectural models, databases, etc.) offers a first holistic understanding of 3D connections and relations

Figure 13. *Aligned point clouds of B.77 scanned in 2012.*

otherwise non-visible or identifiable. For example, the 3D superimposition of different phases of the site (Mellaart excavations with the last archaeological excavations; Figure 4) with Digital Elevation Models, archaeological finds, GIS layers, and any kind of dataset, multiplies enormously the capacities of interpretation overtime. In fact, geospatial 4D modelling is the only possible tool for analysing temporal data and evolution of the site.

The Duke team is currently exploring new research directions in regard to the portability of 3D datasets in virtual immersive systems. The scope is the investigation of cognitive aspects of the digital interaction: how does the interpretation augment in relation to stereoscopic view, holographic projection, head tracking systems, and immersive visualization? For this scope, the first experiments are focused on two systems: a holographic head tracking screen (z-space) and an immersive system, the DiVE. In the case of Z-space, the 3D models, originally in OBJ file format, are exported in Unity 3D where they are scaled and properly adjusted with lights, shadows, and textures. The results of this process are holographic projections and collaborative visualization: the user can interact with a 3D stylus, disassemble, and reassemble the models or modify them.

The DiVE is a CAVE, one of the few 6-sided CAVE-like system in the United States. All six surfaces—the four walls, the ceiling, and the floor—are used as screens onto which computer graphics are displayed. The virtual simulation within the DiVE increases the embodiment and involves a collaborative participation of different users: in the case of the Neolithic house B.89 for example all the projected walls match the same size and position of the real ones and the floor as well. Therefore, the DiVE augments significantly the sense of presence and space within a Neolithic house documented by laser scanning and image-based 3D modelling. For example, it is possible to study in detail all the 3D relationships between empirical data, stratigraphy, and hypothetic reconstructions. This approach introduces a quite unexplored digital hermeneutic circle in archaeology whereas empirical data are synchronized with digital potential reconstructions and multiple visualizations (Forte, in press).

ACKNOWLEDGEMENTS

The 3D-Digging Project is supported by the Bass Connection Grant (Duke University), the Department of Classical Studies of Duke University, and Trimble Navigation. Special thanks are due to all the American and international students who attended the fieldwork seasons at Çatalhöyük and the team of Building 89.

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