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Journal

International Journal of Heritage in the Digital Era, 1(3)

ISSN

2047-4970

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Publication Date

2012-09-01

DOI

10.1260/2047-4970.1.3.351

Peer reviewed

3D ARCHAEOLOGY AT ÇATALHÖYÜK

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1. Introduction

The project “3D-Digging at Çatalhöyük” (fig.1) aims to virtually reproduce the entire archaeological process of excavation using 3D technologies (laser scanners, photogrammetry, computer vision, image modeling) on site and 3D Virtual Reality of the deposits of Çatalhöyük as they are excavated (in lab through teleimmersion). In this way it is possible to make the excavation process virtually reversible, reproducing digitally all the phases of excavation, layer-by-layer, unit-by-unit. In fact key issues in archaeology are: reversibility of the excavation process, transparency of data in the reconstruction of 3D models, accessibility and elaboration of data during the interpretation process, and final representation and communication of data. The interpretation phase uses both a bottom-up and top-down approach. The bottom-up approach concerns the documentation during the excavation, by layer, units, artefacts or contexts, while the topdown phase is related with the interpretation process (identification, taxonomy, cultural contextualization and comparative studies). The final goal of this project is to create a virtual collaborative space where it is possible to make the excavation process completely sharable in both phases.

The Neolithic site of Çatalhöyük in Turkey, can be considered, for many reasons, an ideal case study for facing complex research methodological questions. More than thirty years of studies, archaeological fieldwork and research have been devoted to investigating the ideology, religion, social status, architectural structures, art, environment and landscape of the site, producing several publications, books and other media (<http://www.catalhoyuk.com/>), but only a small percentage of the entire area has been excavated (Hodder, 2000; 2006; 2007, 2007a-b). The UCM team excavates at the site over the summer, but much of the analysis and interpretation are done in home universities and research centers, necessitating global discussion and interaction.

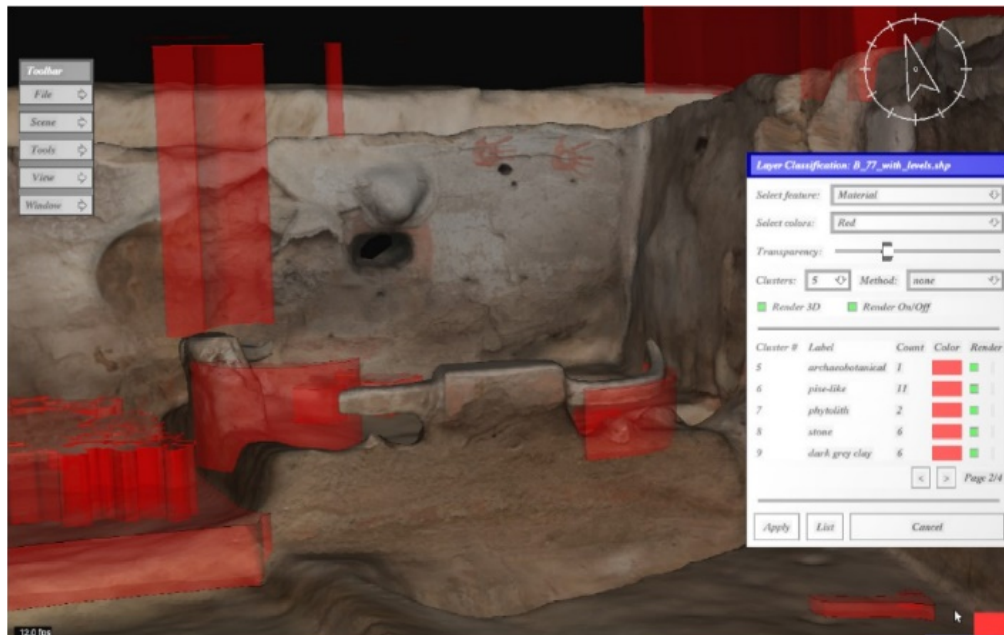


Figure 1: virtual model of Building 77 with GIS layers. Vruil software developed by UCM and UC Berkeley

Unlike traditional 2D technology, 3D reconstruction of deposits allows the archeologist to develop more complex understandings and analyses of the deposits and artifacts they excavate. Digging is a destructive technique: how can we reanalyze and interpret what we excavate? How to simulate an archaeological excavation with all the stratigraphy? And if we simulate virtually an

excavation, how can different archaeologists collaborate in the same virtual space from different locations while sharing the same archaeological data? The digital recording does not per se solve all these issues if not supported by a robust methodological workflow. The 3DDigging project is experimenting with the integration of different technologies with the main goal to post-process all the data during and not after the excavation, to discuss and visualize the data in stereo-vision on site by 3D projectors and to share them for collaborative teleimmersive sessions at the end of the season (Forte, Kurillo, 2010). The key factor is not in data recording but in data handling and interaction.

Below a scheme of the digital workflow:

1. Digital recording by laser scanning (phase shift) and image modeling (DSLR cameras and specific software such as Photoscan). Data acquisition of any single phase of excavation and layer. Time sessions of 15 minutes.
2. Digital recording of artifacts by total station.
3. Post-processing of all the 3D data on site: decimation, interpolation, meshing (software Meshlab, Photoscan)
4. Spatial integration of all data (layers, stratigraphy, models) in one viewer (Meshlab, Vrui Toolkit)
5. Implementation of data and models for the Teleimmersive system (Vrui Toolkit)



Figure 2: laser scanning session in the building 89

The particular innovation of 3D-Digging project is the quick 3D manageability of data on site and during the phases of excavation. These factors significantly increase the capacity to interpret the datum in a new hermeneutic process involving different ontologies: by real data, virtual data reconstructed and by simulation of the digital context in remote (figs.2-3-4). The use of 3D technologies on site as teaching and research aids, and the post processing and the implementation of all the data in the lab for the collaborative virtual visualization systems (see <http://sites.google.com/site/telearch/>) allow for a very advanced workflow (never experimented before in archaeology) for the final interpretation (figs.4-7).

2. Digital methodology

3D archaeology currently is still far from employing standardized methodologies and technologies. Nevertheless in the last two decades we can count several experiments and applications (Forte, 1994; Tsioukas, V., and P. Patias, 2002; Barcelo et al.2003, 2004a-b; Benko et al.2004; Doneus Neubauer, 2003, 2004, 2005; Earl, 2007; Katsianis et al. 2008; De Felice et al.2008; Sangregorio et al. 2008; Galor et al.2010; Gay et al. 2010; Petrovic et al. 2011; Sanders, 2011) generally categorized in the domain of 3D archaeology, 3D excavations, 3D reconstructions and simulations, 3D web, 2.5 GIS and so on. In general, the focus is much more on the 3D interaction with models and data rather than the data themselves. Basic goals are: reconstruction of the stratigraphic sequence, visualization of layers and artefacts, interpretation and contextualization of the site, mitigation of the destructive techniques of excavation. Even if the general scope appears the same, the methodological approach is actually very different when examined case by case. A problematic issue is that too many applications are technologically oriented and not based on specific research questions or a pre-defined hermeneutic circle. In addition, the use of 3D technologies is often more related with episodic experimental activities rather than systematic applications or standalone systems. This of course is very understandable: in the past 3D technologies were very expensive, time consuming, needing specific levels of expertise, high cost of computing, and required

long term post processing. In other words, it was very difficult to get data in real time and really able to have an impact on the archaeological interpretation on site during the excavation. Post-processing, archiving, accessibility and migration of digital models are always the bottleneck of any digital archaeological research.

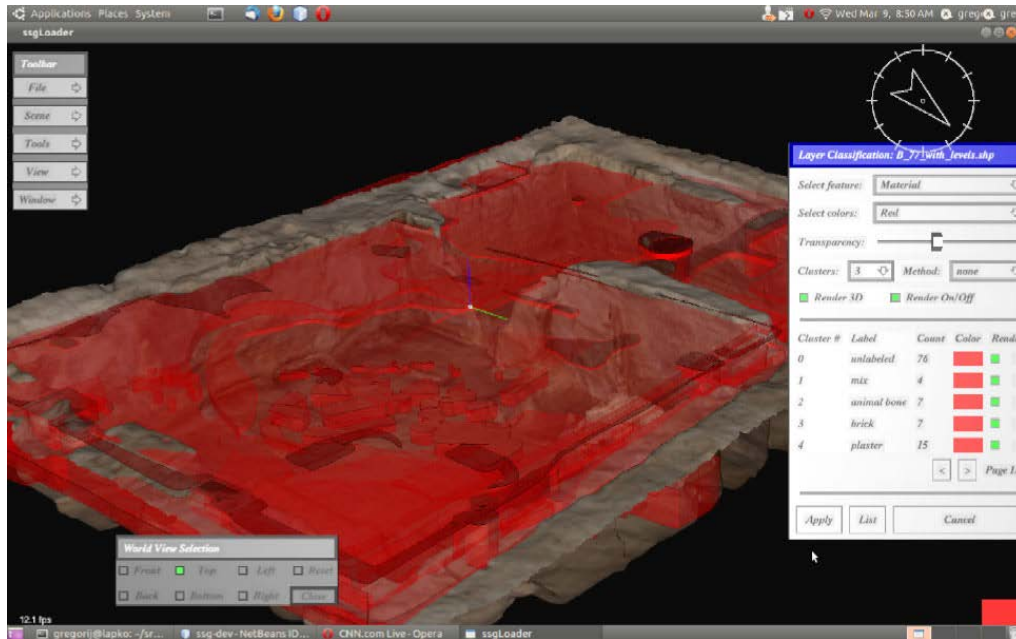


Figure 3: 3D model of the building 77 with a selection of layers in transparency, Vrus software



Figure 4: a session of digital shooting for 3D image modelling (building 89)

If we approach a brief overview of 3D methodological approaches it is possible to categorize them in the following list:

- 3D surface modeling. First experiments of 3D modeling or archaeological stratigraphy and excavation based on the interpolation of multiple points taken by total station with texture overlapping. This was able to enhance the importance of microtopography even before digging (Forte, 1994).
- 2.5 GIS. GIS multilayer surfaces visualized in 3D views. The evolution of GIS from 2D to 2.5 has allowed this kind of visualization (Lock, 2003).
- Macro scale remote sensing. At a macro-scale level: stereo reconstruction (or by DTM) of spectral imagery for the scientific visualization of sites and landscapes.
- Geophysical applications. 3D predictive models based on geophysical prospections (for example, Campana, Piro, 2009).
- Image-based 3D modeling (software photomodeler, image modeler) by first generation algorithms of computer vision.
- Site-wide 3D laser scanning. Applications of time of flight scanners on entire sites just at the end of the excavation (1 single phase of documentation)
- 3D laser scanning by layers (multilayer documentation, for example Doneus, Neubauer, 2005.)
- 3D experiments of digital integrated technologies (for example the REVEAL Project, Gay et al.2010)
- 3D on site processing and teleimmersion (3D-Digging project)

Below a schematic table summarizing the data sheet of the main 3D devices we have experimented during the first 2 years of project.

Laser scanners	Scan range (depth of field)	Accuracy	Field of view	Scanning Speed
Minolta 910: Optical	0.6 to 2.5m	X:±0.22mm, Y: ±0.16mm, Z: ±0.10mm	TELE: Focal distance f=25mm	307,000 pts
Trimble GX: Time of Flight	350 m to 90% reflective surface 200 m to 35% reflective surface 155 m to 18% reflective surface	position = 12 mm @100 m: distance = 7 mm @ 100 m	360 x 60	up to 5000 points per second
Trimble FX: phase shift	up to 60 m (50% reflectivity); 35m (30% reflectivity) 2-pass. up to 80 m (50% reflectivity); 45m (30%)	0.4 mm @ 11m; 0.8 mm @21m; 2mm @ 50 m	360° x 270°	216,000 points per second
Nextengine: optical	0.50 m	±0.005" in Macro Mode and ±0.015" in Wide	5.1" x 3.8" (Macro) and 13.5" x 10.1"	50,000 processed points/sec

Table 1: the table summarizes the data sheet of the main 3D devices employed during the first 2 years of project

3. Recording at Çatalhöyük

Çatalhöyük is a site that is well known for a variety of reasons, the most relevant to this case study being the intended reflexive nature of the excavation and the ongoing experimentation seeking to fine-tune archaeological methodology from preplanning the excavation throughout data publication and beyond. Much has been written on the excavation methods at Çatalhöyük (Hodder, 1997, 1998, 2000,

2001; Farid, et al., 2001; Chadwick 2003; Berggren and Hodder, 2003). This segment, however, is intended to describe only the recording process on site and while there will be a necessary, albeit brief, mention of excavation methodology; the main focus will remain on the recording procedures.

To reiterate some foundational archaeological principles, most archaeological sites, including Çatalhöyük, are the result of formation processes (deposition as well as removal). MIDDLE: Focal distance f=14mm WIDE: Focal distance f=8mm Understanding past activities primarily comes from the contextualization of that activity within the stratigraphic sequence (MoLSM, 1994). Contexts or units-defined as any action that leaves a trace, positive or negative-are ordinarily recorded and excavated one at a time at Çatalhöyük, although there are times when contexts are divided into multiple segments in order to give the excavators a higher level of control-as was the case during the 2011 field season for our team.

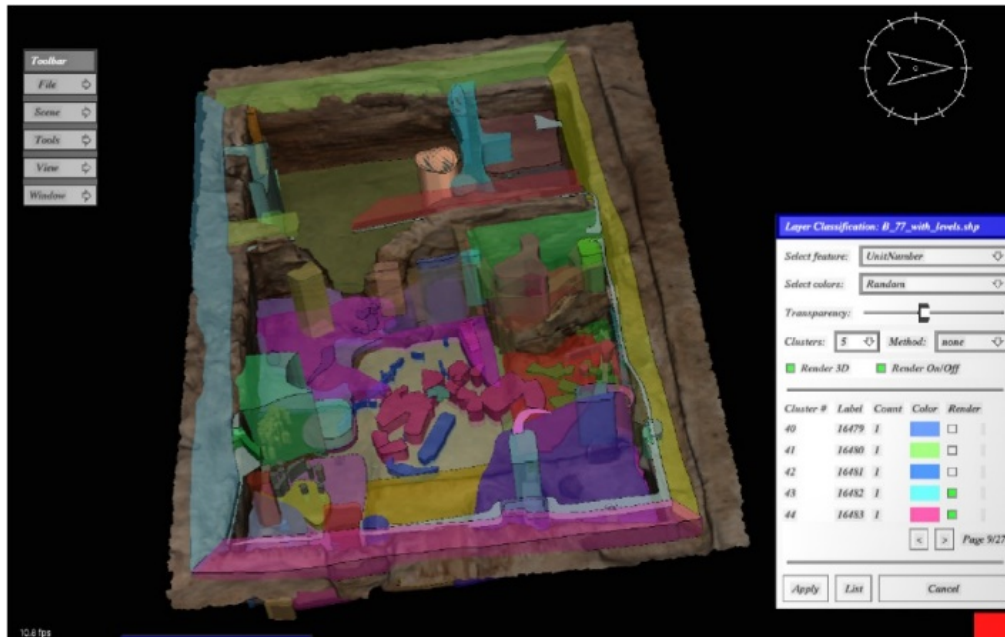


Figure 5: 3D query of several layers in building 77, Vrui software

The excavation, as well as the recording procedures at Çatalhöyük are generally derived from the Museum of London Site Manual, originally published in 1980 and revised in 1990 and again in 1994. The process consists of recognizing, recording and excavating units one by one. Associated with each context is a unit sheet, a plan of the context that is mapped in plan view on a sheet of permatrace on a 1:20 scale and a number of photographs from different angles; some of which include a photo board with more identifying details regarding the context. As the unit is excavated, the information on the unit sheet, as well as the plan, can be amended and adjusted as necessary and X finds-small finds and/or finds associated with floors or features-are planned and bagged separately. All finds are collected and turned into the finds lab at the end of each workday and the process is repeated for each new context and the excavator updates the matrix with every new relationship.

There are, however, a number of variations in place-throughout the excavation and the recording process-that allow and encourage on site interpretation, interaction, multivocality and therefore reflexivity.

From a methodological point of view, it is these variations that distinguish Çatalhöyük from most other archaeological sites. Priority tours, for example, are opportunities for specialists to tour the excavation and interact with excavators. The use of video recording equipment on site allows excavators to narrate their experience through a different medium with fewer restrictions than the more standardized and traditional excavation and recording procedures. Similarly, the utilization of the on-site diary-by all members of the research team- allows for a much less formal narration of not only the excavation but also other events and discussions that take place on site. Sampling methods have also been adjusted. In addition, to regular sampling for flotation and archive extracted for every context, other samples are taken as necessary and are fully described in the appendix of the Farid, et al. article (2001, 30-35). Additionally, a number of these distinct practices have been implemented with the specific objective of softening the strict recording system, as well as, creating a structure that allows for the free dissemination of information-including site data-to research teams working at Çatalhöyük, as well as external researchers and the general public. For example, unit sheets and plans, once completed and checked by the area supervisor, are immediately digitized into the site database and become available to all on-site researchers. Once the field season is over, the database information is incorporated into the official Çatalhöyük website (<http://www.catalhoyuk.com/>) and then available to external research and public curiosity. It is important to note that database entries are later checked in order to avoid data- entry errors; the unit plans are digitized by GIS specialists on site that also integrate them into the larger site map.

Altogether, open access to the database, routines that encourage interaction between team members as well as alternate mediums of data narration and recording, aim to inject more voices, as well as self-critical awareness into a relatively rigid recording system.

4. 3D Laser Scanning

The role of laser scanning in the archaeological documentation process has been widely relegated to that of a pre/postexcavation digital documentation tool. There are a multitude of factors driving this perception, namely the high cost of laser scanning systems and the availability of archaeologists properly trained to utilize the technology, but laser scanning as a technology holds significant potential to revolutionize the way in which documentation of the excavation process is carried out. One of the questions our team sought to address was how does laser scanning fit into the archaeological excavation process, and in which ways could we maximize the utilization of this technology beyond that of a pre-excavation and/or postexcavation digital documentation method (fig.5).

Archaeological Excavation “is tantamount to the destruction of the site and can be thought of as a non-repeatable experiment” (Scollar 1990: 38). Digital archaeology-and laser scanning in particular-affords us the possibility to mitigate the finality of this destructive process in the form of a more comprehensive-as well as digital-method of documentation of the excavation process (figs.2, 5, 6, 7). By scanning individual units and features in situ, and geo-referencing these scans to each other, it is possible to recreate a three-dimensional model of the excavation process, and in effect, make the excavation process reversible.



Figure 6: rendering in computer graphics of building 77

In order to achieve this digital recreation of the excavation process, we were tasked with optimizing a laser scanning protocol that would fit seamlessly into the existing conventional documentation process. The laser scanning workflow can be divided into several steps counting site evaluation, project evaluation, hardware selection, scan setting evaluation, actual scanning, and then several additional steps of post processing through which a final 3D model is generated, including point cloud cleaning, registration, triangulation (meshing), texture application, and optimization for viewing. Arguably the most important step of the process is the initial site and project evaluation, as this step will serve to guide the selection of the laser scanner system and scan settings needed to produce the desired model of the site.

After the evaluation of our excavation space, we determined that the Trimble FX time of Phase scanner was ideal for capturing the intricate details of our excavation area, Building 89*. While the Trimble FX is capable of data capture at a rate of 216,000 points per second (fig.2), that level of point-cloud density is beyond the functional needs for our project. A 270 x 360-degree scan at the highest data capture rate can easily generate a file of several gigabytes that will strain most computer hardware/software systems to unmanageable levels.

Scanning at such high data capture rates also translates into both longer in-field scan times and extended postprocessing time (fig.7). Our goal of digitally documenting individual units and features in an attempt to make the excavation process reversible, required that we generate highly detailed point clouds (and in turn meshes, figs.8, 9, 13). In pursuit of this goal, we scanned with a data capture rate of approximately 24 lines per degree (LPD) by 24 points per degree (PPD), which we found was more than adequate for producing high quality meshes, while taking minimal time in the field to scan (approximately 5 minutes per scan), and resulted in manageable file sizes (approximately 150 megabytes per scan). Laser scanning works along a line of sight principle, so in order to capture a three-dimensional object fully and avoid occlusion, scans must be completed from multiple sides. This process was further complicated by the arbitrary dig method we employed in the excavation of building 89, where we did not excavate each stratigraphic unit to the full extent, but rather to predetermined limits (this method was adopted in order to study in detail the stratigraphic sections).

We would have liked to scan from the same locations as we excavated down but since we were digging arbitrarily for getting more cross-sections we never could establish points over which to scan from as we were only scanning units partially each time. The arbitrary dig pattern also served to increase the difficulty of post processing, as it became more challenging to stitch the scans back together. Our scan strategy employed planning as few scan stations as possible in an effort to both reduce the overall recording time, as well as cut down on postprocessing work.

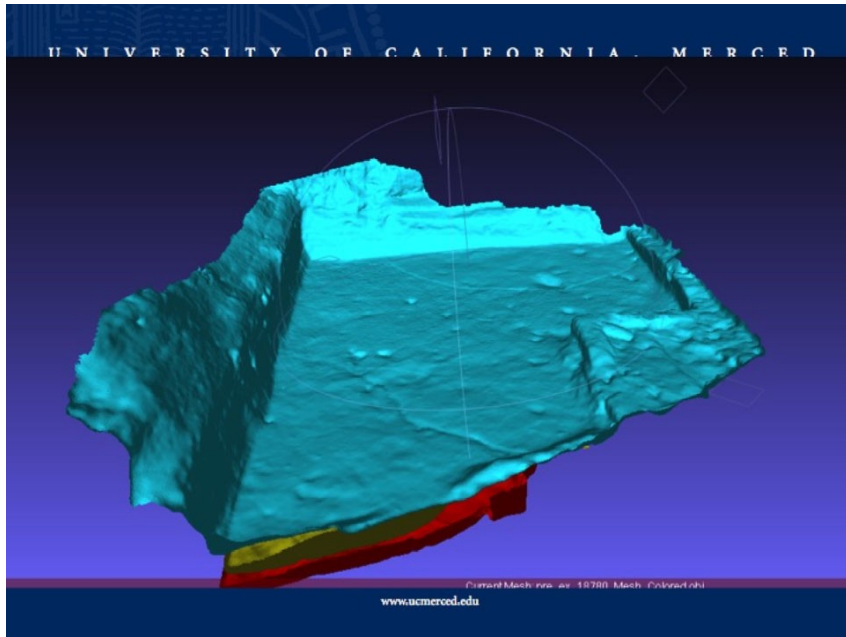


Figure 7: multilayer visualization of data recorded by laser scanning (building 89)

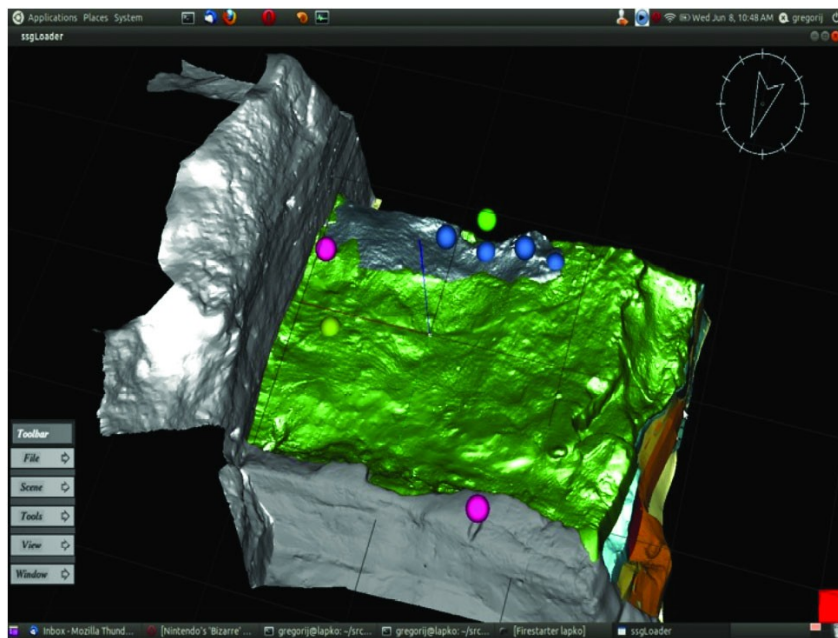


Figure 8: visualization of layers and artefacts recorded by optical scanner (micron accuracy, scanner Minolta 910). Midden area, fieldwork 2011

Typical laser scanner settings were 0.6 mm at 11 m or 0.8 mm at 21 m, and the FX controller software exported triangulated mesh on-site, immediately after the scan. The exported point clouds were saved as an unaltered raw data format, whose function will be to serve as digital archive of the site, while the exported meshes we saved for later post-processing.

The Trimble FX is lacking in an internal camera and so it was necessary to take photographs of the scanned surfaces with which we could later apply as color textures to the created meshes.

Photographs of the cleaned unit were best taken immediately before the scanning commenced, to avoid debris deposited or moved during the setup of the scanner within the excavation area. High-resolution photographs of approximately 15 megapixels were

taken with a Canon 50D DSLR camera. For the texture photographs we adopted a strategy of taking as few pictures with no occlusion of the full area to be scanned, utilizing 'establishing shot' like photographs, meaning shots taken with a wide angle lens range that includes all important features within the space to be modelled. We were not limited to a specific focal length in taking the texture photographs, and used a wide angle range between 22-28mm.

Overall it was our finding that with an approximate time of 12-15 minutes for the complete digital documentation of the stratigraphic unit, via laser scanner and digital photographs, laser scanning as a technology can be an effective digital documentation methodology for daily on-site recording.

5. Data Post-Processing and 3D Models Visualization

Digital documentation is a many-faceted operation that extends practices of digital archaeology far beyond the excavation area, entailing several laboratory activities that are subsequent to site and hardware evaluation and actual data capturing in situ. Archiving and processing vast data set of archaeological information are highly time-consuming tasks; no matter the involved technology is laser scanning, photogrammetry, or computer vision based reconstruction. Yet post-processing can be seen as a bottleneck, as a critical methodological aspect that can undermine the success of the documentation process, both in terms of time and resources consumption. As specified in previous parts of this article, the integrated approach we employed in documenting building 89 created a large amount of archaeological data on a daily basis. Thus we designed a day-by-day post-processing workflow that was able to keep the pace with laser scanning and computer vision data capturing.

Post-processing at Çatalhöyük has been performed through 3 different mobile workstations provided with the same software: MeshLab, an open-source general-purpose tool able to manage and

process large set of 3D models and point clouds (<http://www.meshlab.org>). Since one of the critical tasks of our post-processing activity was to provide valid and accurate data on the excavation process of building 89 to be visualized on a daily basis, we decided to run our tests and execute the processing only on high performing hardware. Available equipment was based on high-end and mid-range mobile workstations such as a Lenovo ThinkPad W520 (configuration was as follows: Intel i7 2650M processor, Nvidia Quadro 2000M graphic card, 2 GB video RAM DDR3, 8 GB DDR3 SDRAM 1333 MHz memory), a Dell Precision M4500 (configuration was as follows: Intel i7 M620 processor, Nvidia Quadro FX 1800M graphic card, 1GB video RAM DDR3, 4 GB DDR3 SDRAM 1333 MHz memory), and a DELL Latitude E6420 XFR Fully Rugged Laptop (configuration was as follows: Intel i7 2640M processor, Nvidia NVS 4200M, 512 MB Video Ram DDR3, 8 GB DDR3 SDRAM 1333 MHz memory). During laboratory activity we addressed several methodological questions such as how to define a scalable postprocessing model to be used system-wide in a large excavation such as Çatalhöyük, and which strategies can be used to enhance the visualization of virtual stratigraphic layers for interpretation and dissemination purpose.

To generate an optimized 3D model suitable for visualization and interpretation of laser scanning data we decided to rely on triangular meshes only. Most scanning equipment comes with accompanying proprietary software to deal with scans registration and decimation, but often-additional software is required to edit and finalize captured data. We sought to simplify the post-processing workflow and took steps to avoid the usage of multiple software and data trans-coding that usually entails issues in terms of compatibility. For this reasons we came to rely on meshes exported from the FX controller software to MeshLab. After an initial noise reduction performed manually, our post-processing methodology involved the optimization of the imported meshes using a surface reconstruction technique based on the Poisson filter in MeshLab. Such a technique allowed for the reconstructing of the meshes using their original surface normals through a triangulation algorithm. This approach provided us an excellent healing tool able to fill potential gaps in captured data, originated by occlusion in the trench or equipment noise. A Poisson surface reconstruction entails a very good preservation of original geometric details. The result of Poisson filter is a closed surface but our excavation area is open-side therefore we had to proceed with a further manual polishing able to reduce noise and outliers. In addition MeshLab gave us the possibility to perform mesh coloring and texture parameterization in the same platform as the mesh editing. In relatively a few simple steps, the software was able to project, with great precision, high quality color

information directly on the triangulated surfaces belonging to previously optimized scans. In this phase photographs taken during data capturing in situ where eventually used to obtain an accurate representation of each stratigraphic unit of building 89. Parameterized color maps to be used for final visualization of the excavation were later created starting from these representations of units and exported as jpeg files (1024x1024 pixels per picture). Later on we registered the colored meshes with each other via a 4 points alignment tool present in MeshLab. The result of such operation was a set of superimposed units, or layers, that we eventually aligned and geo-referenced to the excavation GIS grid. This outcome was possible through the alignment of these layers with a same scale geo-referenced 3D grid, which we previously created by processing total station data in a CAD system (Libre CAD) and a 3D modeling software (Autodesk 3D Studio Max). At this phase of the post-processing building 89's stratigraphy was ready for finalization and export. At the end of our workflow we also employed MeshLab as an excellent visualization tool able to show each geo-referenced context individually or visualize the entire excavation process day-by-day or layer-by-layer. This was possible through an unwrapping of the processed units, which in essence is the possibility of turning the individual contexts on and off using a simple layer menu located in the right part of the window. In addition several rendering modes (ex. wireframe, flat lines, flat, hidden lines, textured, and smooth) and advanced shaders (ex. depthmap, electronic microscope, x-ray, and quality contour, fig.11) are available in MeshLab. These characteristics make such software an advanced tool for geometry inspection and unit visualization able to provide archaeologists with the capability of increasing the contrasts of layers, see through overlapping contexts, and highly clarify the visibility of features (figs.8, 11). Finally we needed to export our data in a suitable

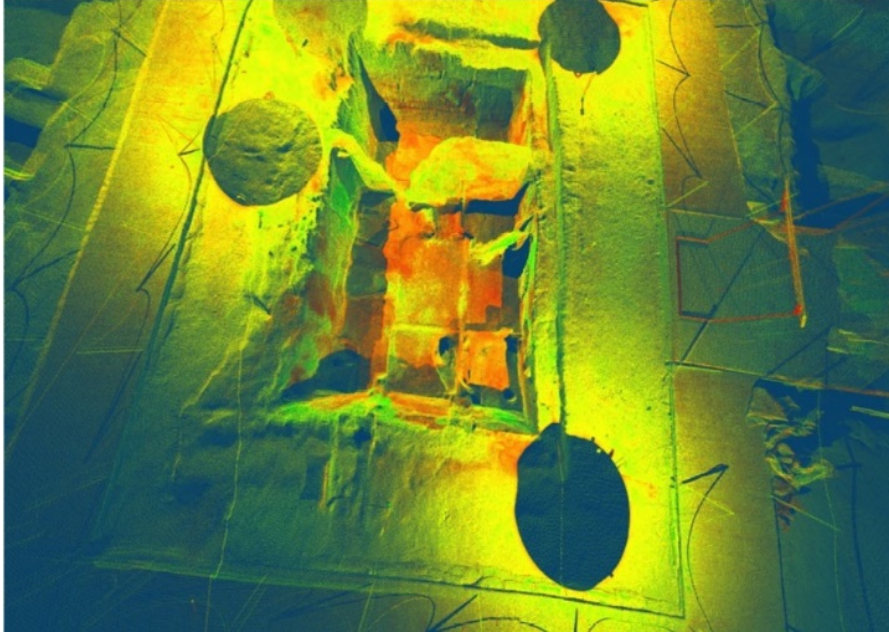


Figure 9: point clouds by time of phase shift laser scanner(3 stations) of building 77

file format for archiving and immersive stereo visualization (figs.10, 15). We identified a pair of .obj and .mat files as the best solution to complete our post-processing pipeline. Such formats fit perfectly the requirements of a stereoscopic visualization system we used in our interpretation discussion and presentation held in the Dig House at Çatalhöyük (fig.10).



Figure 10: This image shows the Nvidia 3D Vision system that UCM team employed at the Dig House at Çatalhöyük during the presentations.

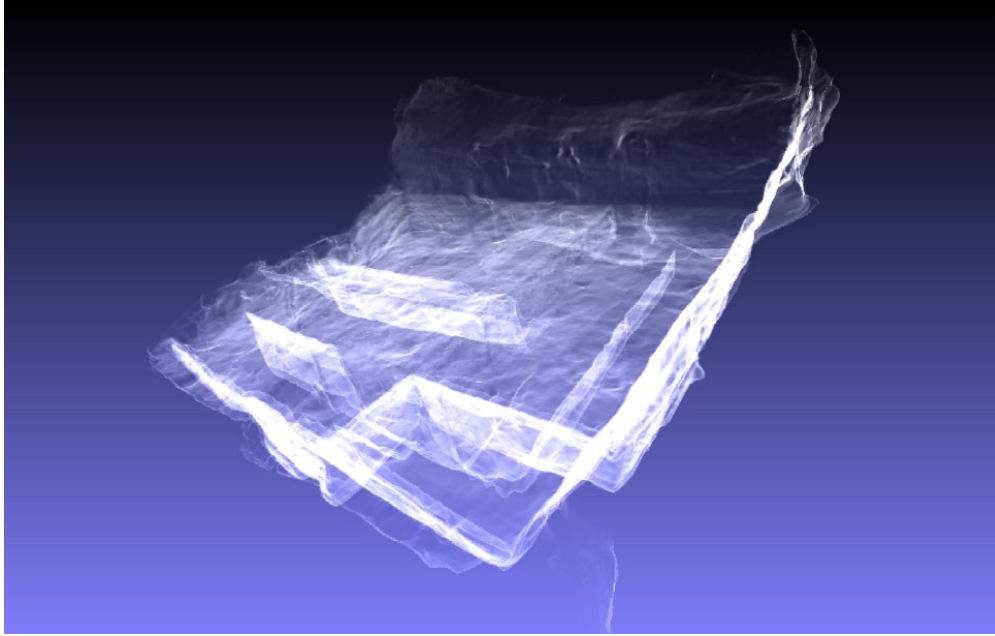


Figure 11. 3D stratigraphy in transparency (building 89). X ray Shader

This system was based on an open-source OpenGL-based viewer (OgreMax Viewer), and a Nvidia 3D Vision system able to render full screen, high resolution stereo pictures at 120 Hz per second and send them as an output to an Acer H5360 projector (specifics as follows: resolution 1280x720 pixels, 2500 ANSI Lumens, and 120 Hz refresh rate). Such visualization system demonstrated to fit excellently our fieldwork activities and methodologies. Besides being inexpensive and very portable, it also visualized crisps and bright stereo images of the excavation area projecting them directly on the laboratory's walls. The Nvidia 3D Vision (<http://www.nvidia.com/object/3d-vision-professional-users.html>) system is an active stereo system able to perform a real-time rendering of 3D models obtained from both laser scanning and computer vision digital documentation workflows. A set of Nvidia shutter glasses connected wirelessly to a radio emitter accompanied the stereo projection, enabling the audience to perceive the models of building 89 in a "true 3D". In this way it was possible to provide an audience of several archaeologists or specialists with an accurate tool for collaborative analysis and interpretation of captured data. Each stereoscopic visualization session was able to represent post-processed information documenting features, details, and contexts belonging to building 89 in a very clear and immersive way. Our findings in laser scanning data post-processing and real-time visualization confirmed that all the methodologies and workflows tested during 2011 fieldwork season can now be conceived as no longer experimental technologies but as reliable tools for archaeological documentation.

6. The Use of Image-Based Modeling in the Archaeological Excavation

In an attempt to enhance our multi-modal approach to the integration of different digital technologies into the investigative process of building 89, we decided to explore the use of Computer Vision (CV) to further supplement our digital documentation process. The goal of this experiment was to test the efficiency of this method in recording and post processing the different excavation units with high accuracy and in a reasonable time frame (fig.12). The results of this experiment allowed for a better understanding of how 3D technology can be used during and after the investigation as an efficient tool to process and elaborate archaeological data. This experiment was run using computer vision application called PhotoScan. This product (<http://www.agisoft.ru/products/photoscan/standard>) combines algorithms of structure from motion and dense stereo matching in order to build a 3D model of a scene starting from an uncalibrated set of images. Despite the huge number of available instruments of the same kind, this product has proved to be among the most robust and efficient instruments to be employed during the field activities.

Differently from other products, such as Arc3D, 123D Catch or Photosynth, Photoscan is not based on a web-service, and the entire workflow can be completely performed locally and without depending from an Internet connection. Moreover, this software has the unique characteristic to generate (at the end of the reconstruction process) a high quality texture map to export together with the model and to use in different visualization platforms. In an excavation context, this is a very important aspect as it allows for the performing of almost the entire data analysis process within one software, which drastically reduces the time spent in post processing.

The 3D documentation of the excavation process is a complex process. In order to be used for the development of the excavation activities and for the daily analysis of the stratigraphy, 3D models of units and features have to be available during the field investigation and possibly before their destruction.

Differently from laser scanner or photogrammetry, where cost and operation time usually discourage their employment during field activities, computer vision allowed us to document most of the excavation features found during the field activity, providing in very short time and with very low budget a complete and detailed 3D description of the on-going process of excavation (Dellepiane, et al., 2012).

Differently from laser scanner or photogrammetry, where cost and operational time usually discourage the employment during field activities, this kind of tool allows us to document with a sufficient precision (Dellepiane, et al., 2012) most of the excavation features found during an archaeological investigation, providing in very short time and with very low budget a complete and detailed 3D model.

Independently from the software tools used to generate the scene, the model reconstruction technique takes place mainly in two steps: the first calculates the image matching and the camera orientation, while the second performs a dense stereo reconstruction (Callieri, 2011). In the first step the camera parameters associated to each image of the set are estimated using algorithms of structure from motion (SFM); at this stage the software extracts and matches features between each couple of images, and calculates their corresponding position orientation in space. At the end of this process, each feature point that was extracted from the images can be associated to a 3D point in space. Hence, the output of the first processing step is a point cloud of a few thousand of points, and the intrinsic and extrinsic camera parameters associated to each image of the set (Verhoeven, 2011). Then algorithms for dense stereo reconstruction are applied in order to generate a very detailed model of the scene. Using the estimated camera parameters, all the pixels of the images are employed to try to build a much denser point cloud, which can be easily transformed in a high-resolution 3D model (Figure 12). The efficiency in using a combination of structure from motion together with dense stereo matching relies on the quality of the images acquired during the acquisition campaign and on the computational capacity of the machine used to process the data.

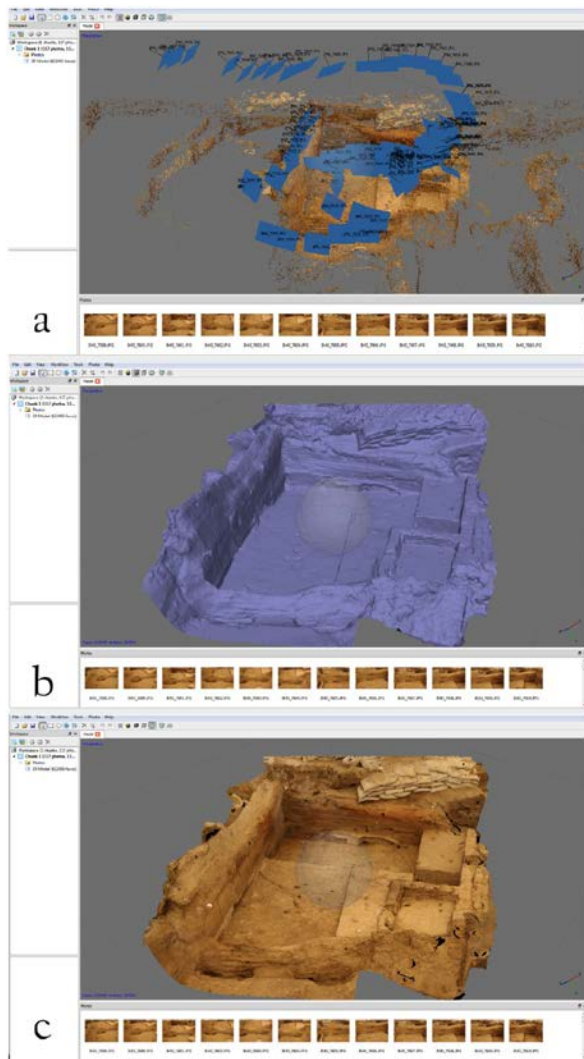


Figure 12: This image shows the three different steps performed by the software to calculate the 3Dmodel of the building: (a) calculation of the camera positions, (b) creation of the geometry, (c) map projection.

The introduction of a new recording instrument during the field activity is not an easy process. In order to be successfully employed during the site investigation, the new tool has to be tested in different conditions and situations with the primary goal of defining its potential and limitations. In fact, the possibility of having complete 3D models already available during the investigation campaign allows to review features no longer available in the field or to perform better evaluations about the excavation strategy to be adopted.

In order to evaluate the efficiency of this approach, we decided to collect a set of images every time a new unit was found. At the end of the day the pictures were processed in lab and a 3D model of the complete environment was generated and stored in a geo-referenced project file (fig.13). The acquisition campaign is the most delicate and important part and requires careful planning and preparation. This approach allowed to keep a high control on the entire area, but generated also a huge amount of unnecessary information, increasing the post processing time. For the acquisition of the images we used a Digital Camera (Canon EOS 550) together with a wide angle lens. Even though the use of a wide angle can negatively affect the model reconstruction process (since the camera parameters estimation becomes harder), the morphological characteristics of the excavation did not allow any alternative solution. The pictures were taken from inside the excavation (to better record features, units and wall sections) and from outside the excavation (in order to provide the software the information about the general context). We followed the same acquisition path for every set of images, keeping the camera constantly locked on the same settings.

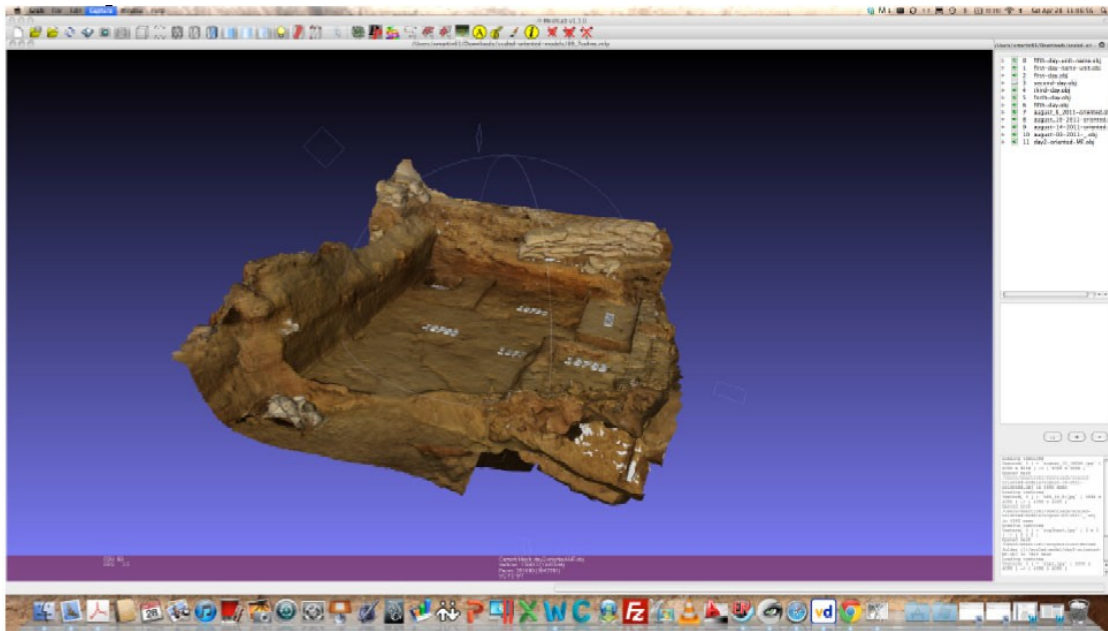


Figure 13: Meshlab interface with overlapping 3D layers in the same space

At the end of the excavation, a total of 1430 pictures were acquired at a resolution of 12 megapixels. A number of 12 markers, previously recorded with a total station, were used as control points in order to provide a grid to scale and orient the models. The total station points were also used to monitor the quality of the 3D scenes. Once acquired, the images were imported into Photoscan in order to be processed with SFM and dense stereo matching algorithms. In both these steps, the software allowed to choose among several different options and parameters, such as the kind of algorithms to use for the geometry reconstruction and the number of polygons to use to describe the model. At the end of the process, texture maps of different resolutions were generated by the software. At this stage it was possible to define the typology of map projection to apply and the size of the map to generate. As explained in the previous

paragraphs, the limits in reconstructing a 3D model with this technique are mainly based on the relation between quality and quantity of the picture acquired in the field and on the computational power of the computer used to perform the operations. The models were completely post processed, almost in real time, during the investigation campaign, using a Laptop equipped with a multicore processor, 16GB of RAM and a 64-bit operative system. The use of such hardware allowed obtaining in few hours the complete and resolute 3D model of the entire context. Once generated, the 3D scenes were imported in MeshLab in order to be scaled and oriented according with the grid of control points previously acquired with the Total Station. Although an in-depth estimation of the accuracy of the approach is hard to obtain with an on-the-field approach, the comparison between common surfaces of the acquisition showed a geometric difference in the order of half centimetre.

7. Teleimmersive Archaeology-Telearch

One of the key problems in 3D post-processing is the management and accessibility of data and models. The latest generation of laser scanners is able to generate millions of point per second, which can translate into an enormous quantity of geometrical information. Any single archaeological season produces terabytes of data to post-process and interpret: textures, models, videos, GIS databases. Given these premises it is crucial for archaeology to test the appropriate tools and to guarantee a correct accessibility and transmission of data. In this domain in the last few years the number of applications on virtual collaborative systems is growing (Acevedo et al.2001; Hall et al.2001; Helling et al.2004; Nie, 2008; Getchell et al.2009; Forte, Pietroni, 2010; Vasudevan et al. 2011; Forte, Kurillo, 2011,12)

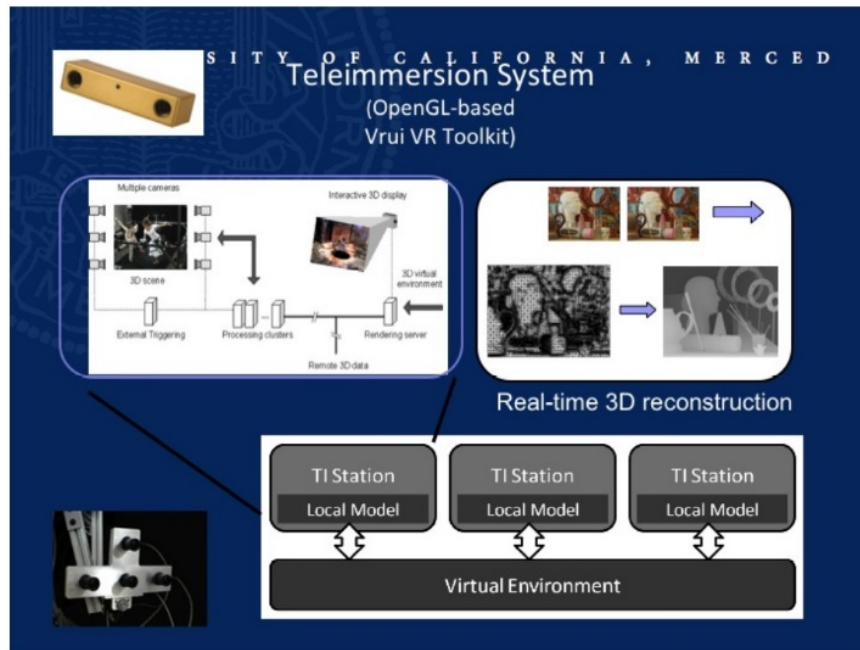


Figure 14: scheme of Teleimmersive Archaeology system (UC Merced, UC Berkeley)

The University of California, Merced, and the University of California, Berkeley, have worked towards the development of a collaborative system for archaeology, based on Teleimmersive Technology named Teleimmersive Archaeology (TeleArch, fig.14). The collaborative framework is built upon Vrui VR Toolkit, developed at University of California, Davis. The Vrui VR Toolkit aims to support fully scalable and portable applications that run on a wide range of virtual reality systems using different display technologies and various input devices for interaction. The applications built with Vrui can thus run on various clients, from laptops to desktop servers, and support different display technologies, such as 2D displays, stereo displays or fully immersive 3D displays (e.g. CAVE). The collaborative extension of Vrui allows linking two or more spatially distributed virtual environments. Thus users from different geographical locations, represented by 3D avatars, can work together in the same cyberspace, interacting in real time with models of artifacts, monuments and sites. (Forte, Kurillo, 2010; 2012). 3D avatars in the cyber space increase the level of embodiment, assist the digital communication between users and allow contextualizing the scale of application. Despite the fact the development of the system is still in progress, a first experiment was started with the building 77 at Çatalhöyük (figs.15, 16, 17).

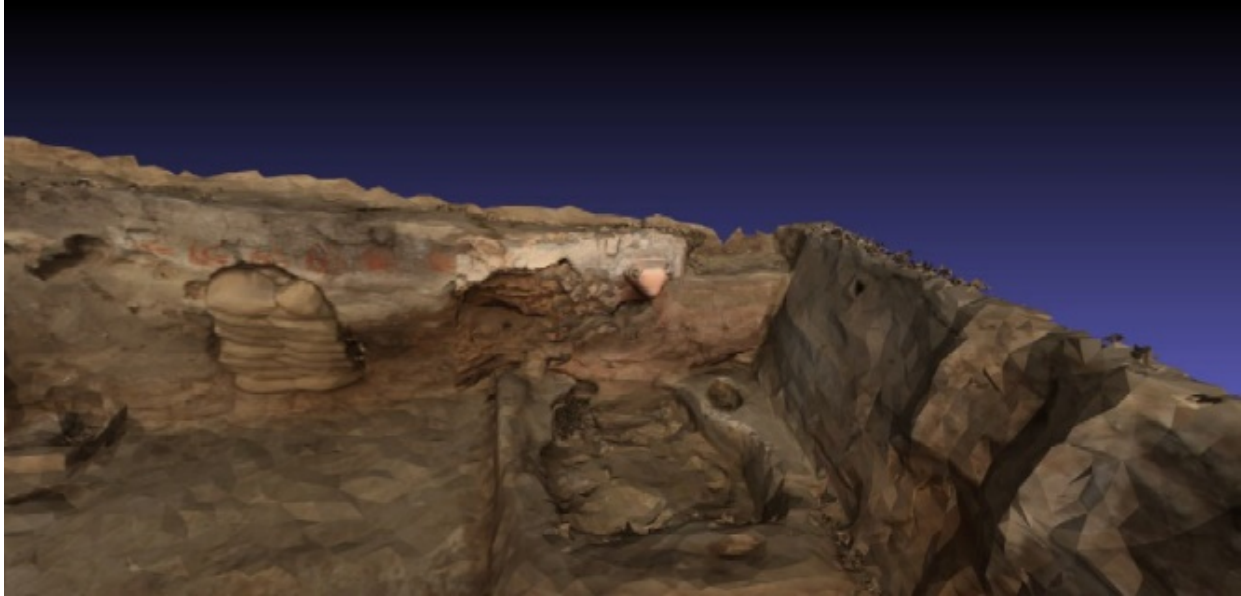


Figure 15: building 77 reconstructed by laser scanning

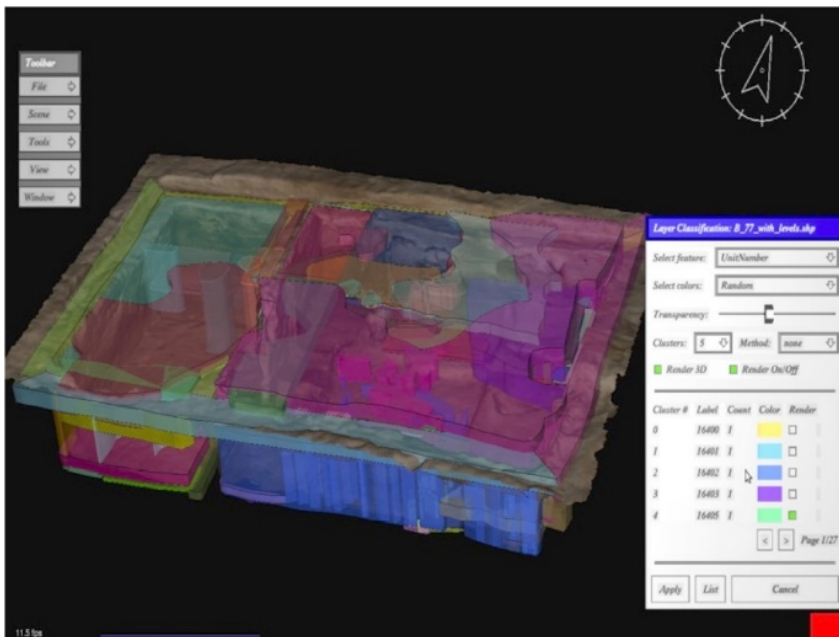


Figure 16: building 77, 3D model and GIS layers

In this case the 3D model recorded by laser scanning was integrated with all the GIS layers recorded from different excavation seasons (Figure 5).

The result is the integration of the 3D building with the 2.5 GIS layers and categories of artifacts: it is multiscale and multitemporal model of excavation. In a teleimmersive session it is possible to browse and measure all the layers, querying data by code and category, turn on and off digital items and finally reconstruct the entire excavation process. Playing with digital levels of transparency allows the recognition of spatial relationships of layers, units and artifacts otherwise not understandable. Then, in this specific case a standalone interaction was tested thanks to the use of a Wii device (Figure 6). This improves consistently the kinesthetic approach of the user and the analysis of data (fig.17).

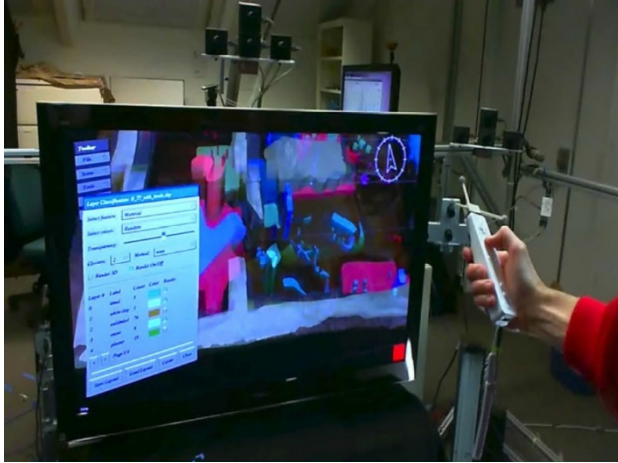


Figure 17: a Teleimmersive session with a Wii. 3D interaction with layers, artifacts and architectural model (B77)

8. Conclusions

The integration of different 3D data recording and visualization technologies-and their subsequent implementation in virtual reality systems-into fieldwork is a very challenging process. In particular it is difficult to evolve from experimental phases of the work to standardized and robust applications. However, the core of the process is in the methodological approach and not in the technologies themselves: in other words the entire system should have a methodology driven approach. Technologies suffer from problems of longevity, compatibility, accessibility, updating and change very rapidly; on the other hand, the methodological workflow for use and interpretation of archaeological data changes very little over time. The 3D-digging Project is still a work in progress, but all the 3D data and models are discussed and available immediately on site and in remote thanks to the Teleimmersive system. In the future they will be available in Internet or intranets through Vrui 3D web players.

The use of such different technologies during the excavation campaign of the building 89 allowed our team to gain knowledge on how to combine and optimize dissimilar techniques to completely record the excavation process. This experience proved that is possible to describe in three dimensions, and nearly in real time, very complicated and diverse archaeological contexts. The results of this approach allowed experiencing a sort of time travel back and forward through time, increasing the perception of the stratigraphic units, and their evolution in the investigated area (fig.18). In fact during the fieldwork it was possible to generate detailed 3D models endowed with high quality color maps and very detailed (but manageable) geometries. A multi-scale approach in 3D real time rendering is a necessary approach for any decision making and ongoing interpretation during the excavation or after during the study and publication of data (fig.18). The multi-scale approach in 3D rendering associated with a sustainable balance between digging speed, accuracy and availability of data was very successful. On daily based all the 3D data were available for a discussion between our teams and other archaeologists on site on laptop computers but also in 3D stereo projection (using OgreMax and Unity 3d): laser-scanning data, 3D models by computer vision and by stereo reconstruction (software Agisoft Stereoscan).



Figure 18: This image shows the entire sequence of 3D Models realized by Photoscan and oriented and scaled in MeshLab during the excavation of building 89.

Also the use of stereo camcorders and stereo cameras was very useful in the documentation process for 3D visualization but also for 3D reconstruction by stereo pairs. In addition, the particular conditions of the site and the critical state of

preservation of the buildings made in mud bricks, makes the 3D data recording an essential aspect of documentation for the archaeological and conservation teams. In fact, it is quite common to have architectural elements that collapse or are seriously damaged by environmental conditions or mechanical actions. For example in the case of wall paintings or wall decorations it is urgent to generate immediately an orthophoto with the full geometry of the structure in order to catch all the decoration before the surface deteriorates. This can be easily done by stereo cameras (in our case a Fujitsu 3D) or image modeling; then on this parametric map it is possible to create vectorial drawings.

Another important aspect of the integration of different 3D technologies concerns the costs: in comparison with the past the current costs of the project are quite sustainable. Low cost and open source software, image modeling by standard cameras and a sponsorship for loans of laser scanners (supported by Trimble navigation) make the entire project feasible with good chances to standardize and export these methodologies to other excavations.

Ultimately, TeleArch system is still in a preliminary and experimental phase of development but with a great potential. The system is flexible, inexpensive and powerful, with an adequate capacity of real time rendering (2 ml polygons) and very useful analytical tools: measuring, lighting, dragging and moving objects, changing textures and colors, uploading 3D models and libraries, exchanging data between different labs and locations. The core system is the collaborative environment able to integrate in real time and in the same space different categories of data and formats. The digital workflow tested starting from the archaeological fieldwork (data capturing) to the Teleimmersion, works and produces different information: a holistic digital view typically not accessible in any single separated domain.

Once all the datasets are in TeleArch it is possible to elaborate on the 3D data in a collaborative way, using the properties of Teleimmersion. The simulation of 3D models in a cross-data platform stimulates new interpretations or can assist the research in the validation of the previous ones. In archaeology this stage of work is crucial since during the excavation a relevant amount of information is removed through digging and hence is not reconstructable anymore afterwards.

Acknowledgments

This project was supported by UC Merced GRC grant (2011), CITRIS (Teleimmersive system 2010-11) and Trimble Navigation (2010-2011).

Below the list of students and participants. Fieldwork 2011: Maurizio Forte, Justine Issavi, Nicolo Dell'Unto, Nicola Lercari, Llonel Onsurez, Nicole Sam. Laser scanning and computer vision: Nicolo' Dell'Unto, Nicola Lercari, Llonel Onsurez. Fieldwork 2010: Maurizio Forte, Paola Di Giuseppantonio Di Franco, Fabrizio, Galeazzi, Carlos Bazua, Julia Cline, Justine Issavi, Llonel Onsurez, Johnathan Wang. Laser scanning and 3D post-processing: Fabrizio Galeazzi. Special thanks are due to Prof. Ian Hodder for this feedback and enthusiastic contribution to the success of the project and Anders Rhodin from Trimble Navigation for his technological assistance.

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