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Authors

Lercari, Nicola
Shiferaw, Emmanuel
Forte, Maurizio
et al.

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Nicola Lercari, Ph.D. – Author Version

Title: Immersive Visualization and Curation of Archaeological Heritage Data: Çatalhöyük and the Dig@IT App

Authors: Nicola Lercari[1], Emmanuel Shiferaw[2], Maurizio Forte[3], Regis Kopper[4]

Affiliation:

[1] University of California Merced, School of Social Sciences, Humanities, and Arts, 5200 N Lake Road, Merced, CA 95340, USA

[2] Duke University, Department of Computer Science, LSRC Building D101, 308 Research Dr, Campus Box 90129, Durham NC 27708-0300, USA

[3] Duke University, Department of Classics and Department of Art, Art History & Visual Studies, Campus Box 90766, Durham NC 27708-0766, USA

[4] Duke University, Department of Mechanical Engineering and Materials Science and Duke Immersive Virtual Environment, Edmund T. Pratt Jr. School of Engineering, Box 90300 Hudson Hall, Durham, NC 27708-0300, USA

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Corresponding Author: Nicola Lercari

Email : nlercari@ucmerced.edu

Phone : +1 209-720-7124

Fax : +1 209-228-4007

1. Abstract:

Advanced data capture techniques, cost-effective data processing, and visualization technologies provide viable solutions for the documentation and curation of archaeological heritage and material culture. Work at the UNESCO World Heritage site of Çatalhöyük has demonstrated that new digital approaches for capturing, processing, analyzing, and curating stratigraphic data in 3D are now feasible. Real-time visualization engines allow us to simulate the stratigraphy of a site, the three-dimensional surfaces of ancient buildings, as well as the ever-changing morphology of cultural landscapes. Nonetheless, more work needs to be done to address methodological questions such as: can three-dimensional models and stratigraphic relationships, based on 3D surfaces and volumes, be used to perform archaeological interpretation? How can a 3D virtual scenario become the interface to cultural data and metadata stored in external online databases? How can we foster a sense of presence and user embodiment in the simulation of ancient cities and archaeological sites? This article aims to provide viable solutions to the methodological challenge of designing a comprehensive digital archaeological workflow from the data acquisition and interpretation in the field to a three-dimensional digital data curation based on interactive visualization, searchable 3D data, and virtual environments. This work describes the results we achieved developing the application Dig@IT, a multi-platform, scalable virtual reality tool able to foster archaeological data analysis, interpretation, and curation in a realistic and highly-interactive virtual environment.

Keywords: 3D Visualization; Çatalhöyük; Cyber-Archaeology; Data Curation; Virtual Reality;

2. Introduction

2.1. Site Background

Çatalhöyük is a large and well-preserved Neolithic and Chalcolithic mound, or *tell*, located in the Konya plain, near the town of Çumra in Southern Anatolia, Turkey [37° 40' 19.64'' N, 32° 49' 24.63'' E] (see Fig. 1a). As an outstanding example of a type of architectural ensemble, which illustrates a significant stage in human history, this archaeological site is widely considered one of the key sites for understanding human Prehistory. Çatalhöyük's large size, dense concentration of art, and excellent preservation, make this site the best example of the agglomeration of people into egalitarian society in the Neolithic and exemplifies the important Anatolian contribution to the development of early societies. Counting eighteen overlaying levels of occupation and an estimated population of approximately 3,500-8,000 people at once, the Neolithic settlements on the East Mound date from 7,100-6,200 BCE (Bayliss et al. 2015) (see Fig. 1b). The smaller Chalcolithic West Mound (8.5 hectares) lies on the west side of the ancient riverbed of the Çarşamba River, now canalized, and includes settlements from the 6th millennium BC (Biehl et al. 2012).
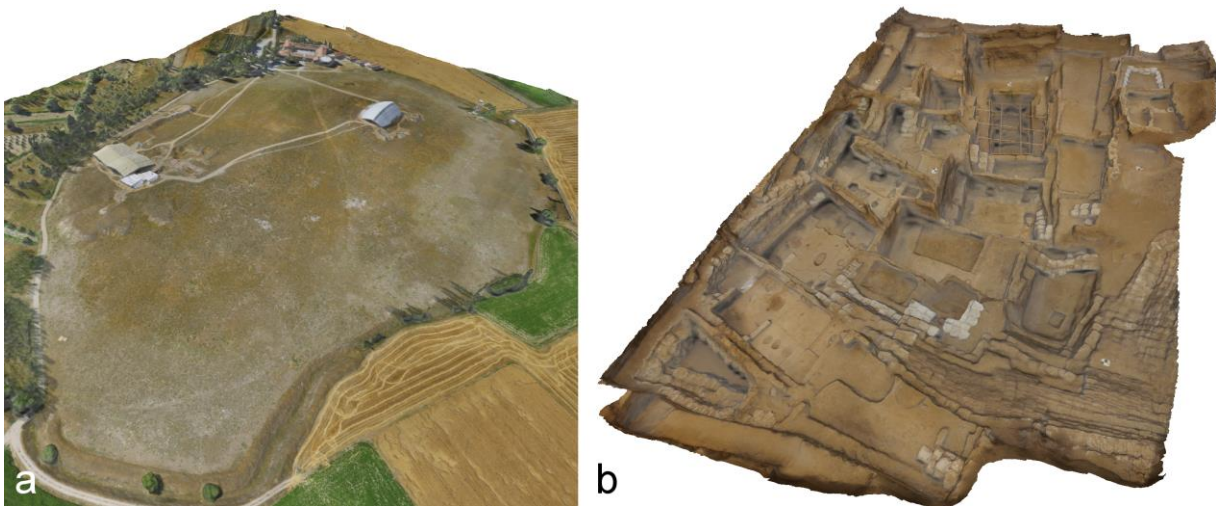

Fig. 1 View of Structure from Motion 3D models of (a) Çatalhöyük East Mound landscape and (b) Çatalhöyük South Area as they were surveyed in 2015 using Unmanned Aerial Vehicles

2.2. Project Background

Between 2009 and 2015, scholars from the University of California Merced, Duke University, and Lund University conducted digital archaeological work at Çatalhöyük within the 3D Digging Project initiative (Forte 2011; Forte, Dell'Unto, and Lercari 2014; Forte 2014; Forte and Lercari 2015). The main goal of this project was to test the viability of a comprehensive method for archaeological heritage research spanning remote sensing, image-based data capture, data processing, spatial analysis, 3D visualization, and data curation (Forte et al. 2012; Forte and Campana 2016). During the project period, our team acquired and digitally post-processed terabytes of data both at intra-site level (e.g. Building 89 and numerous other mud brick houses) and inter-site level (e.g. drone surveying of the entire Çatalhöyük's East and West Mounds). In six consecutive field seasons, we successfully tested a robust 3D documentation workflow based on structure from motion (SfM) techniques (Dell'Unto 2014), terrestrial laser scanning (TLS) (Lercari 2014a), 3D geographic information systems (GIS) based on tablet PCs and standalone computers (Berggren et al. 2015), 3D mapping using unmanned aerial systems (UAS) (Forte and Danelon 2016), and ground penetrating radar (GPR) (Campana et al. 2013).

While the fieldwork phase of the 3D Digging Project was completed in the summer of 2015, our work on data processing, analysis, and curation continues. A comprehensive publication of Building 89 (B.89) including stratigraphic interpretation, notes, drawings, photographs, videos, carbon-14 dates, specialists' results, and georeferenced 3D models will be completed after the 2018 Çatalhöyük study season. In the meantime, heritage professionals, the research community, and the general public can search and browse all the B.89 excavation data and metadata through the open-access *Çatalhöyük Database*'s web interface ("Çatalhöyük Database" 2016). In addition, team members of the Çatalhöyük Research Project, the main research initiative on-site led by Dr. Hodder from Stanford University, can spatially analyze the 3D models and georeferenced data we produced in the GIS platform ESRI ArcGIS for Desktop ("ArcGIS for Desktop" 2016).

To make our data more widely accessible to the public, we are currently exploring new methods in data dissemination through a collaborative project started by Duke University and Old Dominion University (VA), which addresses the 3D visualization and diachronic reconstruction and simulation of the Çatalhöyük archaeological landscape. To enable an online open access to the data discussed in this paper, the University of California Merced and Duke University have partnered with the University of California San Diego (UCSD) Center for Cyber-Archaeology and Sustainability (CCAS) ("Center for Cyber-Archaeology & Sustainability" 2017), to curate online all the 3D models and related metadata representing the three-dimensional stratigraphy of Building 89. Said data will become available to the public in the second half of 2017 through the web portal of the UCSD Library.

Building upon the assumption that the interpretation of three-dimensional stratigraphic models is a complex, non-empirical task that requires an approach different than what's used for the interpretation of bi-dimensional data, this article discusses additional cyber-archaeological tools and methods we developed to simulate in 3D the excavation of B.89 through the custom software Dig@IT. This application (app) is a multi-platform virtual reality software developed at Duke University during 2014-2016, which fosters archaeological data analysis, interpretation, and curation in a realistic and highly-interactive immersive virtual environment. At the current stage of development, Dig@IT simulates the stratigraphic excavation of Çatalhöyük B.89, as it was documented by the 3D Digging Project.

Building 89, the case study of this article, is a perfect test bed for our comprehensive digital workflow for archaeological heritage data documentation and visualization (see Fig. 2a). At Çatalhöyük, a house is the smallest complex social unit that presents consistency of all the elements interrelated with domestic, economic, and ritual activities. As a house that is fairly large in size, B.89 is a rich case study that includes multiple categories of data: archaeological finds, architectural structures, infill/deposits, and burials (see Fig. 2b). Focusing on B.89, our 3D digital documentation and interpretation workflow was able to test the relevance of the methods discussed in this article in a sealed, consistent, and distinct environment (Forte et al. 2016). At Çatalhöyük, every house is a performing space that involves ritual (e.g. primary and secondary burials, feasting) and domestic activities (e.g. food production, cooking, dining). In this context, a strictly taxonomic/descriptive interpretation is not suitable to render a complex built space where affordances are coupled with multiple tasks. For instance, in a typical Çatalhöyük house, a social activity such as dining is performed in the central space of the building in close proximity with ritual platforms and burials. When the "dining" affordance were performed, we assume that the "ritual" affordance had been discontinued in the same space and vice-versa. Thus, we believe that the 3D simulation of archaeological data proposed in this paper becomes crucial to understanding the archaeological past of Çatalhöyük because it enables multiple perspectives and hypotheses

3

on the collected data. For example, our method allows for the "empirical" evidence of data recording (e.g. the layers captured in the field) to be compared with hypothetical 3D reconstructions or multiple simulation scenarios with the purpose of making dynamic arguments and producing different interpretations.
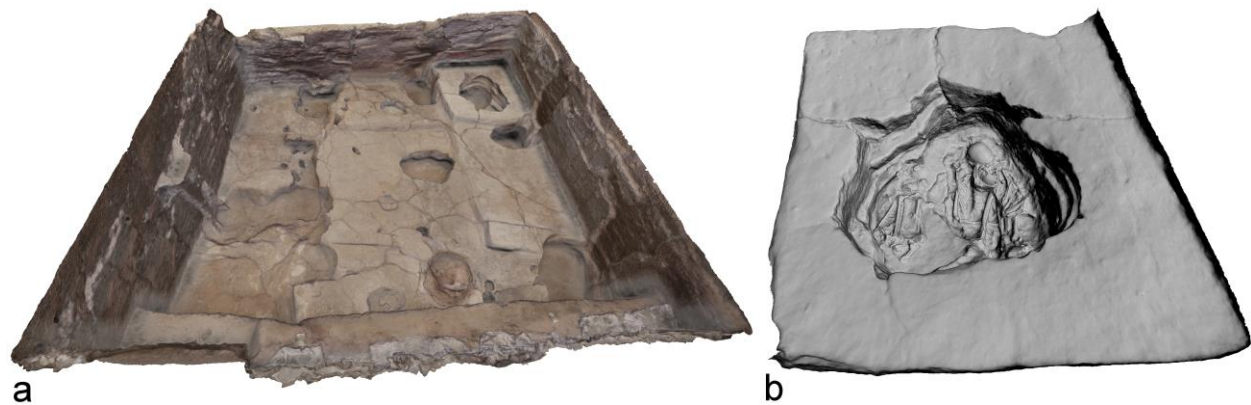

Fig. 2 View of Structure from Motion 3D models of (a) B.89 post-excavation 2014 and (b) burial F.3484 in B.89

3. Related Work

The digital method proposed in this article aims to define new interactive ways to document, visualize, and curate searchable archaeological data using immersive virtual environments connected to a remote Structured Query Language (SQL) database server. To design and develop such a method, our work builds upon influential contributions that focus on ontologies for cultural objects (Kakali et al. 2007; Havemann et al. 2009; Hyvönen 2009; Niccolucci, Hermon, and Doerr 2015), networked methods for cultural data archives and dissemination (Power et al. 2017; Seifert et al. 2017), visualization and annotation of 3D architectural and archaeological models in real-time (Poyart et al. 2011; Snyder 2014), and user interfaces for the digital publication of archaeological excavations (R. Opitz and Johnson 2016).

To record stratigraphic data in B.89 as well as architectural features in adjacent Neolithic buildings (e.g. Building 96 and Building 80), we developed a digital documentation workflow based on redundant information collected by means of SfM and TLS techniques. The scientific value of our multimodal data capture method derives from proven techniques for the documentation of cultural objects and sites based on photogrammetry and computer vision (Marc Pollefeys et al. 2001; Remondino and El-Hakim 2006; M. Pollefeys et al. 2008; Dellepiane et al. 2013; Remondino 2013) as well as from prominent work on survey and measurement techniques for archaeology (R. Opitz 2015; R. Opitz and Limp 2015; Forte and Campana 2016; Dell'Unto et al. 2017), and on the documentation of stratigraphic layers and archaeological sites by means of terrestrial laser scanning (Alshawabkeh 2005; Doneus and Neubauer 2005b; R. S. Opitz and Cowley 2013; Lercari 2016b).

The 3D spatial approach for the representation and interpretation of the archaeological record discussed in this article relies on seminal work on visual reflexivity and visual interpretation in archaeology (Hodder 1997a; Emele 2000; Cox 2011; Perry, Chapman, and Wylie 2014), on previous literature on the documentation, analysis, re-contextualization and multivocal discussion of Çatalhöyük's data using digital technologies (Ashley, Tringham, and Perlingieri 2011) and online virtual environments (Morgan 2009), as well as on previous work on 3D data capture and immersive visualization of Çatalhöyük buildings in virtual environments and mobile apps (Lercari, Matthiesen, et al. 2014; Lercari 2016a, 2017).

4. Data Curation at Çatalhöyük

Çatalhöyük was discovered by James Mellaart in the late 1950's and initially excavated from 1961 to 1965 in four excavation seasons. Rapidly, Çatalhöyük obtained worldwide attention for its street-less settlement structure as well as for evidence for the emergence of pottery, material culture, and extensive amounts of symbolic and ritual artifacts.

In 1993 Ian Hodder started to investigate the Çatalhöyük East Mound, producing further interpretations of the repetition of architectural elements and buildings over time (Hodder 1997b; Hodder and Cessford 2004; Hodder and Pels 2010). Since the early 1990's, Çatalhöyük East Mound has been continuously excavated and studied by numerous teams of specialists encompassing more than twenty-three archaeological subfields (e.g. archaeobotany, archaeometry, digital archaeology, osteology, and archaeological conservation to name a few) using a single-context recording method (Grossner et al. 2012). During an average fieldwork season, hundreds of excavators and specialists collect data and samples at Çatalhöyük producing hundreds of gigabytes of heterogeneous digital data. In addition, a site photographer and an illustrator contribute to visually document and reconstruct the Çatalhöyük archaeological record with collections of photographs, archaeological illustrations, and 3D models.

The documentation of the excavation activities at Çatalhöyük as well as the interpretation of its archaeological record also benefit from a powerful data logging and management tool called the *Excavation Diary*. During each fieldwork season, excavators and laboratory specialists contribute to the reflexive documentation of Çatalhöyük recording their activities and interpretations in the *Excavation Diary*, on a daily basis. The metadata and paradata included in the *Excavation Diary* are a fundamental part of the multivocal interpretation of the site and constitute the daily narrative of diggers and specialists (Mickel 2015).

Since the early 2000's, technologies such as Computer Aided Design (CAD) software, photogrammetry, SfM, and TLS have also been employed to digitally document Çatalhöyük Neolithic buildings. In the late 2000's, the usage of GIS has been introduced at Çatalhöyük to connect field drawings and maps with the information included in the *Çatalhöyük Database*. By the early 2010's, 3D GIS, digital documentation, and three-dimensional visualization have been demonstrated viable components of the reflexive methodology utilized to document and interpret Çatalhöyük (Hodder 2000). More specifically, the adoption of tablet-based digital methods for data recording (e.g. digital drawings, SfM and TLS) and interpretation (3D GIS and WiFi database connection) has amplified the capability of the archaeologist to generate knowledge directly in the field. Integrating GIS, 3D models, and database at the 'trowel's edge', the methods we designed and developed at Çatalhöyük have contributed to 'democratize' the access to specialized knowledge that previously was exclusive to lab specialists while scientifically informing the decision making and interpretation of the excavators in a way that was not possible in a traditional reflexive methodology (Berggren et al. 2015).

Considering the long history of the excavations on the Çatalhöyük East Mound and the ever-evolving array of methods and techniques that have been utilized to document, describe, and interpret the site, one can easily reckon why multiple data curation and information systems have been designed and employed overtime. For instance, the *Çatalhöyük Database* (see Fig. 3a) or the *Çatalhöyük Image Collection Database* ("Çatalhöyük Image Collection Database" 2016) (see Fig. 3b) are two fundamental assets in the documentation of this UNESCO World Heritage site. These custom data curation platforms are searchable data management systems that archive images and archaeological datasets including excavations areas, buildings, spaces, and numerous categories of finds. During every field season, new data are uploaded in these systems locally by the excavators and specialists doing research on-site. In the weeks following each fieldwork season, all the new data stored locally on the *Çatalhöyük Database* and on the *Çatalhöyük Image Collection Database* are made available to the public via a web-based SQL public repository linked to the Çatalhöyük's official website ("Çatalhöyük Research Project" 2016).
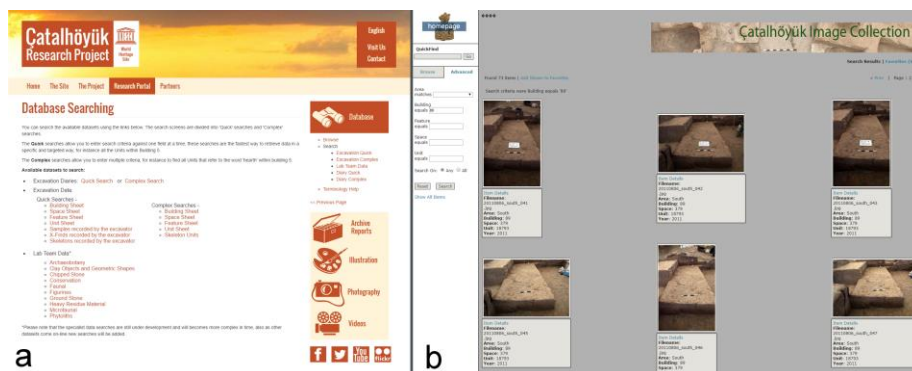

Fig. 3 View of (a) the open-access online data curation platform Çatalhöyük Database and (b) the Çatalhöyük Image Collection Database

More recently, the launch of the *Çatalhöyük Living Archive* has determined a deep transformation of the data curation strategies used by the Çatalhöyük Research Project, the main research initiative at Çatalhöyük led Dr. Ian Hodder at Stanford University, under which the 3D Digging Project and our team have operated since 2009. The *Çatalhöyük Living Archive* enables new ways for online data curation of Çatalhöyük archaeological heritage by proposing a shift from the relational model employed in the *Çatalhöyük Database* to an experimental graph representation. This new data model facilitates the reconstruction of the excavation context through linked data that are organized in groups demarcated by complex attributes criteria defined by an ontology. ("Çatalhöyük Living Archive" 2016). The graph representation allows users of the Çatalhöyük Living Archive to more easily discover patters in the excavation data where finds share a joint location (e.g. a burial where a cluster of phytoliths belonging to a basket were retrieved next to a neonatal skeleton) or other sets of interpretative categories.

One can argue that the *Çatalhöyük Living Archive* has contributed to enhance the curation of Çatalhöyük cultural objects and materials describing them with complex attribute criteria, groups, and interpretative categories. This system also provides spatial and temporal views of the data directly on the web (see Fig. 4), text-mining of the *Excavation Diary* and excavation reports, as wells as an interactive web-based curation based on an application programming interface (API) that may be used by third party archives or research projects to integrate the archived materials in comparative studies.
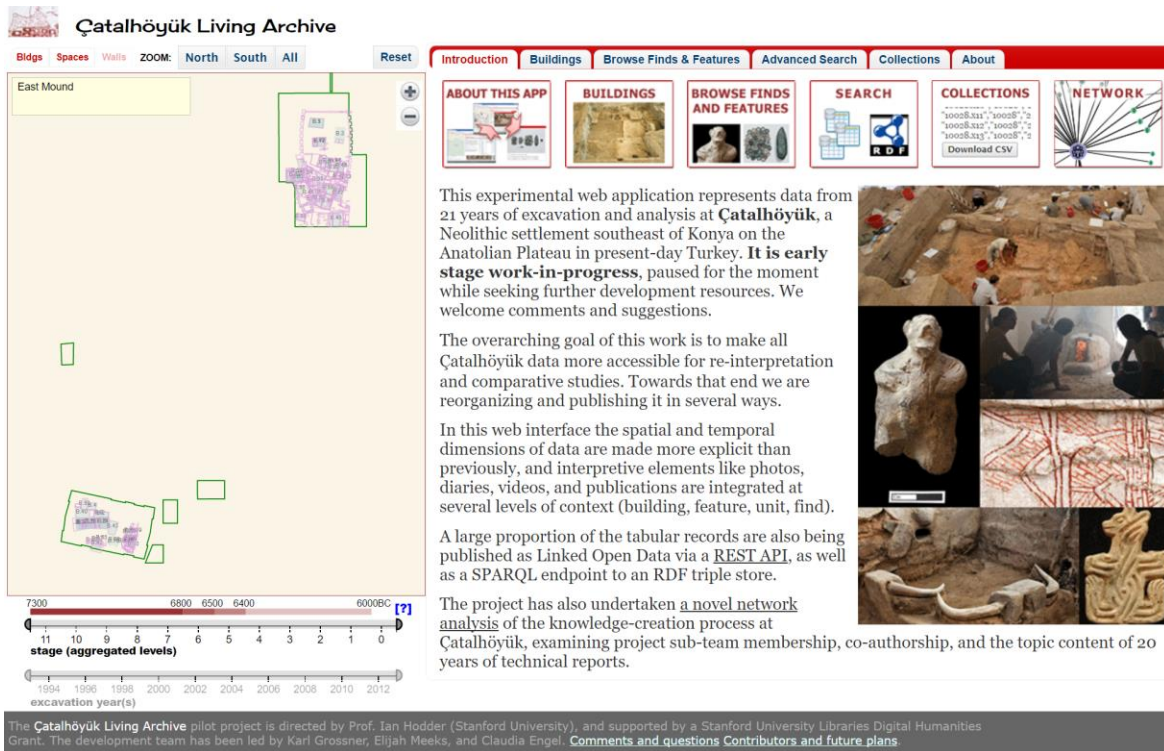

Fig. 4 View of the web app Çatalhöyük Living Archive

The multifaceted and complex scenario described in this section of the paper makes Çatalhöyük an excellent test bed for our new digital method for the documentation, processing, visualization, and curation of archaeological heritage, which is able to deal with multiple datasets and complex ontologies. In fact, the most critical methodological challenge of the Çatalhöyük Research Project, specifically a research initiative made of multiple sub-teams including hundreds of researchers and students, is to perform an effective data integration based on different modalities of data recording, management and curation that were developed over more than two decades.

In the excavation of Çatalhöyük all the datasets are recorded in 2D by a tablet-based GIS and, in some buildings and phases, by TLS and SfM. Such datasets are systematically georeferenced using ArcGIS for Desktop or CAD. Triangular mesh 3D models are also integrated in the GIS while specific buildings (e.g. B.89) are visualized in virtual environments through game engines (e.g. Unity 3D and Unreal 4). This a key point in our digital archaeology approach

because the interpretation of the archaeological record has to deal with datasets integrated in the same cyberspace. Data visualization in a GIS is mostly based on vector graphics while in a virtual environment on 3D models such as point clouds and triangular meshes. Thus, a GIS is the ideal data management tool for maps and field drawings while a virtual environment is best suited for interaction exploration, simulation, and collaborative interpretation. In several field seasons spanning from 2010 to 2015, large scale survey at Çatalhöyük was performed using terrestrial laser scanning and drones, intra-site micro-scale survey by Structure from Motion (using uncalibrated digital single-lens reflex (DSLR) cameras and the SfM processing software Agisoft PhotoScan Pro). Therefore, archaeological interpretation at Çatalhöyük relies on a multimodal method based on multiple spatial entities and different acquisition, processing, and visualization techniques (see Fig. 5).
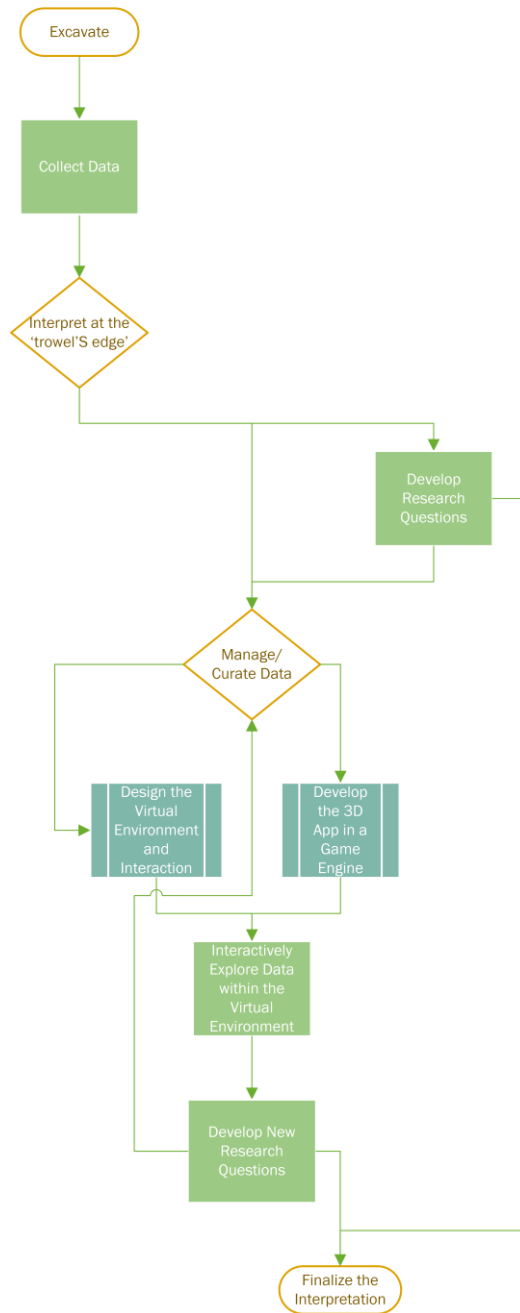

Fig. 5 Flowchart describing our digital archaeological method from the field to the virtual reality interpretation environment

Using such a method as a starting point, our aim is to verify whether the immersive data curation and 3D visualization techniques employed in our custom app Dig@IT can generate new interpretative questions, not just at the 'trowel-edge' stage, as traditionally performed in the reflexive methodology employed at Çatalhöyük, but also afterward, in the virtual simulation environment. We believe that archaeologists, when able to see several stages of the excavation and its stratigraphy in 3D, are incentivized to explore new ideas and questions with the support of three-dimensional spatial perception of complex layers of data (stratigraphic and multimedia) and metadata (Lercari 2017).

5. Cyber-Archaeology Methods in the Dig@IT App

Building on our cyber-archaeological work at Çatalhöyük discussed in the section 1.2, this article strives to provide viable solutions to the challenge of designing a comprehensive method for cyber-archaeology projects focusing on the 3D interactive visualization and curation of searchable 3D data in immersive virtual environments. This section provides an overview of the application Dig@IT, a multi-platform, scalable virtual reality tool able to foster archaeological data analysis, interpretation, and curation in a realistic and highly-interactive immersive virtual environment (see video demo at https://www.youtube.com/watch?v=BNCgOLPCCag) (Lercari 2014b).

The digital workflow we developed in Dig@IT is able to create new inferential models for archaeological interpretation, but further investigation is needed to refine their usage and comprehension. At the current stage of development, the Dig@IT app includes the following digital archaeological tools: (a) three-dimensional visualization of stratigraphic layers, buildings, and surrounding landscape; (b) navigation of the virtual excavation; (c) interaction with single-context layers based on triangular mesh selection techniques; (d) virtual measuring tape tool able to calculate linear distances and length of stratigraphic layers; (e) 3D archaeological data (in .obj file format) run-time import; (f) 'in-app' georeferencing script capable to maintain real world's coordinates; (g) timeline tool to explore buildings and layers through years of excavation; (h) real-time query (via SQL connection) of the *Çatalhöyük Database* that retrieve information on stratigraphic layers and related metadata directly in the virtual environment; (i) 'in-app' metadata visualization through a 'virtual tablet'.

Although digital technology and cyber-archaeology methods are now vastly employed in excavations and projects worldwide (Levy 2013; Forte and Campana 2016), the online curation and dissemination of 3D and geospatial archaeological data is still all but mainstream. Thus, building upon ground-breaking work on immersive visualization (Smith et al. 2013) and multimodal online curation and dissemination of archaeological information (R. Opitz, Mogetta, and Terrenato 2016), Dig@IT can be considered one of the first attempts to develop a multiplatform, fully immersive, three-dimensional tool for archaeological data visualization, interpretation and curation. More importantly, our platform enables an interactive curation and visualization of spatial and 3D data collected in multiple field seasons with the goal to reconstruct the stratigraphic excavation process. Our approach can be compared to a reverse-engineering process of the archaeological excavation. While the visualization of the three-dimensional stratigraphy of a site is not new to archaeology (Doneus and Neubauer 2005a), Dig@IT offers novel interactive and analytical tools that are not available in existing software. The versatility of our method makes our app viable for any single-context excavation. More specifically, the digital content we developed in Dig@IT is specific to a Çatalhöyük Neolithic house (Building 89) and its investigation, but this case study is one of the many instances that can be implemented in our software.

Dig@IT leverages a vast collection of spatial data made of hundreds of 3D stratigraphic layers, architectural features, and related metadata recorded in B.89 over a period of five years using remote sensing and SfM. Our app is able to render and query the stratigraphy of this Neolithic house from its highest post-depositional level (e.g. the interface between the highest infill level of B.89 and the overlaying B.76, partially excavated in 1960's and completed in the 2000's) to early depositional phases of the house "frozen in time" in the numerous plastered floors, burials, and food production areas that the people of Çatalhöyük used before abandoning and partially demolishing B.89.

Dig@IT allows users, scholars, students, and the general public to engage with the visualization, study, and interpretation of a complex archaeological site that is located thousands of miles afar and that is not accessible for most of the year. In fact, due to Turkish regulations on cultural heritage and archaeological sites, the excavations at Çatalhöyük are restricted to the summer season. The harsh environmental conditions of the Konya plain also make visiting the site difficult throughout the year, except in the late spring and summer. Thus, this article presents our proposed solution to the archaeological interpretation of Çatalhöyük using Dig@IT, while it discusses a digital archaeological method and the strengths and limitations of our work and its future development.

6.   Embodied Archaeological Interpretation in Dig@IT

A Çatalhöyük house is the place where diachronic, depositional and post-depositional activities are related with relative chronology sequences and micro-stratigraphy analysis. Such features encourage our interpretation of B.89 to focus more on 3D models and stratigraphic relationships based on volumes, rather than 2D data, such as bi-dimensional section plans and field drawings.

We believe that the methods discussed in this article generate a new type of digital embodiment, defined as *embodied archaeological interpretation*, where a 3D virtual simulation environment for archaeological analysis and visualization creates spatial affordances, otherwise invisible or non-identifiable. The embodied archaeological interpretation enabled by virtual reality and 3D visualization poses new methodological challenges to the understanding of the archaeological past. For instance, past and current interpretation theories on Çatalhöyük (Hodder and Hutson 2003; Hodder 2011) can be argued in an immersive 3D environment through a mediated, multisensory, and multimodal discourse. As a result, the 3D *view-through* analysis enabled by a virtual simulation platform generates discussions and interpretations not achievable in a traditional empirical space, such as the trench. This view-through is particularly relevant in the case of stratigraphic interpretation because it allows users to explore connections and spatial relations throughout the three-dimensional sequence of layers and not just by analyzing stratigraphic units from the top. In the interpretation of B.89, for instance, it is crucial to analyze the latest infill and deposits documented in the first field season in 2011 to understand the retrieval activities of architectural decorations on walls and pillars documented in earlier layers by subsequent field seasons.

In a VR environment, data visualization and simulation enable an embodied archaeological interpretation by allowing archaeologists to see through the morphology and volumetric elements of the stratigraphy and architectural structures of a building using transparency and electrical-microscope-like visual effects, defined graphics shaders. Leveraging virtual simulation, archaeologists can use their bodies and gestures to interact with the data through VR devices while simultaneously browsing metadata and other documentation. In such a visual-analytical environment, sense of presence, immersion, and interaction become important factors that allow archaeologists to analyze the spatial affordances rendered in the simulation. Thus, the embodied archaeological interpretation can be seen as an "augmented" interpretation at the 'trowel's edge' that is not limited by the physical constraints of the excavation and that leverages direct connections and concurrent visualization of data stored in the excavation database, image archive, and stratigraphic 3D models repository.

The embodied and three-dimensional interpretation enabled by our approach is not available in a standardized archaeological mapping system. In a single-context excavation methodology, this is a consequence of the bi-dimensional representation of layers that cannot render the three-dimensional connections in the stratigraphy. The embodied interpretation of B.89 shows several three-dimensional stratigraphic connections between infill, architectural elements, and their tracks on the walls. We believe that such 3D connections, and the method we developed to visualize them, are key elements in understanding the depositional and post-depositional processes of B.89 as well as the natural and artificial actions that were documented in its deposits. By its own nature, three-dimensional information is hyper-informative because it involves texture, geometry colors and volumes. Thus, the 3D simulation of archaeological layers is able to stimulate new discussions and interpretations by leveraging the virtual lighting and shading techniques typical of a VR environment as well as the simultaneous visualization of multiple strata, finds, and datasets. In other terms, while embodied in a visual-analytical simulation environment the archaeologist can see through the layers and ponder connections which are not identifiable in a typical 2D representation (map or photo).
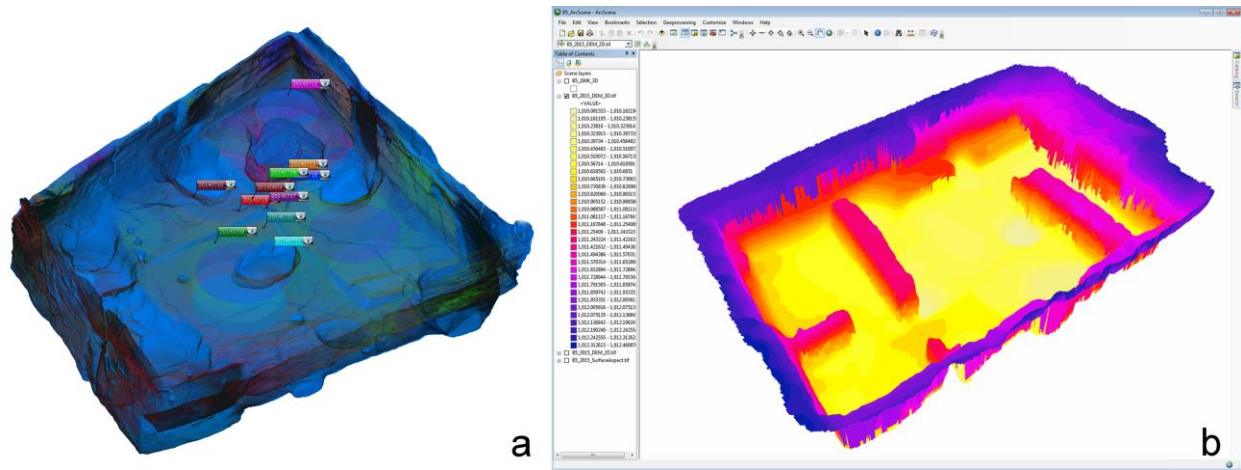
Fig. 6 View of (a) B.89 post excavation 2015 laser scanner point cloud and (b) B.5 3D GIS displaying surface slope visualization in ESRI 3D Analyst plugin used by the 3D Digging Project team to discuss data on-site

Our team has actively employed 3D models (see Fig. 6a and 7), visualization, and 3D GIS (see Fig. 6b) to interpret and discuss Çatalhöyük's stratigraphic data while in the field since the early 2010's. The methods discussed in this section allow scholars and students to embody themselves in the virtual simulation of B.89 during laboratory sessions that follow the end of our excavation in Turkey. We believe that our visual-analytical approach to study the archaeological record is a fundamental component of the embodied archaeological interpretation that occurs in the lab. Therefore, we strived to include in our workflow a 3D, real-time virtual reality application that empowers users with the possibility to visualize, manage, and search stratigraphic, structural, and landscape data (see Fig. 5). Hence in the period 2014-2016, we designed and developed Dig@IT, a research and communication-oriented virtual reality application created in Unity 3D ("Unity 3D" 2016) and Middle VR for Unity ("MiddleVR for Unity" 2016).

Unity 3D is a popular game development platform able to deploy 3D interactive applications on multiple platforms, such as desktop computers, mobile devices, gaming consoles, and the Web. MiddleVR is platform-agnostic plugin that enables virtual reality interaction and immersive visualization capabilities in applications developed in Unity 3D. Leveraging Unity and Middle VR, in 2014 we made Dig@IT available to students and scholars in our home institutions' high-end immersive visualization facilities, such as the Duke Immersive Visualization Environment (DiVE) ("DiVE" 2016) or the Merced Wide-Area Visualization Environment (Merced WAVE) ("WAVE" 2016). After testing a revamped version of Dig@IT, in 2017 we decided to make our app available to the archaeological community (Lercari et al. 2017), as an open source stand-alone platform, distributed under a GNU General Public License ("GNU General Public License v3.0" 2017), that enables the embodied interpretation of B.89 via portable virtual reality devices.
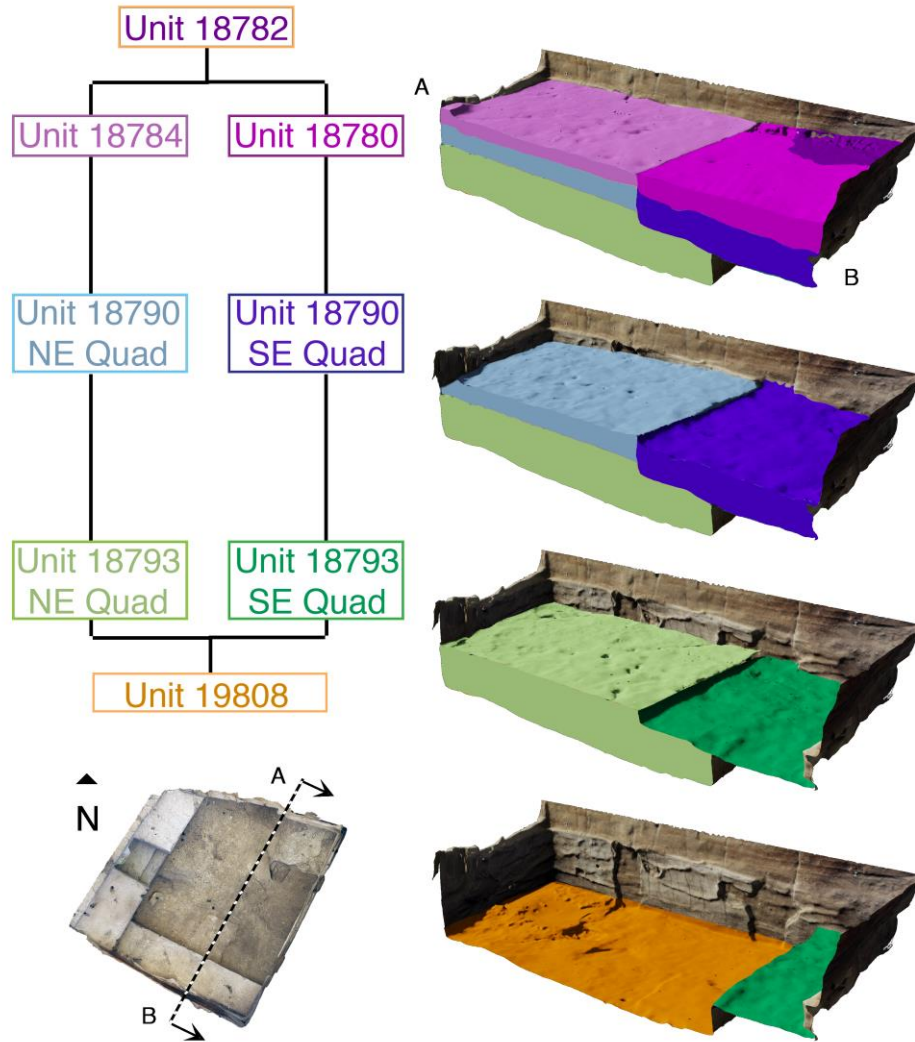
Fig. 7 View of B.89 SfM 3D layers unwrap used by the 3D Digging Project team to discuss data on-site

6.1. User Interface design and Virtual Reality

Dig@IT uses MiddleVR as a middleware between Unity 3D and the various virtual reality input devices and displays to avoid writing boilerplate code necessary for their use; our app uses this plugin to allow a common project to be deployed to several virtual reality platforms simply and rapidly. MiddleVR presents the input devices to the Unity scope with a simple API that models each tracked input device as a GameObject in the hierarchy. Thus, by using MiddleVR we are able to access Dig@IT user's 'head', from a head mounted display such as Oculus Rift ("Oculus Rift" 2016) or a CAVE-type display, such as the DiVE, and our user's 'hand', from a 2-handed wand controller such as Razer Hydra ("Razer Hydra" 2016) as game objects in Unity as well as to apply scripts to them to build our user interface (UI).

Dig@IT features a spatial 3D UI that is optimized for immersive interaction with archaeological geometrical models through an Oculus Rift head mounted display in combination with and Razer Hydra 2-handed wand controller. Alternatively, Dig@IT can be deployed in a CAVE-like system featuring its own optical or magnetic user tracking system. The Razer Hydra controller allows users of our app to browse the 3D stratigraphic layers of Building 89 and to interact with models and artifacts in a 3D space. The tracking system of the wand controller is connected with the Oculus Rift (or with the stereoscopic visualization system of a CAVE) allowing the system to display the correct point of view related to the true head position of the user. Using this approach, we strived to improve the realism of the

simulation and the sense of scale of the virtual scenario in an attempt to enhance the user's sense of presence, immersion, and embodiment in the virtual environment. The significance of this approach is that our method enables the archaeologists to perceive and analyze the depositional and post-depositional phases of B.89 as they were still in the trench (see Fig. 8) by practically recreating in the lab some of the conditions for the interpretation at the 'trowel's edge' used at Çatalhöyük (Lercari 2014b).

Fig. 8 Example of immersive interaction in Dig@IT showing a user manipulating 3D archaeological data through Oculus Rift and Hydra Razer virtual reality devices

Our application features numerous functionalities that are fundamental in a cyber-archaeology 3D data curation platform. For instance, Dig@IT allows users to visualize, manipulate, rotate, transform, measure, and slice stratigraphic units and building features in real-time using the Razer Hydra wand controller.

At the outset of the project, the following features were identified to be implemented as part of Dig@IT and its UI:

- Capability to render a large-scale 3D visualization of Çatalhöyük South Area buildings (documented in 3D between 2012 and 2015) and East Mound landscape (surveyed in 3D in 2015)
- Capability to foster VR interactivity via an 'in-context' main menu that users can toggle, drag. and reposition in the 3D space when they move to new locations (see Fig. 9a)
- Capability to visualize the transformation of Çatalhöyük in different phases of excavation by means of an interactive timeline able to filter 3D buildings and layers using their year of excavation as a filter variable (see Fig. 9b)
- Capability to render a micro-scale 3D visualization of individual stratigraphic layers excavated in B.89;
- Capability to 'virtually dig' and 'bring back' stratigraphic layers in B.89 using a button on the wand controller
- Capability to retrieve information on B.89 stored on the online *Çatalhöyük Database* by 'selecting' stratigraphic layers with the wand controller
- Capability to display information and metadata on selected layers in a 'in-game' separate window, defined 'virtual tablet', that resembles the tablet PCs utilized on-site by excavators
- Capability to toggle a virtual reconstruction of B.89 that shows hypothesis on how the building might have looked before abandonment
- Full georeferencing (one-to-one matching) of the virtual coordinate system with the local coordinate system used by the Çatalhöyük Research Project

- Capability to import 3D models of artifacts at runtime and place them in context within the 3D scene
- Capability to calculate linear distances and length of a stratigraphic layers by means of a "measuring tape" tool operated by a VR wand controller (see Fig. 10b).

Fig. 9 View of (a) in-context menu and (b) timeline selector tool in Dig@IT

6.2. Virtual Tablet & Annotation

One of the most innovative UI features in Dig@IT is the 'virtual tablet'. Mainly, we designed this feature to facilitate the display of metadata and other information (e.g. photographs) stored in the *Çatalhöyük Database* within the virtual environment. Our design choice was to make the 'virtual tablet' resemble the tablet PCs that excavators and osteologists use on-site for the documentation of stratigraphic units, building features, and skeletons. The 'virtual tablet' allows users to browse contextual information, or metadata, stored in a SQL server that describe the 3D models that are selected or hovered in that moment directly from within the 3D scene (see Fig. 10a). To accomplish this task, the 'virtual tablet exploits the tagging system provided by our custom script VRWandInteraction. In addition, all the 3D content in our app tagged with 'feedback', being highlighted when hovered-over, are used to populate the text-fields on the 'virtual tablet' screen. Due to the fact that current game engines are not optimized to access or edit external databases and due to security constraints in the Çatalhöyük Database, the 'virtual tablet' does not allow Dig@IT users to switch from a VR-optimized visualization of tables stored in the database to a full access to the SQL server. These limitations determine the incapability of the 'virtual tablet' to perform custom queries and statistical analysis on the database. The source of the data displayed in the 'virtual tablet' and the limitations of our approach will be explained in more detail in section 7.

To enhance the VR interaction in Dig@IT, the 'virtual tablet' becomes visible when the user looks down towards their left hand. This choice was made to mimic the 'real world' action of an archaeologists gazing at a tablet PC when looking for information on the GIS or web interface of the *Çatalhöyük Database* while in the trench. To allow natural interaction with the tablet, in the Oculus version of Dig@IT we attached one of the Razer Hydra hand controllers to a brick-and-mortar tablet, so that the user can hold the real tablet, and when looking down at it, see the 'virtual tablet' rendered in the same location. For the CAVE version of the system, we used a real iPad, with a custom Unity app connected to Dig@IT through sockets. The information displayed in the iPad is the same as the information displayed in the 'virtual tablet'. Future work will focus on adding the capability for the users to record annotations directly in the 'virtual tablet' for objects tagged with 'feedback'.
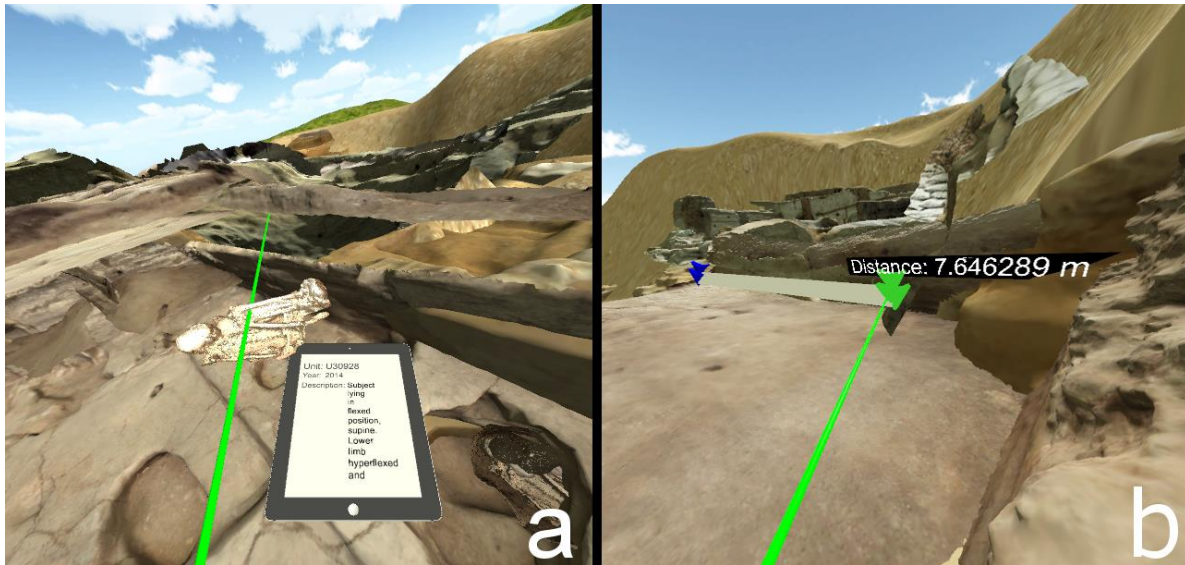
Fig. 10 View of (a) the 'virtual tablet' feature and (b) the measuring tape tool in Dig@IT

7. Data Curation in Dig@IT

7.1. Database Information Retrieval

As mentioned in the previous section of this paper, the Dig@IT app was developed using the popular game development platform Unity 3D. Unity is object-oriented in both its programming model and its storage of data. An entire scene is stored as a hierarchy of logical units called GameObjects. These GameObjects have components attached to them which define their properties and behavior. As anticipated in section 6.3, Unity is not the most suitable tool for accessing and editing databases implemented via a remote SQL server instance, for example the Çatalhöyük Database hosted at the University of Cambridge, in the U.K, that stores more than twenty-three years of excavation data. Being aware of the limitations of the 'virtual tablet' feature and our method to access the Çatalhöyük Database from within our VR app, one needs to underline that Dig@IT users can search specific information on the Çatalhöyük's archaeological record via the Çatalhöyük Database web interface using a regular Web browser. Although such a web interface allows to browse and search the available data, it is still not suitable for custom queries and statistical analysis. Archaeologists and scholars affiliated with the Çatalhöyük Research Project can request full access to the database and then use SQL scripting or the visual interface of Microsoft SQL Server Database Management System to perform advanced operations, such as custom multi-table queries and statistical analysis outside of our VR app.

In Dig@IT, the 3D models of the Çatalhöyük excavation (including each stratigraphic layer of Building 89) and the surrounding landscape are represented as GameObjects. Each GameObject is defined by specific material and texture components that define how the graphics engine will render it. In addition to these components, which define static properties, data and logic can also be attached to GameObjects with components that are actual code (we chose to write our code in C# programming language for performance reasons, but JavaScript programming is also available in Unity 3D). These script components have access to the entire state of the GameObject that they are attached to, and can define logic to be executed before and during runtime of the application.

It is this particular programming model (scripts as components attached to objects), along with the naming convention already employed for the Çatalhöyük Database, that allows Dig@IT to act as a 3D interface to certain tables within the database, with no further work on the database/server-side. As part of the existing excavation process, at the building/unit level, when models are captured and pre-processed, they are given a name that acts as their unique identifier in the database (e.g. the key U19807, for a particular stratigraphic layer, or unit). In all relevant tables and views, information regarding each unit can be queried with this identifier as a key.

In the Dig@IT implementation, attached to each GameObject representing a single layer in Building 89 is a single script which, at runtime, makes a single query to the remote database requesting all information that will be displayed in the 3D interface. This information (excavation year, descriptions) is then stored in components on each layer, allowing it to be displayed in context with tools like the 'virtual tablet' and used for features like the timeline-slider. In Dig@IT, this approach has been used for simple text data, but it is not restricted as such. Using the known unique identifiers as part of the 3D pre-processing stage, *any* storable information related to a specific unit could be retrieved at runtime from a remote database, including textures, images, and audio.

7.2. 3D Model Run-time import and Georeferencing

Another important data management and curation feature we implemented in Dig@IT is the ability for users to upload their own 3D models of archaeological artifacts at run-time. This feature allows users to upload artifacts that are known to exist in the context of Çatalhöyük into the virtual environment while using the app. Implementing this feature posed a challenge to our developers for two reasons: 1) Unity does not support or encourage generation of GameObjects at runtime, and 2) the coordinate system/transformation data belonging to a georeferenced 3D models would need to be converted to be consistent with the coordinate system of Dig@IT's 3D scene. The latter items were of particular essence because an imported 3D models must be placed exactly in the same location using the same coordinates where it was excavated to be meaningful to archaeologists using our application. To solve the first issue, we purchased *ObjReader*, a set of scripts on the Unity Asset Store that allows for importing of Wavefront .obj files during runtime. To solve the second issue, we decided on a new convention for 3D models, that were provided by the archaeologists already georeferenced in the local coordinate system used on-site, only using Wavefront .obj files and ensuring that their internal transformation/coordinate information is preserved. This solution allows the system to place imported 3D models precisely where they belong. A menu option currently exists in the UI for importing sample .obj files, but no UI has been created for accessing the file system to browse for models.

The data management and database information retrieval strategies we implemented in Dig@IT, make our application capable to maintain the 3D models' georeferencing while it allows users to browse textual metadata that reside in an external SQL database from within the virtual environment.

8. Sustainability

As anticipated in section 2.2 of this article, a comprehensive publication of all excavation data and digital documentation of Building 89 will be completed after the 2018 Çatalhöyük study season. In an effort to make our three-dimensional data available to the research community and the wider-public in a timely fashion, we partnered with the UCSD Center for Cyber-Archaeology and Sustainability to curate the currently available 3D models of B.89 and related metadata through an online repository hosted by the UCSD Library.

In an effort to cope with the complexity of the data and metadata we produced, we have designed and implemented Dig@IT as a platform able to facilitate archaeological data analysis, interpretation, and curation in a highly-interactive immersive virtual environment implemented in Unity. Due to current limitations of virtual reality techniques, Dig@IT is not a suitable platform for interfacing with the 3D online repository that will be hosted at UCSD. This is especially true because Dig@IT requires specialized input/output devices (e.g. Oculus Rift and Razer Hydra) for interacting with the virtual scenario and browsing the 3D data. This matter brings forward the currently unsolved issue of the sustainability of archaeological information especially of 3D stratigraphic data.

Being aware that the life-span of custom 3D digital tools, such as Dig@IT, and game engines, such as Unity 3D usually expires in about five years, one needs to emphasize that the sustainability of our method is limited in time and reach. A potential solution to this issue is to make all the available raw data collected in the field (e.g. photos, drawings, videos, metadata) and high-quality 3D models and post-processed information created in the laboratory available to the public in the online repository that will host the final publication of the project. Such a dissemination strategy will require a major investment in terms of data storage and specialized platforms for data curation. It should be noted that a longer term sustainability of Dig@IT and similar 3D platforms for heritage data curation and interpretation could be guaranteed by hardware and operating system virtualization techniques. Although our work explored the virtualization of cultural virtual environments first hand (Lercari et al. 2011), we do not have resources at the moment for considering the virtualization of Dig@IT and its virtual reality capability.

9. Conclusions and Future Work

This article discussed the significance of a cyber-archaeological workflow in the excavation, interpretation, and curation of archeological data retrieved at the Neolithic site of Çatalhöyük. Our work strived to demonstrate that three-dimensional data recording, visualization, and embodied interpretation can be considered fundamental components of the reflexive excavation methodology employed at Çatalhöyük since the mid-1990's. A recent revision of the reflexive archaeological practice illustrates how a broad spectrum of visual-analytical 3D technologies can be successfully integrated with the interpretation at the 'trowel's edge' approach that is employed in the investigation of Çatalhöyük (Berggren et al. 2015). Hence, one can verify that our digital archaeology work has gained legitimacy within Çatalhöyük's archaeological community by implementing interactive analytical and visualization tools able to convey spatial and temporal information on layers, features, and entire buildings by means of 3D real-time simulation platforms (Lercari et al. 2013). To support this conclusion, the excavation of Building 89 should be viewed as a very successful pilot case study because the 3D data recording and simulation methods that we employed allowed the archaeologists involved in this study to discuss features, details, and stratigraphic connections, otherwise not visible in a 2D drawing or photograph. The transparency of the models and the view-through of the layers available in Dig@IT are an example of the advantages of an embodied archaeological interpretation that develops from "within" the stratigraphy, rather than from the usual top-view perspective in the trench or in a traditional interpretation of bi-dimensional documentation data.

The study and publication of our research in B.89 is still a work in progress but we are confident that, when completed, it will contribute to further highlight the effectiveness of the method discussed in this article. We are aware that it might take time for the embodied interpretation and three-dimensional approaches used in cyber-archaeology to have a broad effect on the archaeological interpretation of the past at the intra-site and inter-site level. A foreseeable bottleneck in this process is represented by the fact that current structure from motion and laser scanning documentation techniques only record the 3D morphology of the surface of a layer and not its volumetric components. This implies that the volume of a layer in the simulation environment is usually extrapolated as the geometrical gap between overlaying stratigraphic units during data post-processing. A potential solution to this issue could be the integration of geophysical survey data (e.g. ground penetrating radar) with the geometric information captured by SfM and TLS in an attempt to merge deposits' spectral signatures with their geometrical description.

Using the above starting points, this article presented the immersive visualization and data curation application Dig@IT that we development in the period 2014-2016, illustrating the strengths and limitations of such an experimental software. Although cyber-archaeology methods have become widely adopted, research on the online curation and dissemination of 3D and geospatial archaeological data is still at an early stage. Dig@IT attempts bridge this gap by recreating virtually and systematically the entire process of stratigraphic excavation, starting from three-dimensional data recording in the field and ending with the design and implementation of a virtual reality system for interactive data curation and interpretation.

We believe that the virtual process of excavation performed in our app allows new insights into the three-dimensional interpretation of stratigraphic layers, finds, and buildings, using a 3D spatial approach. The integration of empirical data (the excavation) with potential reconstructions/simulations, raises new research questions and supports the archaeological interpretation in the multiple phases of validation and critical analysis.

Our work at Çatalhöyük demonstrated that the proposed method is now feasible thanks to the very innovative interaction between this empirical evidence, the interpretation in situ, and the virtual simulations created in the labs in our home institutions using 3D immersive virtual environments. In addition, this article discussed how Dig@IT can be easily deployed on multiple platforms using Unity 3D and the middleware MiddleVR; such tools allow a full standardization of our app in multiple devices (e.g. Oculus Rift and other commodity VR headsets) and immersive VR systems such as the DiVE at Duke University or the Merced WAVE, recently built at UC Merced. The Merced WAVE is a panel-based visualization facility for visualization of research-derived content, performance and collaboration featuring the cutting-edge ARTTRACK5 motion tracking system manufactured by Advanced Realtime Tracking ("ARTTRACK5" 2016). This cutting-edge immersive virtual reality system features twenty 4K OLED 3D TVs mounted in a half-pipe configuration resulting in an array of 160 mega pixels which, since fall 2016, is the highest-resolution virtual environment of its kind in the world.

Our work strived to demonstrate that Dig@IT has a great potential as a visual-analytical tool that enables embodied archaeological interpretation. On one hand, we discussed how the virtual simulation of an archaeological excavation is able to generate new research questions and review the entire interpretation process based just on empirical data. On the other, we presented Dig@IT as a tool capable to facilitate the analysis of single-context data using 3D visualization and to link alphanumeric information and metadata with 3D models in the same cyberspace. Our method proposes the integration of bottom-up tentative interpretations (e.g. 3D stratigraphy) with top-down reconstructions (e.g. hypothetical architectural re-composition) with the aim to create new inferential models that go beyond a traditional archaeological interpretation process. Thus, the proposed method leverages an array of affordances in the virtual environment that are associated to different depositional and post-depositional activities identifiable in a Çatalhöyük Neolithic house. One can conclude that the significance of our method relies on the possibility to enable archaeologists to perceive and analyze the depositional and post-depositional phases of a Neolithic building using a cyber-approach that integrates a plurality of data in a single simulation environment that is not limited by reality constraints (Lercari, Forte, et al. 2014; Forte 2014).

This article emphasized that the usage of game engines in archaeology presents strengths and limitations. For instance, Dig@IT is a powerful 3D tool for archaeological interpretation, but it is not ideal as a digital 3D repository to archive archaeological data. This limitation is determined by the fact that current game engines (e.g. Unity 3D and Unreal) are not capable to store and display vast collections of high-resolution 3D data in real-time. Although we designed a solution able to georeference a 3D model in Unity and Dig@IT (see section 5.2), a game engine is not optimized to integrate real-world coordinates and spatial and georeferenced data in the same environment, which causes challenges with compatibility with GIS platforms and remote sensing data currently used in archaeology.

Future work should consider the development of hybrid systems, in which a gesture-based user interface such as the one employed in Dig@IT, will be seamlessly integrated with GIS tools with the goal to promote data interchange between interactive virtual environments, 3D repositories, archives, and interactive annotation systems. Our aim is to further expand Dig@IT by integrating new functionalities and making the app available in a new VR platform that includes the consumer version of the Oculus Rift as well as a wireless, long-range magnetic tracking system such as the STEM system ("STEM System" 2016). Additional development will be also needed to integrate Dig@IT with the Merced WAVE virtual reality system.

By enabling digital access to the three-dimensional simulation of the excavation at Çatalhöyük as well as to the virtual reconstruction of some of its buildings, we believe that Dig@IT is even more relevant today in a period where access to archaeological sites in the Near East and Middle East is made more complicated by current geopolitical developments in such regions. In addition, Dig@IT allows scholars and students to continue investigating Çatalhöyük while the management of this outstanding UNESCO World Heritage site will undergo an upcoming regime change. In fact, in 2018 the current team (Çatalhöyük Research Project) will finish and a new team will take over the management, investigation, and conservation of Çatalhöyük. Currently, these circumstances leave uncertainty on the future accessibility of the site and its large collections of Neolithic buildings and material culture.

Our work strived to illustrate that the use of digital datasets and immersive data curation tools in archaeology requires new methodologies for archiving data collected in the field. As discussed in section 2.2 and section 8 of this article, our partnership with UCSD Center for Cyber-Archaeology and Sustainability work is an attempt to explore new opportunities for establishing a common cyber infrastructure able to guarantee free and open access to three-dimensional information. But the limited diffusion of web-based, open archives and repositories able to store, annotate, and search 3D models and related metadata indicates that future work still needs to address this issue. Nonetheless, we believe that our methodologies proved feasible to visualize, analyze, and curate three-dimensional stratigraphic data in an interactive virtual environment, even when the case study is a large archaeological site such as Çatalhöyük (Forte et al. 2015).

Compliance with Ethical Standards:

Conflict of Interest: The authors declare that they have no conflict of interest.

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