Terrestrial Laser Scanning in the Age of Sensing

Nicola Lercari

Abstract For more than a decade, Terrestrial Laser Scanning (TLS) has been a primary remote sensing technique for disciplines related to archaeology, architecture, built heritage, earth science, metrology, and land survey. The increasing precision, range, and survey speed of TLS make this technology even more viable for large-scale data capturing in the Age of Sensing. This chapter reviews the state of the art of Terrestrial Laser Scanning in 2015 with the aim to assess its applications in a context of lower data capturing costs for alternative technologies, such as new commodity sensors, Image-based 3D Modeling, Unmanned Aerial Systems (UAS), optical 3D scanning, and Airborne Laser Scanning. More specifically, TLS still maintains a fundamental role in the documentation and interpretation of archaeological contexts at intrasite scale: (i) Terrestrial Laser Scanning delivers high-fidelity data of surfaces and structures of buildings as well as ultra-precise measurements of the morphology of stratigraphic layers; (ii) research in remote sensing proved that TLS point clouds can be successfully interpolated with data recorded with other instruments and techniques, such as magnetometry, Ground Penetrating Radar, Unmanned Aerial Vehicles, Image-Based Modeling, in order to generate hybrid documentation and new knowledge on natural and cultural heritage sites. Inevitably, the current advancements in TLS bring new questions. For example, how can micro-differences only visible in the point clouds change the analysis and interpretation of layers and buildings? How to improve the monitoring and conservation of a site via automated analysis of TLS data? How to enhance the mapping process of built-heritage using data segmentation or semi-automatic feature extraction of TLS point clouds? This chapter proposes a new approach to TLS based on multi-modal capture workflows, semi-automated post processing, online archiving, and online visualization and management of point clouds with the aim to open new horizons for digital archaeology, architectural survey, and heritage conservation.

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Overview of New Data Capture, Processing, and Visualization Systems in Relation to Terrestrial Laser Scanning

The second half of the 2010s witnesses a deep transformation in the domain of data recording, data processing, and visualization. A number of cutting-edge remote sensing technologies and methods are now production-ready tools that can be deployed in the fields, do the job, and challenge established survey technologies, such as Terrestrial Laser Scanning. The Age of Sensing is characterized by the rapid diffusion of cost-effective and incredibly versatile technologies such as computer vision-based 3D scanners, inexpensive cameras and sensors, mobile or web apps for real-time processing, and interactive platforms for data sharing in the cloud. Commodity sensors, such as accelerometers, three-axis gyroscopes, proximity sensors, ambient light sensors, and Global Positioning System (GPS) receivers are becoming ubiquitous in smart phones, cameras, household electronics, cars, and wearables.

As of the beginning of 2015, new generations of sensors are ready to go mainstream while their manufacturers openly express the ambition to transform the way people interact with the real world through their digital devices.

Great examples of the new era of commodity sensors are: (i) revolutionary optical 3D scanning solutions, such as the Structure Sensor, now available for smart phones and tablets users to be employed in the digitization of objects, interior environments, and artifacts; (ii) low-cost motion tracking technologies, such as the Intel RealSense, embedded in new tablets and laptops that promise to change the way users interact with computers (Intel RealSense 2015); (iii) commodity thermal imaging sensors, such as the Seek Thermal XR camera, which enable smart phones to detect infra-red light and record thermal information opening new possibilities for basic spectral analysis for the masses (Seek Thermal 2015).

The effects of the mass diffusion of sensing technologies on the society at large are yet to be assessed. What is already clear is that new, low-priced, and increasingly powerful tools for data capture, processing, and visualization have started to transform the field of remote sensing and its applications.

This new scenario opens research opportunities linked to the development of novel methods, bringing scholars to experiment hybrid techniques and workflows that integrates more established tools, such as TLS, with cutting-edge technologies often developed by small, start-up companies, research centers, or universities.

The following sections of this chapter will analyze in detail the transformational shift described above, especially in regards to Terrestrial Laser Scanning. The aim is to ponder new advancements in the fields of data recording, processing, and simulation and discuss whether TLS still matters today.

Alternative 3D Capture Systems

In the Age of Sensing, TLS is no longer the only viable solutions to survey heritage sites, buildings, and archaeological excavations in 3D.

Image-based 3D modeling techniques, also known as Structure from Motion (SfM), have long proved viable for the documentation of heritage (Pollefeys et al. 2001; Remondino and Menna 2008), stratigraphic layers in archaeological excavation (Doneus and Neubauer 2005a, b; Forte et al. 2012), and artifacts (Kersten and Lindstaedt 2012).

What is remarkable is that one can now digitize an entire indoor environment in real-time using commodity 3D data capture systems based on depth cameras technologies or structured light devices. The effects of Microsoft Kinect sensor have been largely documented (Zhang 2012); especially in regards to data capture accuracy (Khoshelham 2011), and mapping of indoor environments (Khoshelham and Elberink 2012). The performance of low-cost 3D scanning devices has also been assessed in relation to their employment in the cultural heritage domain (Guidi et al. 2007).

In 2015, it is now possible to 3D capture, process, and virtually reconstruct both the built environment and objects in real-time using sensors, such as Microsoft Kinect or Structure Sensor by Occipital (Structure Sensor 2015) combined with mobile devices (Raluca Popescu and Lungu 2014). A Structure Sensor records colored triangular mesh of its surrounding space or objects—located within 2 or 3 meters from the device—in a matter of seconds. It uses an iPad, or smartphone, to process the captured data, render its geometry, and align multiple point of views in real-time (Fig. 1).

The possibility to capture, process, and instantaneously visualize the 3D scans on a mobile device implies that the survey of built heritage or archaeological sites can potentially be verified on the go. Differently than TLS, this capability makes data post-processing inexpensive and fast.

Fig. 1 Structure Sensor uses iPad for real-time data processing—courtesy of Occipital

A foreseeable effect of this new technology is that dense data capture becomes now available to anybody who owns a tablet or smartphone and is willing to spend few hundred additional U.S. dollars to purchase a Structure Sensor. There is no doubt that this capability will open new horizons for community-based heritage preservation performed by cultural associations, volunteers, students, and local communities. More broadly, one can envision that heritage diagnostics of the built environment or the digital documentation of archaeological remains could be immediately discussed on site, few instants after the survey is completed.

A discourse on alternative 3D capture systems need to go beyond a cost-benefit analysis of purchase price, survey time, and ease of use. Thus, this chapter needs to assess whether the new optical scanning solutions also challenge TLS in regards to data fidelity. One can now record, align, and process in real-time very precise colored point clouds of the interior of a building or the shape of complex objects using a DPI8 scanner developed by DotProduct (DPI8 2015). This hand-held 3D scanner is operated via the operating system Android and relies on a low-cost tablet PC for processing data in real-time. DPI8 delivers fairly accurate measurements within a range of 0.6–5 m when used with optimal ambient conditions. In February 2015, the author of this chapter had the opportunity to test a DotProduct scanner for a test survey of the interior of a warehouse located at Fort Mason Center, in San Francisco, during the *REAL 2015* conference (REAL 2015). Such preliminary testing showed that a DPI8 optical scanner is able to deliver precise data when scanning the interior of a building, which has been evenly lit. Undoubtedly, further testing on DPI8 is needed to call this portable 3D capture system a mature technology for heritage documentation. Given a price tag of few thousands of U.S. dollars, it is relevant to mention that the data fidelity of this optical scanner is acceptable if compared to a TLS unit, such as a FARO Focus^{3D} X330, which costs about ten times more (FARO Focus^{3D} X330 2015). No doubt, DPI8 already presents the characteristics needed to become a leading technology in the domain of artifacts digitization and documentation of interiors of buildings.

The current revolution of data capture platforms is not solely related to indoor surveys and artifacts scanning. New tools for landscape surveying and built environment 3D mapping are now available. Such new systems combine lightweight Unmanned Aerial Vehicles (UAVs), uncalibrated cameras, and Image-based 3D Modeling software, posing major challenges to the viability of TLS for what concerns intersite documentation or landscape surveying.

In 2015, advanced 3D mapping standalone software, such as Pix4D, allows scholars, architects, and heritage practitioners to perform accurate 3D mapping of entire sites and landscapes (Pix4D 2015). Other cloud-based UAS platforms, such as DroneDeploy (DroneDeploy 2015) provide archaeologists, land surveyors, and geoscientists, with new effective tools for 3D mapping cultural landscapes and natural environments simply using Android or iPad devices to manage mission planning, data capturing, and server-based data processing. Currently, the most widespread technique for the 3D documentation of archaeological heritage is the standalone Image-based 3D modeling software Agisoft Photoscan Pro (Photoscan 2015). In the Age of Sensing, the popularity of this technology is so widespread that Photoscan is becoming a standardized method for intrasite and intersite documentation. Photoscan provides archaeologists and conservators with an incredibly efficient workflow that reduces the cost and time of single context data recording, while enhances on-site data-driven discussion and interpretation (Forte et al. 2015, pp. 45–46) (Fig. 2).

The viability of standalone and cloud-based UAS platforms for 3D documentation in archaeology—specifically Photoscan Pro and DroneDeploy—were positively tested in the summer 2015 at the archaeological sites of Çatalhöyük and Boncuklu Höyük, in Turkey. In the field season 2015, a DJI Phantom 3 Pro multirotor copter equipped with a 4K RGB camera and DroneDeploy server-based mission planning was employed to conduct several missions for indoor survey inside the permanent shelters (Lercari and Lingle 2016), as well as for outdoor 3D mapping survey (Forte et al. 2016). Such UAS operations were aimed to enhance the 3D survey of Çatalhöyük buildings for conservation and monitoring purpose. UAS data capture was also employed to 3D map the landscape of Çatalhöyük and its environs with the goal to provide further understanding of the site's relationship with other Neolithic settlements in the Konya plain, such as Boncuklu Höyük.

The above mentioned survey methods open new horizons for heritage conservation and documentation in a time of decreasing funding for archaeological excavation or cultural heritage preservation. Thus, micro UAS platforms challenge commercial photogrammetry or airborne LiDAR services in relation to intersite surveys. Their capability to render the morphology and multispectral properties of heritage sites and landscapes with high accuracy and in a cost-effective way, allows the new multi-sensor data capture systems to also challenge laser scanning in regards to intrasite documentation.

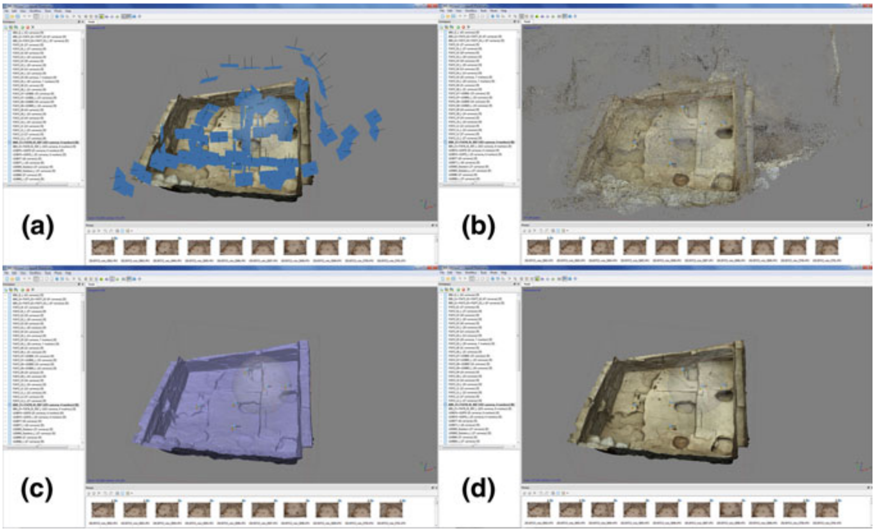

Fig. 2 Processing of 3D data captured at the UNESCO site of Çatalhöyük, Building 89 in Agisoft Photoscan showing. **a** Camera positions and ground control points. **b** Georeferenced dense cloud. **c** Edited triangular mesh in *Wireframe mode*. **d** Optimized triangular mesh in *Shaded mode*

The Historic Buildings and Monuments Commission for England—also known as Historic England or English Heritage—provides surveyors with thorough guidelines with the aim to help identify the best application scenarios for Airborne LiDAR, TLS, or other 3D capture methods in relation to different deliverables and specific precision and accuracy goals (Crutchley and Crow 2009).

Currently available technologies give surveyors the advantage to cut the duration of the survey process from data capture to final delivery by one order of magnitude. For instance, one can now fly an affordable thermal camera, such as a FLIR Tau 2, and a compact RGB camera, such as a mirror-less Sony RX100, mounted on a consumer multi-rotor UAW manufactured by DJI (DJI 2015) or 3D Robotics (3DRobotics 2015) for few thousands of U.S. dollars (FLIR&DJI 2015).

The current major shift in 3D mapping and 3D modeling is due to proven computer vision technologies based on Structure from Motion (SFM) and Dense Stereo Matching (DSM) algorithms (Verhoeven 2011; Verhoeven et al. 2012; De Reu et al. 2013; De Reu et al. 2014). SFM and DSM proved to be reliable technologies that can be used to process large datasets of aerial photographs captured by uncalibrated digital cameras mounted on lightweight aircrafts flying GPS waypoint missions.

Nonetheless, the main disadvantage of the new 3D capture technologies is that the new 3D scanners mostly rely on depth cameras or electro-optical sensors that still do not work outdoors, or at night, or underperform in scenarios where the subject is overexposed or not evenly lit. Thus, the quality and accuracy of the new 3D digitizers highly depend on environmental conditions such as the temperature, illumination, and reflectivity of the area of interest. One needs to notice that such constraints may be overcome by future technological development, but currently represent a strong drawback to the adoption of the new 3D capture technologies in many professional fields and academic disciplines. One also needs to underline that some of the above mentioned limitations might apply to traditional laser-based data capturing tools. For instance, digital archaeological work at the UNESCO site of Çatalhöyük, in Turkey, proved that the documentation of stratigraphic layers may be very complex or not feasible when an high-accuracy optical laser scanner (e.g. Minolta Vivid 910) was employed in the field to document the stratigraphy of a complex midden sequence (Forte et al. 2015, pp. 43–44). When compared to optical technologies, time-of-flight and phase comparison laser scanners are less affected by adverse lighting conditions; the accuracy and precision of such scanners can decrease in heavily lit scenarios, unless such equipment is specifically manufactured for long-range and outdoor usage. More broadly, one also needs to mention that extremely hot or cold temperatures can affect the majority of data capture sensors. Extreme environmental conditions may become an issue for surveyors. For example, the author of this chapter has often experienced TLS equipment warnings and shutdowns while scanning archaeological heritage inside the permanent shelters of Çatalhöyük where air temperature may be above 45° C in a hot summer afternoon.

In terms of survey range, the new commodity 3D scanners offer very limited options when compared with time-of-flight or phase comparison TLS technologies. Optical and TLS structured light data capture systems have very limited survey range—usually from 0.5 m to maximum of few meters from the sensor—and present a number of constraints that make them not very feasible for large sites or whole-building surveys (Fig. 3).

Moreover, mass consumers are not very interested in expensive or complicated calibrations operations or data fidelity. These propensities are reflected in the way the new commodity data capture tools are designed and built. The new 3D digitizers are rarely rugged enough to perform well outdoors or in the fields and do not support custom color and sensor calibration.

A comprehensive cost-benefit analysis of the alternative technologies and methods discussed in the previous pages goes beyond the scope of this chapter, but will need to be examined in future publications.

User-Oriented Data Processing and Open-Source Software

In the Age of Sensing, data processing is also more effective, faster, user-friendly, and occasionally freely available. For instance, the end-to-end 3D platform developed by Matterport allows users to perform the following with great ease Matterport (2015): (i) to scan and upload 3D data via a Matterport Pro 3D camera, an optical solution for data capturing, or simply via any mass-market mobile devices equipped with a Matterport 3D capture app; (ii) to automatically process the captured data in the cloud

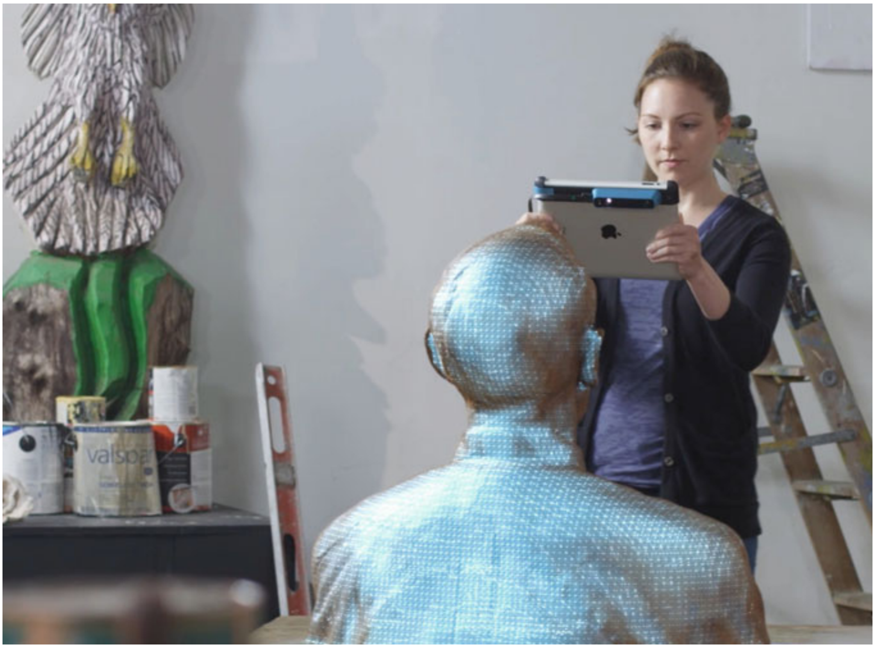

Fig. 3 Indoor usage of the Structure Sensor to record artworks—courtesy of Occipital

using Matterport Cloud Service; (iii) to enable anybody to interact with and share the processed data using a web browser or mobile app (Matterport). The functionalities of the Matterport platform make this tool a comprehensive and very easy to use system able to 3D map the world, display content on virtual reality headsets, such as Oculus Rift (Oculus Rift 2016), HTC Vive, Samsung Gear VR (Samsung Gear VR 2016), or the Web, while enable mass mobile technologies to become 3D capture systems.

Sequoia is a multiplatform, standalone software that allows to easily reconstruct the surface of large point clouds made of several billions of points. Sequoia is able to convert huge data sets of laser scanning data and particle data to triangular mesh geometry in few minutes (Sequoia 2015). The start-up company Thinkbox Software developed Sequoia's architecture to handle massive amounts of laser scanning data through a progressive processing workflow. The result of this approach is that Sequoia is able to visualize the final result of the processing even before all the data is loaded. Moreover, this software is able to handle huge data sets that can be larger than the actual memory available in the computer where the processing is performed. Sequoia also allows users to perform operations such as smoothing, decimation, color and texture projection on mesh (Thinkbox 2015).

One of the exceptional aspects of Sequoia is that this application makes large point clouds processing accessible and easy to handle even for non-experts in TLS data processing. In fact, Thinkbox Software developed this application for architecture, engineering and construction markets with the goal to directly compete with more established data processing platforms such as the 3D authoring tools developed by 3D Systems (3D Systems 2015).

In regards to 3D Systems' products, one needs to spend few words on Geomagic Design X, formerly known as Rapidform XOR. In the Age of Sensing, Geomagic Design X is one of the most advanced point cloud processing software capable of combining the parametric approach of Computer Aided Design (CAD) software with advanced 3D data scan processing capability. Nonetheless this tool is part of a specialized software platform primarily created for reverse engineering and manufacturing projects, Geomagic Design X is user-friendly and presents a number of functions able to automatically extract features and components directly from the point clouds. The applications of Geomagic Design X for the documentation and mapping of sites and the drawing of artifacts are endless; one can employ Geomagic Design X for point cloud to CAD operations. This allows surveyors to generate accurate maps of entire sites or sections of walls and facades starting from TLS survey data. One can also use Geomagic Design X for authoring precise 2D drawing of artifacts and other material culture objects that were previously scanned (Geomagic Design X 2015). The main downsides of the commercial software referenced above are: (i) the high cost for acquiring the license of these proprietary platforms; (ii) the ongoing cost for maintaining them; (iii) the closed-source code; (iv) commercial strategies non-quite friendly to educational institutions.

In the Age of Sensing, viable alternative solutions to the above-mentioned software are available free of charge. MeshLab is an free software application for mesh and point cloud data editing that is incredible popular among scholars, educators, cultural institutions, and private firms involved in the digital documentation of heritage sites and 3D data processing (Cignoni et al. 2008).

The widespread diffusion of MeshLab is due to the powerful tools and filters it provides to its users (Fig. 4) (MeshLab 2016). This software is distributed under GNU General Public License. MeshLab is the product of the invaluable dedication and cutting-edge research of the Visual Computing Laboratory at CNR-ISTI research center. What is remarkable about MeshLab, is that it is developed by a team of scholars committed both to develop free software for cultural heritage as well as to advance virtual heritage research (Callieri et al. 2011; Dellepiane et al. 2012; Siotto et al. 2014).

CloudCompare is a multiplatform open-source solution for 3D point cloud editing that can be also employed to process triangular mesh (Girardeau-Montaut 2011; CloudCompare 2015). This software was initially created in 2004 in the division for Research and Development of the public utility company Électricité de France (R&D E.D.F. TP 2011). In 2009, CloudCompare was released as free software under GNU General Public License. CloudCompare architecture exploits octree structure techniques to visualize and handle large point cloud data sets (Chien and Aggarwal 1986). This application offers a large variety of cloud processing algorithms spanning mesh-cloud comparison, registration, resampling, color and picture projections, and interactive or automatic segmentation. CloudCompare is especially relevant for evaluation and comparison of 3D Data (Scollar and Giradeau-Montaut 2012; Rajendra et al. 2014) (Fig. 5).

Viable workflows for data capture and processing rely on: (i) transparency of the data acquisition process, (ii) use of open file formats (e.g. Wavefront .obj or Polygon

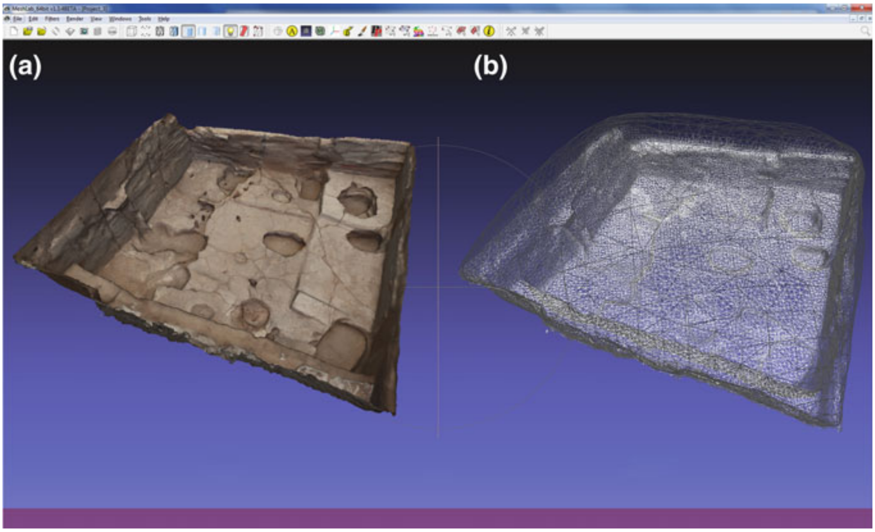

Fig. 4 Triangular Mesh of Çatalhöyük Building 89 in MeshLab. **a** Flat mode view with lighting. **b** Wireframe mode view showing poisson surface reconstruction

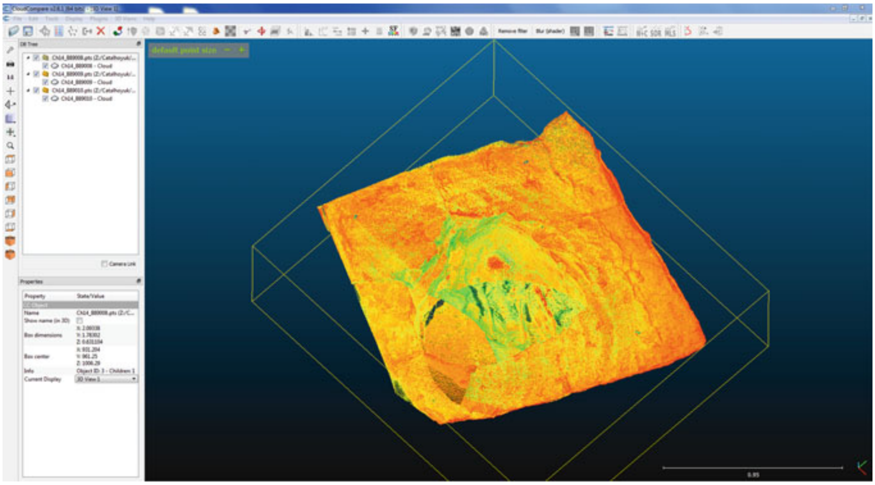

Fig. 5 Çatalhöyük Feature 3484 point cloud analysis and comparison in CloudCompare

File Format .ply) or manufacturer-independent file formats (e.g. ASTM E57 .e57), (iii) delivery of data that can be processed and visualized with open source or free software, (iv) open access to the end results (Lercari 2010). These four factors determine the sustainability of a workflow or technology over time and apply to both TLS and new tools available in the Age of Sensing.

3D Web Visualization and Cloud Services

To further advance this discussion on data recording and processing methods in the Age of Sensing, one has to mention that the increasing diffusion of high-speed networks—such as *next generation* wired connections able to transfer data at 10 or 100 Gb/s or Long Term Evolution (LTE)-A mobile connections able to download data at 1 Gb/s—create new opportunities to process 3D data in the cloud or to render complex 3D scenes directly over the Internet.

Web-based 3D reconstruction services have been utilized for years (Vergauwen and Van Gool 2006), but the availability, effectiveness, and versatility of the cloud services now available for 3D data processing have greatly expanded since the 2010s. In addition, the wide diffusion of open web 3D standards such as X3D (X3D 2015) and WebGL (WebGL 2015) and open-source frameworks, such as X3DOM (Behr et al. 2009; X3DOM 2015), has made it possible to visualize 3D data natively on a web browser, without the need to install additional plug-ins. These new scenarios are enabled by empowered web browsers (e.g. Mozilla Firefox 38.0 or Google Chrome 50.0) that are able to directly access the graphics card's acceleration capabilities to perform online, real-time rendering of 3D content (Evans et al. 2014).

Previous work demonstrates the potential of a complete workflow from the field to the 3D web. TLS data were captured at a natural heritage site, then processed, and finally simplified to be suitable for web visualization using X3D, WebGL, and X3DOM standards (X3DOM 2015; Silvestre et al. 2013).

New scholarship shows the potential of 3D visualization of cultural heritage data on the web using WebGL and SpiderGL (Callieri et al. 2015); as well as custom systems, such as 3DHOP, designed to optimize the online visualization of 3D cultural objects (Potenziani et al. 2014). While cloud computing tools have been used for years in the visualization of 3D cultural data in online virtual environments (Lercari et al. 2011), cloud platforms for 3D data processing and visualization are relatively new.

In recent years, big corporations in the field of remote sensing and 3D authoring software (e.g. Leica, FARO, and Autodesk) have engaged in the development of new cloud-based systems able to process, visualize, mark-up, and share point clouds and triangular mesh over the Internet. Autodesk Recap 360 or Recap 360 Ultimate (Autodesk Recap 2015), FARO SCENE WebShare Cloud (SCENE WebShare Cloud 2016), Hexagon Imagery Programme (HxIP 2015), and Leica CloudPro (CloudPro 2015) are good examples of new commercial cloud platforms created for online 3D data processing, visualization, and sharing of TLS or ALS data.

These new commercial cloud processing and interactive visualization systems enable surveyors, clients, and collaborators, to remotely access and share survey data on buildings, landscapes, and even entire sites. Moreover, these cloud platforms make it possible for stakeholders to work together to create and share mark-ups and interpretations of the TLS post-processed data.

As of 2015, many different models are available for 3D processing and visualization in the cloud. Web-based cloud services, such as Autodesk Recap 360, allow users to process and visualize both TLS and IMB 3D content using their Internet browser (Fig. 6). In addition, the hybrid standalone and cloud-based software Autodesk Recap Ultimate provides further options for TLS automatic data registration and processing. The cost of Autodesk cloud services is U.S. dollars 500/year per user for Recap 360 and U.S. dollars 2000/year per user for Recap 360 Ultimate (Recap 2015).

FARO Technologies also offers a Platform as a Service (PaaS) cloud-based hosting solution that promises to revolutionize access to TLS data online. In fact, FARO SCENE WebShare offers to its users incredibly easy to use tools aimed at data processing, managing, and sharing 3D data directly in the cloud. SCENE WebShare offers different levels of subscriptions that target Small Enterprise (€1.490/year for 100 GB of storage or 1000 scans), Medium Enterprise (€2.950/year for 200 GB of storage or 2.000 scans), and Large Enterprise (€7.750/year for 500 GB of storage or 5.000 scans) (SCENE WebShare Cloud 2016).

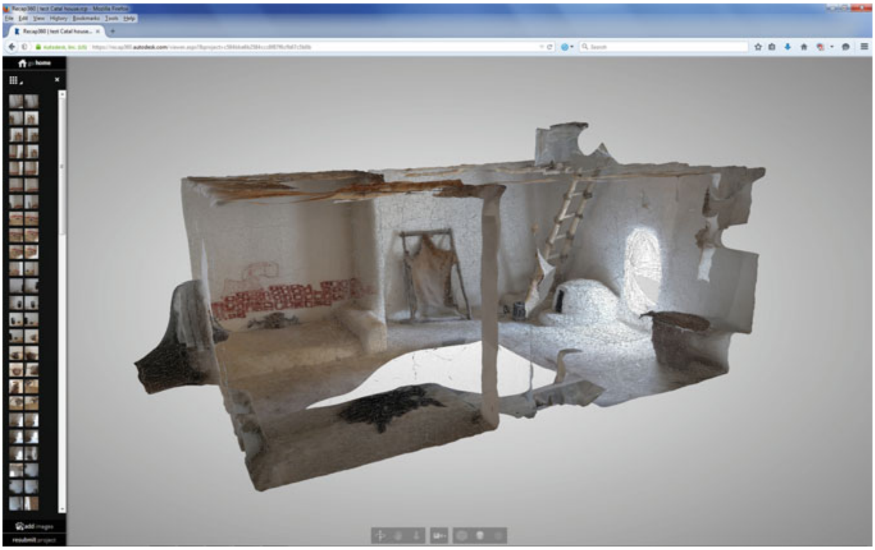

Fig. 6 Image-based 3D model of Çatalhöyük experimental house generated in Autodesk Recap 360

Hexagon Imagery Programme (HxIP) is a cloud platform that promise to take ALS data from the sky to the cloud. HxIP provides on-demand access—via third party software such as ESRI ArcGIS, Valtus, or Hexagon Power Portfolio—to high quality aerial imagery captured by Airborne LiDAR systems manufactured by Leica Geosystems.

It is clear that cloud technologies open new horizons for TLS and ALS in the Age of Sensing. Specifically, cloud-based systems give heritage surveyors the opportunity to show the collected point clouds to other stakeholders who are not physically on-site. A positive consequence of these new cloud services is that a more collaborative and inclusive interpretation of TLS data can now be performed via web browser, without the need to purchase additional software licenses. The downside of TLS data processing in the cloud is related to expensive subscription plans that could make commercial cloud solutions not feasible for heritage projects with limited budget. Whilst open access 3D repositories have been available for several years (Koller et al. 2009; Guidazzoli et al. 2012), open-source cloud solutions, such as HP Helion Eucaliptus (Helion Eucaliptus 2015), are still a rare exception (Nurmi et al. 2009).

To overcome this issue, the expansion of TLS data processing in the cloud would need more support from the research community; national and international institutions for heritage preservation should also provide local communities, local heritage institutions, and educational or not for profit organizations with new opportunities for making cultural data processing and sharing freely available in the cloud.

State of the Art of Terrestrial Laser Scanning in 2015

Since the early 2000s, Terrestrial Laser Scanning has led the process of digital documentation in fields such as architecture, earth science, and landscape and built heritage survey, providing scholars and professionals with incredibly precise and reliable tools for metric measurement and 3D data capture (Mills and Andrews 2011).

Concurrently, archaeologists have extensively tested TLS techniques in combination with photogrammetric methods to document archaeological heritage and entire monuments (Neubauer et al. 2005; Pescarin and Pietroni 2007), or archaeological landscape (Forte et al. 2005; Francovich and Campana 2005). Most importantly, archaeologists proved TLS viable to conduct digital documentation in single-context archaeological excavations where each stratigraphic unit's surface needs to be recorded with geometrical precision and centimeter-level accuracy (Doneus and Neubauer 2005a). Nonetheless TLS could be time consuming, employing a laser scanner in the excavation proved viable and time-effective and allowed. Using TLS, digital archaeologists may manage to save considerable amounts of time in the recording of the morphology and texture of stratigraphic surfaces, walls, and sections, when compared to traditional contact measurements tools (e.g. measuring tape) or other non-contact measurement tools (e.g. total station) (Forte et al. 2012). Seminal archaeological work also proved that the interpretation of the stratigraphy of an excavation can be enhanced by the integration of TLS data and photogrammetric data in a Geographic Information System (GIS) able to render the geometrical, topographical, and stratigraphical characteristics of a site (Doneus and Neubauer 2005b).

In the Age of Sensing, the increasing precision, range, and survey speed of TLS make this technology even more viable for large-scale data capture of buildings and heritage sites; this is especially true when TLS is combined with photogrammetric tools (Andrews et al. 2009). For example, archaeological workflows that integrate reflexive methods and employs 3D technologies in combination with GIS and tablet-based digital drawings proved viable in the digital documentation and interpretation at-the-trowel-edge of Çatalhöyük's archaeological heritage (Berggren et al. 2015).

TLS data processing used to be a bottleneck in 3D survey workflows because it implied lengthy and costly manual procedures for point cloud filtering, registration, editing, segmentation, and surface reconstruction.

State of the art 3D authoring and processing tools (e.g. 3D Reshaper developed by Hexagon Metrology) currently enable faster and more efficient point cloud segmentation and processing (3D Reshaper 2015). Processing functions, such as point cloud automatic separation and cleaning, best geometrical shapes extraction, semi-automatic feature extraction (Fig. 7), and point cloud to CAD are now common in many TLS processing platforms. The availability of new, semi-automatic or automatic processing tools helps to reduce cost and TLS data processing time, making this 3D survey technology more feasible in the Age of Sensing.

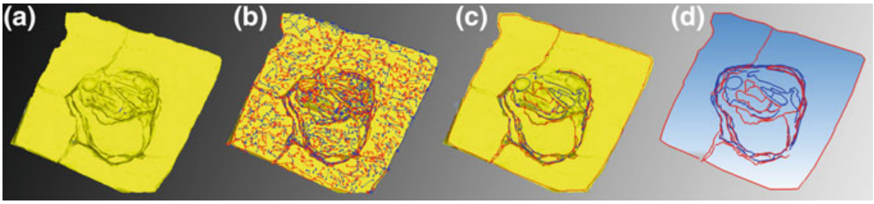

Fig. 7 Semi-automatic feature extraction in 3D Reshaper. **a** Triangular mesh of Skeleton 30928 excavated in Building 89 at Çatalhöyük. **b** Automatic convex and concave lines detection. **c** Semi-automatic lines filtering. **d** Semi-automatic measured drawing of Skeleton 30928

Therefore, new advancements in TLS make it possible to affirm that laser-based metric survey methods still maintain a fundamental role in the 3D documentation and three-dimensional interpretation of archaeological sites at intrasite scale (Forte et al. 2015, pp. 46–48). Thus, the aim of the following section of the chapter is twofold: the first being the discussion of the advantages and disadvantages of TLS when employed for the documentation of heritage; the other being the discussion of the state of the art of TLS through a number of explanatory case studies that best resemble the current advancements in conservation, analysis, interpretation, and visualization of cultural and natural heritage using this metric survey technology.

Pros and Cons of Terrestrial Laser Scanning

Programs developed by the U.S. Department of the Interior, such as the Historic American Buildings Survey (HABS), the Historic American Engineering Record (HAER), and the Historic American Landscapes Survey (HALS), are in charge of developing guidelines and protocols for the documentation of built heritage, historic engineering materials, and cultural landscapes. Among HABS/HAER/HALS (H^3) standards, specific guidelines examine the pros and cons of TLS (Lavoie and Lockett, n.d.). These recommendations underline that TLS offers advantages over other types of heritage documentation in terms of versatility, accuracy, long range, vertical reach, and survey speed. Conversely, H^3 guidelines identify cons in TLS workflows in regards to problems with occlusion between architectural elements, low accuracy in façade details (e.g. molding features), inability to pass through vegetation and built structures, as well as issues with long-term permanence of the digital formats of the point clouds for archival purposes. Cultural preservation guidelines, available in the United Kingdom, also provide thorough recommendations on the usage of TLS for metric survey that can help surveyors better understand advantages and limits of this technology and its applications in the heritage domain (Bryan et al. 2009). Other countries may have developed their own protocols and guidelines, but the above-mentioned sources could provide valuable guidance for TLS surveying to an international audience.

Following the recommendations and standards provided by H^3 and by the Historic Buildings and Monuments Commission for England, the comparison of data capture technologies discussed in these pages needs to analyze the following factors: (a) data acquisition and operation expense; (b) data processing time; (c) survey speed; (d) versatility in relation to environmental conditions; (e) portability; (f) range accuracy; (g) survey range; (h) noise; (i) positioning and/or georeferencing; (j) semi-automated or automated functions for 3D data post-processing, (k) usability; (l) online data curation and sharing.

The main cons related to the usage of TLS in heritage preservation or archaeological fieldwork are related to items (a) and (b). After more than fifteen years since the first terrestrial laser scanning technology was patented (Kacyra et al. 1999), the cost of a non-contact terrestrial laser measurement unit (a) is still very high. In 2015, a time-of-flight or phase comparison TLS unit is still priced between fifty to one hundred and fifty thousand U.S. dollars. More specifically, in January 2015 a FARO Focus^{3D} X330—a top-notch phase comparison TLS that features a long range from 0.6 to 330 m in indoor or outdoor environments, distance accuracy up to ±2 mm at 10–25 m, measurement speed up to 976,000 points per second, noise reduction of 50 %, and a built-in RGB coaxial camera able to deliver up to 70 Megapixel of colors (FARO Focus^{3D} X330 2015)—was priced at fifty eight thousand U.S. dollars.

Annual calibration, warranty extensions, software and equipment updates entails additional maintenance costs to the operation of a TLS unit. For instance, a 3-year Standard Warranty Plan for a FARO Focus^{3D} S120 unit, including annual laser scanner certification/calibration, parts, labor, and return shipping charges, costs a little more than ten thousand U.S. dollars (FARO Warranty department 2015). Thus, this discussion of the state of the art of TLS needs to emphasize that acquisition and operation cost still make this survey technology inaccessible for many cultural institutions, universities, and other stakeholders involved in heritage preservation.

The time needed for data processing (b) may also be another drawback for the adoption of TLS workflows. A typical acquisition and processing workflow entails long and costly operations that may include: (1) survey measurements/scanning on site (Fig. 8); (2) scan registration/georeferencing; (3) deliverables generation, such as point cloud/unrefined mesh, rendered images/2D or 3D drawings, and animations or decimated/edited mesh; (4) analysis; (5) conclusions (Mills and Andrews 2011, pp. 11–15).

The amount of time needed to complete steps (1)–(5) is proportional to the number of scans and to the complexity and extension of the case study. One also needs to bear in mind that highly specialized skills and dedicated software are needed to perform such tasks.

The pros of terrestrial laser scanning technologies over alternative systems are largely related to items (c), (d), (f), (g), (h), and (i).

In the Age of Sensing, cutting-edge time-of-flight and phase comparison terrestrial laser scanners manufactured by FARO, Leica, Riegl, and Trimble features a vast set of advanced functions and sensors. For instance, some of the new TLS units offer incredibly high survey speed (c) that makes these instruments able to record up to 976,000 points/second (FARO Focus^{3D} X330) or even 1 million

Fig. 8 FARO Focus ^{3D} S120 scanning Neolithic buildings in the North Area of Çatalhöyük's East Mound

points/second (e.g. Leica ScanStation P40 and Trimble TX8) (Leica ScanStation 2015); they are very versatile in relation to most environmental conditions (d) (Leica ScanStation P30 and Leica ScanStation P40 operate from 0 to 50 °C), performing optimally in bright outdoor settings, shaded indoor environments, and even in the complete darkness of caves and mines; they are also adaptable in terms of portability (e) (e.g. FARO Focus^{3D} X130 and X330 weigh only 5 kg); they present improved range accuracy (f) up to ±1.2 + 10 ppm over 120–270 m (e.g. Leica ScanStation P40), 2 mm over 120 m (e.g. Trimble TX8), or ±2 mm at 10 m and 25 m (e.g. FARO Focus^{3D} X330); (g) they offer extremely large survey range (g) up to 2000 m (Riegl VZ-2000) or ultra-large range up to 6000 m (e.g. Riegl VZ-6000); they feature enhanced noise reduction algorithms (h) (all the TLS units listed in this page grant noise reduction spanning 20–50 %); they are equipped with integrated GPS receivers (e.g. FARO Focus^{3D} X130 and X330, Riegl VZ-2000 and Riegl VZ-6000), GNSS positioning (e.g. Riegl VZ-2000 and Riegl VZ-6000), compass (e.g. Riegl VZ-2000, Riegl VZ-6000, and all FARO Focus^{3D} X330), altimeter (e.g. FARO Focus^{3D} SX130 and X330), and dual axis compensator or inclination sensor (e.g. all the TLS units listed above) to improve scans positioning and georeferencing (i).

Pondering item (j) and (k), one can infer that the new alternative 3D capture systems present more automated data processing features and seem more usable than TLS units. This is due to the fact that the new 3D digitizers integrate optical, mobile, and cloud technologies. The new optical data capture solutions are often designed and developed by dynamic start-up companies whose goal is to explore alternative ways of process, visualize, and disseminate 3D data, making these new tools incredibly adaptable to new data capture and processing workflows.

In the Age of Sensing, TLS platforms have also improved in terms of semi-automated or automated processing functions (j). For example, SCENE 5.4 (SCENE 2015)—the TLS operating software licensed by FARO Technologies—is able to perform automatic, target-less registration of point clouds using information obtained by the sensors embedded in the scanner, such as GPS, compass, and altimeter, or overlapping scan data (Fig. 9). The point cloud data processing suite Leica Cyclone (Cyclone 2015) offers surveyors the possibility to easily perform features and coordinates extraction through its Cyclone Virtual Surveyor function. In addition, Leica Cyclone-MODEL is able to process TLS point clouds and automatically generate objects for export into CAD systems for additional measured drawing operations. 2D or 3D CAD drawings often represent the most suitable option to manage digital documentation derived from large datasets of TLS point clouds (Christofori and Bierwagen 2013).

In regard to usability (k), one needs to report that TLS tools have also become more user-oriented in the Age of Sensing. For instance, FARO Technologies—one of the leading manufacturers of laser scanners as of 2015—has simplified significantly the operation of its devices. The FARO Focus^{3D} S120, X130, or X330 laser scanners feature touch-panels and smartphone-like user interfaces developed in Adobe Flash, giving users the possibility to use tablet PCs equipped with Wi-Fi connection and a flash-enabled web browser to operate the scanners. This option allows users to preview and download the results of their work one a larger and brighter screen while

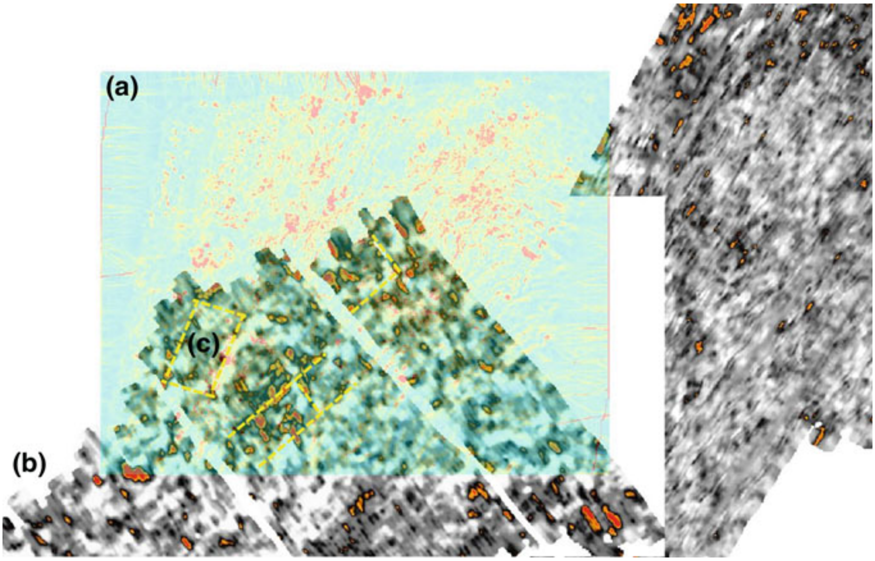

Fig. 9 Comparison of **a** top view and **b** cloud to cloud target-less automatic registration of point clouds of Çatalhöyük's GDA and TPC areas in FARO SCENE 5.4

still in the field, at a cost of few hundreds of U.S. dollars to purchase a standard tablet device.

Online data management and sharing (l), is vastly supported by the alternative 3D capture and processing systems through mobile, 3D web, and cloud technologies. In the last few years, online data management and sharing have also become more and more available in traditional TLS platforms.

In the Age of Sensing, point cloud datasets can be easily managed or viewed online without the need of installing costly and complex, supplementary software. By utilizing free 3D viewers available as web apps (e.g. Autodesk Recap), plug-ins (e.g. Leica TruView for Microsoft Internet Explorer) or standalone clients (e.g. Faro WebShare 2Go) it is now possible to view, measure and mark up point clouds directly over the Internet or local area connection.

The employment of SCENE WebShare Server (SCENE WebShare Server 2016) in combination with WebShare 2Go (SCENE WebShare 2Go 2016) or Cyclone-SERVER (Cyclone SERVER 2016) and Leica TruView (TruView 2015) offer even greater functionalities to FARO and Leica customers. These client-server technologies allow surveyors to install a robust application on their own server, enabling them to publish and manage point cloud data on the Internet or local area network. Other parties can interact with the recorded 3D survey data using FARO SCENE WebShare 2Go or Leica TruView plugins to directly access the point clouds from their web browsers. Affordable cloud service subscriptions are related to WebShare Server or Cyclone-SERVER. The option to curate 3D data in-house is particularly relevant to heritage and cultural institutions that want to protect the copyright or public access to their content while avoiding potential controversies related to uploading their data onto third party repositories.

The above list of facts and functions that belong to some of the terrestrial laser scanners available in the Age of Sensing is far from being comprehensive. The goal of this section is to provide the reader with arguments and facts able to show that TLS still presents competitive advantages over other non-contact 3D capture methods based on computer vision and depth cameras. This is especially true in regards to intra-site archaeological survey, outdoor survey, and documentation of vast areas and entire buildings. Thus, this chapter reiterates that current TLS features, such as extremely high accuracy, user-oriented interfaces, range accuracy, and interactive data curation, shows that Terrestrial Laser Scanning is far from disappearing in 2015.

Case Studies

The goal of this section is to illustrate six explanatory case studies that define new directions in remote sensing applied to cultural heritage for purposes such as conservation, analysis, interpretation, processing, and visualization.

Some of the following examples will describe the integration of TLS with other remote sensing technologies to obtain hybrid data capture workflows and data fusion. Others will illustrate new, semi-automated or automated ways to interpolate and interpret Terrestrial Laser Scanning data to produce drawings, maps and, more in general, new knowledge in a fast and effective way.

Finally, other case studies will discuss the state of the art of 3D web visualization of TLS data that rely on versatile technologies and new ways of data curation over the Internet.

Case Study 1

Drones in archaeology

Authors	Neil Smith, Luca Passoni, Said al-Said, Mohamed al-Farhan, and Thomas E. Levy
Year	2013
Methods	Integrated data capture, processing, and dissemination in archaeology
Data acquisition and processing	Unmanned aerial vehicles, terrestrial laser scanning, image-based modeling
Site	Dedan, al-Ula Valley, Saudi Arabia

In the last decade, small Unmanned Aerial Vehicles have been employed in archaeology to create 3D models of built structures, orthophotos and digital elevation models (Lambers et al. 2007; Guidi et al. 2008).

UAVs has been instrumental in the 3D mapping of Nabatean remains at the excavation of ancient Dedan in the al-Ula Valley in Saudi Arabia (Smith et al. 2014). Low-altitude photographs taken from multi-rotor copters equipped with GPS and barometric sensors were integrated with image-based 3D models and laser scanning data (captured with a FARO Focus^{3D} laser scanner) to produce and test new ways for rapid documentation of cultural heritage (Smith et al. 2014). This integrated approach proved feasible to document building features as well as entire built structures, such as the Lihyanite “lion tombs’, specifically monumental tombs carved in the city’s cliff faces using a construction style comparable to the one employed in the Nabatean capital of Petra. The combination of different survey methods allowed a team of scholars from UC San Diego and King Saud University to exploit the advantages of the three survey technologies that were utilized. Specifically, this project represents the state of the art in data capture because it was able to integrate: (i) reach and versatility typical of drone survey to access occluded and vertical features; (ii) easy-of-use, high survey speed, and short post-processing time typical of Structure from Motion; (iii) high resolution and precision measurements typical of terrestrial laser scanners.

Case Study 2

Surface and subsurface multimodal data capture at Çatalhöyük

Authors	Nicola Lercari, Maurizio Forte, Stefano Campana, Gianfranco Morelli, Gianluca Catanzariti, Krishopher Strutt, Ashley Lingle
Year	2011–2015

(continued)

(continued)

Authors	Nicola Lercari, Maurizio Forte, Stefano Campana, Gianfranco Morelli, Gianluca Catanzariti, Krishopher Strutt, Ashley Lingle
Methods	TLS for intrasite spatial analysis; integration of multiple technologies for above/below surface archaeological survey
Data acquisition and processing	Hybrid data capture bridging together terrestrial laser scanning, magnetometry, GPR, and Image-based 3D modeling
Site	Çatalhöyük, UNESCO World Heritage site, Turkey

Çatalhöyük is a Neolithic proto-city and a UNESCO site located in the Konya plane in central Anatolia, Turkey. Terrestrial laser scanning underpins the digital recording process of Çatalhöyük East Mound at intrasite level. In 2011, terrestrial laser scanners, such as Trimble FX (phase comparison) and FARO Focus^{3D} S120 (phase comparison), proved successful in the documentation of stratigraphic layers of a Neolithic house, specifically B.89 (Forte et al. 2012). To comply with UNESCO site management guidelines, Çatalhöyük requires thorough and systematical survey of the archaeological remains for conservation purpose. In 2012, TLS started being employed for scanning entire areas (North Area and South Area); this type of survey continued in 2013 also including the TPC area where archaeologists study the late Neolithic phases of the site. In 2014 all the currently excavated areas were documented via TLS (Forte et al. 2015, pp. 46–48). In 2015, a DJI Phantom 3 Pro multirotor copter equipped with a 4 K RGB camera and Drone Deploy server-based mission planning was also employed to enhance the survey speed of the areas inside the permanent shelters (Lercari and Lingle 2016) as well as for outdoor 3D mapping survey (Forte et al. 2016). This case study represents the state of the art of TLS because it fosters the integration of multimodal data capturing techniques for intrasite survey that combine TLS, IBM, and UAS platforms with other sub-surface survey techniques. More precisely, in 2012 TLS was employed to measure the morphology of small quadrants of the East Mound landscape located south and north of the North Area. This data were subsequently interpolated with magnetometry and GPR prospections elaborated by the University of Siena and the University of Southampton (Campana et al. 2013) to produce new knowledge on the sections of Çatalhöyük that have not been excavated.

Case Study 3

Informing historical preservation with the use of non-destructive diagnostic techniques

Authors	Michael Hess, Dominique Meyer, Aliya Hoff, Dominique Rissolo, Luis Leira Guillermo, and Falko Kuester
Year	2014
Methods	Non-destructive methods for cultural heritage diagnostics and new processing techniques for immersive visualization in C.A.V.E. systems

(continued)

(continued)

Authors	Michael Hess, Dominique Meyer, Aliya Hoff, Dominique Rissolo, Luis Leira Guillermo, and Falko Kuester
Data acquisition and processing	Terrestrial laser scanning, stereo panoramas, high-resolution imagery, aerial photography, thermal imaging, immersive visualization
Site	16th-century Church of Boca Iglesia, Ecab, Quintana Roo, Mexico

A team of experts affiliated with the Center of Interdisciplinary Science for Art, Architecture and Archaeology (CISA3) at UC San Diego surveyed the ruins of an early church and curate's house at the site of Ecab, located in a remote area in the tip of the Yucatan peninsula, in Mexico. The site of Ecab witnesses the first interaction between the Spanish and Maya communities in the early 16th century (Hess et al. 2014). The goal of the project was to deploy an array of non-destructive technologies such as terrestrial laser scanning, stereo panoramas, high-resolution imagery, aerial photography, and thermal imaging to digitally document the site. Survey data were provided to Mexico's National Institute of Anthropology and History (INAH) to develop a site conservation plan (Hess et al. 2014). In a very short time span of only two days, a FARO Focus^{3D} scanner was used to measure more that 800 million points of the built structures at Ecab and conduct visual and structural diagnostics off-site and serve as a digital scaffolding for other digital data collected on site. Multi-rotor UAVs were also employed to perform low-altitude photography to be used for structure from motion 3D reconstruction in combination with high-resolution imaging recorded with a stereo photography rig (CAVEcam) to improve color depth in the visualization of the ruins in immersive virtual environments (Smith et al. 2013). Previous work on monitoring ancient buildings using thermal imaging (Grinzato et al. 2002) inspired the UCSD team to employ Infrared thermography (FLIR A615) at Boca Iglesia with the goal to create thermal imaging mosaics able to document surface and subsurface data on the ruins that are not visible on site.

Case Study 4

Combined use of ground-based systems for cultural heritage conservation monitoring

Authors	Antonio Montuori, Guido Luzi, Salvatore Stramondo, Giuseppe Casula, Christian Bignami, E. Bonali, Maria Giovanna Bianchi, Michele Crosetto
Year	2014
Methods	Multi-technique approach for cultural heritage monitoring and restoration based on the integration of GBSAR, RAR and TLS sensors
Data acquisition and processing	Ground-based Synthetic Aperture Radar (GBSAR), GB Real Aperture Radar (RAR), and Terrestrial Laser Scanner
Site	Church of Sant'Agostino, Cosenza, Italy

New advances in cultural heritage monitoring entail new surveying methods able to provide dynamic and sustainable response to climate change and natural disasters. In addition to widely used techniques such as manual and topographic measurements, 3D mapping, GPS surveys, and multispectral imaging, this case study proposes the adoption of new radar techniques, usually employed to monitor earthquakes, avalanches, and flash floods, in combination with laser scanners (Montuori et al. 2014). More specifically, conservation work at the Church of Sant'Agostino, Cosenza, in Southern Italy developed a new monitoring approach that integrates ground-based systems, such as Ground-Based Synthetic Aperture Radar (GBSAR) and GB Real Aperture Radar (RAR), with TLS. A GB Radar System is a powerful tool with interferometric capabilities for both topographic deformation and structural vibration monitoring and measurements (Casula et al. 2009). Structural vibration can be measured via interferometric techniques that capture the position of an object comparing the electromagnetic waves it reflects at different time (Montuori et al. 2014). The radar systems employed in this project produced maps of topographic deformation via interferometric processing—with an accuracy of cm/year—as well as displacement time series of vibrating structures, with a precision of tens of microns (Luzi et al. 2012). This case study illustrates the state of the art in TLS because proposes a completely new approach to heritage conservation and monitoring that integrates TLS and radar technology in a new, feasible way that opens new perspectives for risk assessment related to heritage and natural and structural hazards.

Case Study 5

Automatic extraction of façade details of heritage building using TLS

Authors	Kenza Ait el Kadi, Driss Tahiri, Elisabeth Simonetto, Imane Sebari, and Hakim Boulaassal
Year	2014
Methods	Geometric and radiometric heritage survey, automatic point cloud segmentation and features extraction
Data acquisition and processing	Terrestrial laser scanning, custom methods for data segmentation using Delaunay triangulation and alpha-shape algorithm
Site	Casablanca old Medina, Morocco

The restoration of historic buildings in the old Medina district in Casablanca, Morocco pushed local authorities to require the production of a high number of CAD-based measured drawings of façades and built structures for leading the conservation planning. A mixed team from the Hassan Institute in Rabat, Morocco the School of Land Surveyors in Le Mans, France and the University of Science and Technologies, FST, Morocco was involved in the project. Scholars from the three institutions completed the task using new methods that involve TLS and automated systems for point cloud segmentation. This project represents the state of the art of point cloud post-processing because it proposes a new approach that exploits both geometric and radiometric information contained in a colored point clouds (Aitelkadi et al. 2014). RGB values, reflectance, and position of scanned points are used to perform automatic segmentation operations able to extract the façade of buildings from the rest of the point clouds with the aim to automatically generate 3D CAD drawings. The methodology used in this project proposes a four-pronged approach that includes: (a) geometric processing; (b) radiometric processing; (c) noise reduction; (d) component and contour detection (Aitelkadi et al. 2014). The automatic processing methods implemented in this project are able to filter the data resulting from segmentation of point clouds through Delaunay triangulation. Moreover, an alpha-shape algorithm is employed to detect the contour of details of the façade with the aim to categorize and separate the interior and exterior boundaries of various features in the façade. This work also presents thorough evaluations of the proposed automatic façade detail extraction methods that validate the feasibility of this technique in comparison to other manual or semi-automatic approaches.

Case Study 6

The Visionary Cross Project—3D Scanning and web dissemination of 3D content

Authors	Chiara Leoni, Marco Callieri, Matteo Dellepiane, Daniel Paul O'Donnell, Roberto Rosselli Del Turco, Roberto Scopigno
Year	2012
Methods	3D digitization of artifacts via TLS, 3D Web visualization based on HTML5, JavaScript, XML, WebGL, SpiderGL and Nexus library
Data acquisition and processing	Triangulation terrestrial laser scanning, high-res photography, point cloud, mesh editing, and color projection in MeshLab
Site	7–8th-century Ruthwell Stone Cross, Ruthwell Church, Dumfriesshire, Scotland

This case study discusses methods and techniques used to digitize the 7–8th century monumental stone artwork known as the Ruthwell Stone Cross, located in the Ruthwell Church, Dumfriesshire in Scotland, and to create its interactive 3D visualization on the Web. This initiative was developed as a collaboration between the Visionary Cross Project (Visionary Cross 2015), ISTI/CNR, the University of Pisa in Italy, and the University of Lethbridge in Alberta, Canada. The main goal of the project was to develop a web-based digital edition of the *Dream of the Rood*, one of the earliest Christian poems written in Old English, whose text is carved in runes on the Ruthwell Stone Cross (Leoni et al. 2015). A Minolta Vivid 910 triangulation laser scanner and digital cameras have been employed to capture in great details the geometry of the artwork, runes, as well as the true color of their surfaces. The 3D scanning data were later post-processed using MeshLab software (Cignoni et al. 2008); advanced tools for color data processing where also employed to apply the true color of the Cross to the recorded point clouds in MeshLab (Ranzuglia et al. 2012). A multimedia presentation of the scanned content was then prepared to make the recorded data available to the general public of the Web. Specifically, a critical edition of the *Dream of the Rood* that combines digitized images of the 10th century text *Vercelli book*, which contains a more recent version of the poem, was curated online. This case study represents the state of the art in TLS and 3D content online data curation because it proposes new ways to display laser scanning content on the Web using cutting-edge technologies and new standards such as HTML5, WebGL, Spider GL. Additional compliance with standards used in the digital humanities is granted by XML support for data curation and presentation (Leoni et al. 2015).

Conclusions or Why Terrestrial Laser Scanning Matters in the Age of Sensing

Since the early 2000s, Terrestrial Laser Scanning has been a primary remote sensing technique for disciplines related to archaeology, architecture, built heritage, earth science, metrology, and land survey. The increasing precision, range, and survey speed of TLS make this technology even more viable for large-scale data capturing in the Age of Sensing.

This chapter discussed novel methods and techniques for data capture, processing, and visualization of archaeological, cultural, and natural heritage data. The goal was to illustrate the state of the art of Terrestrial Laser Scanning as of 2015 as well as to analyze advantages and disadvantages of the usage of laser-based metric survey techniques for heritage conservation, analysis, interpretation, processing, and visualization. At the same time, this contribution wanted to verify the feasibility of TLS as a data capture technology in relation to alternative digital documentation methods such as new commodity sensors, Image-based 3D Modeling, UAS, optical 3D scanning, and Airborne Laser Scanning.

Therefore, Section "Overview of New Data Capture, Processing, and Visualization Systems in relation to Terrestrial Laser Scanning" discussed alternative data capture and processing tools, illustrating the current advancements in computer vision-based 3D capture systems, processing software, and visualization platforms on the Web and in the cloud. The analysis conducted in this section confirmed that the employment of new optical techniques for 3D data capture is not yet a feasible alternative to TLS because the new platforms still do not match the accuracy of laser scanner units nor can be used in outdoor surveys and scientific documentation of heritage sites.

Section "State of the Art of Terrestrial Laser Scanning in 2015" explored new horizons for digital archaeology and heritage conservation projects that need accurate, fast, and large-scale survey technologies. More specifically, Section "Pros and Cons of Terrestrial Laser Scanning" referred to standards and guidelines for historic preservation and heritage conservation to illustrate a series of principles and technological requirements that still define terrestrial laser scanning as an indispensable asset for the monitoring and survey of heritage sites and material culture.

Thus, this section discussed the state of the art of Terrestrial Laser Scanning in relation to disciplines such as architecture, earth science, and landscape and built heritage survey, with particular focus on single context archaeology.

The six case studies discussed in Section "Case Studies" shed light on the significant changes that involve TLS in the Age of Sensing. The proposed examples underlined current trends related to TLS: laser-based metric survey techniques are increasingly integrated with other survey methods (e.g Airborne LiDAR, Image-based 3D Modeling, UAS, and commodity sensors) with the goal to produce data fusion-based documentation able to provide data redundancy and reliability of the final deliverables. These new hybrid forms of data capture define multimodal workflows for heritage documentation that had already proved viable in relation to digital documentation of archaeological heritage and built environments (Forte et al. 2012; Campana et al. 2013) and digital data curation in museums and historic parks (Lercari et al. 2013, 2014) (Fig. 10).

The ultimate aim of this chapter was to ponder the significance of Terrestrial Laser Scanning and respond to the following question: does TLS still matter in the Age of Sensing?

The discussions and reflections brought forward by this chapter strived to provide a response to such dilemma. For instance, Section "State of the Art of Terrestrial Laser Scanning in 2015" thoroughly discussed new advancements in TLS, making it possible to affirm that laser-based metric survey methods still maintain a fundamental role in the 3D documentation and three-dimensional interpretation of archaeological sites at intrasite scale (Forte et al. 2015, pp. 46–48). The discussed examples showed that TLS still presents competitive advantages over other non-contact 3D capture methods based on computer vision and depth cameras. This is especially true in regards to intra-site archaeological survey, outdoor survey, and documentation of vast areas and entire buildings. Thus, this chapter has reiterated that cuttently available TLS features (e.g. extremely high accuracy, user-oriented interfaces, range accuracy, and interactive data curation) strongly underline that Terrestrial Laser Scanning still matters in 2015.

What this chapter makes evident is that the increasing precision, range, and survey speed of the most current TLS units, make this technology even more viable for large-scale data capture of buildings and heritage sites. This is especially true when TLS data are integrated and fused with information collected using other remote sensing techniques such as Image-based 3D Modeling, UAS, magnetometry, GPR, radar, and Airborn Laser Scanning.

To conclude this reflection on the significance of Terrestrial Laser Scanning in the Age of Sensing, one can affirm that laser-based metric survey techniques still play a fundamental role in highly specialized fields such as the digital survey of built environment, the digitization of artifacts, and the three-dimensional documentation of archaeological heritage.

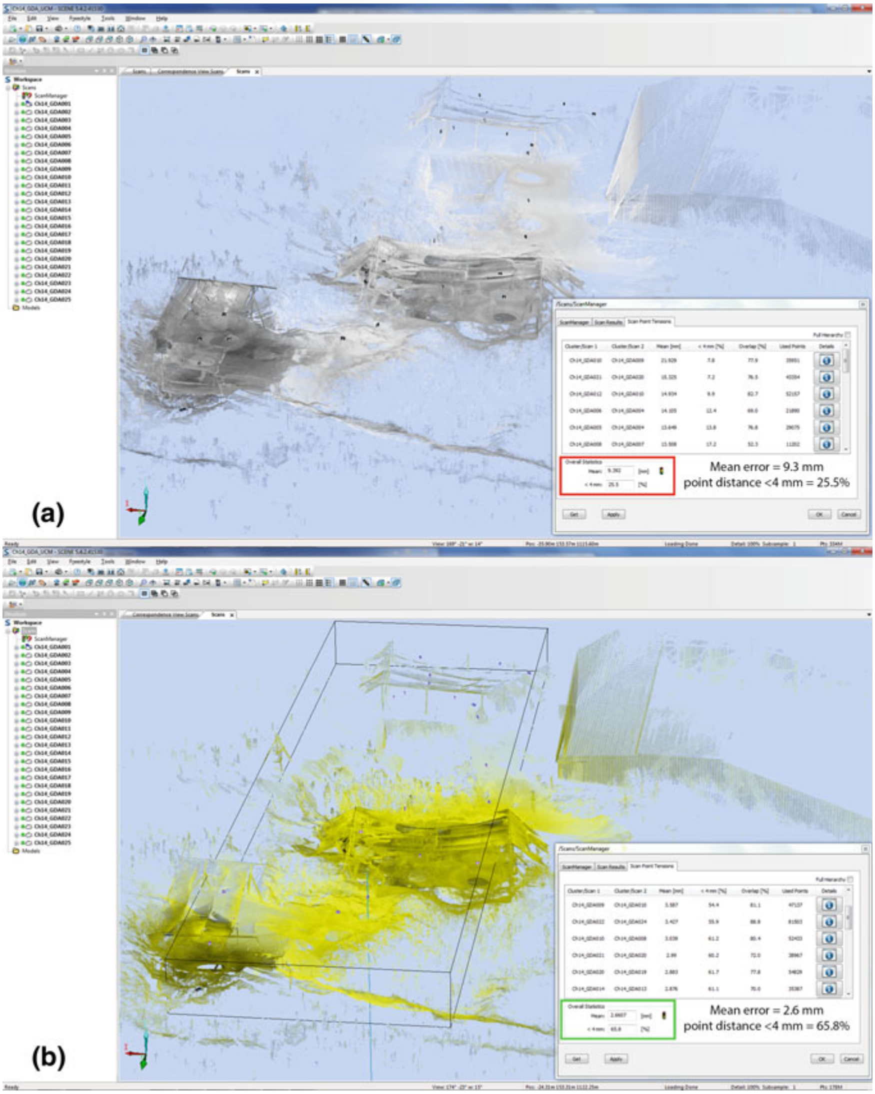

Fig. 10 Comparison of **a** top view and **b** cloud to cloud target-less automatic registration of point clouds of Çatalhöyük GDA and TPC areas in FARO SCENE 5.4 showing improvement in mean error and point distance <4 mm

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