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ABSTRACT:

The paper presents the experience and in particular two case studies of 3D recording undertaken by two laboratories of the University of Siena, Italy (LAP&T and LAAUM). The case studies focus respectively on landscape and on historical building recording. The paper describes the first step in a new approach to the documentation and interpretation of the archaeological record, discussing and emphasising the need to collect and analyse 3D documentation at different scales of detail: from artefact to landscape. As first result, this approach should improve the documentation of cultural contexts and therefore increase the opportunity to achieve archaeological understanding. The first part of the paper describes the contribution of LiDAR data in landscape analysis, underlining the importance of very accurate DTMs in geomorphological analysis and their influence on landscape archaeology. The geographical background is southern Tuscany and the Po Valley in northern Italy. At a completely different scale of detail the final part of the paper presents the results of the laser scanning and stratigraphical analysis of an historical building in southern Tuscany.

Key words: 3D modelling, Landscape Archaeology, LiDAR, Remote Sensing, Architecture, Building Stratigraphy, Laser Scanner.

1. Introduction

Since many years the Department of Archaeology of the University of Siena has focused on the archaeological study of Tuscan landscape (about 22,000 sqkm), moving progressively to an approach that nowadays could be defined as *total archaeology* (Darvill, 2002). The late Prof. Riccardo Francovich started collecting data on the landscape of Tuscany in the early

1970s, mainly through a systematic programme of field-walking survey and archaeological excavation, along with the collection of information from written sources, the examination of historical air photographs and the stratigraphic analysis of historical buildings and medieval towns (Francovich 2006). As a result of about thirty years of work in the Tuscan landscape it has proved possible to assemble a huge database of information (about 25,000 sites), but, notwithstanding this, a large amount of essential evidence has remained effectively undetectable, making it impossible to answer important archaeological questions within the confines of this methodological approach (Campana, Francovich, 2006). Some years ago we identified at least three contributory factors. Firstly, the nature of the landscape itself, with its clay soils, large areas of forestry, intensive agricultural exploitation and distinctive morphological patterns. Secondly, the peculiarity of the material culture, constantly changing over time and with related difficulties caused by postdepositional processes. As last - but not least - the definition and range of the evidence in terms of artefacts but also ecofacts and environmental factors.

It is important to emphasise here that the main aim of the University's research is to discern and describe historical patterns and to develop and improve the archaeological interpretation of sites and landscapes. In pursuit of this the Department has moved progressively from a 'thematic' approach to a more 'global' consideration of historical processes and archaeological interpretation.

In essence this has meant switching from a site-based approach to a 'landscape' perspective: in the study of castles, for instance, this has brought into play the consideration of related field systems, communication routes, production centres and cemeteries as well as geomorphology, palaeo-environmental factors and archaeo-zoology etc. A central tenet of this new methodology has been the need to view the context as an organic system, developing over time rather than as something that can be related, as in many previous approaches, to specific themes, time-periods or site types such as castles, Roman villas, oppida and so on. We feel that this broader perspective on the past will enable us to describe historical patterns in a more nuanced, balanced and representative way. Nowadays, through the use of field-walking survey and other research methods, our maps and therefore our archaeological models have become more and more rich in features that were previously invisible. While this has allowed us to close some gaps in our basic data we have realized that the cultural context on which we are working hides a new challenge, beneath our very our eyes – landscapes, historical buildings, monuments, stratigraphic layers, artefacts, finds and so on are still documented and then interpreted as if they existed only in two dimension!

This is clearly a paradox. Paul Cezanne said *"all living things have volume"*. We maintain that this concept applies with equal force in archaeological research and particularly in the archaeological study of material culture. It has long been acknowledged that all products of human activity, whether objects, structures or landscapes, can be described in three spatial dimensions (and of course in their development through the time). The third dimension has been from long time recognized as a substantial component in the description of the archaeological features but often through symbolic representations, avoiding the opportunity to get accurate metric measurement and therefore any accurate representation of volume. The problem is closely associated with the instruments and forms of graphic documentation available in the past: maps, plans and excavation photographs etc. The hypothesis that underpins our current approach is the need to use new technologies in the recording and representation of archaeological entities, from large-scale landscapes to the smallest individual find. To build 3D models and to develop 3D information systems will help us to expand our archaeological thinking from 2D (sometime $2^{1/2}$D) to 3D, expanding our analytical capabilities and therefore helping us towards a better understanding of the complexity of archaeological contexts.

2. LiDAR

LiDAR (Light Detection and Ranging) measures the relative height of the ground surface and features such as trees and buildings across large areas of landscape with a resolution and accuracy hitherto unattainable except through labour-intensive field survey or photogrametry. It provides, for the first time, highly detailed and accurate digital 3D models of the land surface at metre and submetre resolution. LiDAR operates by using a pulsed laser beam which can be scanned e.g., from side to side, as the aircraft flies over the survey area, using the time of flight that between 20,000 and 100,000 pulses per second take to return to the aircraft so as to build an accurate, high-resolution model of the ground surface and the features upon it. LiDAR was conceived in the 1960s for submarine detection and early models were used successfully in the early 1970s in the US, Canada and Australia. The possibility of using the technique for archaeological recording was first recognised in the United States thanks to pioneering research in the vicinity of the Arenal Volcano in Costa Rica under the leadership of Tom Sever. In an archaeological study in 1984 Sever and his colleagues used LiDAR, TIMS (Thermal Infrared Materials), synthetic aperture radar and colour infrared photography to detect pathways of prehistoric settlers, documenting trade routes and movement between settlements (Sheets, Sever, 1991). In Europe the potential of LiDAR applications in archaeology was first discussed at a workshop in Leszno, Poland, in November 2000. This related to a survey covering the River Wharfe in Yorkshire which revealed evidence for the earthwork survival of a Roman fort that had previously been thought to have been completely levelled by ploughing (Holden et al., 2002). A few years later, at Gent University in Belgium, Robert Bewley, then Head of English Heritage's Aerial Survey Unit, argued that "… the introduction of LiDAR is probably the most significant development for archaeological remote sensing since the invention of photography" (Bewley, 2005). In the following years LiDAR applications have been developed widely around Europe and particularly in the UK, Austria, France, Germany, Norway and Italy. Currently the principal advantage of LiDAR survey for archaeologists is its capacity to provide a high-resolution digital elevation model (DEM) of the landscape that can reveal microtopography which is virtually indistinguishable at ground level because of erosion by ploughing. Techniques have been developed for the digital removal of 'modern' elements such as trees and buildings so as to produce a digital terrain model (DTM) of the actual ground surface, complete with any remaining topographical traces of past human activity. An extremely important characteristic of LiDAR is its ability to penetrate woodland or forest and so to reveal features that are not distinguishable through traditional prospection methods or that are difficult to reach for ground-based survey (as, for instance, in work at Leitha Mountain, Austria, described in Doneus, Briese, 2006). There have been other notable applications at Elverum in Norway (Risbøl et al., 2006), Rastatt in Germany (Sittler, Schellberg, 2006), in the Stonehenge landscape and at other locations in the UK (Bewley et al., 2005; Devereux et al., 2005) and, returning to America, at Caracol in Belize (Weishampel et al., 2010).

In 2005, through a Culture 2000 project of the European Union, entitled *European Landscapes: past, present and future*, the University of Siena took its first steps in LiDAR data acquisition, processing and interpretation for four sample areas in the provinces of Siena and Grosseto. This was made possible through the good services of colleagues in England at the Natural Environment Research Council and the Unit for Landscape Modelling at the University of Cambridge. The results were processed in the Department of Geography at Durham University (UK) under the supervision of Prof. Daniel Donoghue and Dr. Nikolaos Galiatsatos. Success was achieved in one of the case studies, aimed at penetrating the tree canopy so as to record underlying archaeological features long protected from plough-erosion or other human activity by woodland cover (Figure 1). We saw this success as only the tip of the iceberg, however, and were absolutely convinced that advances in the use of this technique would in subsequent years have a decisive impact on our understanding of ancient landscapes (as has in fact proved to be the case).

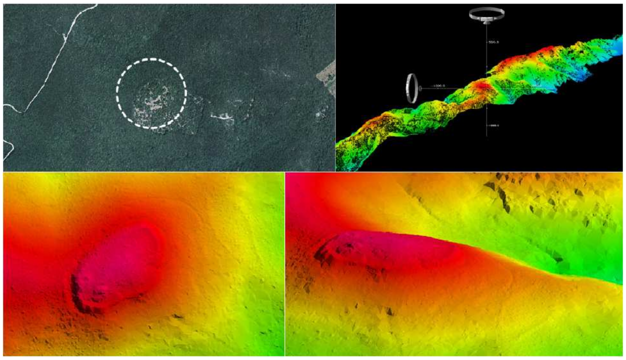


Figure 1: Sample area in Maremma, Tuscany, where the landscape is characterized by dense tree cover. Top left: in the centre, under dense vegetation, are the well-known ruins of a medieval castle. Top right: point cloud collected by the UK Natural Environment Research Council and pre-processed by the Unit for Landscape Modelling at the University of Cambridge. Bottom left and right: data processing and filtering in the Department of Geography at the University of Durham has here allowed 'removal' of the dense vegetation to achieve a digital terrain model showing the previously hidden archaeological features.

LAP&T gained further experience in 2009 when the laboratory took the lead in the so-called BREBEMI project in northern Italy (Campana, 2011). BREBEMI is the acronym for a motorway construction project linking the cities of *BRE*scia, *BE*rgamo and *MI*lan over a total distance of approximately 100km. The motorway will be constructed through the typical landscape of the Po Valley, with its extremely flat morphology and sand-and-gravel soils, heavily affected by intensive arable cultivation involving the systematic use of heavy-grade tractors and deep ploughing over at least the last sixty years. The area also has substantial concentrations of industrial and related residential development. For the first time in Italy we had within this project the opportunity to make systematic and innovative use of a range of non-invasive techniques to minimise the risk of archaeological damage in advance of large-scale motorway construction. The project design thus envisaged the systematic collection of historical and geographical data and interpretations from documentary sources, along with geomorphological studies, the analysis of vertical historical air photographs and the initiation of oblique aerial survey, in some cases including a substantial buffer zone on either side of the intended motorway route. Also included was the systematic collection of geophysical data, both magnetic and geo-electrical, across large and contiguous areas of between 200 and 750 hectares respectively, building on an approach successfully tested in Italy, France and above all in the UK (Campana, Piro 2009; Dabas 2009; Powlesand 2009). Systematic test excavations were also planned to verify anomalies identified by any or all of these techniques. Independently, the regional Superintendency designed a pattern of random test trenches amounting to a 5% sample of the motorway corridor.

The project also involved the capture 150sq.km of LiDAR data at a resolution of 4 points per square metre, covering the full length of the motorway corridor along with a 1km buffer zone on either side. As noted earlier, the morphology of the area is to all intents and purposes completely flat and the land-use devoted for the most part to intensive cereal and maize production. The collection of LiDAR data was essentially aimed at identifying barely perceptible ridges, elevated areas and depressions, many of them perhaps related to former water courses. The first stage of data processing, to create a basic digital terrain model, was carried out by CGR of Parma, the survey company that undertook the initial data capture. The second step involved a collaboration between LAP&T and Prof. Dominic Powlesland in the UK, using his own visualization software, LidarViewer. This software is a unit of Gsys software developed by Prof. Powlesland – Landscape Reasearch Center to enable the processing, analysis, management, and presentation of LiDAR data. Gsys has been developed for applications in archaeological research and its functions are designed for specific archaeological purposes (Powlesland et al., 2010). High resolution LiDAR datasets revealed some noise in the resulting DTM and DSM: the subsequent surfaces were in fact affected by noise that reduced the readability of topographic evidence. The next step of data processing was the implementation of an algorithm to reduce the ruffle and to smooth the surfaces: this was achieved with the aid of the Gsys software designed by Prof. Powlesland and used for archaeological visualization and interpretation within the project. The smoothing algorithm was carefully applied to DTM and DSM in order to find the best compromise between accuracy and readability of the archaeological evidences. Next, the datasets have been visualized using LidarViewer (Gsys) that allows the user to envisage the dataset, exaggerating the z (height) readings to empathize the micro-morphology of the recorded surfaces. The light source can be moved in height and position with respect to the surface in an interactive way in order to find the best setting to emphasize the micro-topography. Furthermore, Gsys provides the user with a tool to intersect the DTM with a theoretical plan parallel to the sea level so as to emphasize depressions, ridges and other elevated areas. This approach allowed the identification of 509 potentially significant features, consisting of 173 depressions, mainly interpretable as palaeo-river channels on the basis of their size, continuity and sinuous shape, along with 336 ridges or ‘elevated’ areas, at least some of them interpretable as fluvial ridges. The information currently available shows a clear tendency for known archaeological 'sites' to occupy fluvial ridges and other 'elevated' areas within the plain. This is not to imply, of course, that these 366 raised areas correspond to a similar number of archaeological sites, only that these areas have a higher potential for the recovery of traces of past human activity (Figure 2).

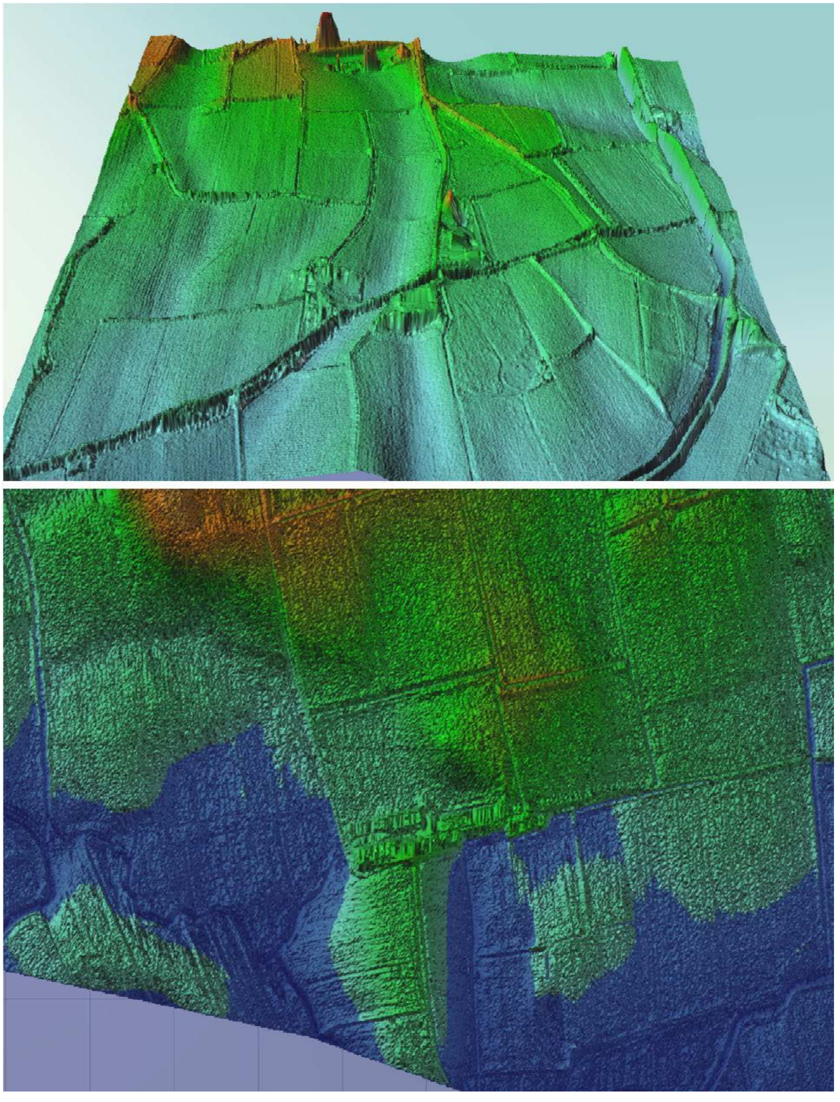


Figure 2: top, paleo-river channels; bottom, elevated areas.

Considering that our experience with LiDAR is still in progress – we are currently working on a very large LiDAR data sample in the province of Grosseto, in Tuscany – we believe it is possible to recognize also in the Italian context that LiDAR technique, if properly applied, could prove revolutionary in its impact on the process of archaeological mapping by making it possible to record the previously hidden archaeological resource within woodland areas as well as in apparently levelled landscapes like those of the Po Valley. In favourable circumstances it may even be possible to uncover whole 'fossil' landscapes beneath present-day vegetation cove. This could have a dramatic impact on opportunities for archaeological and landscape conservation and management, as well as on scientific investigation of settlement dynamics in various phases of history and prehistory. Nevertheless, a degree of caution is needed. Mediterranean woodland areas are covered by very dense vegetation and should be also considered that the production of DTM using LiDAR technology is a complex process which involves numerous assumptions and decisions throughout the workflow of project preparation, data acquisition and subsequent analysis. To achieve a secure interpretation the archaeologist has to consider and understand the meaning of meta-information about the original point density, the time of flight, the instrumentation used, the type of aerial platform and the DTM-generation procedure etc (Doneus, Briese, 2011).

3. TLS Data for Architectural Analysis

From the perspective of the authors, the prime aim in the 3D documentation of historical buildings is the improve the understanding of the historical buildings or of the monuments and generally speaking to advance the archaeological knowledge. In this process a key role is played by the methodologies of Archaeology of Architecture, along with laser scanning and photogrammetric techniques. This kind of analysis makes it possible to read the stratigraphy of the building (phases of construction, destruction and transformation) and then to recognize aesthetic choices and external influences, as well as to reconstruct the character of the construction-yard, the choice of workers, their degree of technical specialization and their country or place of origin. The case study we present in this occasion was aimed at testing the usefulness and effectiveness of these approaches in comparison with traditional methodologies (2D mapping), as well as verifying the dataquality and the additional information that could be obtained through photorealistic 3D modelling. A further objective was to estimate the possibility of standardizing the methodology of relief recording.

Over the past thirty years Archaeology of Architecture or Architectural Archaeology has formalized its role as an historical discipline, developing and applying specific methods of investigation to the analysis of historical buildings: from the ruins of farmhouses or abandoned castles, to complex urban architectural structures. The initial goals of the discipline are concerned with identifying and interpreting phases and transformations within the monument, analysing the dynamics of archaeological contexts through the determination of the building's structural phases and through characterization of the building techniques that are discernible within the structure. The application of the stratigraphic method to the study of walls constituted a key step in development of the discipline, establishing that masonry is the result of a series of constructive and destructive actions (Stratigraphic Wall Units), that, as in horizontal archaeological layers, are connected to one another through a direct physical relationship and a related temporal relationships of anteriority, posteriority and contemporaneity. At the same time sophisticated and extremely effective methods have been developed for the analysis of 'finds' contained within the vertical stratigraphy. In fact, these finds are functional to understand the formal (articulation plan, development of the high, etc.) and the technological aspects of the artefacts (identification of the production cycle, building-yard organization etc..). A considerable degree of maturity has been reached in the discipline, allowing some experienced researchers to go beyond the formal and technological analysis of the building elements to begin relating the construction process to economic history and to local political or social contexts.

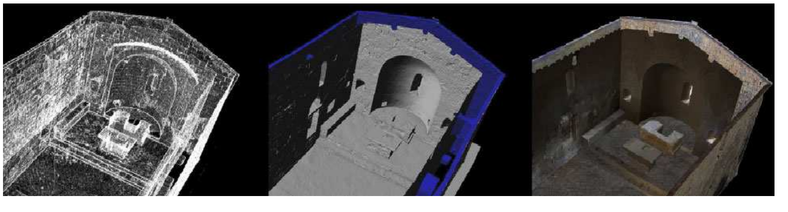
In this development the pioneering work of the Ligurian research group coordinated by Tiziano Mannoni (Mannoni, 1976) has been followed in Lombardy by work on secular and religious buildings in both rural and urban contexts under the leadership of Gian Pietro Brogiolo (Brogiolo, 1984), and later by a number of studies in Lazio (De Minicis, 1997). The Tuscan research team of the Department of Archaeology and History of Arts at the University of Siena has also contributed to the growth of the discipline, developing methods of analysis as well as undertaking the interpretation of individual buildings and of historic towns studied in their entirety (Parenti, 1992; Quiròs Castillo, 1999; Bianchi, 2007). The development of interdisciplinary relationships with studies such as science and social anthropology has led to a progressive strengthening of the proposition that changes in architectural and settlement patterns correspond to specific mindsets, to a complex interaction of social, political and economic practices that are reflected in the techniques and typologies in which different settlements was made. The development of the concept of the stratigraphy of walls could not leave out a total analysis of the historical context, thus following the "archaeology of context" (Francovich, Bianchi 2003). This looks upon a single building or an entire town centre as the source for a range of information not only about the building itself but also about society, economy and forms of power relative to the context in which the construction is located.

The study which we illustrate below shows how the traditions of archaeological research can form the basis for the study of an important building that has not previously been subjected to archaeological analysis. At the same time it demonstrates the way in which "traditional" archaeological approach can be enriched by the application on new methods in the verification and integration of the acquired data and in the scientific dissemination of the results.

Figure 3: The church of Sant'Alberto, Asciano (Siena, Italy).

The case study concerns the Romanesque church of Sant'Alberto, situated on mount Montalceto in the territory of Asciano (Siena, Italy) (Figure 3). The church has a single nave, an eastern apse and a gabled west façade. The roof has recently been restored according to a hypothetical reconstruction of the original design. The interior and exterior walls are made of unplastered ashlar masonry, with regular courses of squared sandstone and limestone blocks. On some of the internal walls there are areas of plaster that prevent a complete examination of the wall's stratigraphy. There is little information in documentary sources about the history of the church. The oldest document quotes a papal degree of Alexander IIIrd, dated 1178, which confirms the jurisdiction of the *pievano* (priest) of Asciano in the church of Sant'Alberto.

Figure 4: Representation of church of Sant'Alberto, from point cloud to textured model.



Both the interior and exterior of the building were surveyed using a terrestrial laser scanner. High-resolution digital images were also acquired as part of the recording process. The resulting data provided the basis for the archaeological analysis and interpretation outlined below (Figure 4). As a final step the data from the study, including the three-dimensional photorealistic model created from the laser data and photographic images, were imported into a GIS environment. The laser scanning surveying of the church was realized using the Time of Flight (TOF) scanner Leica Scanstation I, from 12 stations and with an average geometric resolution of 5 mm. The scans were processed according to the pipeline: cleaning (Figure 5), alignment, mesh generation and editing, geometric simplification, and finally texturing.

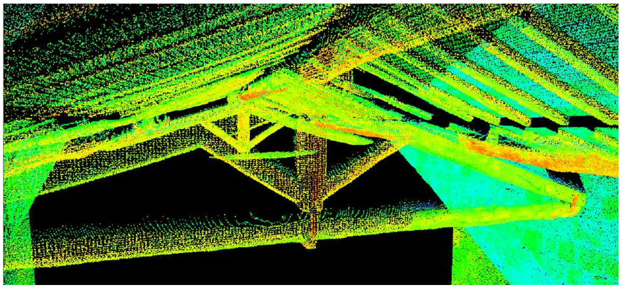


Figure 5: Point cloud cleaning with Leica Cyclone 6.0.

This last steps was facilitated through use of the high resolution images to permit the creation of a three-dimensional photorealistic model. Exposure and brightness were balanced in each of the merged images so as to eliminate discontinuity. High Dynamic Range (HDR) is a photographic technique which consists of taking multiple pictures of the same scene with different exposures, the wide range and balanced brightness attainable by merging the multiple images allowing the recording of all intensities of light and shade. In our case, for each piece of wall, we took a series of five photographs at different exposures, with the lens set to a fixed focus and with the camera mounted on a tripod. The merged HDR images were then applied to the relevant portions of wall so as to 'texture' the 3D model. To map the images in to the 3D model we used Technodigit 3D Reshaper software. This tool allows the user to project images in to 3D model using the reference point method: position, orientation and the optical parameters of the camera are determined with 3-5 point couple; each point couple consist of one point on image and one point on 3D model, selected by a click on each dataset.

The 3D photorealistic model was then used to make geometrical measurements, to correlate surfaces with volumes, to subdivide the building into structural phases, to relate interior and exterior walls to one another and to extrapolate all the graphic tables supporting scientific research through the principles of Archaeology of the Architecture. Concurrently with the laser survey we collected information through the direct examination of the masonry. Finally, in the GIS environment we created a GeoDatabase into which we imported both the data related to each of the three identified structural phases and all of the files containing the texturing information (Figure 6).

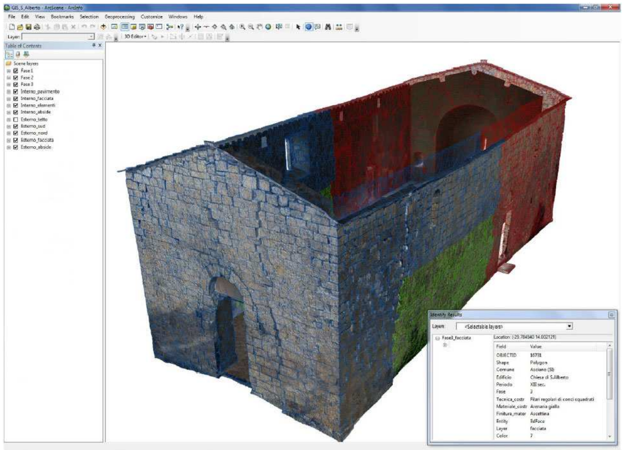


Figure 6: Visualization of three structural phases and data entry in GIS environment.

We stored the attributes obtained from the archaeological study in separate layers so as to make it possible to query each layer of group of layers in order to identify the material and technique of construction, to present photographic information and to ‘disassemble’ or ‘reassemble’ the building in terms of structural phases. Thanks to the wall-analysis and other observations and measurements taken from the 3D model it proved possible to:

- recognize three phases of building construction;
- propose a relative chronology;
- formulate hypotheses about the origin and degree of specialization of the workers and the origin of the construction materials.

As a result we can affirm that, within a substantial homogeneity of design and chronology, the construction of the church was carried out through joining together successive blocks of masonry, the pauses between the three episodes of work being clearly legible in the walls surfaces. The first phase saw the construction of the apse and parts of the north and south walls, extending along the nave to just beyond the two lateral doorways. The second phase consisted of a block of masonry in both in the north and south walls, including two internal semicolumns. The third and last phase involved completion of the two side walls and construction of the west façade. Both in the north and south elevations we can note the different construction material in the first phase in comparison with the second; we can see a change in the size of the ashlar blocks and a clear line of caesura that indicates a temporary suspension of the building work. Tiziano Mannoni and Anna Boato define such caesuras through the term *"giunti d'attesa"* or *"morse d'attesa"*, this last term encompassing the idea both of a momentary pause and a subsequent continuation of the building work (Mannoni, Boato, 2002; Boato, 2008). Close observation of the walls allows us to distinguish numerous L-shaped ashlar blocks that were created in the building yard and then placed in the wall so as to 'clamp' the next phase of construction to the existing walls and to reconcile the non-matching horizontal courses.

In conclusion, it is possible to affirm that, as usually happens in the construction of a church, the building process started at the apse, using sandstone blocks (Phase 1). Then, for some unknown reason, the work was momentarily interrupted and subsequently restarted with the use of a different building material (limestone) that for a period became the only stone available (Phase 2). Finally, there arrived in the building yard a new stock of sandstone and the workers completed the church in the original technique (Phase 3).

The caesuras were important markers in the identification of the three phases. The contribution of the methodologies of Archaeology of Architecture, and the experience of the researchers, were fundamental in distinguishing the precise constructional processes.

These are characteristic of the medieval period, widely seen in ecclesiastical buildings but sometimes reflected in a very similar way in building destined for secular use.

As far as chronology is concerned it is difficult to recognize in the architectural elements the early dating indicated by the written sources. The side portals with segmental arches recall common motifs in the architecture of Pisa, widely present also in the Romanesque churches of Siena. In general the typology and structural characteristics of the walls seem to point to the beginning of the XIII century rather to the later part of the XIIth or even earlier as suggested by the key documentary source.

Close to the south wall there were found four small ceramic fragments: two sherds of "graffita" pottery, a fragment of archaic majolica and a piece of glazed pottery. The research described here has resulted in a preliminary understanding of the church of Sant'Alberto. However, both the scientific analysis and the historical study could well be expanded and the geographic database constantly updated while awaiting the development of new GIS tools for the analysis and examination of 3D data. Indeed this present stage of investigation has been carried out with the express intention of facilitating future uses and further investigation.

4. Conclusions and Next Developments

As we argued in the introduction, this paper describes only the first step of our a new approach to archaeological research.

Indeed, at this stage, our contribution demonstrates mainly the impact and some potentiality of 3D surveying and modeling using multiple geomatics tools in landscape analysis and on the analysis of historical buildings. This is only a small part of the general picture, missing archaeological excavation, finds but also improving 3D archaeological prospection methods and the development of 3D virtual environment aimed to integrate archaeological features in deep association with their physical and cultural context exploring relationships across a different scale of detail moving from landscape to find.

We are currently focusing our work on both side, 3D data collection on archaeological excavation (involving TLS methods and UAV photogrammetry) and find as well the development of an "open-space" environment within which it is possible in every moment to measure and compare historical evidence, stratigraphical relationship and other datasets but also where is possible to improve and upgrade the record in the future on the basis of new field work or post-processing. This approach should, therefore, allow us to achieve:

- overcoming space and time sharing complex "objects" with other experts all around the world;
- the demonstration (firstly addressed to archaeologists) that digital reconstruction is a complex exercise and projective interpretation and also is much more than a graphic reconstruction, is a simulation, that allows exploration of three-dimensional model perspectives through endless investigations and non-invasive documentation;
- virtual reconstruction and simulation scenarios address to specialist as to the general public developing new tool to share but also preserve the memory of cultural heritage;
- development of 3D archaeological thinking.

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