AN ALGORITHMIC APPROACH FOR 3D RECONSTRUCTION OF ARCHAEOLOGICAL SITES

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Abstract - The article outlines a novel method for the 3D reconstruction and creation of BIM models for the built heritage through low-cost technologies (digital photogrammetry), computational techniques and open source software. The first part of the article presents method using as case study the abandoned Albergo Diurno Venezia *in Milan, while the second part discusses the applications of the parametric techniques and the use of BIM for the archaeological park Solunto, Palermo, Sicily and the potentialities in facilitating the accessibility to archaeological sites, their maintenance and documentation.*

In the last years, the concept of cultural heritage has greatly evolved, including in its practice increasing number of fields of expertise. Multidimensional recording and reproducing of excavated structures could potentially mediate in and ex-situ preservation and management of heritage sites[1]. Well-designed information systems, integrating and interpreting multifaceted data sets, have the potential of facilitating data access and becoming powerful tools for interdisciplinary communication[2]. This article manifests a research agenda aiming at establishing links between the currently disconnected domains of cultural heritage, its management and valorisation and the use of innovative technologies, placed under a common Building Information Modelling (BIM) platform. Advanced design, fabrication tools and free/open source software (F/OSS) could generate important benefits in the realm of cultural heritage. Their implementation can drive the shift from strictly procedural preservation and conservation programs towards the development of bespoke processes able to address specific problems in the management and reuse of heritage buildings and sites. In this article is illustrated an innovative approach focusing on digital photogrammetry and open source software for an accurate data recording, elaboration and reconstruction to facilitate the access to the heritage, replacing the need of specialists and high-end equipment (laser scanners, total stations, specific software for processing large point clouds)[3]. The process of the development of the technique together with the results are exposed in the first part of this article investigating as a case study the abandoned *Albergo Diurno Venezia*. The second part explores the methodology for the three-dimensional reconstitution of a part of archaeological park Solunto in Sicily. Using Casa di Leda, this case study aims at testing the limitations of the workflow together with the potentialities the use of parametric tools offer for the semi-automated reconstruction of complex and irregular geometries in archaeological contexts. The broader goal is the production of a highly accurate BIM model as a multi-use platform applied to archaeological sites to support further activities of restoration, conservation, enhancement, communication and management.

BIM for archaeology - For some time the importance of BIM as a digital representation of physical and functional characteristics of a patrimony has been acknowledged and widely discussed[4,5]. BIM is recognized as an essential technology addressing the growing demand for a multi-disciplinary knowledge base[6]. The recent advances in digital archiving and image-based 3D modelling allowed the recording of a large number of heterogeneous data and description of very complex and not always accessible historical sites and buildings[7]. In the archaeological domain, the accurate and complete digital documentation is a prerequisite for further analysis and interpretation which calls for a facilitated approach for appropriately surveying, recording and documenting artefacts and sites[8]. Extending the BIM concept to cultural heritage could promote easier organization, storage, use, web-based visualization and communication of archaeological data. This research intends BIM as a collection of many data-rich models and databases, easily and effectively shared between disciplines and their platforms and software programs[9]. Within this definition, an "as-built" BIM model, as the state of the heritage site or building at the moment of the survey, integrates the initial survey and geometry, the results of the tests and analyses performed prior to the interventions, and all documentation related to future actions of repair, conservation or reuse and new additions (*Fig. 1*).

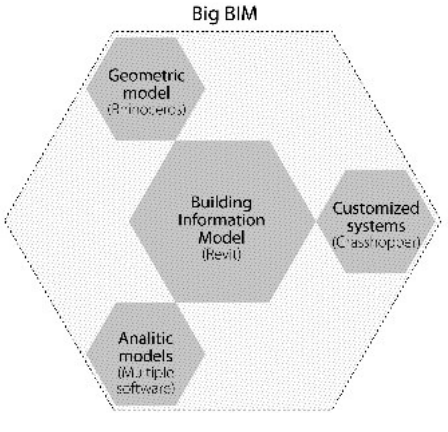


Fig. 1 - BIM is not a software, rather as a collection of many data-rich models and databases, easily and effectively shareable between disciplines and their software platforms.

An enhanced workflow for creating an as-built BIM - The process of creating an *as-built* BIM usually involves three phases. The first is the survey of the heritage and data collection, followed by a second phase of data processing, object recognition and semantic labelling - the most intensive part involving manual modelling. The last phase is the compiling of the final semantically enriched 3D model[10]. The proposed methodology aims at enhancing the current workflow for creating an *as-built* BIM introducing algorithmic modelling tools and free/open source software in the phase of data processing, considered fundamental for the precision of the final model. In Grasshopper custom algorithms are developed to automatically rebuild complex shapes and irregular geometries from polygonal mesh, towards the creation of a NURBS-based 3D model. The latter is then losslessly converted into BIM objects through already consolidated procedures where further layers of information are added (*Fig. 2*).[11]

Grasshopper is a free graphical algorithm editor tightly integrated with Rhino's 3-D modelling tools that can process automatically great amounts of data, reducing arbitrary and manual operations and the

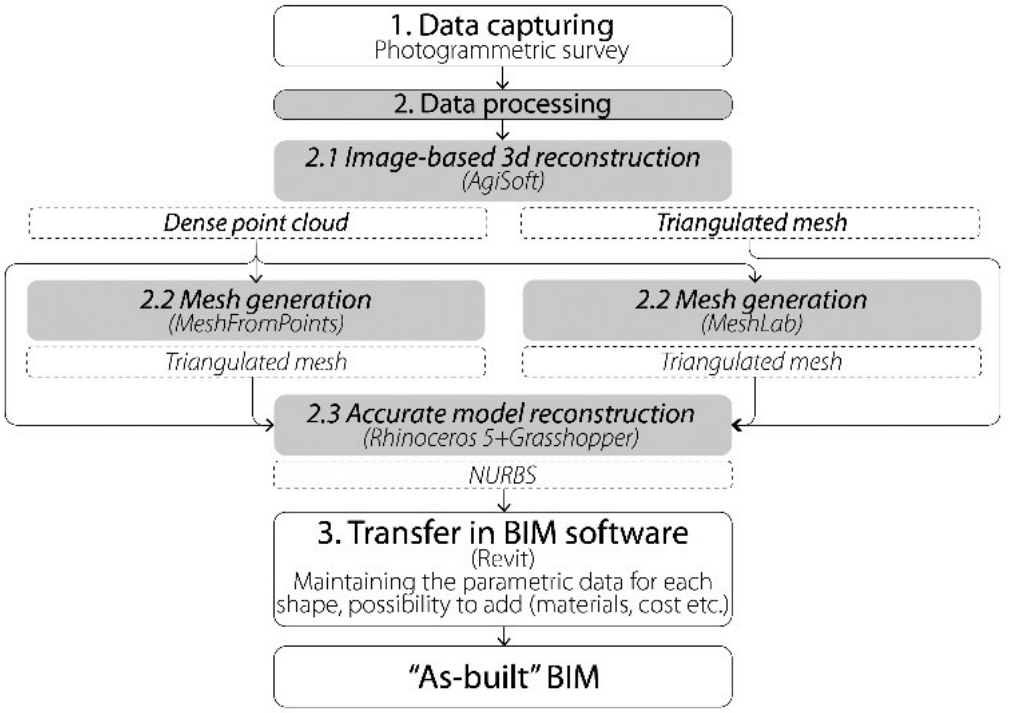


Fig. 2 - An enhanced workflow for creating an as-built BIM model.

possibilities for mistakes. The model developed with this plug-in is associative i.e. allowing the automatic improvement in the model definition when more precise input is feeding the algorithm, offering the opportunity to relate the precision of BIM models in accordance with the needed Level of Detail (LOD). This opens new opportunities in understanding the survey and 3D reconstruction as a flexible and upgradable process, according to multi-disciplinary needs. This approach adopts NURBS (Non-uniform Rational Basis Spline) as the most appropriate mathematical model for representing the complexity present in historic settings in order to answer the incapability of current BIM software to reconstruct free-form shapes and register minor irregularities in building elements as well as to eliminate the automatic application of characteristics (e.g. horizontality of pavements) which do not regard ancient contexts. Moreover, NURBS uses several industry-standard methods for exchange, which favours the easier transfer of data among different software.

A parametric-assisted workflow for 3D reconstruction: the case study of Albergo Diurno Venezia - The parametric-assisted method for 3D reconstruction is illustrated by a streamlined workflow following three main phases - data acquisition, data elaboration and development of custom algorithms for rebuilding polygonal models. The approach relies on digital photogrammetry and image-based 3D reconstruction software, technologies able to generate point cloud densities comparable to the LiDAR ones[12]. The highly precise results obtained together with the cost-efficiency and accessibility of this technology, make photogrammetry extremely useful for recording large archaeological sites without compromising on the level of detail. The first phase of the data acquisition involves a photographic recording of the building (*Fig. 3*). The requirements include a standard consumer grade camera and the condition the photos to be taken with 60% horizontal and 80% vertical overlap, thus ensuring each part of the heritage is present on at least two different photos. During the case study of *Albergo Diurno Venezia*, photogrammetry proved a reliable method for surveying cultural heritage even in unfavorable conditions - the images taken were defined enough to obtain an accurate dense point cloud, despite the building was located underground and no electric current was provided.[13]

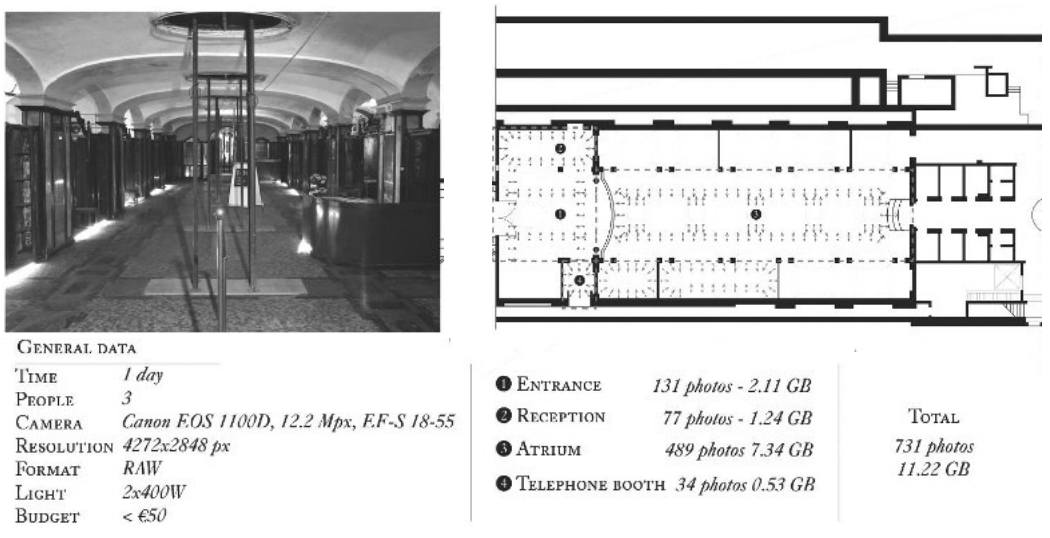


Fig. 3 - Albergo Diurno Venezia: survey and general information.

An image-based modelling software (AgiSoft PhotoScan) was used for the elaboration of the survey data. The multi-view 3D reconstruction technology operates on uncalibrated camera and arbitrary images. This software allows full control of the user over the final precision. It first processes the images, aligning them and matching common points among them leading to a sparse point cloud and then builds a dense point cloud based on the estimated camera positions and the pictures. The conversion of point clouds to polygonal models is an essential process for the 3D restitution for the very accurate results it gives, mainly because the meshes are generated through direct interpolation of the points in the dataset[14]. With the methodology proposed here, a mesh is created automatically from the point cloud, in difference with many common procedures for 3D model reconstruction using surface and volumetric representation, as the precision and the number of vertices are again user-defined. Previous studies have shown the methodology could be applied to various polygonal models obtained through different algorithms. Open source tools like Meshlab and plug-ins like MeshFromPoints are able to derive accurate and light polygonal models comparable to highly expensive tools commonly used.[15]

The conversion of meshes into smooth surfaced NURBS objects is not a direct but rather complex and difficult process. The tools existing for direct conversion of meshes to NURBS use algorithms creating polysurface models hardly usable especially in BIM environment. The methodology for the automated reconstruction allows the design of specific algorithms for the various polygonal models which use as input the meshes and output a replicated smooth NURBS geometry. The opportunity to create custom algorithms, versus using already developed tools, allows to interpret specific morphological characteristics of the building with the human comprehension of the construction logics and the topological characteristics. While a manual reconstruction involves subjectively selecting and interpolating curves from points and the following creation of free-form NURBS object, the method developed excludes the human factor in the actual reconstruction thus allows for the fully automated manipulation of much larger amount of data (*Figg. 4,5*). Parametric software could be used not only for the phase of 3D reconstruction but also as a tool for analysis. Algorithms were designed to randomly select points from the initial point cloud and project them on the reconstructed mesh thus allowing the quantitative estimation of the deviation from the original data set (*Fig. 6*).

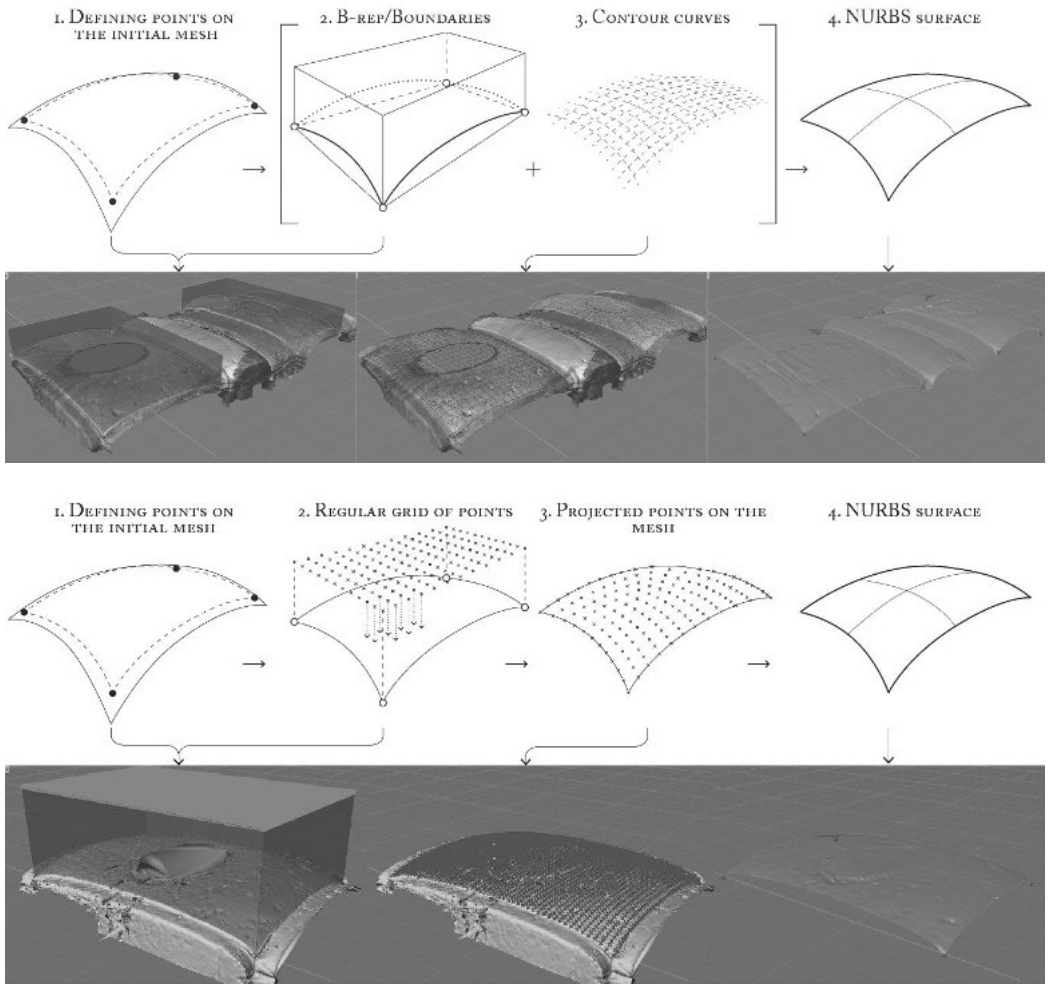
Innovative tools and their application in archaeological context of Solunto: Conservation as a process rather than a list of actions - The urban settlement of Solunto was founded around VIII c. BC by the Phoenicians. Kfr (Solunto) together with Zyz (Palermo) and Mothia (Mozia), comprised one of the three chief Phoenician colonies based in Western Sicily. Built on the promontory of Sòlanto, and destroyed by Dionysius I of Syracuse in the early fourth century BC, the Punic city was rebuilt

on the slopes of nearby Mount Catalfano again by Dionysius, following a Hellenistic-roman model and a regular orthogonal urbanistic structure firstly theorised by Hippodamus of Miletus. The mid-third century, after the First Punic War, Solunto passed under Roman rule. Divided rigorously in residential and public areas, in the archaeological park are still preserved the remains of luxurious homes in the peristyle, lavishly decorated with mosaics and wall paintings mostly from the Roman period.[16]

What makes Solunto unique besides its clearly readable hippodamian urban structure, is the 360º panoramic view. The ruins of Solunto dominate the valley stretching below, combining an archaeological and scientific value with the rich landscapes of the Tyrrhenian sea with the Palermo Gulf, Capo Zafferano and the cities of Santa Flavia and Bagheria. This scene emphasizes the harmonious co-existence of artificial and natural in the archaeological park. Furthermore, the city structure itself has been conceived and informed by the natural characteristics of the terrain, visible from the terraced *insulae* to the channels (*ambitus*) using the natural inclination for transporting rainwater and cooling the *domus*. In this regard, the archaeological site of Solunto, as many others, being placed in a constantly changing natural environment suggests a culture of conservation acknowledging the irreversible passage of time. Taking in consideration the natural phenomena, connecting and conditioning the heritage and giving rise to various scenarios, the focus should not be the conservation in itself but rather the conservative processes that vary in time depending on the interaction with the people and the ambience[17]. The formalization and analysis of such processes could be achieved through rigorous study of all related data. Heritage information is the dynamic process through which the documentation of a heritage place is systematically collected, archived, and made available in order to provide a sound basis for the implementation of informed conservation strategies, research, investigation, day-to-day management, maintenance, or provision of services for visitors[18]. BIM is a platform able to combine various kinds of information and integrate them into semantically rich three-dimensional digital repositories. The multidisciplinary approach in the BIM technology allows those involved in these activities to have access to documentation and to be able to add new records to the existing stock of information.

Applications of BIM strategies and the parametric-assisted reconstruction method in Solunto - In this framework of contemporary archaeological heritage management, the methods for data recording and organizing should be fast and accurate, easily accessible and manageable for the communities and oriented towards a three dimensional way of data-storage and reproduction of the structural components from the archaeological heritage[19]. In the current practices, these procedures involve expensive tools and software operated by highly specialised team of experts. Nevertheless, one of the greatest difficulties that the archaeological parks are facing is economic. Most heritage sites are auto financed, relying on occasional funds from the European commission or external partners[20]. Solunto makes no difference, as the lack of consistent funding impacts on the activities of regular maintenance as well as the auxiliary functions of promotional activities and touristic information, improvement of the visitors experience and supporting services and staff. The need of a complessive documentation of the archaeological park Solunto and an overall strategy for its maintenance and monitoring combined with the economic aspect call for accessible, low-cost methodologies for the creation of a semantically rich three-dimensional models. The parametric-assisted method for 3D reconstruction illustrated in this article presents a great opportunity for Solunto, allowing an accurate recording of the artefacts as a fundamental step towards creating an integrated database in a BIM environment. This approach allows the involvement of academic institutions and external partners since it uses open source standards and free software to create models which are shareable and accessible.

According to the new model of *CRPR* (*Centro Regionale per il Restauro*), Solunto (together with Selinunte and Morgantina) has been classified as heritage in high risk. The evaluative criteria for such classification have considered the environmental air, the proximity to the sea that exposes the archaeological assets directly to the erosion of the wind loads of sand and salt[21]. Having this in mind, the creation of detailed 3D models of the archaeological area and the more valuable artefacts becomes imminent. With high accuracy and reliable detailed 3D models, the destructive processes could be registered and analysed, shape and variations in shape could be investigated and quantified. The reconstructive approach afore presented proposes an associative (updateable) 3D model development where acquired data could be replaced in time and the result would be automatically updated. Such methodology allows the tracing of the processes of destruction and variations in shape employing customized and open source tools. Moreover, the software enables the output of 3D models with abundant detail which accuracy is adjustable according to the overall needs and use, the size of the investigated area or artefact and hardware capacity. Among the analytic possibilities are also the calcu-



Figg. 4, 5 - Parametric reconstruction from contours and using grid of points.

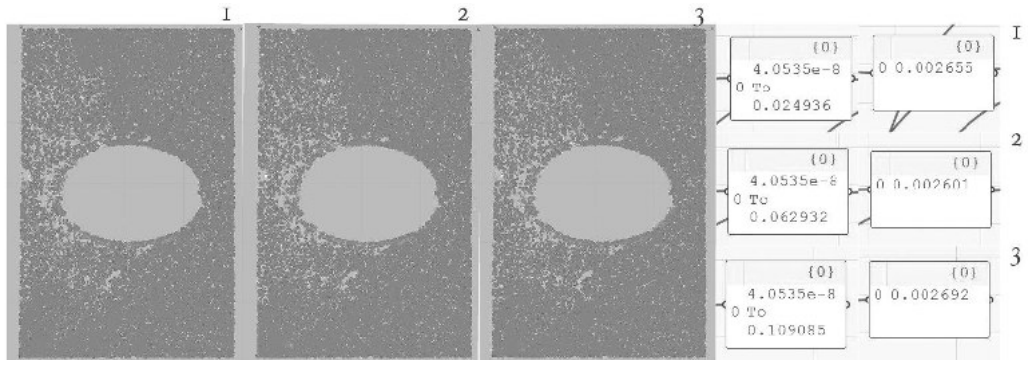


Fig. 6 - Comparison between point cloud and reconstructed surface.

Fig. 7 - Insula VI, Casa di Leda.

lation of volumes and the comparative study of size, height, depth and other metrics, running different analytic software and performing tests.

Besides its scientific value, 3D documentation of archaeological excavations also has an important communicative and educational value. The visual character of a 3D model offers possibilities to attract the attention of the general public to the archaeological heritage[22]. Nowadays, heritage can be digitized and virtually accessed, even remotely via the web. Through the current 3D modelling technology, the use of open source standards and BIM, web-based interactive models/repositories could be created where the public can further discover the heritage virtually exploring it. Such models serve as highly effective and intuitive means of communication or as interfaces to share and visualize information collected. Given the possibility to link 3D geometries to external data, 3D models can be analysed, split in sub-components, and organized following proper rules for a range of purposes[23]. Solunto could greatly benefit from such application which would enhance the quality of the site and allow a personal participation of the visitors.

The process of recording and 3D reconstruction of a part of Insula VI - Revising and improving the knowledge gained during the work on the case study *Albergo Diurno Venezia*, the methodology for 3D reconstruction has been applied to a part of *Insula VI* (*Casa di Leda*) in Solunto for the accurate recording and the following reconstruction of a three-dimensional NURBS model (*Fig. 7*). This undertaking aimed to test the limitations of the methodology and to further better the approach. In a two-day campaign 976 photographs (5760 X 3840 px) were taken with a Canon 5D Mark III camera for the generation of a sparse point cloud containing 4 563 126 points (*Fig. 8*). A team of only two people was needed for the proper photographic recording of the quite vast area of insula VI. This demonstrates the high applicability and cost- and time-efficiency of the photogrammetric technology which allows accurate results to be achieved with minimal efforts. The focus of the experiment has been a room with mosaics overlooking Via Ippodamo da Mileto. In *AgiSoft Photoscan*, a dense point cloud with 9 179 797 points has been created only for this room, thus indicating the flexibility of the software permitting the split of the process into various parts each reconstructed with variable accuracy (*Fig. 9*). The dense point cloud has been then imported in Rhinoceros using custom Python script and referenced in *Grasshopper*.

Using the *Volvox* Plug-in for *Grasshopper*, contours were obtained by the intersection of the point cloud with different planes (with XY and YZ coordinates). The use of algorithmic tools allows the adjustment of the contours density, hence adapting the precision of the final model - the more the contours, the more accurate the model would be since it interpolates more points from the cloud (*Fig. 10*). Subsequently, the sections has been confined by a

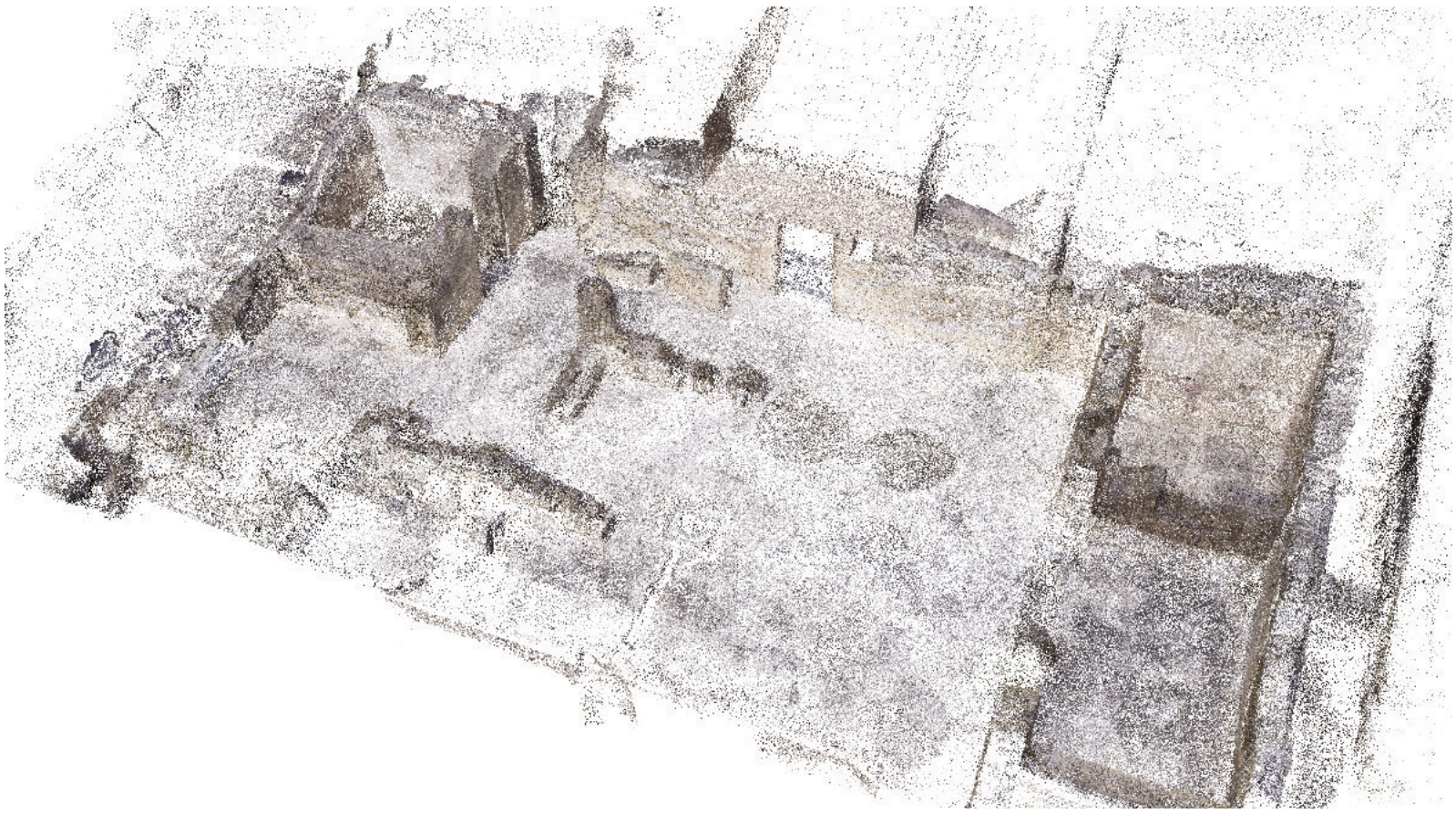


Fig. 8 - Sparse point cloud of a part of Insula VI*: 976 photographs (5760 X 3840 px) taken with a Canon 5D Mark III camera have been used for the generation of a sparse point cloud containing 4.563.126 points. The photographs were taken during a two-day shooting campaign by a team of two people.*

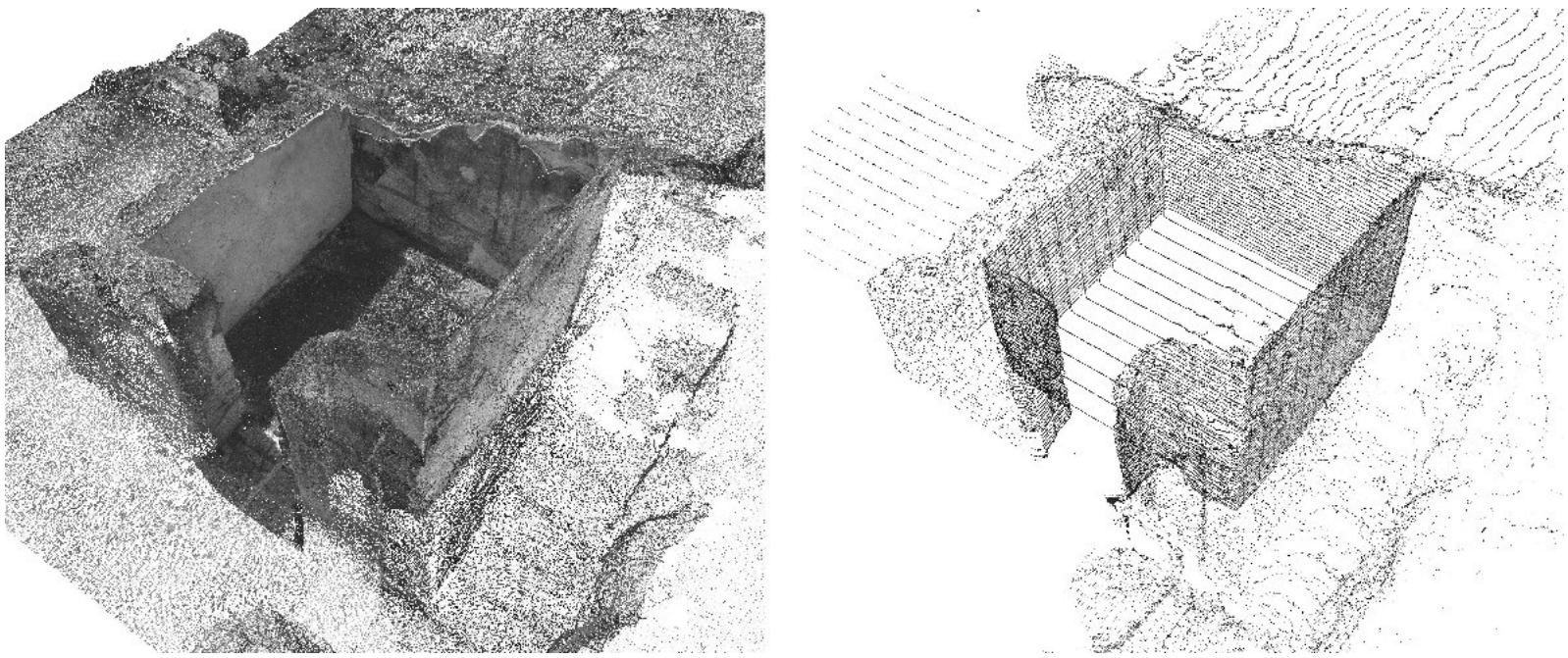


Fig. 9 - Dense point cloud and contours: using the Volvox Plug-in, contours were obtained by the intersection of the point cloud with different planes; the use of algorithmic tools allows the adjustment of the contours density.

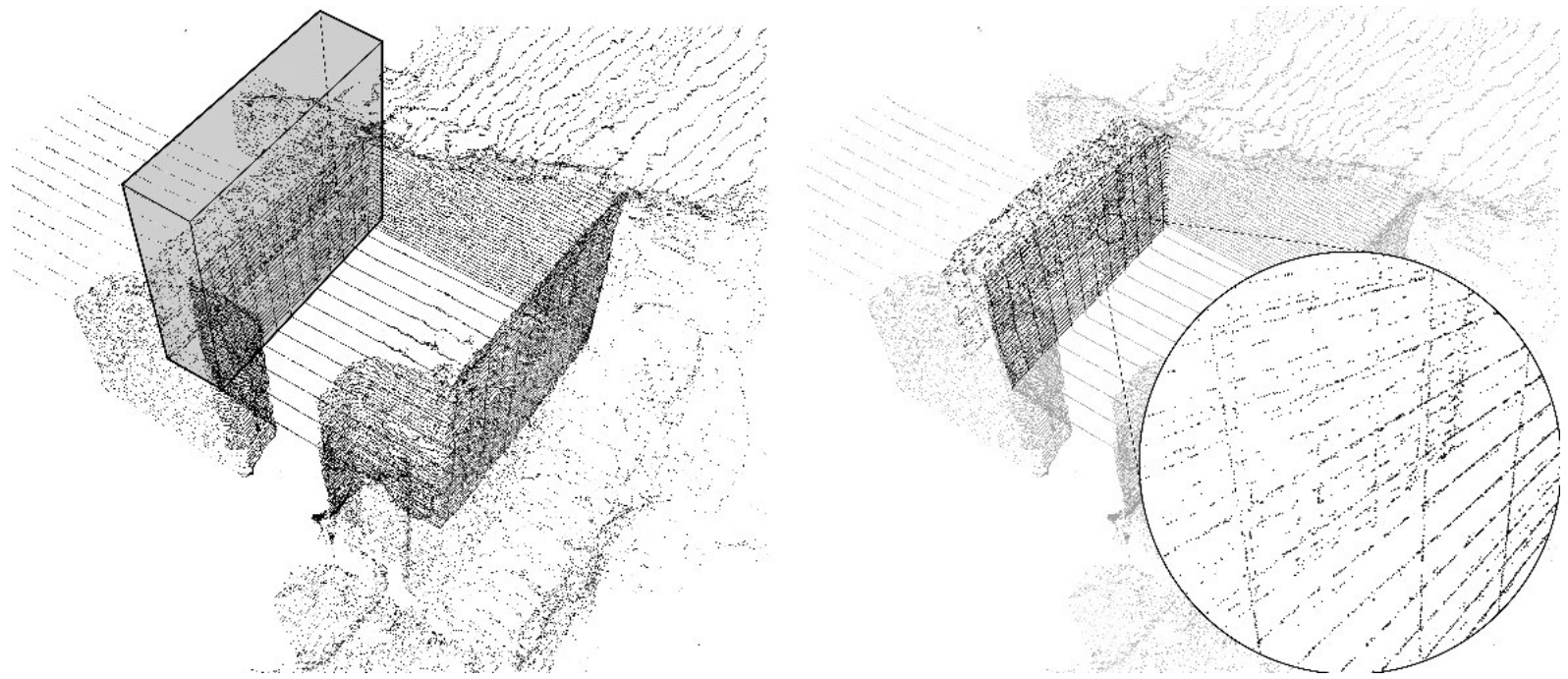


Fig. 10 - Identifying regions: a closed b-rep (boundary representation of shapes through limits) was created in order to be used for the identification of the building element to be reconstructed; the algorithm applied extracts points directly from the initial point cloud.

closed b-rep (boundary representation of shapes through limits) which was used for the identification of the building element to be reconstructed, in this way cancelling the unneeded points out of the selection (*Fig. 10*). Then, the points obtained were re-ordered and further used for the reconstruction of curves through direct interpolation (*Fig. 11*). The generated curves (which accuracy could also be controlled) then defined the U and V variables used to parametrize a NURBS surface (*Fig. 11*). The reconstructed surface was overlaid on the existing point cloud, giving the opportunity for visual evaluation and comparison (*Fig. 12*). The advantage of using algorithmic tools, as mentioned earlier in this article, gives possibility for the automatic tuning of the precision by controlling different parameters and receiving an immediate feedback.

Future possibilities - The archaeological park of Solunto is currently missing recreational and sun-protective covers which if present would impede the destructive processes on some mosaics and decorations while significantly improving the visitors experience. Cost-efficient, demountable structures and innovative techniques is the solution best fitting the current economic and environmental demands on site. Roberto Naboni[24] have developed methodology for design and manufacturing of lightweight structures adopting advanced computational and digital fabrication techniques. Through the use of form-finding design approach, such structures are shape-optimized yet self-supporting, thus lowering economic impact and controlling material usage and transportation. An accurately reconstructed 3D model preserving material imperfections and structural deviations could provide the right input for creating of site-specific covers and sun-protective shades which take in consideration factors like environmental conditions, material behaviour and assembly process.

NOTES

1) J. D. Reu et al., *Towards a Three-Dimensional Cost-Effective Registration of the Archaeological Heritage*, 'Journal of Archaeological Science', 40(2), 2013, pp. 1108-1121.

2) R. Letellier, W. Schmid, F. Leblanc, «Guiding Principles. Volume 1», in R. BENNET, Recording, Documentation, And Information Management for the Conservation of Heritage Places, The Getty Conservation Institute, Los Angeles 2012.

3) M. M. Zheliazkova, R. Naboni, I. Paoletti, *A parametric-assisted method for 3d generation of as-built BIM models for the built heritage*, 'Proceedings of 14th International Conference on Studies, Repairs and Maintenance of Heritage Architecture STREMAH 2015', volume 153 of WIT Transactions, 2015, pp. 693-704.

4) Y. Arayici, *Towards Building Information Modelling for Existing Structures*, 'Structural Survey', 26(3), 2008, pp. 210-222.

5) H. Penttila, M. Rajala, S. Freese, *Building Information Modelling of Modern Historic Buildings*, 'Proc. of the 25th eCAADe Conf. Predicting the Future', eds. V. Bourdakis, D. Charitos, Frankfurt am Main 2007, pp. 607-613.

6) S. Fai, K. Graham, T. Duckworth, N. Wood, R. Attar, *Building Information Modelling and Heritage Documentation*, 'Proc. of the 23rd CIPA Symposium', Prague 2011.

7) A. Scianna, G. Susanne, S. Paliaga, *Experimental BIM*

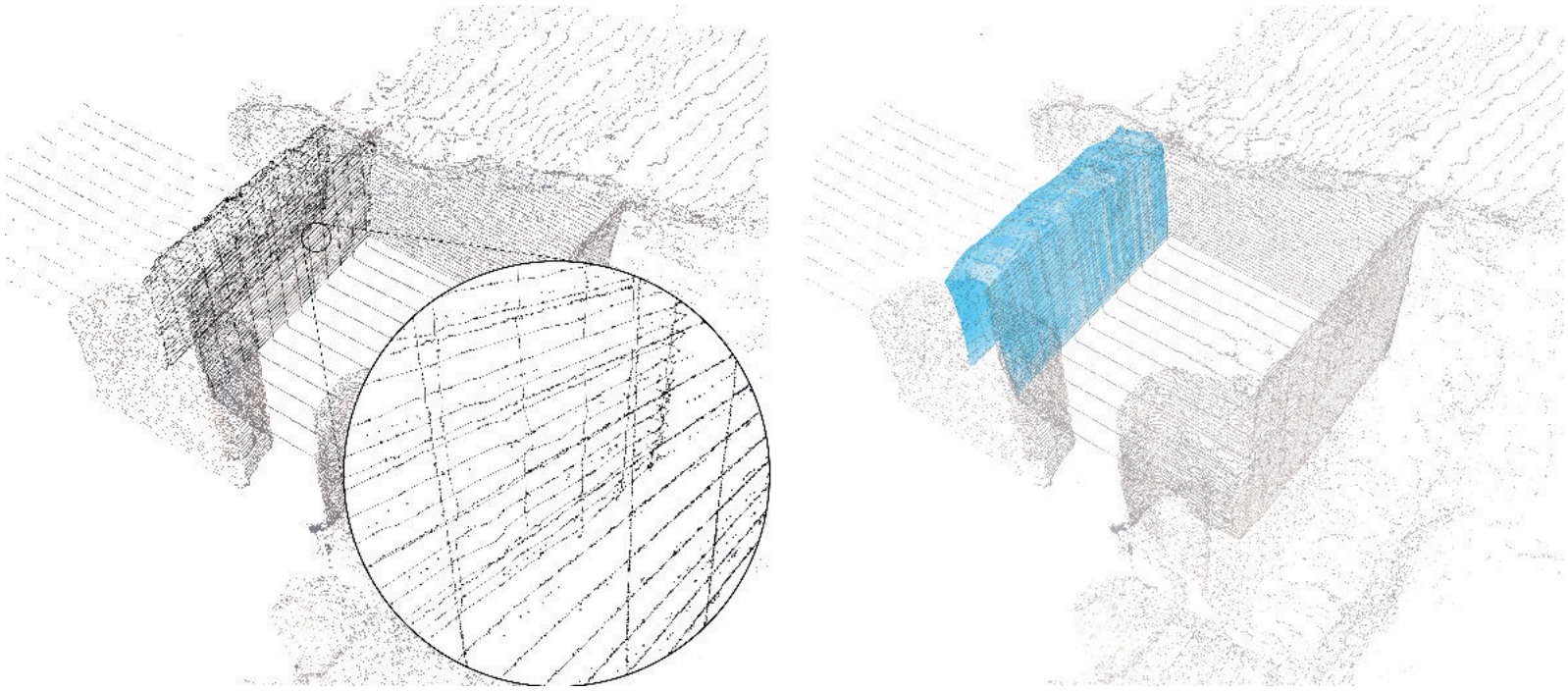


Fig. 11 - Curves reconstruction and NURBS surface: the points obtained in the previous step were re-ordered in order to be used for the reconstruction of curves through direct interpolation; the previously generated curves were used for the reconstruction of a NURBS surface.

Applications In Archaeology: A Work-Flow, 'Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection Lecture Notes in Computer Science', 2014, pp. 490-498.
8) S. G. Barsanti, F. Remondino, D. Visintini, *3D Surveying and Modeling of Archaeological Sites. Some Critical Issues*, 'ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences', II-5/W1, 2013, pp. 145-150.
9) K. M. KENSEK, *Building Information Modeling*, Routledge, Oxon and New York, 2014.
10) R. Volk, J. Stengel, F. Schultmann, *Building Information Modeling (BIM) for Existing Buildings - Literature Review and Future Needs*, 'Automation in Construction', 38, 2014, pp. 109-127.
11) D. Oreni, R. Brumana, F. Banfi, L. Bertola, L. Barazzetti, B. Cuca, M. Previtali, F. Roncoroni, *Beyond crude 3D Models: from Point Clouds to Historical Building Information Modeling via NURBS*, 'Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection', Switzerland 2014, pp. 166-175.
12) R. Rinaudo, F. Chiabrando, F. Nex, D. Piatti, *New Instruments and Technologies for Cultural Heritage Survey: Full Integration between Point Clouds and Digital Photogrammetry*, "Digital Heritage", Berlin 2010, pp. 56-70. http://link.springer.com/chapter/10.1007/978-3-642-16873-4_5
13) M. Zheliazkova, R. Naboni, I. Paoletti, *op. cit.*, pp. 693-704.
14) M. Berger, A. Tagliasacchi, L. M. Seversky, P. Alliez, J. A. Levine, A. Sharf, C. T. Silva, *State of the Art in Surface Reconstruction from Point Clouds*, 'Proc. of the 34th Eurographic Conf", 2014, pp. 161-185.
15) M. Zheliazkova, R. Naboni, I. Paoletti, *op. cit.*, pp. 693-704.
16) C. Greco, *Il Parco Archeologico di Solunto,* Web. http://www.regione.sicilia.it/beniculturali/dirbenicult/bca/L_Parchi/parco_solunto.html Accessed: 01/09/2015
17) A. Sposito, *Solunto: Paesaggio, Citta, Architettura*, «L'ERMA» di BRETSCHNEIDER, Roma 2014.
18) R. Letellier, W. Schmid, F. Leblanc, «Guiding Principles. Volume I», *op.cit.*
19) J. D. Reu et al., *op.cit.*, pp. 1108-1121.
20) L. Fricano, A. Gargano, *Solunto risorgerà con i ragazzi, il teatro, la musica*, 2015, Web. http://www.bagherianews.com/component/content/article/14477-l-fricano-direttrice-del-parco-archeologico-solunto-risorgera-con-i-ragazzi-il-teatro-la-musica.html Acessed: 28/08/2015.
21) A. Rosciglione, *Evitare una Pompei siciliana? La carta del rischio è il primo passo*, 'StrumentiRes - Rivista online della Fondazione Res', Anno II, n. 7, 2010, Web. http://www.strumentires.com/index.php?view=article&catid=3%3Acultura-a-societa&id=254%3Aevitare-una-pompei-siciliana-la-carta-del-rischio-e-il-primo-passo&format=phocapdf&option=com_content&Itemid=110 Accesses: 03/09/2015.
22) S. Hermon, *Reasoning in 3D: a critical appraisal of the role of 3D modelling and virtual reconstructions in archaeology*, 'Beyond Illustration: 2D and 3D Digital Technologies as Tools for Discovery in Archaeology. BAR International Series 1805', Oxford, 2008, pp. 35-44.
23) H. Richards-Rissetto, J. Von Schwerin, G. Girardi, *Kinect And 3D GIS in Archaeology*, '18th International Conference on Virtual Systems and Multimedia', 2012, Web. Accessed: 26/08/2015
24) Cfr. R. Naboni, *Form-finding to Fabrication of Lightweight Structures*, 2015.

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Fig. 12 - The reconstructed surface is overlaid on the existing point cloud in order to be compared and evacuate.