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Documentation and Interpretation of an Archeological Excavation: an experience with Dense Stereo Reconstruction tools

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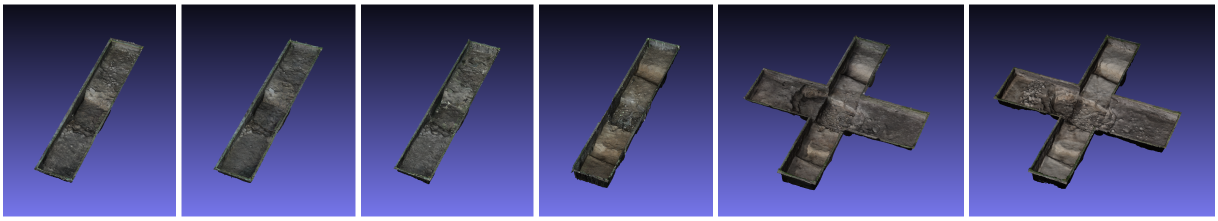

Figure 1: *Snapshots of some of the layers acquired for the documentation of excavation*

Abstract

An archeological excavation is usually a rapidly evolving environment: several factors (weather, costs, permissions) force the work to be concentrated in a few weeks. Moreover, excavating is essentially a mono-directional operation, which constantly modifies the state of the site. Since most of the interpretation is performed in a second stage, it is necessary to collect a massive amount of documentation (images, sketches, notes, measurements). In this paper we present an experiment of monitoring of an excavation in Uppåkra, South Sweden, using dense stereo matching techniques. The archeologists were trained to collect a set of images every day; the set was used to produce a 3D model depicting the state of the excavation. In this way, it was possible to obtain a reliable geometric representation of the evolution of the excavation. The obtained model were also used by the archeologists, by the means of an open-source tool, to perform a site study and interpretation stage directly on the geometric data.

The results of the experimentation show that dense stereo matching can be easily integrated with the daily work of archeologists in the context of an excavation, and it can provide a valuable source of data for interpretation, archival and integration of acquired material.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism —

1. Introduction

Excavating an archaeological site is like unrolling the past: layer after layer, each one older then the previous one, the past of the site is unearthed and explored. This operation, however, does destroy the current state of the site as soon as it has been revealed, making it a mono-directional exploration. Keeping track of all the intermediate steps, a sort of dense time-lapse of the excavation, is of invaluable importance for the study of the site by the archaeologists, but also to teach students how a field work is managed in details. However, due to the time and resources required in producing an accurate documentation of one intermediate step, it is often impractical (for time and resources constrains) to be able to obtain a sufficiently time-dense documentation.

While 3D scanning technologies are able to precisely capture the geometry of the excavation, thus, preserving an intermediate state of the site, their cost and operational time discourage an intensive field use. An alternative is represented by recent dense reconstruction technologies, which are able to obtain a 3D model of a scene starting from a set of uncalibrated images. Their main advantage stands in the fact that a simple digital camera can be used, and no preliminary calibration of the camera or of the scene is needed.

Moreover, tools to process and manage 3D data are nowadays freely available. Dense reconstruction can be exploited using low-cost commercial products [Agi] or freeware solutions based on web-services [Arc] or local processing [SFM]. In addition, open source solutions [Mes] provide tools to improve the quality of the geometry, integrate additional data and visualize results.

We believe that these technologies may be easily integrated in the excavation work, for a number of reason. Among them:

- The easiness to use and low cost: the requirements of this acquisition technique (both in terms of hardware and expertise) lead to a very small overhead, especially compared to the gain in terms of richness of information.
- The integration with classic documentation: more than *replacing* the standard documentation pipeline, this method is well suited to *integrate* with the known documentation procedures, making them easier to manage and opening up new possibilities.
- The usefulness in the study of the site: three-dimensional information can be analyzed on-site, in order to drive the excavation analysis and strategy.

The use of tools for 3D documentation, in order to record and study archaeological features, cannot be considered an unexplored area; laser scanners or photogrammetric techniques have been largely employed in this field, but because of the long time required to post process the data and the high costs of these devices, 3D models have been rarely used to have a daily documentation and interpretation of ongoing excavations. In this project we did not only tried to obtain 3D models to get a complete description of all the phases of an archaeological excavation, but we also tested the use of the 3D models as a tool to brainstorm about and take notes of the ongoing interpretation process. One of the goals of this work is to achieve a better comprehension of how to merge these new investigation methods into the excavation time life. Our idea is that the use of high resolution 3D models during the investigation process increases exponentially the capacity of the archaeologists to interpret the site, obtaining a deeper knowledge of the entire process also after the destruction of the archaeological stratigraphy.

1.1. Work Outline

In this work, we used dense matching tools to obtain a time-dense, detailed 3D documentation of the excavation site. The acquisition of its evolution was performed day-by-day. Both the acquisition and the processing of data (after a short period of training) was made directly by the archaeologists.

The test case, in the context of the archaeological excavation of Uppåkra, was the search for a possible presence of a grave mound from the Iron Age (Section 3). Thanks to the fast and simple acquisition procedure, it was possible to obtain a lot of models, one at the end of each working day, describing the evolution of the excavation (Section 4.1). All the time steps were processed using low-cost or free/open solutions, trying to define a simple pipeline which could be replicated in the general case (Section 4.2). In order to be able to compare, measure and present the evolution of the excavation, the acquisitions were put in a common reference (Section 4.3). Moreover, preliminary experiments to improve the model and integrate heterogeneous data were performed.
The obtained 3D data is then used to produce effective and precise documentation of the excavation, easy to integrate in the normal documentation framework carried out by archeologists during a field work (Section 5). For this task, we used some of the rendering and presentation features already implemented in the MeshLab tool, and designed new operations tailored to exploit this specific kind of dataset.
Then (Section 6), the 3D models and the visualization tools were directly used by archeologist to analyze the site and do on the 3D data some of the studies normally carried out on photos or surveys of the excavation. In particular, the use of a simple painting tool enabled the archeologists to highlight the evolution of the important features of the explored layers, giving important indications for further excavations.

2. Related Work

2.1. Dense Stereo Tools

The idea of dense stereo reconstruction tools is to obtain three-dimensional data starting from a series of unordered images. The main advantage of having un-calibrated cameras or devices is the possibility to use large datasets like the ones that can be retrieved from the Web.
The process of 3D reconstruction is usually composed by different steps: image matching, camera parameters estimation, dense matching. Computation effort of large scale structure from motion is dominated by image matching, which is often obtained (except for some real-time applications) by performing exhaustive pairwise image matching. Several approaches have been proposed [BL05, MP07, VVG06, GSC*07], and most of the current research is focused on how to index and organize the images in order to reduce the image matching operations and possibly clustering similar images [HTP10, FFG09]. An overview of all the approaches in literature is well beyond the scope of this paper.
The results of this computation may be similar to a series of range map (like the ones produced by range scanners), associated to each input image. These range maps are then merged together to generate a single triangulated surface.

Some other tools may produce as results a single point-cloud or even a triangulated surface.

In general, the amount of time needed for the processing of image sets is in the order of hours. Most of the methods which have been made available to the public are based on web-services like ARC3D [VVG06], where the user uploads the data to a server connected to a cluster of computers, which process the data and send the results back. Recently, Bundler [SSS06] was released as an open-source software for structure-from-motion reconstruction of 3D scenes from unordered photographic datasets. One notable implementation of the bundler tool is inside the PhotoTourism [Pho] application, which works quite similarly to Arc3D, since it is implemented as a web service. Bundler, coupled with a dense matching tool (PMVS2 [FP07]) is able to generate a single pointcloud from all the matched points in the input image dataset.

Cultural Heritage may appear one of the most interesting fields of application for this kind of acquisition, being a non-contact, low cost alternative to 3D Scanning. Some experimentation in this direction has started [REMA09], but the main problem in its use for 3D acquisition is the lack of scale information. Previous and current reconstruction processes [GRZ03, REHB*08] still rely on the integration with 3D Scanning or photogrammetry. Hence, although some claim that dense stereo matching is a mature alternative to 3D Scanning, no convincing comparison has been presented until now.

Recently, some starting effort in this direction [HPA*10, FdBG11] has been made, but methodology definition and accurate data assessment are still missing.

2.2. Excavation Monitoring

The archaeological excavation is a unique research context and its investigation is mainly based on analyzing and interpreting data collected during the excavation process. The archaeological excavation is an unrepeatable experiment where all the information, once identified, are recorded and removed from their original context [Bar05]. The main goal of this process is the reconstruction of the diachronic evolution of the site during the different ages.

The interpretation of every archaeological site is mostly performed during the excavation period, when the archaeologists have the unique opportunity to see and analyze the data in their original and complete aspect; once interpreted, all the information is recorded and removed from its context.

Today there are several ways to describe the investigation process of an archaeological site. In the last decade the introduction of new visualization technologies and tools for the spatial documentation have represented an important opportunity for archaeologists to record the data in a more complete and efficient way. In particular, the possibility to describe the spatial relations of all the elements which compose the different historical layers allows representing a high number of details from the original information. These new data category allows a better and more complete description of the state of the art of the excavation during all steps of its investigation.

Figure 2: *The Uppåkra excavation site*

3. The archaeological site of Uppåkra

The archaeological site of Uppåkra (Figure 2) is considered one of the most relevant examples of Iron Age central place in Sweden. The site, situated 5 kilometers south of Lund, has an extension of approximately 100 acres. Field and landscape investigation have confirmed the existence of a settlement from the beginning of the 1st century BC to the end of the 11th AD with a large presence of buildings and finds. The site was discovered in the 1934 and from the 1996 the area is under archaeological investigation. Since the beginning of the excavation campaigns, the site proved to be incredibly rich; during the initial phase of the investigation (1996-2000) the metal detector survey highlighted the presence of almost 20.000 findings, suggesting a sequence of human activities from the Pre-Roman Iron Age until the Viking Age [Lar07]. During the spring 2010 a geophysical inspection highlighted the presence of anomalies in an area located in the North West part of the settlement; a first interpretation was the possible presence of a grave mound belonging to the early Iron Age. Since the beginning of May 2011, an excavation campaign is being carried out in order to investigate the nature of the anomalies and their relation with the site.

This particular excavation has been selected because, while having all the characteristics of a standard archaeological field work, presented two peculiarities which made this case especially suited for this study:

- The planned time extent of the excavation was relatively short: a few weeks. This, in our study would mean a shorter time needed to gather all the data, but also a chance to demonstrate how this acquisition strategy could fit in such a short schedule, maximizing the effectiveness of the fast paced data acquisition.

- Since the planning stage, it was clear that the excavation would encounter multiple layers. This would be one of those cases where interesting findings are promptly removed and each layer is destroyed to be able to reach the next one. Keeping track of all these changes would be of great importance for the study of the site.

3.1. Excavation details

The investigation of the area started with the excavation of a rectangular trench of 1,90 m x 11 m that crossed the circular structure highlighted by the geophysical inspection (see Figure 3). The archaeological context was recorded, using the standard documentation techniques, through the use of a Total Station and several sets of images, with a resolution of 6 MPixels, were acquired every time a new cultural layer was recognized.
During the excavation of the trench, ditches of circular shape were found in the north and south part of the excavation, at the level of 0.70 cm depth (see Section 6). The ditches were interpreted as the possible border of the grave mound. In the middle of the trench a large pit of 1.89 m x 3.88 m was discovered and at the bottom of it, a stone paving was found. From a preliminary analysis, this element could belong to the main body of the grave. In order to find a confirmation of the circular structure that should delimitate the grave mound, a second trench, perpendicular to the first, was excavated (Figure 1).

4. 3D Data Generation

The generation of 3D models, even with the recent advances of software and hardware, is still not a "single button press" operation. However, we believe that the dense stereo technology, coupled with state-of-the-art processing tool can provide a good cost/benefit ratio, and its use may be in the reach of non experts. In this work, one of the aim was also to validate this point; for this reason, all of the acquisition and processing task has been carried out not by personnel with a 3D graphics background, but by archaeologists with limited experience in the use of 3D tools and. From this point of view, this experimentation was a real success. Not only all the time steps were correctly reconstructed in 3D, but it was also possible to appreciate the improvement of the people working with these tools during the course of the excavation. This may be partly due to the fast feedback cycle of this technology (the result is visible after some minutes), which helps the user to understand his errors, and makes the learning process much faster.

The basic idea was to have a photographic acquisition at the end of each working day, and to process it as soon as possible. Since the dense reconstruction tool used, PhotoSynth/Bundler + PMVS2 [SFM], worked on a local machine, it was possible to check the result almost immediately. Before starting this test case, we experimented with similar photographic datasets of excavations using different dense reconstruction tools (Arc3D, PhotoSynth/Bundler + PMVS2, AutoDesk PhotoFly, AgiSoft Photoscan). While it was possible to obtain good results with all the tools, the possibility of running the reconstruction on a local machine, coupled with its high quality and high density reconstruction, made us decide to use PhotoSynth/Bundler + PMVS2.

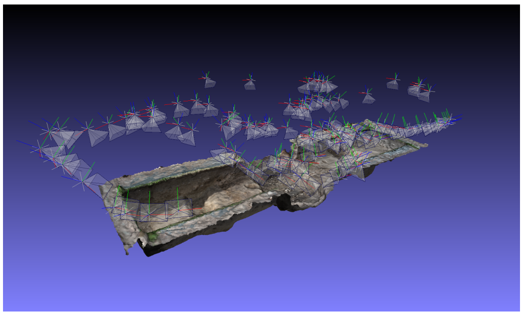

Figure 3: *The 3D model of the initial rectangular trench, together with the positions of the images used for 3D reconstruction.*

4.1. Acquisition

The quality of the photographic sampling is crucial for the reconstruction: the success of the reconstruction depends then on the presence of enough high level features to compute the initial calibration and, later on, on the possibility for the dense matching algorithm to find correspondences for all the image pixels. The photographic sampling should be good from two different points of view: image quality (sharp focused, with low distortion and low noise level) and coverage (enough overlap, complete coverage). For the image quality, any medium-range DSLR camera is enough to obtain good photos, it is not necessary to have incredibly high resolution, it is more important to have sharp photos taken with a a good lens. Two different cameras of the same category were used for the acquisition campaign: a Nikon D70 and a Canon EOS Rebel ISX. The images used in the reconstruction were at 6 MPixels, more than enough to obtain a good resolution of the reconstructed 3D data.

On the other hand, it is necessary for the photographic campaign to cover all the parts of the excavation, from multiple point of views, and with enough overlap to find feature matches. A basic strategy is to plan a simple, regular path, which goes around and inside the area of interest and then, following this path, take a shot every few steps. This method is good to avoid forgetting to sample some parts of the excavation (which may happen, especially when moving around without a precise plan) and generate photos with a clear order (each photo has some overlap with the previous one), which help the matching algorithm. As visible in Figure 3,

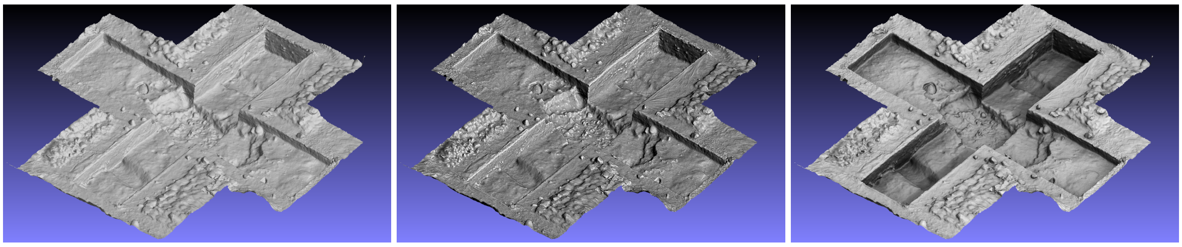

Figure 4: *Different ways to visualize the geometry may help understanding the features of interest of the excavation. From left to right: simple flat shading, Radiance Scaling (surface roughness and small details are enhanced), Ambient Occlusion and cast shadows.*

in this case, the acquisition pattern is just a path which goes around the trench, a photo is taken every few steps, trying to frame as much of the trench as possible.

The first 6 steps have been acquired by an archaeologist expert in the use of 3D software and reconstruction tools, while the remaining one were undertaken by an archaeologist with practically no experience with such technology. Nevertheless, all the time steps has been reconstructed successfully, with a similar quality. This proves that the acquisition task may be carried out by non-experts, with just a very simple training.

4.2. Processing

The creation of the 3D model is still, despite the recent improvement of sotware tools, not completely automatic, requiring for the user to use a 3D processing tool. While it is common for an archaeologist to have experience in surveying and measurement techniques, it is not common to be able to use CG tools. However, we trained in the use of this kind of tools people with very different background, and the processing tools proved to be usable with just a few days (1-2 weeks) of experimenting.

Depending on the dense reconstruction tool used, the nature of the resulting data may change a lot. The data produced by the reconstruction tool may be raw clouds (one for each input image), a single point cloud, or an already triangulated model. In most cases, some form of processing is necessary to obtain a usable 3D model. This processing may include the cleaning of the raw data, the alignment of the 3D data coming from the various photos, the creation of a triangulated surface, the photo texturing or just a geometrical simplification. MeshLab [Mes] does provide all the functionalities needed to this task, making it a suitable tool for this kind of experimentation.

In this case, the PhotoSynth/Bundler + PMVS2 tool generated a dense point cloud, which can be cleaned of outliers, cropped to the area of interest and then triangulated using one of the merging filters available in MeshLab, for example, the Poisson Merging. The color mapping may be derived from the generated cloud (which is usually colored), or by reprojecting the photos used in the reconstruction (which are already geo-referenced at reconstruction time), as detailed in Section 5.

4.3. Integration

While each model is a representation of a particular moment of the excavation, it's important to organize the acquisitions so that they can be easily compared in order not only to help visualization, but also to obtain quantitative data. One of the main issues related to the reconstruction from uncalibrated images is the fact that obtained data are at arbitrary scale. A scaling and alignment phase is hence necessary to put all the acquisitions in the same reference system (at the proper scale).

To this aim, it was used the data coming from the Total Station, gathered during the standard documentation procedures (see Section 3.1). Since the reference grid that is normally used to indicate the position of findings inside the excavation is visible on the reconstructed 3D data, it was possible, by just picking some points in the model and on the total station data, to derive the scale factor needed for correct sizing and the roto-transformation needed for the global geo-referencing of the various 3D models.

5. Visualization and presentation

Even if the definition of an effective workflow for the use of dense reconstruction tools to generate 3D models of archeological excavation has a potential on its own, the most important part of this test is about the actual use of the gathered 3D data in the framework of the archaeological studies of this excavation.

The first direct use of a 3D model in studying an excavation is the extraction of measures. While a basic feature, like the "measuring tape" tool, can be used to take point-to-point measures on the 3D models, it would be interesting to be able to obtain more information from the acquired 3D models and, even more important, be able to work on more than a single time slot. Having all the time slots loaded at the same time, would make possible to take more complex measurements *across* the different layers. MeshLab already support layer visualization: it is then possible to load all the generated 3D models and work on the entire set of time steps, turning on and off the various layers. To make this time-wise exploration more intuitive, we developed an additional widget: a "time slider" which, using a simple slider component, can show the model of a specific time slot and quickly go back and forth in the excavation timeline.

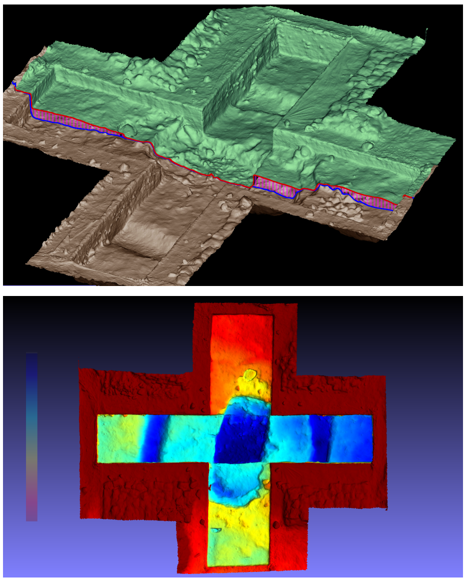

Figure 5: *Top: a snapshot of the slicing tool, showing the difference between two moments of the excavation. Bottom: color-coded depth. Everything above ground level (depth 0) is dark red, everything below the lowest explored layer (depth -1m) is dark blue.*

The possibility to use different rendering modes, advanced shaders, and being able to control lighting and rendering parameters is also essential for an effective visual inspection of the recovered geometry. Specific characteristics of the geometry or hard-to-see features may become much more apparent employing one of the different visualization modes available (see Figure 4). MeshLab provides a snapshot functionality, able to generate high resolution images of a given view and rendering mode. To cope with this kind of datasets, the snapshot functionality in MeshLab has been extended to give the possibility to generate an image for each layer, producing perfectly overlapping images of the evolution of the excavation (as visible in Figure 1). The possibility of instantly switch between canonical view positions (top, bottom, left, right, front, rear) and projection modes (perspective and orthographic), coupled with the snapshot feature, speeds up the creation of visual documentation of the site.

To have a better visual comparison of the evolution of the excavation it is possible to use a specific shader to slice in realtime one or more layers along a plane, showing the difference between models along pre-defined direction. Figure 5(top) shows the amount of excavation between two layers, clearly indicating the parts where most of the work was focused. Moreover, the possibility of generating cut-through sections and export them in a vector format (SVG) is another useful feature to produce accurate metric documentation, easily integrable inside a standard documentation workflow. Figure 5(bottom) shows an example of false coloring which gives information about the different depths of the excavation.

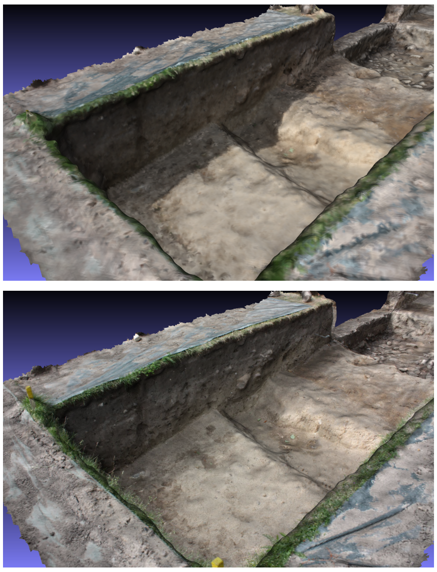

Figure 6: *A rendering of a model before (top) and after (bottom) image re-projection*

As already stated, another added value of using 3D models would be to integrate any other kind of material, like photos, sketches or annotations. The first improvement was to reuse the images already aligned to the 3D model (as shown in Figure 3) to improve the color information obtained from reconstruction. Essentially, color information was projected again on the 3D model using the approach proposed by Callieri [CCCS08]). Figure 6 shows a rendering of a model before and after color re-projection. It can be easily noted that a much more accurate color information was recovered, improving the realism of the navigation.

Using the image alignment feature, it is also possible to geo-reference to the 3D model(s) also images that has not been used for the reconstruction: like images taken during the excavations, sketches, drawings/surveys, or even historical photos. In this way, the 3D model would be used as a spatial index for such kind of material.

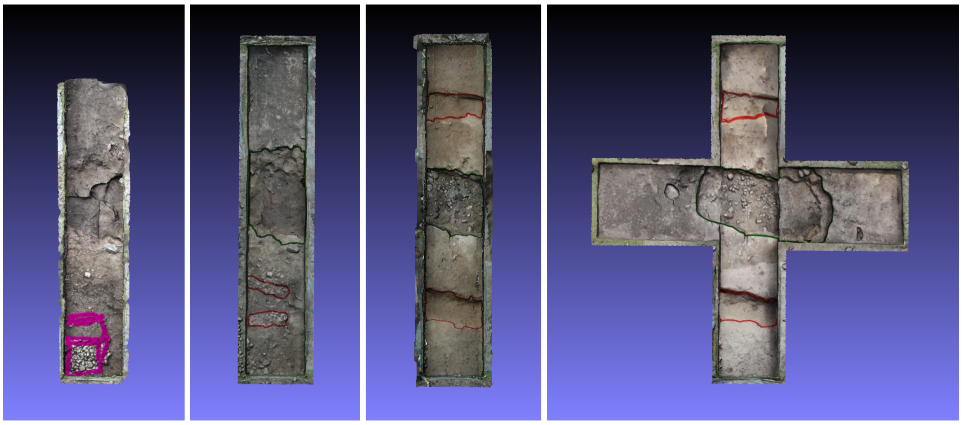

Figure 7: *Evolution of the annotated excavation*

While a true "annotation system" is still lacking in the current version of the MeshLab tool, at the moment the simple painting interface may be used by archaeologists to highlight important features, define areas of the excavation and plan possible interventions. This kind of direct study of the 3D model is detailed in the next section.

6. An experiment of archaeological interpretation

The use of this technique allowed to generate models to be used during the interpretation of the ongoing excavation. In particular, using MeshLab, it was possible for the archaeologists to analyze day by day all the investigation process, taking note directly on the 3D models, of the archaeological features discovered during the entire archaeological campaign. The possibility offered by simulating different light conditions, measuring the geometry in real time or exploring the site from an arbitrary point of view, exponentially increased the visibility of specific features, such as the shape of pits and their relation with the body of the central structure.
One of the most appreciated features by the archaeologists was having all the the time slots models geo-referenced and loaded at the same time, with the option of quickly switch between different time slots. This, not only made really easy to monitor the evolution of the excavation work, but also helped to annotate the interpretation of the excavation layers (Figure 8), since it was possible at any time to inspect the "before" and "after" state with respect to the working slot.

A very simple painting tools was used, where lines and areas of different colors were created on the 3D model to indicate important zones. This is a very simple example of annotation, but its use proved to be very intuitive. The archeologists were left free to interact with the model, and find the most straightforward way to get information from the data set.
One of the main advantages of handling a 3D model is the possibility to define an arbitrary point of view. The archaeologist worked almost all the time in a bird's eye fashion. This is the typical point of view which is used after producing plans of ortho-photos, which are produced after a processing effort on acquired data. Hence, the archeologist obtained the "classic" point of view in a few seconds, although additional experience could show that other points of view (usually not available with typical documentation) could provide even richer information. Figure 7 shows some of the annotations made by the archaeologists, following the evolution of the excavation. In the first image the purple zone indicates a group of stones, placed by humans but probably not directly connected to the grave. The availability of a 3D model will help in the interpretation of their origin and use, during the posterior analysis of acquired data. In the second image, the first interpretation of the grave mound border is shown in green, while its possible final shape is shown in the other two models, following the excavation evolution. In parallel, red lines show the discovery and unearthing of the hypothetic external limit of the grave.

Figure 8: *The archeological interpretation on the 3D model.*

6.1. Conclusions

This experiment demonstrated the possibility to document, in three dimensions and with a very low budget, an archaeological excavation during all the steps of the investigation process. This work highlighted how the use of 3D data to monitor and document an archaeological context radically increases the perception of the site and its evolution.

Dense stereo matching techniques were used to obtain a daily representation of the geometry of the excavation. The time needed for data acquisition and processing is quite short, making the use of these technique possible also directly on-site. The availability of a time-dense representation of the evolution of the excavation as a series of georeferenced 3D models, helps in the interpretation of the site. Moreover, the typical documentation material (notes, images, sketches, plants) can be easily integrated with the 3D models to enrich the analysis experience.

The 3D raw data has been generated using freely available tools and all the data processing and visualization has been managed inside an Open Source tool, a factor which may help the diffusion of such technologies.

The produced data were used to create standard documentation (measurements, orthographic views), and for a preliminary interpretation phase, where important features were indicated using a simple paint tool. The future improvements of the proposed approach include:

- The development of more advanced annotation tools, which could be used in a collaborative environment during the interpretation phase.
- An in-depth analysis of the accuracy and repeatability of the results of dense stereo matching techniques, together with the definition of precise guidelines for the acquisition and processing of data.
- The creation of new features for the integration and exploration of the typical documentation material with the three-dimensional data.

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References

[Agi] AGISOFT: Photoscan: an advanced image-based 3d modeling solution for creating professional quality 3d content from still images. More info on: http://www.agisoft.ru/products/photoscan/. 2

[Arc] ARC3D: A family of web tools for remote 3d reconstruction. More info on: http://www.arc3D.be. 2

[Bar05] BARKER P.: *Techniques of archaeological excavation / Philip Barker*. B. T. Batsford, London :, 2005. 3

[BL05] BROWN M., LOWE D. G.: Unsupervised 3d object recognition and reconstruction in unordered datasets. In *Proc. of .Int. Conf. on 3-D Digital Imaging and Modeling* (Washington, DC, USA, 2005), IEEE Computer Society, pp. 56–63. 2

[CCCS08] CALLIERI M., CIGNONI P., CORSINI M., SCOPIGNO R.: Masked photo blending: mapping dense photographic dataset on high-resolution 3d models. *Computer & Graphics 32*, 4 (Aug 2008), 464–473. for the online version: http://dx.doi.org/10.1016/j.cag.2008.05.004. 6

[FdBG11] FRATUS DE BALESTRINI E., GUERRA F.: New instruments for survey: On-line softwares for 3d recontruction from images. In *Proc. of 3DARCH11* (2011). 3

[FFG09] FARENZENA M., FUSIELLO A., GHERARDI R.: Structure-and-motion pipeline on a hierarchical cluster tree. *Proceedings of the IEEE International Workshop on 3-D Digital Imaging and Modeling* (2009). 2

[FP07] FURUKAWA Y., PONCE J.: Accurate, Dense, and Robust Multi-View Stereopsis. *Computer Vision and Pattern Recognition, 2007. CVPR '07. IEEE Conference on* (2007), 1–8. 3

[GRZ03] GRUEN A., REMONDINO F., ZHANG L.: Image-based Automated Reconstruction of the Great Buddha of Bamiyan, Afghanistan. *Comp. Vision and Pat. Rec. W. 1* (2003), 13. 3

[GSC*07] GOESELE M., SNAVELY N., CURLESS B., HOPPE H., SEITZ S. M.: Multi-view stereo for community photo collections. *ICCV 0* (2007), 1–8. 2

[HPA*10] HERMON S., PILIDES D., AMICO N., DŠANDREA A., IANNONE G., CHAMBERLAIN M.: Arc3d and 3d laser-scanning a comparison of two alternate technologies for 3d data acquisition. In *CAA* (2010), Melero F. J., (Ed.), p. (in press). 3

[HTP10] HAVLENA M., TORII A., PAJDLA T.: Efficient structure from motion by graph optimization. In *ECCV (2)* (2010), pp. 100–113. 2

[Lar07] LARSSON L.: The iron age ritual building at uppåkra, southern sweden. *Antiquity 81* (2007), 11–25. 3

[Mes] MESHLAB: an open source, portable, and extensible system for the processing and editing of unstructured 3D triangular meshes. More info on: http://meshlab.sourceforge.net/. 2, 5

[MP07] MARTINEC D., PAJDLA T.: Robust rotation and translation estimation in multiview reconstruction. *Computer Vision and Pattern Recognition, IEEE Computer Society Conference on 0* (2007), 1–8. 2

[Pho] PHOTOTOURISM: exploring photo collections in 3D. More info on: http://phototour.cs.washington.edu/. 3

[REHB*08] REMONDINO F., EL-HAKIM S., BALTSAVIAS E., PICARD M., GRAMMATIKOPOULOS L.: Image-based 3D modeling of the Erechteion, Acropolis of Athens. vol. 37 of *The international archives of the photogrammetry, remote sensing and spatial information sciences*, ISPRS, pp. 1083–1091. 3

[REMA09] RODRIGUEZ-ECHAVARRIA K., MORRIS D., ARNOLD D.: Web based presentation of semantically tagged 3d content for public sculptures and monuments in the uk. In *Proc. of the 14th Int. Conference on 3D Web Technology* (New York, NY, USA, 2009), Web3D '09, ACM, pp. 119–126. 3

[SFM] SFMTOOLKIT: a complete photogrammetry solution based on open-source software. More info on: http://www.visual-experiments.com/demos/sfmtoolkit/. 2, 4

[SSS06] SNAVELY N., SEITZ S. M., SZELISKI R.: Photo tourism: exploring photo collections in 3d. In *ACM SIGGRAPH 2006* (2006), ACM, pp. 835–846. 3

[VVG06] VERGAUWEN M., VAN GOOL L.: Web-based 3d reconstruction service. *Mach. Vis. Appl. 17* (2006), 411–426. 2, 3