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Fast and Detailed Digital Documentation of Archaeological Excavations and Heritage Artifacts

Abstract: Prompted by the increasing requirement for the fast but precise and detailed digital documentation of archaeological excavations and heritage artifacts, in this article we report our latest experience in capturing detailed 3D geometric information of two sites in Tuscany, Italy, using the image-based approach. We present a 3D recording workflow, based on multi-image matching, capable of retrieving quickly and precisely all the information needed to document, analyze and visualize excavation sites or archaeological monuments. The 3D modeling method is flexible and can be employed with convergent ground-based or oblique air-photo images, both critical configurations for commercial modeling software.

Introduction

Nowadays our cultural heritage is under constant threat and danger. Architectual structures and sites are threatened by pollution (air pollution, acid rain, birds, etc), tourists, wars as well as environmental disasters like earthquakes or floods or climatic changes. Hidden cultural heritage (under the earth's surface or those partially visible above ground as earthworks, industrial sites, etc.) are affected by agriculture (vineyards, olive cultivation, erosion processes), change of agricultural regimes due to economical change, mining, gravel extraction, contraction of infrastructures (roads, railways), industrial areas and those factors lead to its constant destruction. The available technologies and methodologies for digital recording of archaeological sites and objects are very promising and the whole heritage community is trying to adapt these approaches for fast, detailed and easy-to-use 3D documentations. Indeed 3D modelling could be extremely powerful in improving identification, monitoring, conservation and restoration. At the landscape scales digital 3D modeling and data analysis allow archaeologists to integrate, without breaks, different archeological features and physical context and to better document the area. At the monuments/sites scale, 3D can give accurate measurements and objective documentation as well as a different point of view. At the artifact scale, 3D modeling makes it possible to reproduce accurate digital/physical replica of every artifact that can be studied, measured, showed, and so on, as well as data for general public use, virtual restoration and conservation.

In archaeology, 3D models for documentation and conservation have recently begun to be used the systematically and correctly, but 3D is still only rarely applied in case studies for various reasons: (i) the high "cost" of 3D; (ii) the difficulties in achieving good 3D models; (iii) the consideration that it is an optional process of interpretation (an additional "aesthetic" factor); (iv) the difficulty of integrating 3D worlds with other 2D data and documentation; (v) the episodic use of 3D models for scientific analyses.

Nowadays the most common techniques used for 3D modeling are based on images (e.g. photogrammetry) and range data (e.g. active sensors like laser scanners). Both approaches have advantages and disadvantages and generally the choice is made according to the budget, project size, required detail, and objectives. Image-based methods (Remondino / El-Hakim 2006) are widely used for the 3D reconstruction of architectural objects (El-Hakim 2002) and for the precise modelling of terrain and cities (Gruen 2000) or monuments and statues (Visnovcova et al. 2001; Gruen et al. 2004). They use projective geometry when the primary goal is visualization or a perspective camera model for more detailed and accurate documentations. On the other hand, range-based methods (Beraldin et al. 2000; Blais 2004) are based on active sensors that directly capture geometric 3D information of an object using artificial laser light or projecting a pattern onto the object. These instruments recover the 3D information by applying different measurement principles like triangulation, time of flight or amplitude modulation. Their costs and problems of transportation, along with the time-consuming and complex nature of the related data management, often raise serious problems of practicality at some archaeological sites. In many applications, the combination of image- and range-based methods is also realized, in particular for the recording of large architectural objects or complex archaeological sites, where no technique by itself could efficiently and quickly provide a complete and detailed model (Beraldin et al. 2002; Voltolini et al. 2007; Lambers et al. 2007).

In this paper we want to give an overview of the image-based modeling method, describing in particular photogrammetry as an essential and important technique for the 3D documentation, reconstruction and interpretation process in the archaeological field. We present a newly developed multi-image matching algorithm and its performances using ground-based and oblique aerial images. We present fast but detailed and accurate 3D documentations of an excavation site and a heritage area in Tuscany, Italy.

Image-based Approach in Terrestrial Applications

Compared to other recording and modeling methods, images can be acquired with inexpensive and very portable systems and contain all the information for the generation of a textured 3D model. But deriving a complete, detailed, accurate and realistic 3D image-based model is still a difficult task, in particular for large or complex objects, if the images are acquired by non-experts or if uncalibrated or widely separated images are used. According to the project requirements, automated, semi-automated or manual image-based approaches should be employed to produce digital models usable for inspections, visualization or documentation. 3D image-based modeling methods can be classified according to the level of automation or the required input data while their strength is reflected by the variety of scene that can be processed and the level of detail that can be reconstructed. The entire photogrammetric workflow used to derive metric and reliable information of a scene from a set of images consists of (i) calibration and orientation, (ii) 3D measurements e.g. via image matching, (iii) structuring and modeling, (iv) texture mapping and visualization.

For many years photogrammetry has dealt with the precise 3D reconstruction of objects from images. Even if it is often considered as time-consuming and complicated, the heritage community is starting to consider it for digital documentation also at terrestrial scale as a very promising alternative to range sensors, traditionally used as easy and efficient instruments, even if not always portable and usable. Photogrammetry requires precise calibration and orientation procedures, but different commercial packages are nowadays available. In the terrestrial case, those packages are all based on manual or semi-automated measurements. They allow, after a (manual) tie point measurement and bundle adjustment phase, the user to obtain sensor calibration and orientation data, 3D object point coordinates from a multi-image network, as well as wireframe or textured 3D models. Fully automated 3D modeling procedures have been also widely reported in the vision research community (Pollefeys et al. 2004), even if they generally produce results which are mainly good for simple real-time 3D recording, quick visualization and VR applications. The key to the success of these fully automated approaches is the very short interval between consecutive images, the absence of illumination or scale changes and the good texture in the images. These are all constraints that cannot always be satisfied during the image acquisition, in particular the small baseline. Moreover illumination changes can always appear in a sequence as well as image-scale differences. To face the wide baseline and the image-scale problems, different strategies have been proposed (Lowe 2004; Mikoljczyk et al. 2005), although further research in this area is still needed. Indeed their reliability and applicability for automated image-based modeling of complex objects is still not satisfactory, as they yield mainly a sparse set of matched feature points. Automated dense reconstruction has been presented as an alternative (Strecha et al. 2003; Megyesi / Chetverikov 2004), but no accuracy tests were reported.

In some applications, manual measurements are also performed, generally for complex architectural objects or in cultural heritage documentations where highly precise and detailed results are required (Gruen et al. 2004). Manual measurements are time consuming and provide for less dense 3D point clouds, but have a higher reliability compared to automated procedures. Therefore, the modeling steps are generally separated, having automation where possible and interaction where reliability and precision are necessary.

Afterwards, the surface measurement approach developed at ETH Zurich to derive dense and detailed 3D surface model from oriented images is presented. It is based on the precise least squares measurement method (Gruen 1985) and is able to employ multiple images (>2) at the same time.

Dense, Accurate and Detailed 3D Modeling

For a precise documentation and 3D modeling of sites or objects, images should be acquired under certain acquisition rules and with a calibrated camera (or else calibrated afterwards in the lab at the same settings used on the field). After the image orientation phase to recover the camera poses, the surface measurement step can start to extract (dense) 3D point clouds of the investigated area. This phase is generally performed using manual procedures if an architectural or very complex object is surveyed. Indeed, the former needs only few points to recover the 3D geometry by means of lines and planar surface, the latter needs user interaction and recognition to derive correct details and 3D results.

On the other hand, for landscape, excavation areas and most of the heritage objects, automated procedures can be employed for a reliable generation of a dense digital surface model. With this purpose, we have developed a procedure able to derive detailed and accurate surface models from any kind of set of images. It is a multi-image matching procedure, originally developed for the processing of the very high-resolution TLS Linear Array images (Gruen / Zhang 2003) and afterwards modified to accommodate any linear array sensor (Zhang / Gruen 2004; Zhang 2005). The matcher has then been extended to process other image data such as the traditional aerial photos or convergent close-range images (Remondino / Zhang 2006; Lambers et al. 2007). It is based on the Multi-Photo Geometrically Constrained (MPGC) matching concept (Gruen / Baltsavias 1986) and the Least Squares B-Spline Snakes (LSB-Snakes) method (Gruen / Li 1996). After image pre-processing for noise reduction and radiometric optimization, different levels of image-pyramids are generated. The matching then combines an edge matching method with a (feature and interest) point matching method through a probability relaxation-based relational matching process. Feature points are suitable to generate dense and accurate surface models but they suffer from problems caused by image noise, occlusions and discontinuities. Edges generate coarser but more stable models as they have higher semantic information and are more tolerant to image noise. The combination of both leads to very successful results. The approach does not aim at pure image-to-image matching but it directly seeks for image-to-object correspondences. A point is matched simultaneously in all the images where it is visible and, exploiting the collinearity constraint, the 3D coordinates are directly computed, together with their accuracy values. Exploiting the multi-image concept, highly redundant matching results are obtained, compared to classical stereo approaches. The high redundancy also allows automatic blunder detection. Mismatches can be detected and deleted through the analysis and consistency checking within a small neighbourhood. Apart from the known camera parameters, the matcher requires some seed points between the images to start the automated matching procedure. These points can be measured manually in mono or stereo-view as well as imported from the orientation phase. The accuracy of the method has been demonstrated in different studies (El-Hakim et al. in press; Rizzi et al. in press) showing how the matcher is able to retrieve 3D results very similar to range sensors.

In the following, our experiences with archaeological excavation areas and objects are reported and commented.

Examples

Our first case study focuses on the excavation of a late antiquity / early medieval church at Pava in the province of Siena, Italy *(Fig. 1)*.

The site has been identified through the integration of archaeological / geophysical fieldwork (Campana / Francovich 2006) and documents relating to a dispute between the bishops of Siena and Arezzo in 714–715 AD which indicate the existence of the parish church of "San Pietro in Pava" (Schiaparelli 1929). The exegesis of the documents allows us to surmise the earlier existence of a cult shrine building. We also know that San Pietro in Pava stood close to the River Asso, in the locality named in the Extent of 1320 as "Pieve Vecchia", not far from the present-day Pieve a Pava. The building is again attested in 1029, though by this time it was probably reduced to a ruin, abandoned and replaced by the nearby sister church of Santa Maria in Pava, which in 1045 appears in the documents under the title of "pieve". However, other documents record that

Fig. 1. The excavation area of Pava (40 x 30 m) near Siena (Italy) from the original inspection through the first excavations to the actual situation. The aerial images have been acquired for simple documentation without any planning for 3D modeling. A zoom 1:1 of the details is also presented.

it was still the responsibility in 1320 of the rector "Ser Finus presbiter plebis Pievevecchia". Nowadays, the excavated area measures approximately 40 x 30 m. A very big parish church (33 x 10 m) was found, characterized by a peculiar plan, double apse, the first one on the east and the second one on the west part of the church (Campana et al. 2006). During a documentation flight with a light aircraft (Cessna 172), a set of oblique air photographs were acquired, using a Canon EOS 20D consumer grade digital camera (8 Mega pixel, 6.4 micron pixel size). As the image acquisition was not done with the final goal of modeling in 3D the excavation site, different focal settings were used, mainly 47 mm, 53 mm, 60 mm and 135 mm. This in fact generated a nice set of documentation images around the site, but all with different camera interior parameters, conditions not really favourable for easy and precise modeling. Nevertheless, we were able to orient a group of 5 images (average footprint ca. 2 cm) and apply our

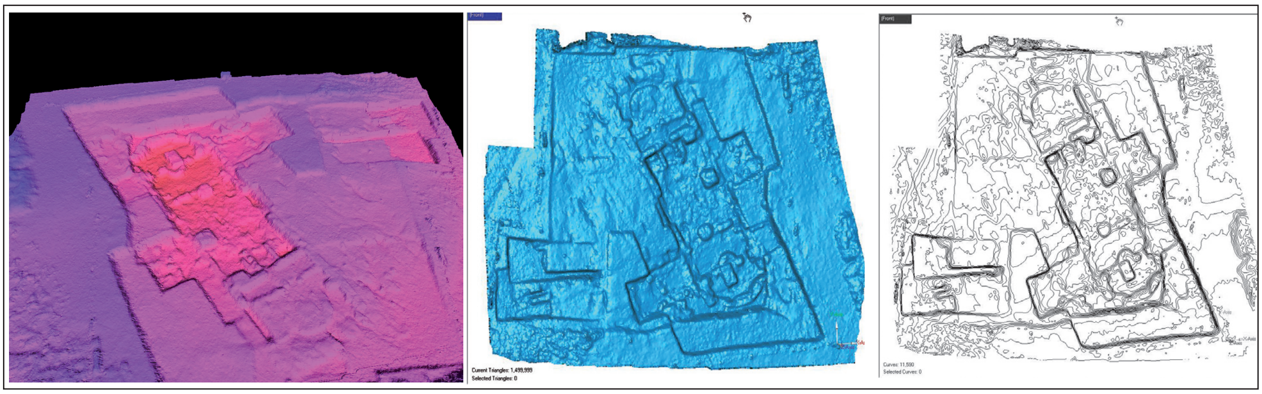

Fig. 2. DSM of the excavation site derived using amateur oblique aerial images visualized as colour- and shaded mode. The generated contours have an interval of 5 cm.

Fig. 3. S. Silvestro rock near Piombino (Italy) and the detailed 3D modeling of its rock walls, simply from 3 convergent images acquired with a consumer grade digital camera with 6 Mega pixels.

matcher to produce a dense digital surface model (DSM) of the excavation. Approximately 5 million points were obtained in around 3 hours of work. Afterwards, they were meshed, and contours were then derived *(Fig. 2)*.

The second study relates to a masonry castle on the coast near Piombino (Italy), excavated by the University of Siena in the 1980s. Here, we generated a 3D model of the defensive walls and some of the buildings in the interior using ground-based photographs. As it is possible to see in *Fig. 3*, it is quite hard to get close to the monument because of the steep and rocky morphology of the site. Here the goal was to test whether images could be the best solution documenting some details of the archaeological site. In particular, a part of the wall of the castle and the interior of an old church were selected. We generated a 3D model of the defensive walls using three images acquired with a simple, portable and very cheap digital camera. The derived DSM *(Fig. 3)* is quite detailed and the single elements of the wall are well recognizable.

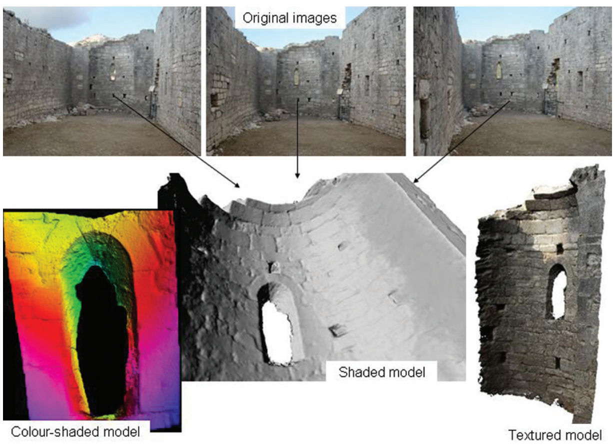

Fig. 4. The interior of a church, modelled using three convergent images.

Furthermore we modeled the apse of the church, deriving once again in this case a reasonably detailed DSM *(Fig. 4)*. In this case, the church walls could be easily modeled using few points and geometric entities. Nevertheless a dense surface model could be very useful to study the stratigraphic pattern of the wall, architectonic details, to produce restoration plans, etc.

Considerations, Conclusions and Outlook

The balance of the last decades of archaeological research concerning the use of 3D digital documentation/representation in scientific investigation is quite disappointing if we think of the possibilities offered by newly developed software and hardware. The use of 3D images was typically oriented to suggest final reconstructions and not to contribute to scientific interpretation. On the contrary 3D should constitute a bridge between knowledge and communication. It is remarkable to say that archaeological excavations using 3D technologies in the phases of acquisition and reconstruction are still only few in number. Therefore the documentation process is fragmented in many different ontologies, where the 3D information is often missing. The following key points summarize benefits and properties of the 3D digital world in archaeology:

- Interaction: a 3D model involves a high degree of interaction.
- Difference: the representation in 3D produces more difference in a cybernetic sense; interacting with 3D data we develop a major exchange of information.
- Spatial relationships: 3D spatial features visualize, model and develop relations generally not

identifiable in 2D space. 3D interaction stimulates our cognitive system to adapt and follow the spatial coordinates of reference, in scale and size.
- Light: 3D interaction and movement involves changes of the light and shadow conditions of the reconstructed model so that a better perception is achieved.
- Geometry: the more complex the geometry on an object is, the greater our capacity for analysis.
- Transparency: the reconstructive processing of information can be validated and shown by a sequence of 3D spatial maps in overlay or different representations.
- Multimodality: 3D information allows a multi-modal and multi-sensorial interaction with the 3D model.
- Connectivity: each piece of 3D spatial information multiplies in a conceptual network of links to its communication model.
- Preservation: 3D digital data is useful for site / object documentation and storage in case of loss or destruction.
- Fruition: a 3D model can be exchanged between users or used in a virtual museum for people who cannot visit the real site.

We have demonstrated how accurate and detailed 3D results can be easily derived using simple digital cameras. Of course active sensors allow a relativly rapid acquisition of a large quantity of 3D information but we must point out that the costs of the equipment and the problems of transportation, along with the complexity of the related data management, raise serious problems of practicality in many archaeological missions. Therefore, as an alternative, we argue that images acquired with low-cost digital cameras (or even mobile phones), by non-specialist research workers, can be used to create realistic 3D models, with good geometric detail by applying appropriate image-processing algorithms.

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