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03 | 3D DATA ACQUISITION AND PROCESSING

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Optical 3D Measurement Techniques in Archaeology: Recent Developments and Applications

Abstract: This paper is intended to give an overview on current surveying techniques that use remotely sensed data, and their applications in archaeology. The focus is on optical 3D measurement techniques based on image and range sensors. Data and methods are briefly reviewed, whereas data processing and related problems are only touched on in passing. For the purpose of this review we distinguish three scales of archaeological research at which the surveying techniques discussed here can be applied: (1) the regional scale, to record the topography of archaeological landscapes and to detect and map archaeological features, (2) the local scale, to record smaller sites and their architecture and excavated features, and (3) the object scale, to record artefacts and excavated finds.

Introduction

On many occasions during archaeological research, the archaeologist is confronted with the task of recording what he or she is investigating, since thorough documentation is a prerequisite for any analysis and interpretation. Among the geomatic methods currently available to address this fundamental part of archaeological research, optical 3D measurements based on digital data are a versatile tool as they have a number of advantages:

- they can be applied at a wide variety of scales;
- contactless data acquisition prevents damage of archaeological objects;
- archaeological fieldwork can proceed while data processing and analysis is still under way;
- an ever increasing variety of sensors, data, products, and processing and analysis tools have become available in recent years.

There are basically three categories of optical 3D data acquisition: (1) image-based methods, e.g. photogrammetry (Remondino / El-Hakim 2006), (2) range-based methods, e.g. laser scanning (Boehler 2002), and (3) combinations of both (El-Hakim et al. 2004). The choice of the most appropriate technology for a given task depends on the object or area under investigation, the experience of the user, the available budget and time, and further parameters. In the following sections, current trends and developments in optical and related measurement techniques are reviewed with particular regard to their application in archaeological research at the regional, local and object scale. This overview, while necessarily incomplete due to space limitations, will hopefully give potential users an understanding as to which data and techniques might be suitable for their own project.

Archaeological Research at the Regional Scale

The necessity of investigating archaeological sites in a larger context requires work at a regional scale. While excavations tend to focus on important sites and their graves, architecture or artefacts, these remains can only be understood in their cultural, socio-economic and environmental framework. This requires a thorough study of the site's hinterland including its network of other sites with domestic, religious, economic, and other functions, as well as its topography, natural resources, and paleoclimatic conditions. Moreover, ancient landscapes are study

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objects in their own right, as they were imbued with cultural meaning that changed through time. The landscape always shaped, and was shaped by the cultural development for which it provided a spatial framework.

There are thus two tasks for optical 3D and related measurement techniques in regional archaeological research: (1) the recording and modelling of the topography and (2) the detection and mapping of archaeological sites and features. Spaceborne and airborne sensors provide suitable data for these tasks.

The generation of Digital Elevation Models (DEMs) is a key element of topographic mapping. Spaceborne sensors are a valuable data source for regional DEMs. A DEM with a resolution of 90 m has recently become available nearly worldwide through NASA's Shuttle Radar Topography Mission (SRTM) undertaken in 2000, during which 80% of the Earth's surface was measured by Synthetic Aperture Radar (SAR) interferometry. This is a valuable source of terrain data especially in remote areas where no digital elevation data is available from other sources, even if gaps and the rather low resolution limit the DEM's suitability especially in mountainous areas. Nevertheless, SRTM data has been successfully used to detect and map large-scale archaeological features such as ancient tells and dams in the Near East (Hritz/Wilkinson 2006; Menze/Ur/Sherratt 2006). Other spaceborne radar sensors that allow DEM generation at a higher spatial resolution (such as RADARSAT, ERS, and ASAR) have been applied under less favourable conditions to detect and map archaeological ruins under forest canopies, such as in the Maya lowlands (Lira / López / Rodriguez 2005; Weller 2006; Oštir / Kokalj / Šprajc 2006). However, spaceborne radar data is most beneficially used for archaeological studies when combined with data from other sources.

A straightforward and affordable alternative for DEM generation is provided by low and middle resolution satellite imagery (ASTER, LANDSAT, SPOT series, etc). In particular, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an optical sensor with 14 multispectral channels, out of which band 3N and 3B provide along-track stereo coverage in the near-infrared spectral range at a horizontal resolution of ca. 15 m. The spatial resolution of ASTER DEMs is usually sufficient for regional archaeological investigations even in mountainous areas, while the accuracy depends on the availability of ground control data. Just like SRTM, ASTER data has been used to detect archaeological sites (Altaweel 2005), but due to its limited spatial resolution this is not its primary use. High resolution satellite imagery, on the other hand, is better suited to archaeological research at the local scale (see section "Archaeological Research at the Local Scale").

Turning to airborne sensors, analogue frame cameras are still a valuable source of imagery for DEM generation, in particular for the mapping and documentation of damaged sites using archive data (Sauerbier et al. 2004). Analogue sensors are partly being replaced by digital frame cameras such as Vexcel's UltraCam and Z/I Imaging's DMC, or by linear array CCD sensors such as Leica's ADS40 or DLR's HRSC-AX (Lillesand / Kiefer / Chipmann 2004). The latter type of sensor represents an alternative concept of image acquisition in which the terrain is simultaneously scanned from different viewing angles through a single lens, thus providing continuous along-track stereo coverage suitable for photogrammetric 3D analysis (Pateraki / Baltsavias / Recke 2004). These new airborne digital sensors cover not only the visible, but also parts of the infrared spectral range. The resulting multispectral imagery is suitable for digital image analysis as described in the following section, but at a resolution in the centimetre range. The potential of these sensors for archaeological prospecting is self-evident. However, archaeological applications have so far focussed mainly on multi- and hyperspectral imagery provided by airborne sensors such as MIVIS, CASI, ATM and AHS that have a higher spectral, but lower spatial resolution (Traviglia 2005; Rowlands / Sarris 2007; Winterbottom / Dawson 2005; Rejas et al. 2006).

Finally, ALS (Airborne Laser Scanning) or LiDAR (Light induced Detection And Ranging) (Lemmens 2007) has recently proven to be a real breakthrough for archaeological research. This technique currently complements aerial imagery as the primary data source for topographic mapping. Measurements with a ground sampling distance of 1m or less are routinely undertaken, from which high resolution DEMs are then derived. Archaeologists have been quick to realise the potential of high resolution terrain data for the detection of near-surface archaeological residues (Challis 2006; Crutchley 2006; Bofinger / Kurz / Schmidt 2006). Case studies in archaeologically well documented areas revealed that ancient walls and ditches, described many decades ago but then thought lost due to heavy ploughing, were still clearly visible in the LiDAR DEM as subtle alterations in terrain elevation (Bewley / Crutchley / Shell 2005). Importantly, the ability of the LiDAR sensor to record several signals of the reflected laser pulse enables terrain surface to be recorded under forest canopies (Devereux et al. 2005; Doneus / Briese 2006; Sittler / Schellberg 2006), which allows the generation of digital terrain models (DTMs) as opposed to digital surface models (DSMs). This makes LiDAR a valuable source of 3D information when detecting archaeological residues in forested areas where other prospection methods largely fail.

Archaeological Research at the Local Scale

The site is the principal unit of archaeological investigation at the local scale. Regardless of its actual size, function, and duration of occupation, the material remains of activity at a defined location hold important clues about the social, cultural, technological and ideological background of the ancient inhabitants. A thorough record of the material remains of sites is the basic requirement for archaeological research at the local scale.

In many regions, archaeological sites are marked by ruined architectural remains that are visible on the surface such as earthworks, terraces and ditches. These features define the location and, even if roughly, the extent of the site. Many other archaeological sites are partially or completely covered by natural (erosion, sedimentation) or man-made processes (continued use of the site). While the recording of remains visible on the surface is an important task for optical measurement techniques in the former case, excavation is usually required in the latter. Features to be documented thus include architectural elements as well as excavation layers. Suitable optical sensors for the 3D recording of the above features may be mounted on spaceborne, airborne or terrestrial platforms and provide either image or range data. Furthermore, the topography of the site often needs to be recorded at a higher temporal and spatial resolution than at the regional scale.

The latter can be achieved using satellite imagery with a spatial resolution of 5 m and better, enabling the generation of local high resolution DEMs. Most of the available sensors (e.g. SPOT 5, Cartosat 1, Eros A/B, Ikonos 2, Orbview 3, Quickbird 2) provide stereo coverage (Lillesand / Kiefer / Chipmann 2004; Lemmens 2006) and multispectral data (Campana 2003). Despite their high potential for accurate stereoscopic DEM generation (Baltsavias et al. 2006), they have so far rarely been used for this purpose in archaeological applications due to the high cost involved. With satellites launched by public space agencies entering the high resolution domain (e.g. ALOS-PRISM, FormoSat 2, Kompsat 2) the cost will probably decrease, and their use will become more and more common. As its resolution begins to rival aerial images, the imagery from these satellites has increasing potential to detect archaeological residues. Visual inspection of high resolution imagery in order to identify archaeological remains (Lipo / Hunt 2005), through crop marks or other features, perpetuates traditional but highly effective methods of aerial archaeology (Bewley 2003). A qualitative step forward in this regard is the application of proven methods of image analysis and classification (Lillesand / Kiefer / Chipmann 2004; Richards / Jia 2006) to detect either visible remains, such as walls and terraces, or subsurface residues that cause changes in the vegetation cover (Beck et al. 2007; De Laet / Paulissen / Waelkens 2007; Lasaponara / Masini 2007; Saturno et al. 2007).

High resolution satellite imagery, airborne frame or linear array imagery, and airborne LiDAR as previously mentioned are potential data sources to map architectural remains visible on the surface of a given site. Especially airborne sensors provide data at a resolution suitable for recording archaeological surface features and the surrounding terrain in 3D (Holden / Horne / Bewley 2002; Lambers 2006). However, the vertical perspective basically allows ground plans to be mapped, provided that conditions are favourable, whereas the recording of upright surfaces requires platforms that operate closer to, or on the ground and are thus able to provide image or range data from a tilted or horizontal perspective.

Aerial photogrammetry from platforms flying at low altitude, such as balloons, has been used in archaeology for a long time. Recent innovations include low-cost digital cameras (Kemper et al. 2004) and the tilting and rotation of the camera via remote control (Martínez et al. 2005). Compared to balloons, Unmanned Aerial Vehicles (UAV) such as remotely controlled model helicopters are much better manoeuvrable and thus enable more flexible and reliable image acquisition. GPS/INS-based navigation allows flight paths and image acquisition locations to be defined prior to the flight, while the actual flight requires only minimal interaction

(Lambers et al. 2007). Such systems allow a precise photogrammetric recording of the topography and, to a limited degree, architecture. UAVs hold a great potential for the recording of complex archaeological sites and may partially account for the problem of occlusions resulting from a terrestrial recording, as described next.

Medium to long range Terrestrial Laser Scanners (TLS) usually measure distances by the time of flight (ToF) of the reflected laser beam or by the amplitude modulation principle (Boehler 2006). In contrast to airborne LiDAR, TLS sensors are stationary during measurements, requiring frequent repositioning to completely cover a complex surface. In spite of the still considerable cost and processing time involved, TLS have been frequently used in cultural heritage applications, mainly when architecture or preserved pieces of art, such as reliefs or statues, were involved, but also to document exposed surfaces of occupation layers in stratigraphic excavations (Doneus / Neubauer 2006). A review of the numerous reports on recent TLS applications shows that archaeology has been quick to adapt new technical developments like marker-less or image-based registration of ToF laser point clouds (Bendels et al. 2004; Aguilera / Lahoz 2006; Haala / Alshawabkeh 2006). However, due to the highly complex surfaces of archaeological features, occlusions, and incomplete modelling resulting from them, often cause problems in archaeological TLS applications.

Terrestrial image-based 3D recording has become much easier to use for the non-professional in recent years thanks to the availability of suitable consumer cameras, low-cost software, and a fully digital workflow. While special hardware is no longer required, and image acquisition and analysis is rather straightforward, photogrammetric recording still requires some experience, a careful acquisition of images, calibration procedures and control points (if georeferencing is required). If used correctly, photogrammetry is a powerful tool, as successfully demonstrated by many recent applications to document architectural remains, rock art, and excavation layers of archaeological sites (Tack et al. 2005; Fryer / Chandler / El-Hakim 2006; Chandler / Bryan / Fryer 2007).

As both TLS and images have advantages and disadvantages, the choice is generally based on the project´s budget, objectives, and the required level of detail. In some projects, different techniques (high and low resolution satellite imagery, laser scanning, terrestrial images, and total stations) have been combined to take advantage of the inherent strengths of each approach (Kadobayashi et al. 2004; Gruen / Remondino / Zhang 2005; Bitelli et al. 2007).

Archaeological Research at the Object Scale

Artefacts recovered during excavations or stored in museum deposits are the material expression of cultural, socioeconomic, and technological concepts shared by their creators. Thorough documenting of stone or metal tools, worked bones, ceramic vessels, sculptures, and other pieces of ancient craftsmanship is not only a prerequisite for typological and chronological studies, but also for investigations into the exchange of goods and ideas, iconography, technology, and a variety of other topics. While artefacts are until now usually recorded in 2D through drawings and photographs, 3D recording literally adds a new dimension to archaeological studies at the object scale by providing additional information that enables new kinds of investigation, such as morphological comparisons, 3D fragment fitting, and so on. Furthermore, virtual replicas of artefacts enable web-based exhibition and facilitate the production of physical replicas, thus helping to preserve the original artefacts.

Digital 3D documentation and virtual reconstruction of artefacts is usually performed with active sensors or images. The former approach employs sensors which actively record the shape and geometry of the surveyed object using the triangulation measurement principle. Compared to the time delay principle, triangulation-based sensors are limited to smaller working volumes (0.5–500 cm) but can achieve accuracies in the order of 30–50 μm. This mainly includes laser scanners (Salvadori 2002; Kampel / Mara / Sablatnig 2006) or stripe-projection systems (Sansoni / Docchio 2005; Akca et al. 2006).

On the other hand, images are cheaper and contain all required information to produce geometric 3D models including texture. For simple and quick visualisation, the classic computer vision approach called ‘Shape-from-motion’, ‘Video-to-3D’, or ‘Shape-from-Video’ can be employed (Pollefeyes et al. 2004). The key to success of these fully automated approaches is a very short interval between consecutive images, the absence of illumination change, and good texture in the images. Among the available tools capable of performing automated reconstructions from a generic set of images, worth mentioning is one developed by TU Leuven, Belgium (http://homes.esat.kuleuven.be/~visit3d/webservice/html/) which allows, under favourable conditions, cultural heritage professionals to reconstruct 3D models by uploading images of scenes or objects to a webserver. Nevertheless, when the modelling task demands precise, reliable, and detailed results, semi-automated or manual measurements must be performed (Gruen / Remondino / Zhang 2004; Remondino / Zhang 2006). At the object scale it is difficult to decide which approach yields better accuracy, whereas in terms of acquisition, straightforwardness and processing, active sensors are generally preferred by non-experts (Boehler 2002).

Discussion

In this brief contribution we have tried to demonstrate that optical 3D and related measurement techniques already play an important role at all scales of archaeological research, but their full potential has yet to be recognised and exploited by archaeologists and the wider cultural heritage community. The quantity and quality of available new digital sensors, data and tools for processing and analysis has increased dramatically in recent years. While cutting edge technology is expensive, many of the data acquisition methods reviewed here are already within the reach of archaeological research projects. Beside budget constraints, the principal limiting factor for the use of the technologies discussed here seems to be the notion that the added value of a digital 3D documentation might not outweigh the often considerable time and training efforts that inexperienced users have to invest before achieving the desired results. A case in point is the limited application of image-based recording of archaeological excavations in spite of the availability of a wide range of low-cost and user friendly tools for data acquisition, processing and analysis. A closer cooperation between archaeologists and technical experts is clearly required to allow for a faster and more precise documentation that yields better results.

At all scales discussed here, we have at our disposal a wide variety of technologies and methodologies for data acquisition, ranging from off-the-shelf digital cameras to expensive active sensors and from satellites to LiDAR. When comparing photogrammetry and active sensors, the former is generally well suited to capture edges and textures, whereas the latter is usually better suited to capture surfaces. Both techniques have been successfully combined in a variety of applications, making the most of the inherent strengths of both approaches. Nevertheless, recent developments in image matching have demonstrated the potential of photogrammetry to derive, with very little interaction and quite good accuracy, all the fine details of an object with geometric results from a relatively small number of images very similar to active sensors. Therefore, we can safely say that with the appropriate surface modeller algorithm, there are no differences between image-based and range-based approaches, and the aspect of accuracy and detail of the final 3D model is no longer decisive in the choice of the modelling and documentation technique, at least in most applications at the local and object scale. Visually appealing 3D models (such as those derived by 'structure-from-motion' approaches) are of limited interest for precise and detailed heritage documentation, but mainly usable in quick visualisation applications. Therefore the documentation and modelling technique should also be selected considering the other variables of a project, e.g. budget, location constraints, time needed for the acquisition, final goal of the model, objectives, and so on, in order to achieve satisfying results that provide an added value for archaeological research.

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