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DIGITAL SURFACE DEVELOPMENT OF LARGE CYLINDRICAL AND CONICAL STRUCTURES WITH A SINGLE-IMAGE TECHNIQUE

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Abstract

Normally, regular surfaces of architectural or archaeological interest can be accurately mapped with single-image techniques. Whenever possible, such surfaces are developed digitally, or they are presented as suitable cartographic projections. This paper describes the raster development of two large towers, one conical and one cylindrical, with heights of 19 m and 12 m, and diameters of approximately 10 m and 8 m, respectively. The towers, dating from circa 300 BC, are situated on Greek islands and are accessible only on foot. The first tower was imaged from its surrounding hills with several lenses, including powerful telephoto lenses. The other tower was recorded from up to 9 m above ground level by means of a modified fishing rod carrying a lightweight 35 mm camera. All the non-metric photographs, taken at a negative scale of approximately 1:350 which allowed an overall accuracy of 3 cm to 4 cm to be achieved, were developed digitally and then mosaicked. The raster products are described and discussed.

KEYWORDS: architectural photogrammetry, cylindrical and conical structures, digital photogrammetry, non-metric cameras, single-image techniques, surface development

INTRODUCTION

DUE TO the potential of digital techniques, close range photogrammetry has become more efficient and inexpensive, especially with regard to the documentation of cultural heritage. Among the novel possibilities now available, images obtained with non-metric cameras for the production of high quality raster products, using PCs, are of particular value. Geometrically transformed and mosaicked digital images can be produced in both static and visually animated forms. In contrast to line drawings, such approaches reproduce the pictorial wealth of the original images. Due to its simplicity, digital rectification remains a very popular photogrammetric tool for archaeological and architectural documentation. Unfortunately, not every object satisfies the requisite tolerances of planarity. The existence of considerable surface relief, it is often said, calls for stereo configurations. However, once stereoviewing is introduced, more involved techniques and additional instrumentation are required.

It is possible to avoid such complications by using purely monoscopic techniques when confronted with objects which fall into two categories. The first category covers objects which consist of planar surfaces defined by straight edges. Single perspective images can be handled successfully in these cases and can even be presented in impressive three dimensional (3D) displays, as demonstrated on several web sites (TG2, 2000). The second category, which forms the topic of this paper, represents smooth surfaces which may be approximated analytically by quadric solids, partly or fully encompassing their shape. Structures with such cylindrical, conical, spherical, parabolic or ellipsoidal surfaces which are often encountered in close range applications include ancient theatres and tombs, churches and monasteries, towers, mills, lighthouses, aqueducts, factories and chimneys, and rotundas, domes, cupolas, vaults and ceilings. This list can be further enlarged with various industrial objects. The fundamental concept for single-image mapping is that the analytical expression of the surface represents a third equation which can be "intersected" by the projective bundle of *one* image (expressed by two collinearity equations for each ray) to provide the space coordinates of the surface points measured on this image.

While not unimpressed by the merits of 3D visualisations, users (such as architects, archaeologists and conservationists) generally demand mapping for measurement purposes. In this context, they do not find conventional orthogonal projections of curved surfaces to be helpful. As final products, these users normally require that developable surfaces, such as cones or cylinders, are developed ("unfolded" or "unwrapped") onto a plane and that non-developable ones, such as spheres, are presented in a suitable cartographic projection ("flattened"). Questions of developing or projecting mathematically expressed surfaces have been successfully addressed in the past, as fully documented by Theodoropoulou (2000a). Earlier answers relied, in principle, on advanced photogrammetric instrumentation, such as digitally controlled differential rectifiers or analytical plotters, producing vector data or analogue photographic results. In the current digital era it is completely feasible to rely on suitable PC-based techniques for generating non-conventional photogrammetric products of high quality at low cost. These methods include both vector developments, produced by "monoplotting", as well as entirely raster developments (Karras et al., 1996; Hemmleb and Wiedemann, 1997). On the other hand, colour cartographic projections of Byzantine wall iconography on spherical surfaces have been presented by Karras et al. (1997) as examples of a treatment for more "demanding" curvatures. Such results have been welcomed by users as being the only practical means available for representing regularly curved surfaces (for which conventional orthoprojection is clearly not acceptable). In this paper, the subject of developable surfaces is examined.

SURFACE DEVELOPMENT

Surface Fitting

Best-fitting analytical expressions of quadrics in a given space coordinate system are usually determined by fitting to redundant points measured geodetically (or photogrammetrically, although this would run counter to the single-image character of the approach discussed). A distinction needs to be made here between instances where the surface type is obvious and instances where the surface type cannot be unquestionably assumed in advance. In the latter case, the full second order equation of nine independent unknown parameters is fitted to the 3D point set. These coefficients incorporate the three parameters of the canonical form, defining shape (surface type) and size, and the six elements of a rigid body transformation, fixing surface position and orientation within the coordinate system. Theodoropoulou (2000b) discusses the basic aspects of treating the resulting equations and the use of surface invariants to classify quadrics (see also Restlé and Stephani, 1988). With the surface type known, its specific equation can subsequently be used.

On the other hand, assumption of a specific surface type allows the corresponding equation to be directly employed. In this case, the focus is on conical and cylindrical surfaces (for the latter, see also Chandler and Cooper, 1991; Robson et al., 1992). In doubtful cases, the pertinent equations are used in their general forms. Five parameters (four to fix the axis in space and one to fix the radius) are required for a circular cylinder, reducing to three (those of a circle on a horizontal plane) if its axis is assumed to be vertical. The circular cone needs six parameters (four to fix the axis in space, one to fix the vertex on it and one to fix the cone angle), two of which are redundant if the axis is constrained as vertical. Finally, the fitting process also yields the deviations of sampled points from the mathematical surface. According to the prepared algorithm, these may be either in the form of residuals in the X, Y, Z directions or normal to the surface, as adopted in this paper.

Mapping of Developable Surfaces

If line drawings are required, space intersection of each projective ray (defined through the elements of interior and exterior orientations) with the surface produces the 3D coordinates of the digitised image point. Obviously, intersection of a second order solid with a ray yields more than one solution. Therefore, the algorithm has to distinguish concave from convex surfaces to select the correct point. The 3D vectors thus produced may be subsequently developed (Karras et al., 1996).

For raster products, on the other hand, the mapping process starts from the final image, in a similar manner to digital orthorectification. Indeed, a known analytical surface is equivalent to a surface digital elevation model (DEM) in practice; thus, production of digital ortho-images of the solid is possible. As already mentioned, however, for developable surfaces of architectural or archaeological interest, users mainly require developed surfaces rather than conventional ortho-imaging. Such raster representations cannot be directly based on conventional DEMs, but rather on DDMs (digital development models), namely grids in the planar system X_D, Y_D of development, uniquely referenced to the actual surface. According to the basic scheme shown in Fig. 1, where the example of a conical surface is depicted, the process would evolve in the following steps, assuming that the image-to-space relationship is known.

(1) For each image, the area to be developed is defined.
(2) The transformation, D, of development defines a corresponding area in the development system X_D, Y_D.
(3) The pixel size in the "developed object space" is chosen, thus fixing the size of the unwrapped image.
(4) Each pixel in the image uniquely defines an object point X, Y, Z through the inverse transformation D^{-1}.
(5) Back projection via DLT leads to a corresponding location on the original digital image. (If the collinearity equations are employed, these define points in the analogue image coordinate system which are subsequently related to the digital image via affine transformation.)
(6) The desired grey or colour value to be inserted into the unwrapped image is interpolated at the location identified on the original digital image.
(7) Images thus resampled are then adapted radiometrically and combined into a single mosaic to provide the raster end product of surface development.

Of course, regardless of whether the perspective (collinearity) or the projective direct linear transformation (DLT) equations are used, well-distributed control points are required.

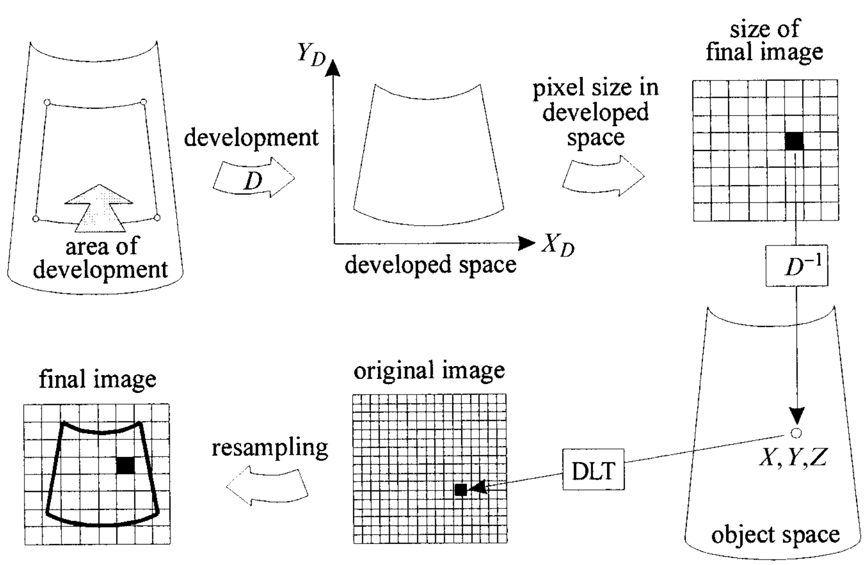

FIG. 1. Basic scheme for the development of conic surfaces by means of direct linear transformation (DLT).

A point to be stressed is that the accuracy of development strongly depends upon the angle of intersection of the projective rays with the surface. Small angles magnify the effects of orientation errors on reconstruction; the same holds true for the effects of local discrepancies from the mathematical surface. Therefore, when planning photography of such objects, an accepted minimal angle of intersection needs to be fixed which will define the usable area of the image. If the image scale allows it, cylindrical or conical objects can usually be covered from at least six points evenly distributed around them. For a given mean photographic scale, normal angle lenses allow mapping of somewhat larger areas from each image than wide angle lenses (Karras et al., 1996).

Before presenting the practical applications, a final remark needs to be made regarding the single-image character of the approach. Raster development is, by definition, a single-image task because it consists of a geometric transformation of individual images, similar to orthorectification. Of course, surface points that are subsequently to be fitted and also image orientations could well be determined in a multi-image context, by bundle adjustment. However, a requirement would then arise for additional images to be involved in order to provide tie points visible on three successive images. A more important disadvantage of this approach, for the examples described in this paper, is caused by the conditions of the applications which dictated the use of different cameras, lenses and zoom values; in the case of the conical object, in particular, almost every image has its own camera parameters. A bundle adjustment with so many "block-variant" interior orientation values would have created a problem in itself. Thus it was much simpler to measure points geodetically and perform individual space resections. In this sense, the tasks described here have been tackled by a purely single-image approach.

PRACTICAL APPLICATIONS

The Objects

The Greek Ministry of Culture was interested in the geometric documentation of the exterior surface of two archaeologically important towers of the Hellenistic period (*circa* 300 BC), both situated on islands in the Aegean Sea. The tower of Drakanos, on the island of Ikaria, has a cylindrical shape with an external diameter of 8·5 m and a height of 12 m (Fig. 2); the conical tower of Ag. Petros, on the island of Andros, is even larger, with a diameter of about 10 m at base level and a height reaching 19 m (Fig. 3). Although apparently the best preserved of numerous similar towers in the Aegean, both have suffered severe damage over time, resulting in gaps, missing and displaced stones, and overall deformation and erosion. The authors were asked to produce raster developments of the exterior surfaces at 1:25 scale, although it was accepted that an accuracy no better than 3 cm would be achieved due to the nature of the objects themselves.

The size, shape and location of the towers posed several problems, with obvious implications regarding the approach to be adopted. In the first place, the surfaces displayed considerable discrepancies from a smooth surface, both "inherent" (the Drakanos stones were pulverised) and due to eroded or misplaced stones; hence, a relatively dense image coverage with highly overlapping frontal photographs was required to attempt to minimise perspective distortions and occluded areas. The

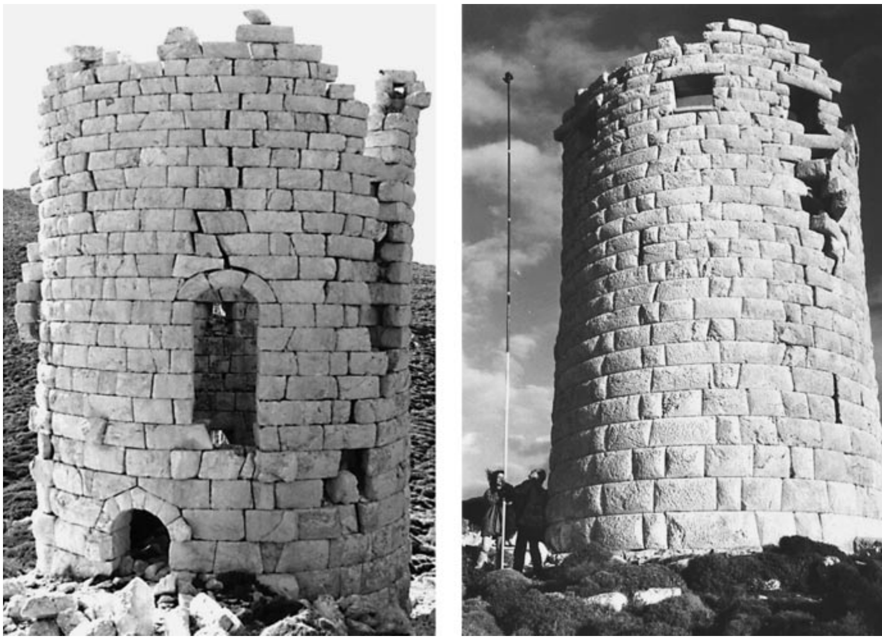

FIG. 2. Views of the cylindrical Drakanos tower. The modified fishing rod used for raising the camera is seen in the right hand image.

Drakanos tower is located on relatively flat ground; as a result, the camera had to be raised for frontal photography. Even worse, the ground around the (much higher) Ag. Petros tower is steeply sloping and falls rapidly at one side. The fact that both monuments are in isolated areas and accessible only on foot (45 minutes and 10 minutes walk, respectively) effectively excluded the use of bulky mechanical means for raising the camera. Thus, neither metric nor reseau cameras could be considered (also, the latter are clearly unsuitable for raster products). Furthermore, targeted control could not easily be established but in any case should also be avoided in raster end-products, particularly in view of the large scale required here. Finally, image acquisition had to take place in the winter. The anticipated (and actually encountered) strong winds of the Aegean discouraged any thoughts of using a "flying" camera platform, such as the small meteorological balloon successfully applied on a different occasion (Karras et al., 1999).

Geodetic Control and Surface Fitting

A large number of detail points were surveyed for surface fitting: about 100 points for Drakanos and about 200 points for Ag. Petros. These points also served as control points. The high redundancy allowed the convenient rejection of about 5% of the points which had been mistakenly marked on the enlarged prints, a problem to be expected when surveying detail points on monotonously repetitive stone patterns (under difficult pointing conditions). The estimated precision of the

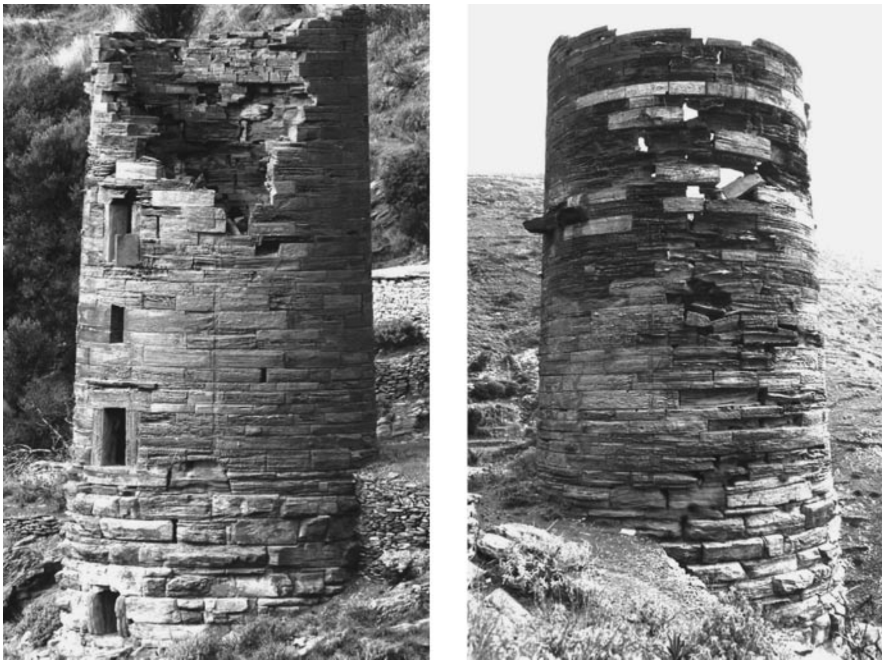

FIG. 3. Views of the conical Ag. Petros tower, located on steeply sloping terrain.

surveyed points was approximately 3 cm, with uncertainties in identification contributing to this figure.

With regard to surface fitting, it was initially established that the surfaces were "what they looked like", namely right circular, using general second order fitting routines (Theodoropoulou, 2000b). For the Drakanos surface, for example, unconstrained fitting gave a cylinder axis with a negligible inclination of 0·02° from the vertical, while cone fitting diminished the rms deviation by less than 1 mm. In contrast, cone fitting to the Ag. Petros surface resulted in a 45% reduction of the rms deviation compared to cylinder fitting; the unconstrained axis here was found to be inclined by only 0·12° from the vertical. For both surfaces, fitting of elliptical rather than circular surfaces did not affect the results. Thus, the Drakanos tower was fitted with a right circular cylinder by minimising the sum of the squares of radial deviations from the surface; the Ag. Petros tower was fitted with a right circular conical surface by minimising the sum of the squares of deviations normal to the surface. After the exclusion of few outliers, the final results referring to the average best-fitting analytical surfaces are given in Tables I and II.

Table I shows that the cylinder is defined precisely. The somewhat large rms deviation is due to the fact that points had been measured both on the embossed faces of the stones as well as on the joints to produce a best mean fit. Very high planimetric accuracy is also obtained for the vertex of the conic surface, as shown in Table II. On the other hand, the small angle β of the cone and the fact that the elevation range of object points was small (about 20 m) compared to the total

TABLE I. Surface fitting for the Drakanos tower (cylinder).

Parameter	*Value*
Number of points	91
Radius (m)	4·210 ± 0·007
Planimetric precision of cylinder axis (m)	$\sigma_X = \sigma_Y = \pm 0{\cdot}010$
Rms radial deviation (m)	0·068
Range of radial deviations from the surface (m)	−0·096 to 0·200

TABLE II. Surface fitting for the Ag. Petros tower (cone).

Parameter	*Value*
Number of points	208
Angle β of inclination from the vertical (°)	2·592 ± 0·044
Elevation of the vertex above threshold (m)	107·766 ± 1·646
Planimetric precision of the vertex (m)	$\sigma_X = \sigma_Y = \pm 0{\cdot}005$
Rms deviation normal to the surface (m)	0·052
Range of deviations normal to the surface (m)	−0·151 to 0·156

vertical extent of the mathematical surface above the ground (about 110 m) understandably produce a large standard error for the vertex elevation. However, its value is, of course, extremely highly correlated with that of angle β ($\rho = 0{\cdot}999$), which means that their "combination" precisely describes the shape and size of the actually existing range of the solid. Indeed, error propagation revealed that at all elevations the corresponding radii of the tower are estimated with a precision of better than 1 cm.

Photography

As already pointed out, non-metric cameras were to be used. In view of the expected accuracy of approximately 3 cm, the negative scale was not to fall below a minimum of approximately 1:350. In the case of Drakanos, the camera had to be raised. A telescopic fishing rod was adapted and extended with aluminium bars to reach a maximum height of 9 m above ground. The lightweight autofocus Nikon F70 35 mm camera was mounted on top with a horizontal imaging axis (Fig. 2). This arrangement allowed the monument to be fully covered by two overlapping "circular strips" taken from eight different angles. All areas with marked relief were also recorded frontally from closer points. The normal-angle 50 mm and wide-angle 28 mm Nikkor lenses were used. Despite the windy weather, images of good quality were acquired.

This camera platform was unsuitable for the Ag. Petros tower which was considerably higher and situated on steeply sloping ground. A substantial part of the monument could be imaged from higher locations on the rising terrain using a medium format (45 × 60 mm) Mamiya 645 camera with its wide-angle 45 mm, normal-angle 80 mm and zoom 105 mm to 210 mm lenses. For the remaining part of the object, there was no alternative to exploiting positions on the surrounding hills and using very long focal lengths. A 35 mm Nikon F4 camera was employed with the Nikkor ED 300 mm telephoto lens, enhanced with the × 1·6 and × 2

Nikon teleconverters. This combination allowed a maximum focal distance of 960 mm ($1{\cdot}6 \times 2 \times 300$ mm) and imaging distances of up to 350 m. Despite a certain degradation of image quality due to haze compared to the other photographs, the resulting images were sufficiently sharp for the purpose required. Other zoom lenses were also used with this camera. With these camera/lens combinations, the monument was finally covered in two "strips" from seven directions.

Photogrammetric Processing

The pixel size of the final raster product was fixed at 100 μm, which is equivalent to 2·5 mm in the "developed" object space. The images should be scanned at a somewhat higher resolution to allow for smooth resampling. Hence, the object pixel size was set to 2 mm, which corresponds to approximately 6 μm at negative scale, a resolution not achieved even by photogrammetric scanners. Therefore, the digital images were produced by scanning good quality enlarged ×7 paper prints at 600 dpi with a desktop A4 scanner.

A total of 17 and 14 images were selected for the Drakanos and the Ag. Petros towers, respectively. Apart from the radial distortion polynomial of the Nikkor 28 mm lens which was known in advance from self-calibration (Karras et al., 1999), no interior orientation data was available for the lenses of the non-metric cameras that were used; nor was it expedient to resort to camera calibration procedures, partly in view of the many lenses used but also because several of the images had been acquired with very different zoom settings. In such cases, the well-documented DLT approach provides a welcome alternative. This approach allows direct projective 2D to 3D relationships to be established between the image and object systems. Here, the conventional image coordinate system (defined via the frame corners in non-metric images) was bypassed by carrying image coordinates measured in pixel dimensions directly into the adjustments. This procedure also permits digital images to be conveniently "cropped" to minimise file size. The DLT approach requires control with adequate extent in depth, which in this case was readily available due to the marked curvature of the recorded surface. Even for the telephoto images, for which object depth was a small percentage of the imaging distance, no significant problems were encountered. The minimal requirement of this approach for six control points also posed no problem because of the large number of surveyed points used in surface fitting. No image had less than 15 and most images had about 25 to 30 well distributed control points.

The results of the DLT "space resection" were subsequently employed in raster development, as illustrated in Fig. 1, where the original images were resampled at a pixel size of 2·5 mm in the development systems (all images taken with the 28 mm lens were corrected for radial distortion in both the space resection and the resampling processes). Of course, the "unfolded" images did not exactly fit with each other. Mosaicking was performed manually by editing the adequately overlapping images, in their own "transparent" layers over the background of the "developed" control points, within a commercial image processing environment. Areas displaced due to relief, or occluded, were locally supplemented from frontal large scale images. Furthermore, certain areas (such as gaps and background) had to be "cut". The final radiometric adaptation into a uniform grey-scale mosaic was also performed manually. The raster end-products, shown in Figs. 4 and 5, were printed on photographic paper at 1:25 scale.

The final accuracy of the developed surfaces, shown in Table III, was assessed by affine transformations between the mosaic and the "developed" control points, which also allowed final adaptation of the results by correcting the differential scales in the two mosaic directions.

FIG. 4. Final raster development of the cylindrical Drakanos tower (a total of 17 "unwrapped" images have been mosaicked).

FIG. 5. Final raster development of the conical Ag. Petros tower (a total of 14 "unwrapped" images have been mosaicked).

TABLE III. Accuracy of mosaics after affine transformation.

Parameter	*Drakanos tower*	*Ag. Petros tower*
Rms deviation in the direction of development (cm)	3·7	4·6
Rms deviation in height (cm)	2·3	2·4
Correction of differential scale (affinity) (‰)	4·2	3·3

The final rms deviations are of the order of 3 cm to 4 cm and were regarded as totally satisfactory by the users (who were impressed by products new to them). Inaccuracies are somewhat larger in the "stretched" horizontal direction of development in which the presence of small remaining perspective distortions is more significant. It should be stressed, however, that this estimated accuracy refers only to the measured points which are assumed to lie on the "smooth" surface (so that they may be developed). In areas of local relief due to object deformation, the stones have been slightly moved and scaled manually to occupy what were regarded as their "correct" places. Although it is expected that, in view of the large number of points checked, the given accuracy is indeed representative for the whole tower, local inaccuracies at areas of 3D deformation and relief cannot be fully assessed. This minor detraction is the inevitable result of developing surfaces which are, strictly speaking, non-developable due to their deviations from a mathematical solid. However, the main task here was not to measure deformations but to map the undeformed areas, giving the shape to which damaged areas should be adapted at the restoration stage.

CONCLUSION

This contribution is regarded as a further step towards exploiting the potential of digital monoscopic techniques. A single-image approach has been presented and applied to the digital development of 3D geometrical surfaces to which analytical surfaces are fitted. The problems posed by the large size and unfavourable location of the towers were tackled by resorting to a specific combination of simple methods, by exclusively relying on non-metric cameras. Furthermore, since no suitable commercially available software was known to the authors, the whole processing task was programmed on a PC. The final outcome indicates the high potential of digital photogrammetric tools for producing sophisticated results at low cost.

Of course, difficulties are also present in such an approach. For instance, certain stages in the procedures, such as geometric and radiometric matching of successive images, were somewhat tedious since they had to be performed manually. Furthermore, the final accuracy does not depend solely on the photogrammetric process but also on the fact that an attempt was made to develop a surface which is not strictly developable due to local fluctuations in relief. Such error sources have to be assessed and controlled in the planning phase (larger deviations from a smooth surface will necessitate more frontal images). At a more general level, it should be pointed out that low-cost single-image techniques with non-metric cameras and specially designed camera platforms are not necessarily equivalent to "simple" methods that should be unquestionably adopted by any user. Rather the contrary is the case, namely that the "simpler" a method, the deeper is the understanding required of the specific task and the underlying geometric assumptions.

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Résumé

On peut tout à fait cartographier avec précision des surfaces de forme régulière qui présentent un intérêt architectural ou archéologique, avec des méthodes qui ne nécessitent qu'une seule image. Chaque fois que c'est possible, on développe numériquement ces surfaces, ou on les représente dans des projections cartographiques adéquates. On décrit dans cet article le développement en mode raster de deux grandes tours, l'une conique et l'autre cylindrique, dont les hauteurs sont respectivement de 19 m et 12 m et les diamètres d'environ 10 m et 8 m. Ces tours, qui datent des alentours de l'an 300 avant notre ère, se trouvent dans les îles grecques où elles ne sont accessibles qu'à pied. On a pris des images de la première tour à partir des collines environnantes avec plusieurs focales, dont de puissants téléobjectifs. On a enregistré la seconde tour en fixant une caméra 35 mm légère sur une canne à pêche modifiée qu'on a levée jusqu'à 9 m au-dessus du sol. On a développé numériquement puis mosaïqué l'ensemble des photographies non-métriques, prises à une échelle de 1:350 environ, qui permet d'obtenir une *précision globale de 3 cm à 4 cm. On présente et on analyse les produits rastrés résultants.*

Zusammenfassung

Normalerweise können reguläre Oberflächen von architektonischem oder archäologischem Interesse mit Hilfe von Einbildverfahren genau kartiert werden. Wo immer möglich, werden solche Oberflächen digital entwickelt oder in geeigneter kartographischer Projektion dargestellt. Im Beitrag wird die Rasterentwicklung von zwei hohen Türmen, einem konischen und einem zylindrischen mit Höhen von 19 m und 12 m und Durchmessern von etwa 10 m bzw. 8 m beschrieben, die auf griechischen Inseln liegen und nur zu Fuß erreicht werden können. Der erste Turm wurde von umgebenden Bergen mit verschiedenen Objektiven, darunter sehr leistungsfähigen Teleobjektiven aufgenommen. Der andere Turm wurde aus etwa 9 m über der Erdoberfläche mit Hilfe einer angepaßten Angelrute, die eine leichte 35 mm-Kamera trug, photographiert. All die nichtmetrischen Photos, die mit einem Bildmaßstab von etwa 1:350 aufgenommen wurden und eine Genauigkeit von 3 cm bis 4 cm ermöglichten, wurden digital entwickelt und dann als Mosaiks dargestellt. Die Rasterprodukte werden beschrieben und diskutiert.