A SIMPLER METHOD FOR LARGE SCALE DIGITAL ORTHOPHOTO PRODUCTION

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ABSTRACT:

Digital orthophotography has been a powerful tool for large scale geometric documentation of monuments for over a decade. However, several factors prevent the smooth implementation of commercially available software for the production of digital orthophotos. The production of orthophotographs presents even more special problems, as it usually is a case of a highly demanding true orthophoto. Special techniques have been proposed in the past to address these problems in the best possible way. However no clearly defined solution to the above has been implemented. Terrestrial laser scanning techniques have helped the situation a lot, as they are able to provide a more detailed description of the object's surface, a fact which contributes to a more successful implementation of traditional orthophoto production algorithms. However, even this solution is by no means complete, as it imposes limitations to the orientation of the stereopairs, the position of the projective planes for the final orthophoto and, of course, to the completeness of the final product. Several attempts have been reported in the past in order to help overcome these limitations. In this paper a novel and simple method developed for the production of orthophotography at large scales is described and assessed. This method successfully attempts to produce orthophotos at large scales using a point cloud and freely taken pictures of the object, thus achieving two goals. Firstly the user may work independently from the practical constraints imposed by the commercially available software and secondly there is no need for specialized knowledge for implementing complicated photogrammetric techniques, or specialized photogrammetric or pre-calibrated cameras, since self-calibration may take place, thus making the method attractive to non-photogrammetrists.

1. INTRODUCTION

1.1 Orthophotography

The photogrammetric textured representations, using mainly orthophotomosaics, have been proved to be powerful products of documentation as they combine both geometric accuracy and visual detail. They convey quantitative, i.e. metric, as well as qualitative information, so valuable for the integrated restoration studies. However, there is still an unsolved problem with the complete orthoprojection of complex objects though, as the description of the analytical shape of the object cannot always be accurate, especially in areas where points with the same planimetric coordinates show different heights. Regular grids integrated by break-lines and DSMs (Digital Surface Models) are the most popular and investigated solutions used to build-up a mathematical shape description of such an object. In both cases complex algorithms and expensive computation times must be used before and during the orthophoto production.

Although their production has already reached a high level of maturity as far as aerial images are concerned, for the Geometric Recording of Monuments at large scale, i.e. larger than 1:100, it presents several difficulties and peculiarities, which call for special attention by the users. Consequently, orthophotography is not yet fully accepted by the user community for applications related to geometric documentation of cultural heritage monuments. Architects and archaeologists are still reluctant to concede working with orthophotographs instead of the traditional vector line drawings. As a consequence orthophotography usually is not included in the standard specifications of the geometric recording of monuments. The situation is becoming worse due to the need for special instruction for planning and executing the photographic coverage to face the problems of orthophoto production for the monuments at large scales (i.e. ≥1:100). The major of such problems are (Mavromati et al., 2002a, 2002b and 2003): (1) Large elevation differences compared to distances between the camera and the object, (2) Presence of "vertical" surfaces, i.e. surfaces parallel to the camera axis, (3) Convergence of camera axes, often due to space limitations, (4) Failure of automatic DTM production, as all available commercial algorithms are tailored to aerial images, (5) Necessity for large number of stereomodels in order to minimize occluded areas, (6) Difficulty of surveying convex objects.

For the first two problems special measures should be taken during both field work and processing of the data. They are the main source of practically most difficulties encountered in producing orthophotographs and the relevant mosaics. The elevation differences call for elaborate description of the object's surface, in order to allow for the orthophotography algorithm to produce accurate and reliable products. Usually, problems due to the image central projection and the relief of the object (e.g. occlusions or complex surface) can be solved by acquiring multiple photographs from many points of view. This may be compared to the true orthophoto production for urban areas (Baletti et al., 2003). However, processing can be seriously delayed for DTM generation requiring possibly intensive manual interaction or even a complete failure to produce a reliable model.

1.2 Terrestrial Laser Scanning

The appearance of terrestrial laser scanning has already shown promising contribution in overcoming such problems (e.g. Barber et al., 2002; Bitelli et al., 2002; Drap et al., 2003; Guidi et al., 2002) and also confronting other similar applications (Baletti & Guerra, 2002). The volume of points and high sampling frequency of laser scanning offers a great density of spatial information. For this reason there is enormous potential for use of this technology in applications where such dense data sets could provide an optimal surface description for applications of archaeological and architectural recordings.

The recently published literature has shown that in many cultural heritage applications the combination of digital photogrammetry and terrestrial laser scanning can supplement each other in creating high-quality 2D and 3D presentations. Specifically, laser scanning can produce the dense 3D point-cloud data that is required to create high resolution dense DEM for orthophoto generation and can be considered the optimal solution for a correct and complete 3D description of the shape of a complex object. However, a correct DSM cannot always guarantee the generation of accurate orthophotos or even acceptable photorealistic images. This is due to a number of problems such as the perspective deformations of an image and the relief of the object (i.e. occlusions). When stereopairs are taken with a certain inclination of the optical axis it can result to a different ground resolution over the image and the effect of tilt on the image geometry can cause distortions in the resulted orthophoto. In order to maintain the visualisation effect and have photorealistic models, it is possible to supplement the distorted areas of the orthophoto by texture mapping using both the image and laser data. The extremely high number of points produced using Terrestrial Laser Scanners on the object's surface, which replaces the need for producing the Digital Object Models (DOM's) from carefully taken stereopairs, may be suitably exploited to free the user from severe constraints in positioning the camera. Thus a procedure is sought to combine TLS point clouds and freely taken photography for the production of orthophotos at large scales.

2. METHODOLOGY

2.1 Previous Efforts

The method is based on a previously reported idea (Georgopoulos et al., 2005) of thoroughly and suitably colouring the available point cloud. In this paper the idea of producing an orthophoto by projecting a coloured -extended-point cloud was firstly reported. However in that case the point cloud was produced by stereophotogrammetric techniques, which increased tediousness and time necessary.

Another similar approach is the creation of a coloured 3D model comprised of triangular elementary surfaces. These are created through a Delaunay triangulation of a point cloud using the colour from a digital camera rigidly attached to the scanner, thus saving the necessity of performing orientations. Such attempts have already been reported (Dold and Brenner, 2006, Abmayr et al., 2004, Reulke et al., 2006) and led to manufacturing such devices, mainly the series LMS-Z by Riegl company (http://www.riegl.com/).

Colouring TIN 3D models from digital images irrespective of their orientation or source have also been attempted (Brumana et al., 2005), in which case the DLT was employed. As an extension to this, more images may be used for picking the right colour, through a series of selection procedures (Grammatikopoulos et al., 2004). This helps avoid selecting the wrong colour for occluded areas (Abdelhafiz and Niemeier, 2006).

Finally in the stage of experimental development is a revolutionary device, which combines information from a laser scanner and a digital camera through a common optical centre (Seidl et al., 2006). Such a device, when operational will be able to produce coloured point clouds without the necessity of any processing.

2.2 Description of the Developed Method

The developed algorithm includes the determination of the interior and exterior orientation of the image, the correspondence of the colour information from the image to the points of the cloud and, finally the projection of the coloured points onto the desired plane. It is obvious that no rigorous photogrammetric setup is necessary for the image acquisition phase. Contrary to the conventional procedure, where image tilts are of utmost importance for the quality of the final product, they play no significant role in this present case. The final projection plane may be defined at will, thus enabling the production of a multitude of orthophotos from the same point cloud.

Thus the presuppositions of the method are at least a point cloud, with suitable point density, and a digital image of the object. The algorithm firstly relates geometrically the image to the point cloud making use either of characteristic points recognized in both data sets, or pre-marked targets. A self calibration of the camera may also be performed at this stage if required, as a metric camera may not always be available. Then the algorithm assigns a colour value to each point, through a careful selection process, in order to avoid double projections, or projection and colouring of hidden points. After the point cloud has been coloured, a suitable projection plane and the size of the pixel of the final orthophoto are defined. Projection of the coloured points on the plane results in assigning colour values to each orthophoto pixel, through a suitable interpolation process. In the case that the initial density of the point cloud does not suffice for the production of a perfectly continuous orthophotography at the desirable scale, black pixels may appear in the resulting image. A basic hole-filling algorithm has been implemented in order to handle and compensate the colour for those pixels by interpolating through the neighboring pixels' colour values. In this way the final orthophotography is produced. It is obvious that the orientation of the projection plane may be defined at will, independently from the orientation of the camera axis, or axes in the case of more pictures available, since the orthophotography is derived from the projection of the point cloud rather than the differential transformation of the initial image as is the case in the traditional photogrammetric method. This allows for the production of multiple orthophotographs projected onto different planes without the need for a dedicated image or image pair for each projection plane.

3. DEVELOPMENT OF ALGORITHM

3.1 Open Source Software

The above described algorithm has been implemented using open source software and is released under the terms of the

GNU General Public License (GPL) in order to enhance its wide applicability, its low cost and its flexibility, as modifications may be possible by third parties according to future needs. The algorithm has been applied to a couple of cases of geometric monument documentation with impressively promising results. A thorough test has been performed using several check points and the results are presented and discussed.

The algorithm has been developed mainly in the object oriented C++ programming language (http://zpr.sourceforge.net/), using at the same time ANSI C elements. The whole application was written within the (IDE) Code::Blocks open code environment. Finally the following open source libraries were also used: (a) GNU Scientific Language (GSL) for the necessary mathematical operations (http://www.gnu.org/software/gsl/) (b) OpenCV, distributed by Intel and used mainly for machine vision applications (http://opencvlibrary.sourceforge.net/) and (c) GetPot, a simple library for parametrizing the execution of the algorithm (http://getpot.sourceforge.net/).

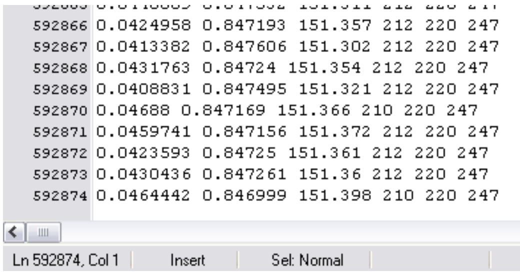
3.2 Description of basic steps

As already mentioned, the current approach follows a somewhat different course than the conventional one. The orthophoto is produced through the orthogonal projection of a suitably coloured point cloud. Hence the space relation between the initial point cloud and the available digital image should firstly be determined, in order for the individual points to be aasigned a colour value. The basic steps of the algorithm are:

- Determination of image and point cloud orientation
- Point cloud colouring by relating points to pixels
- Selection of projection plane
- Coloured point cloud rotation
- Point visibility classification depending on their distance from projection plane
- Hole filling on the resulting orthophoto

3.2.1 Data Entry

The necessary data for the execution of the algorithm are briefly described in the following:



```
592866 0.0424958 0.847193 151.357 212 220 247
592867 0.0413382 0.847606 151.302 212 220 247
592868 0.0431763 0.84724 151.354 212 220 247
592869 0.0408831 0.847495 151.321 212 220 247
592870 0.04688 0.847169 151.366 210 220 247
592871 0.0459741 0.847156 151.372 212 220 247
592872 0.0423593 0.84725 151.361 212 220 247
592873 0.0430436 0.847261 151.36 212 220 247
592874 0.0464442 0.846999 151.398 210 220 247
Ln 592874, Col 1    Insert    Sel: Normal
```

Figure 1: Extract of an ASCII point cloud file.

<u>The point cloud</u>

Every point is described by a triplet of space co-ordinates (X, Y, Z) and another triplet (R, G, B) determining the colour. The description may be augmented by a point name, or an intensity value as recorded by the laser scanner. For enabling the various modules to work together the point cloud is stored in an ASCII format (Figure 1), which may result to large files. A suitably selected binary format would certainly improve the efficiency.

<u>The initial digital image</u>

The necessary digital image, which will be used to assign colour values to the points of the cloud, may be stored in any of the standard digital image file formats (e.g. BMP, DIB, JPG, PNG, PBM, PGM, PPM, SR, RAS and TIFF).

<u>Data for the image orientation</u>

In order to determine the space relation between the image and the point cloud, which in turn will lead to the assignment of a colour value to each point, at least six control points are necessary. They are used by the orientation algorithm and may be selected either manually or digitally, with the help of two ASCII files. Moreover an initial value for the camera constant in pixels is needed in order for the algorithm to determine the interior and exterior orientation parameters, as will be described later.

<u>Determination of the projection plane</u>

For defining the projection plane of the final orthophoto, the user should either enter the three parameters a, b and c of the equation aX+bY+cZ=D, where D is defined by the algorithm, or alternatively may draw the straight line footprint of the plane on an orthogonal projection of the point cloud, provided that the latter is suitably georeferenced so that the Y-axis is vertical. Finally the pixel size of the resulting orthophoto should also be defined at this stage.

3.2.2 Photogrammetric Orientations

For the camera calibration the algorithm developed by J. Heikkilä is used (Heikkilä, 2000). The algorithm is complemented by a model for the description of the camera-to-object relation and augmented by the radial and decentering distortion models for off-the-shelf cameras.

The mathematical model used is given by:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \propto \begin{bmatrix} \lambda u \\ \lambda v \\ \lambda \end{bmatrix} = \begin{bmatrix} sf & 0 & u_o & 0 \\ 0 & f & v_o & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \bullet \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix}$$

where $[u\ v\ 1]^T$ the image co-ordinate vector in homogeneous co-ordinates
λ scale coefficient
s the skewness factor of the pixels
f the camera constant
u_o, v_o the principal popint co-ordinates
$t = [t_x\ t_y\ t_z]^T$ the translation vector from the image system to the world system
R the classical rotation matrix (ω, φ and κ)

The solution is linear and experimental results proved that an accuracy of 1/50 of a pixel may be achieved, provided qualitative image errors have been removed. The algorithm is available in MatLab (http://www.ee.oulu.fi/~jth/calibr/) and may be found in OpenCV library through the *CvCalibrateCamera2()* routine, which was used in this project.

3.2.3 Colouring the points

Collinearity condition is applied through the *cvProjectPoints2* routine of OpenCV, in order to assign colour to each point of the cloud. This routine accepts as entry the ground co-ordinates of the points and using the determined elements of the interior and exterior orientations determines the corresponding image co-ordinates. A suitable interpolation is performed in order to select the suitable colour from the digital image. The resulting R, G and B values are added to each point in the point cloud file. Points outside the image boundaries are not coloured from this image. The result of this procedure is a point cloud, which may be considered as an extended DSM (Georgopoulos et al., 2005).

3.2.4 Point Cloud Projection

The last step of the procedure is the orthophoto production, which actually is the projection of the coloured points on the desired plane. Depending on the way the plane has been defined by the user, the rotation matrix is determined for the transformation of the point cloud so that the Z axis is vertical to the plane. Not all points should be projected, as some of them may be obstructed by others. Hence the projection procedure starts from the most distant points, while the closest ones replace the previously projected points.
Based on the X and Y extremes and the selected pixel size, the size of the resulting orthophoto is determined and the transformation from X and Y values to i, j pixel co-ordinates is performed.

3.2.5 Hole Filling

Because of the projection method, it is possible to get non-coloured -black- pixels in the final orthophoto, which appear as “holes” (Figure 2).

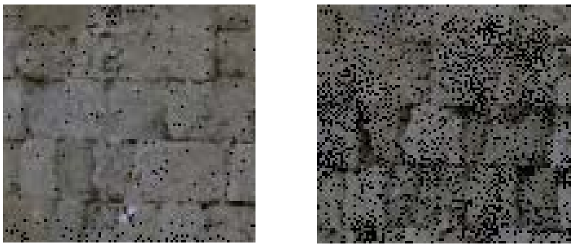


Figure 2: Examples of “holes” in the orthophoto

A hole filling algorithm is applied in order to remedy this problem. The routine *holefill()* is used for this purpose and the procedure followed examines the neighborhood of the black pixel and interpolates the colour accordingly, while paying attention for cases of pixels outside the initial digital image borders.

4. IMPLEMENTATION

For assessing the performance of the developed method, a suitable object has been chosen. The Eastern façade of the Church of the Holy Apostles in Ancient Agora of Athens (Figure 3) was considered appropriate.

Figure 3: The Church of the Holy Apostles in Athens

4.1 Data Acquisition

For the above task it was decided to produce orthophotographs both with the proposed algorithm and with the Z/I SSK Image Station. This would enable the comparison of the orthophotos and the assessment of the proposed methodology.

A Leica Cyrax 2500 time-of-flight laser scanner was used for collecting the point cloud. This scanner has a capability of a pulse laser beam of 6mm width at 50m and performs the distance measurements with an accuracy of ±4mm, with a maximum capability of 1 million points per scan. The digital images were acquired with a Canon EOS 1D Mark II, with a CMOS 8 megapixel chip with physical dimensions $28.7 \times 19.1 mm^2$, which results to a 8.1μm pixel. This camera was equipped with a 24mm lens.

A point cloud was collected from a distance of approx. 10m with a density of 10mm, thus resulting to a total of 514281 points. Moreover 15 control points on the object were also measured geodetically using a Leica TCR303 total station (Figure 4). These points were premarked using the special Cyra reflective targets for accurate location and determination both by the scanner and the total station. The point cloud was processed in order to keep the points only of the area of interest, thus keeping 473736, i.e. 92% of the original points, stored in an ASCII file.

The façade was photographed from various distances and various angles. “Vertical” photos were taken for use in SSK and several additional photos were also taken in order to enable experimenting with the developed algorithm. In some highly oblique images information on the object was deliberately occluded and the results will be commented upon later.

With the above data various orthophotos were produced with different pixel sizes (5mm, 10mm, 15mm and 20mm) and using different number of GCP’s (6, 7, 8, 10 and 15) for the image orientations. For the data to be operational in SSK, some processing was necessary, as the DPW requires TIN information for the DSM. The procedure is estimated to have lasted around two hours for the production of the orthophotos.

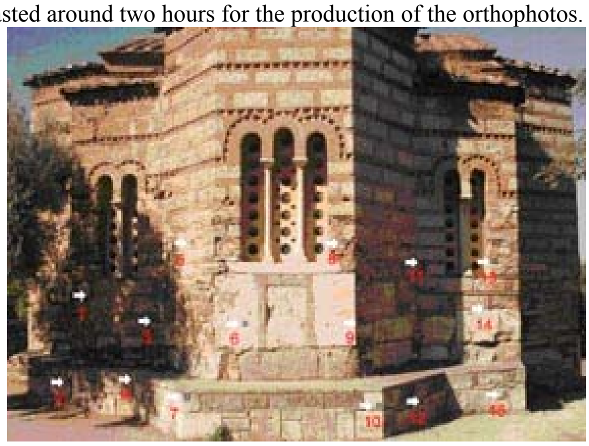


Figure 4: Target positions measured on the façade

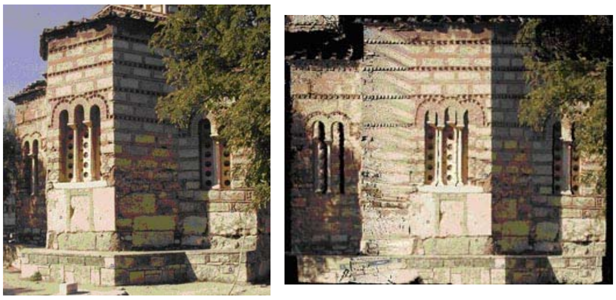
4.2 Orthophoto production and quality assessment

The same number and combination of orthophotos have been produced by applying the developed algorithm. In addition orthophotos were also produced using different images (“vertical” and “oblique”), but the same number of GCP’s.

These orthophotos could not be produced using the SSK ImageStation, as the commercial algorithm seems unable to accommodate large image tilts. Two such images, produced with exactly the same input data appear in Figure 5.

(a) (b)

Figure 5: Orthophotos produced using 10 GCP's and the same DSM with Z/I SSK (a) and the proposed method (b)



(a) (b)

Figure 6: Orthophoto produced with the proposed method (b) using initially "oblique" image (a)

The produced orthophotos with the commercial DPW are correct in the area surrounded by the GCP's. In addition their quality is not affected by the final pixel size. On the other hand the proposed method produces orthophotos correct over the whole area, even outside the GCP's. However, pixel size variation affects negatively the final quality, as expected since the final orthoimage is directly dependent to the density of the point cloud.

Highly tilted initial images produced orthophotos only with the proposed method. However the information contained in these images is distorted in occluded areas (Figure 6).

4.3 Assessement of quantitative results

The metric accuracy of the orthophotos was also examined. As in almost all cases there were some of the initially 15 available GCP's which were not used for the image orientations, their co-ordinates and distances were measured and compared. The results for orthophotos produced with the developed algorithm with pixel size 10mm are summarized in Table 1.

	#GCP's	**6**	**8**	**10**	**15**
RMS (mm)	**Δx, Δy**	10	8	3	3
	Δs	15	11	5	3

Table 1: Summary of quantitative results

It is obvious that as the number of used GCP's increases the resulting accuracy becomes better. At the same time the increase of GCP's beyond 10 does not appear to significantly affect the accuracy. However the requirements of a large scale (e.g. 1:50) orthophoto, even the minimum required number of GCP's (i.e. 6) returns acceptable results.

5. CONCLUDING REMARKS

5.1 Assessment of the method

The results presented show that in most of the cases the orthophotos produced with the developed algorithm are of acceptable quality and their accuracy is within the limits of a pixel, even when the initial conditions, i.e. image orientation, DSM density, number of GCP's, are not exactly ideal, as required by commercial DPW's.

The orthophotos produced based on the initially tilted images, present similar accuracy characteristics with the others, thus freeing the data acquisition procedure from strict geometric setups. However, occluded areas still remain a problem and should be taken into account at the stage of data collection. Ideally the images should be taken approximately from the position of the terrestrial laser scanner.

The merits of the proposed method may be summarized as follows:
Simplicity and speed, as the method is fast and does not require special knowledge from the user. The procedure of orthophoto production takes about 15 minitues. In addition there are practically no restrictions in the geometry of image acquisition.
Limited need for GCP's, as the method works satisfactorily even with the least number of control points (i.e. 6).
Non-metric camera usage, as no prior knowledge of the interior orientation parameters of the camera is required, since they are computed for every image by the algorithm with the self calibration routine.
Flexibility in producing end products, as with this method orthophotos at practically any plane may be produced, with no extra effort.
Availability and expandability, as the algorithm has been developed using Open Source software and is available for everyone willing to adapt it to his own needs.

On the other hand there are some drawbacks in the method:
- The orthophoto scale is limited by the accuracy of the scanner and the density of the collected points of the point cloud
- Terrestrial laser scanners are costly, bulky and (yet) not easily available instruments and
- The algorithm does not offer an occlusion detection routine at the stage of point cloud colouring, which results to wrong colouring in cases of steep anaglyph on the object.

5.2 Future Outlook

The most important prospects for future additions to the algorithm could be the following:
- Automatic location of GCP's, which would greatly contribute to the full automatization of the process. The same result could be achieved with the automatic orientation of the image using characteristic features extracted from the point cloud, such as lines or edges, planes etc.

- Visibility control between the TLS and the image, in order to ensure the correct colouring of the points in cases of steep anaglyph, high image tilts and unfavourable taking distances. Techniques to confront this problem have already been reported (Grammatikopoulos et al., 2004).
- Using multiple images to colour the point cloud would definitely improve the resulting orthophotos, as this would practically solve the problem of non-coloured, i.e. black, points.
- The orientation of the projection plane could be such that the plane would create a section of the object, thus resulting to a multitude of more useful orthophotos for cases of occluded details on the object.
- Of course increase of the execution speed and addition of a Graphics user Interface could also be included in future improvements possible.

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