RECORDING AND DOCUMENTATION OF ARCHAEOLOGICAL AND ARCHITECTURAL FRAGMENTS USING AUTOMATED STEREO PHOTOGRAMMETRY

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ABSTRACT:
Research in building history is based on detailed analysis of building remains. Therefore, archaeological finds and building fragments are measured in high detail and in a classical approach documented in plan, elevation and section drawings. These drawings are the basis for all further research, and finally means of argumentation and presentation in reconstruction drawings. All scientific progress is based on an intensive hands-on work with the object. However, this traditional manual survey needs more and more time as geometrical complexity of the object increases. Consequently there is a long list of attempts to reduce this time by technological means. All of these technologies need to be compared in respect of accuracy, time and costs. For example scanning is used in a relatively small number of projects, due to high costs to date and very specific fields of application of each scanner type. Digital stereo photogrammetry offers efficient and flexible surveying of building fragments and finds. The photos can be taken by the user through a calibrated but otherwise usual digital single lens reflex camera on a stereo-bar. Relative orientation of the photos is achieved by automatic image correlation in image pyramids in a software solution. In a batch of two to four oriented images automatic image matching generates 3D object points in a high density. The resulting point cloud is the basis for the deduction of the final result, which can be ortho image projections, sections, or textured 3D models of the original object. The application of digital photogrammetry in building history and archaeology will be presented in a selection of recent projects. Furthermore a prospect of future development and improvements will be presented as a result of practical tests and experience with this technique.

1. INTRODUCTION

Building archaeology is a historical science that tries to retrieve information about architecture, society, technology, and most other aspects of the cultures of past times. As opposed to other historical sciences building archaeology is based on the analysis of architectural remains as its primary source of information. For this reason the survey and complete documentation of the architectural remains is vital for the following analysis and scientific work. The classical survey comprises hand drawings to scale supplemented by photos, descriptions and catalogues as a systematic compilation of these different pieces of information. The drawings encompass floor plans, elevations, sections of a complete building as well as of technical or ornamentation details. That is why scales can vary greatly, from 1:1 in detail drawings to 1:100 or larger in drawings of one or more buildings. The level of accuracy in these representations is limited by the scale of the final drawing. At the same time the required level of accuracy for the survey is only determined by the scientific goal it is made for. According to this, sketches with supplementing measures will be fine for most typological comparisons, whereas even reflectorless tacheometry may be hardly sufficient for work on the curvature of a Greek temple. Consequently the appropriate level of accuracy is defined for each particular project.

The object of survey and documentation is to collect all relevant data to answer the actual scientific objective. This high density of information requires a lot of time to collect. The time needed to complete the hand-drawings increases disproportionately for spatially complex geometries. Drawing badly preserved fragments possibly needs more time than drawing the best preserved examples. The technical development to reduce the time spent and enhance accuracy in surveys started long before Albrecht Meydenbauer and will continue for a long time coming. Today it is near possible to do virtual 1:1 representations by modern scanning technologies (Akca et al, 2006), and we can discuss the "objectiveness" of documentation (Riedel & Bauer, 2008). However for or the best part of work in building archaeology the maximum accuracy of surveying techniques is not a limiting factor any more. More crucial factors would be expense of time and money and, more important, usability.

For acquisition of 3D data procedures using digital amateur cameras proved to be an alternative to recent scanning technology (e.g. Booches et al, 2007). In the following stereophotogrammetry shall be presented as a time- and cost efficient technique for the survey of building fragments and archaeological finds, as two possible fields of application. It is designed to enable the end user to perform a survey that meets the requirements using only a calibrated, but otherwise standard, Digital SLR camera.

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2. PHOTOGRAHMETRIC RECORDING

In the fields of archaeology, building archaeology and preservation of historical monuments photogrammetric techniques are frequently used for documentation and data acquisition, as numerous papers at the CIPA symposia of the last years show (e.g. CIPA, 2005 and CIPA 2007). Photogrammetric techniques offer a big advantage over discrete measuring techniques, like hand measurements, tacheometry and laser scanning, in continuous covering of the objects surface in a high resolution at the time of the exposure. Photogrammetry offers high-resolution documentation of the surfaces at the given time of exposure which is largely free of interpretation. Thus it can be understood as a most objective method of data acquisition. Given the appropriate means of storage photos can be used as original measured data for photogrammetric evaluation at any later date.

Image rectification of planar object areas is a common technique for 2D documentation since application oriented software is an established product, whereas advanced photogrammetric methods are rarely used by the end user due to their complexity.

2.1 Standard stereo configuration

Using stereophotogrammetry it is possible to document non-planar objects and free-form surfaces three-dimensionally. The process of evaluation can be split from data acquisition and postponed to a later date. During stereo evaluation the user is offered a three dimensional spatial representation through which can analyse the actual state, quality of finish, and depth differentiation of the surface. The technology introduced here will enable the end user to perform 3D documentation and evaluation of building fragments as well as archaeological finds on the basis of stereoscopic images. Starting in the beginning of the 20th century the know-how of aerial stereophotogrammetric evaluation has been used to develop special techniques and instruments for terrestrial use (Szangolies, 1986).

According to classic stereometric cameras with fixed calibrated base distances a simple base-bar can be used to provide a calibrated distance for two standard cameras (Figure 1). Making use of such a base bar it is possible to ensure an image configuration that complies with the advanced normal case of stereophotogrammetry. By purposefully keeping roughly parallel viewing directions it is still possible to achieve stereoscopic perception in analysis and presentation of the object. Additionally this configuration facilitates the automated correlation of homologous image points in image orientation and evaluation.

Through the known basis of the image configuration the model system of a relative orientation can be scaled to the object space without further reference information. This allows for time efficient documentation of small objects like building fragments and archaeological finds on site. There is no need for further reference points, and still the objects can be evaluated to scale later. Alternatively objects with known 3D coordinates can be inserted to the object space which means a calibrated base-bar can be omitted. This way one or more stereo models can be assembled in a consistent object coordinate system through absolute orientation.

For image recording digital single lens reflex cameras with fixed-focus lenses are used that have been calibrated for specific focus settings. For the requirements of photogrammetry this camera type combines high sensor resolution with good lens quality and sufficient geometrical accuracy (Läbe, Förstner, 2004). As Läbe and Förstner show the use of digital zoom cameras would generally be possible as well, but under the prerequisite of higher effort. In this case unstable interior orientation and lens distortion changing with different focal lengths require higher effort for simultaneous determination of the interior camera parameters in image acquisition as well as in image orientation.

2.2 Extended four camera configuration

In classical stereo configuration with only two images the process of automatic image correlation can result in wrong correlations and object points due to possible ambiguities along the epipolar band (Maas, 1997). Maas proposes to extend the stereo configuration to three or more camera positions, which reduces the probability of wrong correlations calculating the intersection of epipolar lines of two or more images.

The configuration described in 2.1 can be easily extended to four camera positions by moving the basis (model A) vertically (Figure 2). Basis A and basis B should be kept approximately parallel in this process to ensure automatic image correlation over all four images. During image orientation the calibrated base distances of two models allow for an additional check of
the orientation. As an extra the additional image pair (model B) can be used to add information on areas not covered in model A, and thus help to avoid bad spots in the 3D Model.

2.3 Combination of overlapping models

For the entire coverage of building fragments multiple stereo models need to be linked. After relative orientation of single image pairs neighbouring models can be transformed into one consistent coordinate system via identical object points. For this it is useful to insert 3D tie points into the object space that can be identified clearly and measured precisely from different positions. The use of white tetrahedrons as tie points for multiple stereo models is shown in Figure 3. The determination of these 3D tie points can be automated by extracting edges of a tetrahedron and calculating their intersection point. A combined orientation of all images in a bundle block adjustment would possibly be a natural choice from the perspective of photogrammetry. Still for development of a user-oriented system the step-by-step concept introduced here has been chosen deliberately.

Figure 3: Using white tetrahedra as 3D targets for the linkage of several stereo models

3. AUTOMATED STEREO EVALUATION

Due to the substantial similarities of stereoscopic image pairs, manual stereophotogrammetric evaluation can be supplemented or substituted by automated image correlation. First an automated depth measuring function was implemented for easy positioning of the floating mark on the object surface that works according to the Vertical Line Locus procedure (Cogan & Hunter, 1984). For comparison of image patches the normalized cross-correlation coefficient (see i.a. Piechel, 1991) is used which provides the position of best correlation in one-pixel accuracy. Sub-pixel localisation is achieved in a second step via least squares matching (LSM, see i.a. Ackermann, 1984; Förstner, 1982). LSM is used to determine the parameters for geometric and radiometric transformation of two image patches by an iterative calculation of grey level differences between reference and search matrix. It offers an improved accuracy especially for images with larger perspective differences. Moreover the adjustment calculation of LSM provides statistical estimation of the obtained inner accuracy.

A time efficient non-iterative sub-pixel localisation can be achieved via paraboloid-interpolation (Rodehorst, 2004). Taking the maximum of the cross-correlation as a starting point and using the correlation coefficient of eight neighbouring positions a biquadratic paraboloid can be calculated. The maximum of which provides the sub-pixel difference to the position of the one-pixel correlation maximum.

3.1 Image orientation

The first step of relative orientation is the calculation of orientation parameters in a model system through homologous image rays in both images. The measuring of homologous image points in two or more images for relative orientation is facilitated substantially by the integrated correlation techniques. The user does not have to insert specially marked tie points into the object space, but can rely on natural points for an ideal point distribution. For manual evaluation image points with sufficient texture information will be defined in one image. The search area for the corresponding image points has to be specified by the user. After the first calculation of relative orientation parameters, the search area for the correlation process can be automatically limited to the corresponding epipolar band.

Figure 4: Homologous image points, extracted using Förstner-Operator, followed by cross-correlation

By extracting relevant point features in both images using an interest operator determination of image points can be automated completely. For this the Förstner-Operator (Förstner, 1986) has proved to be very reliable. Afterwards identical interest points are correlated in sub-pixel accuracy via image correlation (Figure 4). For orientation of extended four-camera-models first identical image points are measured either manually or automatically in all four images. Separated relative orientation for both stereo models provide approximate parameters for a consecutive
bundle block adjustment. For this adjustment the base distances are used as known parameters.

3.2 Dense surface and profile measurement

On the basis of known parameters for interior and outer orientation in the next step 3D coordinates of image points in the object space can be calculated via forward intersection. The image matching can start in single or multiple points and expand to neighbouring image areas through a special algorithm. In the end the automated documentation of object surfaces results in a dense 3D point cloud (Figure 5). The user can define the increment for expansion and the size of the search area for matching depending on image resolution and surface structure of the object as well as the image area that shall be evaluated.

Figure 5: 3D point cloud generated with image matching

For evaluation of horizontal and vertical profiles a profile line for the automated measurement is defined in an aligned perpendicular coordinate system. The evaluation can be generated similar to surface determination using expansion algorithms for image matching. The resulting dense profile of 3D points can be exported to a DXF file for use in any CAD system. Thus the profiles can be combined with other measurements for a virtual reconstruction (Figure 6).

4.1 Surface triangulation and texture mapping

Digital surface models can be generated from point clouds using the Ball Pivoting Algorithm (Bernardini et al, 1999) (Figure 7). This algorithm can be compared to a virtual sphere rolling over the point cloud surface. The radius of this sphere needs to be large enough so the sphere will not “fall through” the point cloud surface. Starting from a position resting on three points the sphere is pivoted around two points to find a new third one. This procedure is repeated until there are no new triangles of three points to find. Because of the uneven spatial distribution of points in a point cloud one radius is not enough to ensure the ball pivoting algorithm can triangulate a complete point cloud. The solution to this problem was found in triangulation with multiple radii (Vetter, 2005).

Figure 6: Anaglyph image with automated measured horizontal and vertical profile lines

4. RESULTS OF STEREO EVALUATION

The primary results of automated stereo evaluation are dense point clouds of the object surface similar to those of scanning techniques. Extracting the 3D information out of images automated stereo photogrammetry allows for assigning colour information to every point directly. This “textured” point cloud gives a very illustrative first impression of the digital 3D model.

Figure 7: Result of surface triangulation using Ball-Pivoting-Algorithm

For the final textured 3D model the points of each triangle are projected into the relevant images via the collinearity equations (Figure 8). The angle between normal vector of the triangle and the image ray determines which image colour information is taken from. Finally the image coordinates for every triangle are saved as texture coordinates and can be exported with the 3D model as STL or VRML files.
4.2 Ortho image generation

For work on architecture and building fragments two-dimensional projections like elevations still are the most important means of documentation. The survey is normally done in hand measurement. Only objects that are difficult to reach, that show a complex three-dimensional structure, or especially those that are so badly preserved that large parts of the object show an amorphous surface take a long time to survey. As geometrical support for drawn documentation ortho images can help to save the best part of this time. After setting scale and resolution of the ortho image a projection plane needs to be defined using points or planes of the model itself. For every point of the image the piercing point, that is located orthogonal to the projection plane on the model, is determined. The coordinates in the stereo-images are calculated through collinearity equations and the colour information for the ortho image is determined via suitable interpolation (Figure 9). The generated images can be imported to CAD systems, or printed out as scaled reference for hand drawings.

5. FURTHER AREAS OF APPLICATION

Collaboration with building historians and archaeologists has shown further areas of application for stereoscopic object documentation in archaeological research projects. For example this technique can be used for documentation of finds and sherds. Due to the smaller size of these objects base distance and object distance need to be reduced. At the same time the reduced size meant it was possible to develop a frame with defined pass-points marked up to hold the objects (Figure 10). Using this installation, stereo models of both sides of an object can be related directly. For the archaeological analysis of sherds high resolution 3D models and especially profiles are needed for classification (Figure 11). Another area of application is documentation of archaeological sections and soundings. Automated stereo photogrammetry is a time efficient and easy to apply technique to cover layers of different colour and objects in archaeological profiles. Again ortho images are result most asked as they can be used as a base for hand drawings.

6. CRITICAL REVIEW AND PROSPECTS

At the present stage it is proven the concept of automated stereo photogrammetry is suitable for a number of different applications in archaeology and building history (see Boochns et al, 2007 or commercial software PhotoModeler-Scanner by Eos Systems Inc.). Using digital SLR cameras for stereoscopic image acquisition a light weight and cost efficient surveying system has been developed that offers a high level of flexibility. There is no need for special lighting of the object. Batteries inside the cameras allow for fieldwork independent of additional electricity.
The automated functions presented here facilitate accurate and comprehensive documentation that needs little time and hardware. The level of detail and accuracy depends on the image configuration and the cameras used. The quality of the resulting point clouds is on par with scanning technologies that necessitate much higher expenses. At the same time evaluation of high-resolution images offers additional information on surface quality on top of geometrical data. These advantages over other scanning technologies recommend stereo photogrammetry for many different applications in archaeology and building archaeology.

At the same time an extensive series of tests has shown potential for further development. Automated stereo photogrammetry is based on the correlation of two image patches in both images. This is possible only if there is an irregular surface structure to compare. Surfaces without, or with a regular structure cannot be covered with this technique as well as gleaming surfaces. In those cases auxiliary measures like speckle texture projection or temporary surface coating are needed.

In a standard workflow evaluation of stereo models will be separate from data acquisition. Thus a check of the results will be possible only after fieldwork. The time needed for generating a point cloud depends on the chosen density of image points, image resolution and scale of the image. At present calculation of one point cloud from one image pair typically takes 1–2 hours using recent hardware. An implementation of batch handling allows to go through a swift procedure of set up before starting the user-independent evaluation process for more than one model at a time. Further work steps to produce 3D models or ortho images are identical in time and effort to processing of point clouds of other scanning techniques.

As a result of the technical approach edges are smoothed or rounded depending on the size of the search matrix in the matching process. Future work will focus on an implementation of automatic edge detection for 3D - modelling.

Linking multiple stereo models via interactively defined pass points has been proven to be the part of the workflow that is most inflexible and complicated in handling. A better solution should be found in orientation of models using overlapping point clouds via surface matching (see i.a. Gruen & Akca, 2004). For this only the relative orientation of a stereo model is needed. The point clouds are generated independently in different model spaces and transformed into one object system later. This is achieved minimizing the point distances of overlapping areas of point clouds.

Another potential field for optimization is data acquisition on site. Major simplification of the process can be achieved through use of two calibrated cameras for synchronous recording of images. This would mean a serious saving in time as it affects different aspects of the workflow. As a one-camera system has to rely on a very stable basis there is need for a heavy camera system that could possibly be operated without support. And further parts of the evaluation process could be automated like the identification of image pairs by the time taking the image. As a surplus accuracy would be further increased by the then fixed stereo configuration.

For the tests until now calibration of the cameras was limited to only a number of focus settings. This predefined set of required focus accuracy for different focus settings. And finally the system is in a prototype stadium that shows a lot of potential for optimizing weight and handling. Quality and accuracy of the results in this technology depend on stereo configuration on site, and later on a number of parametrical settings during evaluation. This refers to orientation, and automated measuring as well as triangulation and final production of ortho images. The layman user of the software has to rely on preset parameters in the software and cannot objectively evaluate quality of the result. At the same time the professional needs access to as many parameters as possible. To make the system an easy and reliable tool for the end-user the software part of it needs to be as self-explanatory as possible with an appropriate level of guidance that does not put off either professionals or first time users.

The functionalities of automated orientation and evaluation in stereoscopic image pairs have been developed in collaboration between focus GmbH Leipzig and the chair of surveying at University of Technology Cottbus. The software metigoStereo is being developed as a user-oriented tool in the field of architecture, building archaeology, archaeology and preservation.

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