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OPTIMIZING THE PHOTOGRAMMETRIC NETWORK TO RECORD MOZART'S PIANOFORTE

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Abstract

The pianoforte in the Mozarthaus at Salzburg is a state of the art instrument of the late 18th century. It was recorded photogrammetrically in order to enable fundamental musicological investigations to be carried out. An important aspect of the piano survey was high precision three dimensional point determination performed by combined bundle adjustment. The process was optimized by use of software tools for simulation, automatic error detection and graphical analysis of the adjustment results. This procedure considerably increased the efficiency and reliability of the photogrammetric reconstruction.

INTRODUCTION

DURING THE past decade, close range photogrammetry has been successfully applied to a large number of measuring tasks in architecture, industry, medicine and other fields. This development has been substantially advanced by the introduction of efficient software tools, in particular programs for bundle triangulation (Rüther, 1989). Bundle adjustment is now a well established method for:

(a) three dimensional reconstruction of discrete object points;
(b) spatial orientation of photogrammetric bundles (analogue and digital images);
(c) simultaneous processing of various types of photogrammetric and geodetic observations;
(d) calibration of analogue and digital imaging systems; and
(e) deformation analysis.

Objects to be surveyed in close range photogrammetry vary considerably in size and shape. User defined, object specific accuracy requirements and environmental conditions together with time constraints must be taken into account. Image acquisition equipment, network design and data reduction software have to be combined in order to perform both the on site survey and the object restitution precisely, reliably and economically.

In this paper, the varied and complex process of optimization is not treated theoretically, based on a general once and for all design concept. Optimization also embraces a series of considerations, practical tests and decisions which relate to subjects such as selecting the imaging system, the planning and simulation of the photogrammetric network, image measurement, and bundle adjustment including blunder detection and analysis of the measurement results. The PC based software package CAP (Combined Adjustment Program) (Hinsken, 1989; Hinsken *et al.*, 1992) was used for the investigations described. As a very attractive case study, Mozart's pianoforte exhibited in the *Mozarthaus* museum at Salzburg, Austria was chosen (Fig. 1).

The main purpose of the paper is to give some practical hints and present some useful tools for surveying close range objects efficiently.

Mozart's Pianoforte

Around the year 1700, the first effective hammer mechanisms for keyed instruments were constructed (Restle, 1991). During the course of the 18th century, a great number of different types of mechanisms were developed. The instruments were called *Piano-Forte, Fortepiano* or even *Cembalo*, despite the fact that hammers were used instead of quills to produce tones.

Unfortunately, only poor or non-existent geometrical information is available on the early pianofortes, in particular on instruments made in Austria, Germany and Italy (Badura-Skoda, 1980). Plans do not exist and it is a complicated task to obtain precise and reliable measurements over the entire instrument which relate to a common object co-ordinate system. However, such information is necessary for the detailed investigations required to understand this part of our cultural heritage, in other words to allow for the correlation between the geometrical arrangement and the sound pattern, for comparison of several pianofortes of the same epoch and for the construction of replicas.

These ideas have been combined in a research project established by musicologists which includes the photogrammetric survey of about 15 major instruments of the 18th century.

Old and valuable pianofortes, being sensitive to variations in temperature, are usually exhibited in museum rooms with air conditioning. To date, surveys have been accomplished, by hand measurement only, whenever an instrument was partially dismantled for restoration. These measurements are not sufficiently accurate for research purposes and they do not relate to a common co-ordinate system. Precise investigations and also the construction of replicas require a measuring accuracy of about a few tenths of a millimetre. However, precious and famous musical instruments have to be surveyed on site as quickly and carefully as possible. Photogrammetry is thus the appropriate measuring technique.

The pianoforte in the *Mozarthaus* at Salzburg (Fig. 1) is a state of the art instrument of the late 18th century, a masterpiece of mechanical engineering and craftsmanship (Restle, 1992). One important aspect of the photogrammetric survey of this instrument is the determination of three dimensional co-ordinates of discrete object points yielding, for example, the ground plan of the piano. The survey also includes the calculation of the positions of hundreds of pins which are driven into the bridge, nut, wrestplank and hitchpin-rail of the instrument to enable the stretching and fastening of the piano strings. All the spatial data obtained are to be transferred to a CAD system (AutoCAD) for further processing by a musicologist.

Network Design and Optimization

In order to optimize the photogrammetric survey of Mozart's pianoforte, the object specific requirements can be summarized as follows:

(a) the *in situ* measurement has to be carried out rapidly (within hours) and with care;
(b) the environmental conditions in the museum demand lightweight and easily portable recording equipment;
(c) a digital ground plan of the instrument has to be derived;
(d) three dimensional co-ordinates are required for a multitude of pins; and
(e) the accuracy of the resulting three dimensional object co-ordinates to be introduced into the CAD system should amount to a few tenths of a millimetre.

These requirements can be fulfilled by means of satisfactory measuring equipment and efficient software, including tools for optimizing the network design.

FIG. 1. Mozart's pianoforte.

Imaging System

The preconditions mentioned above allow neither the application of conventional metric cameras nor of non-metric 35 mm and CCD cameras. Metric cameras are too heavy, cumbersome and difficult to handle, in particular for vertical photographs taken from above the pianoforte. On the other hand, the use of small format cameras leads to a very large number of photographs being required to cover the instrument completely because otherwise the accuracy of object reconstruction would decrease substantially as a result of the smaller image scale. Therefore a partially metric, medium format Rolleiflex 6006 réseau camera equipped with 50 mm wide angle lens was chosen. Due to the flexible camera handling and automatic camera operations such as exposure metering, remotely controlled shutter release and film transport, an image block can be taken in a short time. Where there are high accuracy requirements, it has to be appreciated that the interior orientation of a partially metric camera can neither be assumed to be stable for a long period of time, nor to be known *a priori*. Therefore, the network design must enable a simultaneous ("on-the-job") camera calibration within the object reconstruction process (Wester-Ebbinghaus, 1986).

Definition of the Object Co-ordinate System

Prior to the description and analysis of the network design used to survey the pianoforte given in the following section, the datum definition must be discussed, in other words the way that the photogrammetric network, consisting of camera stations (projection centres), bundles of rays and object points, can be linked with an object-specific "piano co-ordinate system".

Three dimensional co-ordinates of control points on the pianoforte determined by geodetic measurements enable a transformation to be made between photogrammetric data and a piano reference system (absolute orientation with seven parameters: shift in

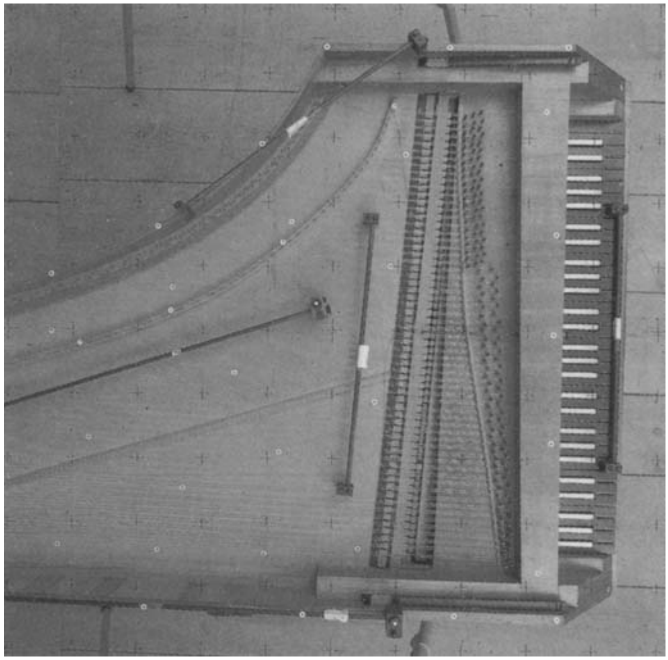

FIG. 2. Vertical photograph of the instrument.

X, *Y* and *Z* directions, rotation about *X*, *Y* and *Z* axes, and scale factor). However, a geodetic survey, for example using theodolites, is not acceptable in museum rooms.

A well-known and efficient solution of this problem is to define the photogrammetric network in an arbitrary local object co-ordinate system that is only correctly scaled. Information with regard to scale can be obtained simply and quickly by adding distances of known length to the object, for example calibrated scale bars.

The use of distances as the sole information in object space leads to an equation system which is rank deficient, because the datum of the network is still incomplete in shift and rotation. The best remedy in this case is provided by a partially free network adjustment that allows the determination of the remaining datum parameters without imposing any constraint on the shape and scale of the object. The standard deviations *a posteriori* of the datum points (object points onto which the network is fitted in order to remove the rank deficiency) become a minimum. In addition, the object point accuracy is obtained homogeneously and is unbiased (Koch, 1988).

Network Planning and Simulation

As mentioned previously, the Rolleiflex 6006 réseau camera is well qualified for a fast and versatile photogrammetric survey. At a first glance it seems to be straightforward, even sufficient, to "fly" over the pianoforte in order to produce an image strip or several strips of vertical photographs at an appropriate image scale (Fig. 2). The entire area of interest can be covered and the ground plan can be generated by stereocompilation. This approach is comparable to the use of aerial triangulation, but at a larger scale. The question is whether such an image block can fulfil the accuracy requirements.

Simulation studies have proved to be a useful tool for establishing an optimum network design. The CAP bundle triangulation program incorporates such a simulator called CAPSIMU as an optional module. CAPSIMU works interactively in the graphics mode of a personal computer. The user can easily choose suitable parameters for camera stations and exposure directions. A cluster of object points with given three

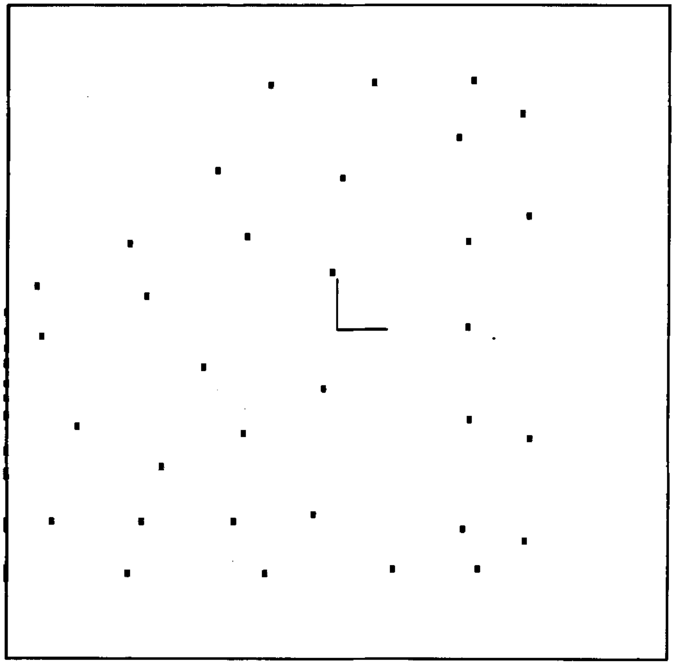

FIG. 3. Simulated image data for vertical photograph shown in Fig. 2.

dimensional co-ordinates is then projected into pre-selected image planes. The graphical representation of these data is immediately displayed on the monitor (Fig. 3). Simulated images which are considered to be essential for setting up the image block can be saved for the combined adjustment with CAP. Even complex image blocks may be generated with CAPSIMU within minutes.

The simulation for the pianoforte project was started with an image strip taken from above the instrument (vertical photography as represented by Fig. 2). With a forward overlap of 70 per cent, a base to height ratio of 1:3 and an image scale of 1:20, six vertical photographs were sufficient to cover the object. The piano was represented by some 70 object points with three dimensional co-ordinates derived from the approximately known size of the instrument. It was intended to use targets for the triangulation due to the lack of well defined natural points. The image co-ordinate accuracy was assumed to be ± 3 μm (σ_0 *a priori*) in accordance with the measurement accuracy of an analytical plotter.

The partially free adjustment of this image block revealed the following effects:

(a) the internal accuracy in the exposure direction (the Z co-ordinate of object points) was too poor (standard deviation *a posteriori* = $\pm 115 \times \sigma_0$ *a priori*);
(b) the lack of height control deformed the object point field, mainly in the Z direction, by a magnitude of 0·40 mm (a typical deformation experienced with strip triangulation in aerial photogrammetry); and
(c) the depth of the object field relative to the exposure distance was less than 15 per cent, which is not sufficient for simultaneous camera calibration.

The results of the adjustment were unacceptable for the piano survey. However, convergent images can easily be taken in addition to the vertical photography in order to improve the ray intersection geometry and stabilize the network. Therefore, convergent photographs forming a closed image block around the object were added to the previous image strip (Figs. 4 and 5). These photographs substantially improved the

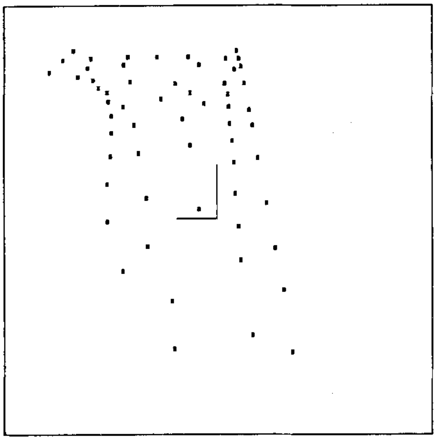

FIG. 4. Simulated image data for convergent photograph.

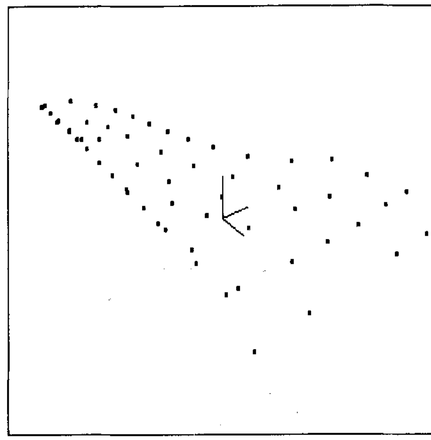

FIG. 6. Simulated image data for convergent photograph taken for point positioning of pins.

network geometry and increased the number of rays per point. The relative depth of field now amounted to 50 per cent or more. The adjustment demonstrated satisfactory stability and reliability in the following respects:

(a) the overall internal accuracy of the object point co-ordinates is very homogeneous and is better than $\pm 13 \times \sigma_0$ *a priori* in all directions;
(b) no block deformation in the Z direction exists; and

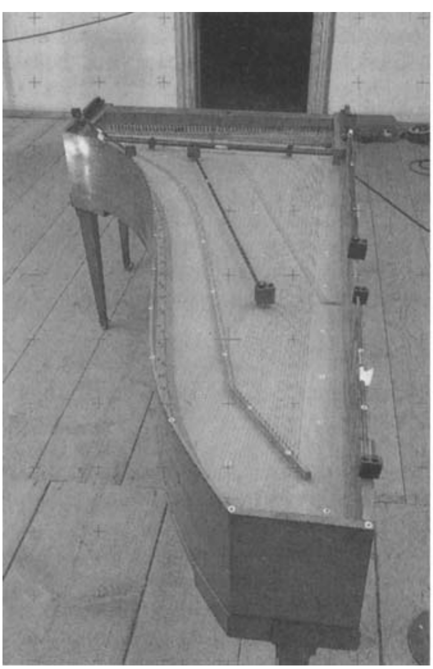

FIG. 5. Convergent photograph corresponding to Fig. 4.

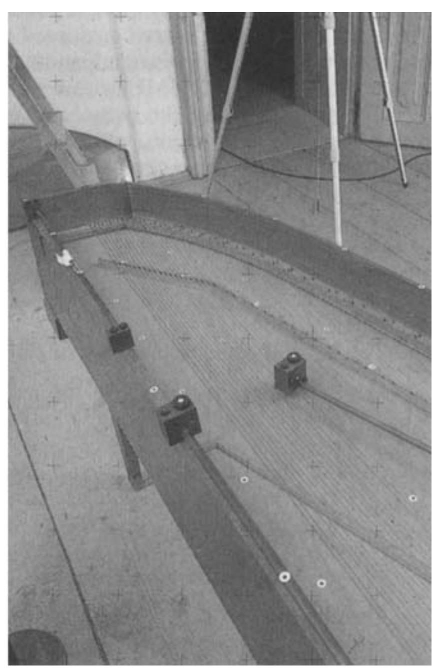

FIG. 7. Convergent photograph (detail) corresponding to Fig. 6.

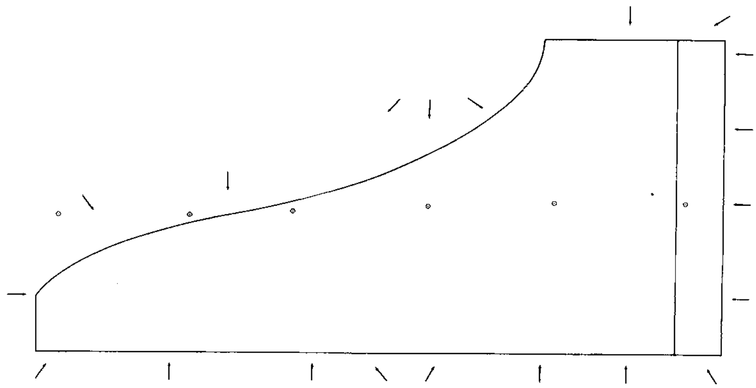

FIG. 8. Schematic ground plan of the piano with exposure station positions (circles indicate vertical photographs, arrows represent convergent photographs).

(c) the camera can be reliably calibrated with an accuracy of better than $\pm 2 \times \sigma_0$ *a priori* for the position of the projection centre in image space.

This arrangement guarantees an accuracy of a few tenths of a millimetre for the piano reconstruction and also for stereocompilation if the stereomodels are oriented by means of the adjustment results.

Consideration also had to be given to the determination of the positions of some hundreds of pins. For this purpose additional convergent photographs were simulated using the same camera (Figs. 6 and 7). These images must have a larger scale in order to identify the pins clearly. The extended image block did not improve the network geometry significantly. Moreover, it was decided to exclude the pin points from the bundle triangulation, allowing them to be determined by intersection using the orientation parameters calculated in the adjustment. Further reasons for this procedure were:

(i) the image measurement accuracy of the pins (non-targeted points) is two to three times lower than that for the targeted triangulation points; and
(ii) simultaneous mass point determination increases the computing time of the adjustment process.

The analysis of the intersection showed that the pin point co-ordinates could be determined with an accuracy of $\pm 17 \times \sigma_0$ *a priori* resulting in $\pm 0{\cdot}10$ mm for an image measurement accuracy of $\pm 6\ \mu$m.

By means of CAPSIMU and CAP, the network design studies could be completed and analysed within a few hours.

PROJECT ACHIEVEMENT AND ANALYSIS

The photogrammetric network for the survey of Mozart's pianoforte was set up according to the results of the simulation (Fig. 8). For the purpose of triangulation, some 70 points (self-adhesive, removable targets) were distributed over the instrument. Scaling information was provided by six carbon fibre scale bars with a calibrated target spacing of approximately 0·5 m and 1·0 m $\pm$ 0·05 mm (Figs. 2, 5 and 7).

The co-ordinates of all marked points were measured in the 26 images on a Zeiss Planicomp P2. Film deformations were corrected by means of a meshwise réseau correction (bilinear spline interpolation: Kotowski, 1984).

Initial values of object point co-ordinates and exterior orientation parameters were determined with the CAP option INIVAL, a set of orientation programs (relative orientation, absolute orientation and spatial resection). These programs do not need any initial estimates to be given as input information. Algorithms for automatic blunder

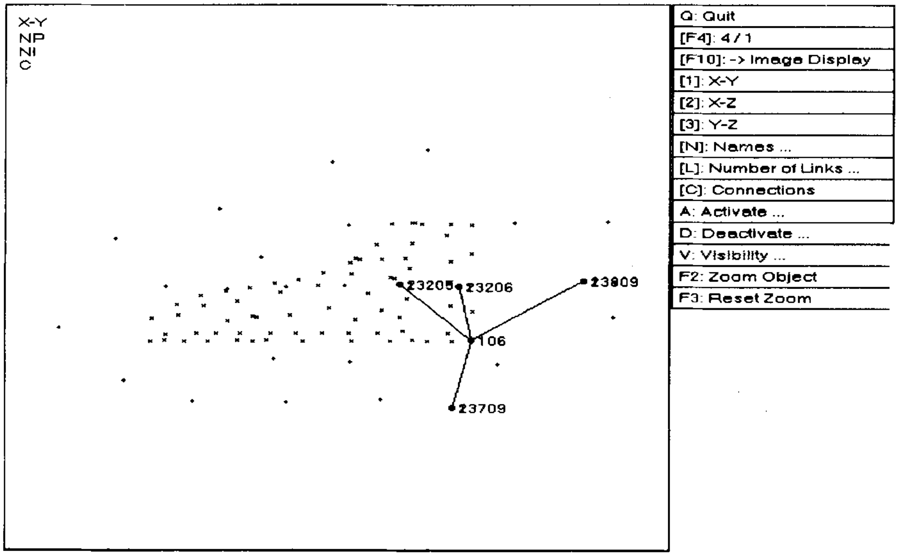

FIG. 9. Graphical analysis (object mode): ground plot of exposure stations, object points and the connecting rays for object point 106.

detection and elimination are implemented. Severe measuring errors can be detected in this preparation phase and prevented from interfering with the bundle adjustment.

The triangulation of the photogrammetric bundles, including simultaneous calibration of the partially metric camera, was performed as a partially free adjustment to solve for the rank deficiencies in shift and rotation of the object co-ordinate system. The three dimensional point co-ordinates were calculated with an accuracy of better than $\pm$ 30 μm, confirming the results of the simulation studies. Finally, these co-ordinates were transformed into a piano reference system defined by the musicologist. Spatial point co-ordinates and image orientations determined by the bundle adjustment were used for subsequent object restitution by stereocompilation and intersection.

The complete adjustment procedure, including error propagation and blunder detection, only takes a few minutes to complete. Optionally, CAP produces files for the graphical analysis of adjustment results with the GRAV program module. GRAV allows the network geometry to be visualized with respect to point distribution (according to different point types, for example, control points, new points, datum points), camera stations, ray intersections and detected blunders (Fig. 9). In the image mode, which can be chosen simultaneously, the point distribution of each individual image can be displayed and the residuals can be checked for remaining systematic errors (Fig. 10).

In conclusion, it can be stated that the software tools added to the well-established CAP close range bundle adjustment package proved to be suitable for the design and optimization of the photogrammetric network for the reconstruction of Mozart's pianoforte. In particular, the use of simulation studies and graphical data representation resulted in increased efficiency and reliability for the triangulation procedure.

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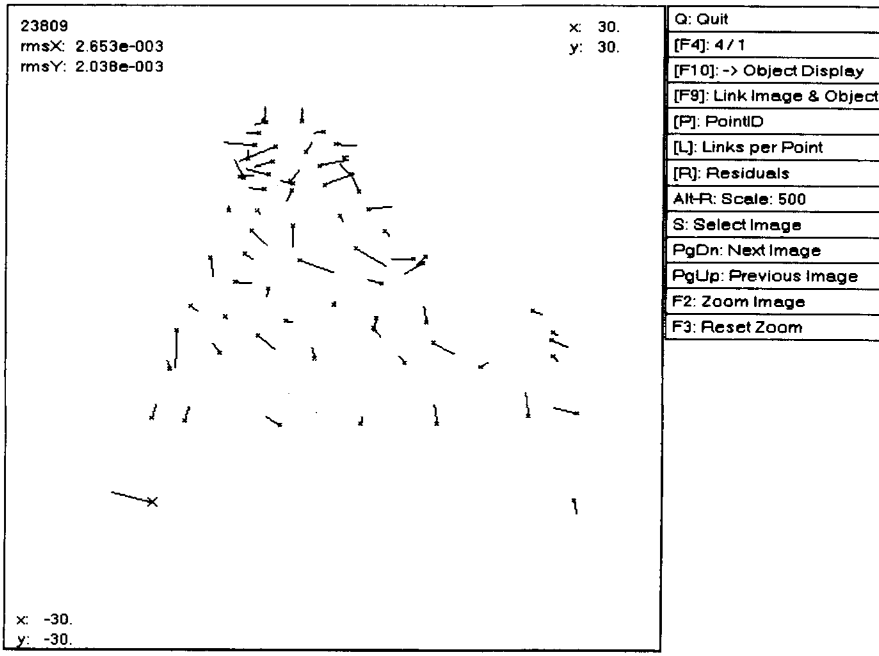

FIG. 10. Graphical analysis (image mode): image points and residuals of image 23809 (corresponding to Fig. 1).

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Résumé

Le piano du Mozarteum de Salzbourg est un instrument caractéristique de l'état de l'art de la fin du 18ème siècle. On l'a archivé photogrammétriquement, de façon à pouvoir effectuer les recherches musicologiques de base. Une phase importante de relevé de ce piano a été la détermination de haute précision de points en trois dimensions, que l'on a effectuée avec une compensation combinée par faisceaux. On a optimisé la méthode en utilisant des *outils logiciels permettant la simulation, la détection automatique des erreurs, et l'analyse graphique des résultats de la compensation. On a pû ainsi, avec ce procédé, accroître l'efficacité et la fiabilité de la reconstitution photogrammétrique.*

Zusammenfassung

Das Hammerklavier im Salzburger Mozarthaus zeigt den hohen Stand des Instrumentenbaus gegen Ende des 18. Jahrhunderts. Es sollte photogrammetrisch aufgenommen werden, um grundlegende musikwissenschaftliche Untersuchungen zu ermöglichen. Hochgenaue dreidimensionale Punktbestimmung war eine wesentliche Aufgabe der Klaviervermessung. Sie wurde durch kombinierte Bündelausgleichung gelöst und mit Hilfe von Programmen für Simulation, automatische Fehlererkennung und graphische Analyse der Ausgleichungsergebnisse optimiert. Diese Vorgehensweise steigerte die Produktivität und Zuverlässigkeit der photogrammetrischen Rekonstruktion erheblich.