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BUNDLE TRIANGULATION IN ARCHITECTURAL PHOTOGRAMMETRY: THE BASILICA OF SAN FRANCESCO IN SIENA

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Abstract

Bundle triangulation is an efficient tool for spatial point determination in architectural photogrammetry. All the information available in image and object space may be introduced in a combined adjustment yielding high precision and reliability. Camera calibration performed simultaneously with the object restitution process enables the application of convenient and flexible imaging systems based on professional photographic technology. Thus the survey of monuments can be carried out rapidly with a minimum of personnel and equipment. The photogrammetric recording of the basilica of San Francesco in Siena is presented as an example of the application of this survey procedure. The field work was accomplished in a few days. The equipment used consisted of a partial metric camera, an engineering theodolite and a tape. The bundle adjustment results gave spatial object co-ordinates with a r.m.s.e. of ± 15 mm for a point.

INTRODUCTION

ANALYTICAL TRIANGULATION of metric photographs covering the earth's surface has been a standard procedure in aerial photogrammetry for a long time. The exterior orientation parameters of the photographs and the spatial co-ordinates of ground points are calculated by block adjustment. For the past few years bundle triangulation has also been applied to close range photogrammetry in the industrial and engineering sectors, as a combined adjustment of photogrammetric bundles and additional geodetic information such as object co-ordinates, distances, height differences and directions. Powerful software packages provide the precise and reliable determination of all net parameters (Kager, 1980; Brown, 1982; Fuchs and Leberl, 1982; Larsson, 1982; Kruck, 1984; Müller and Stephani, 1984; Wester-Ebbinghaus, 1985).

Compared with the conventional analogue optical/mechanical approach, numerical restitution methods, in general, lead to increased accuracy. All the information available in image space and object space may contribute with an appropriate weight to the solution. Deviations from the central projection as the standard mathematical model of photogrammetry (caused by lens distortion, film deformation and so on) can be modelled and eliminated as far as possible. It is feasible to take advantage of the application of partial metric cameras which are based on professional photographic technology instead of metric cameras. Moreover, numerical restitution methods allow flexible network design, for example by including convergent photographs and various geodetic observations.

Bundle triangulation has rarely been utilised for the survey of architectural objects up to now. The recording of a large building, the basilica of San Francesco in

Siena, Italy, is presented in order to illustrate the efficiency of this photogrammetric restitution method. The project was carried out in co-operation with the *Deutsches Kunsthistorisches Institut, Florenz.*

The basilica of San Francesco (Figs. 1 to 3) was built in the Gothic style between 1326 and 1475. It has a T-shaped ground plan typical of a church of a monastic order. The monument is more than 80 m long and is situated on the outskirts of Siena. Along three sides of the building the ground drops steeply down to a valley (Fig. 4).

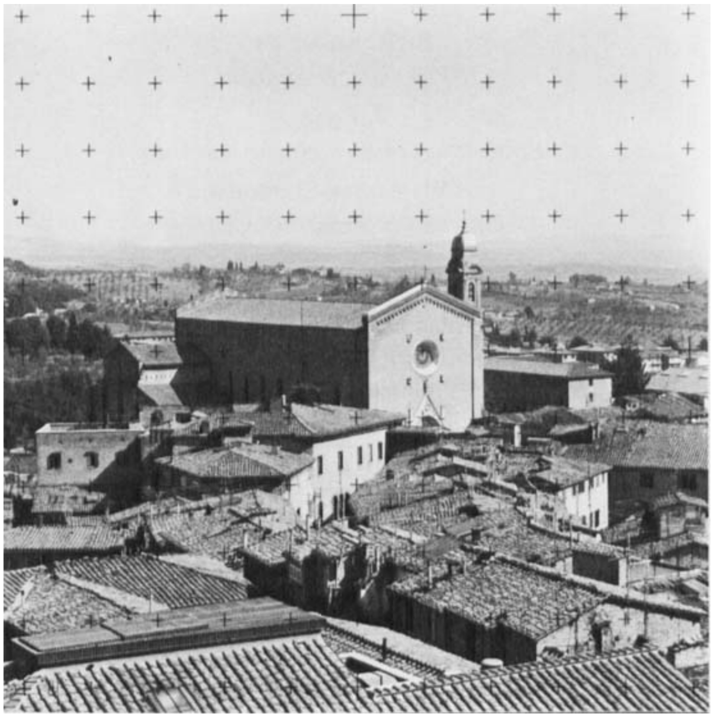

FIG. 1. Basilica of San Francesco, Siena: view from the west to north-west and south-west façades.

The work *in situ* was completed in a few days. The equipment used consisted of a partial metric camera, the Rolleiflex SLX Réseau, an ordinary engineers' theodolite and a tape. Spatial point co-ordinates were determined by bundle adjustment with the program MOR.

The objective of the photogrammetric work was to establish a dense three dimensional point field inside and outside the church relating to a common co-ordinate system in order to obtain control points for stereoplotting and to calculate distances, height differences and angles of interest. The results of the survey provide the basis for an inventory and for proportion studies in architectural geometry as part of a research project entitled "The churches of Siena" (Riedl and Seidel, 1985; Kotowski *et al.*, 1986).

Bundle Triangulation

Fig. 5 shows that object points can be spatially defined by the intersection of at least two bundles of rays. If the rays are measured in local co-ordinate systems (for example X^*, Y^*, Z^* in Fig. 6), the intersection of rays can be realised by the spatial orientation of these local systems. A triangulation network consisting of more than two bundles provides higher accuracy and increases the reliability of detecting gross data errors (Fig. 7). Instead of measuring the rays on site by means of a theodolite (Fig. 8), they can be recorded photographically with a photogrammetric camera and

FIG. 2. Basilica of San Francesco, Siena: view from north to north-east façade.

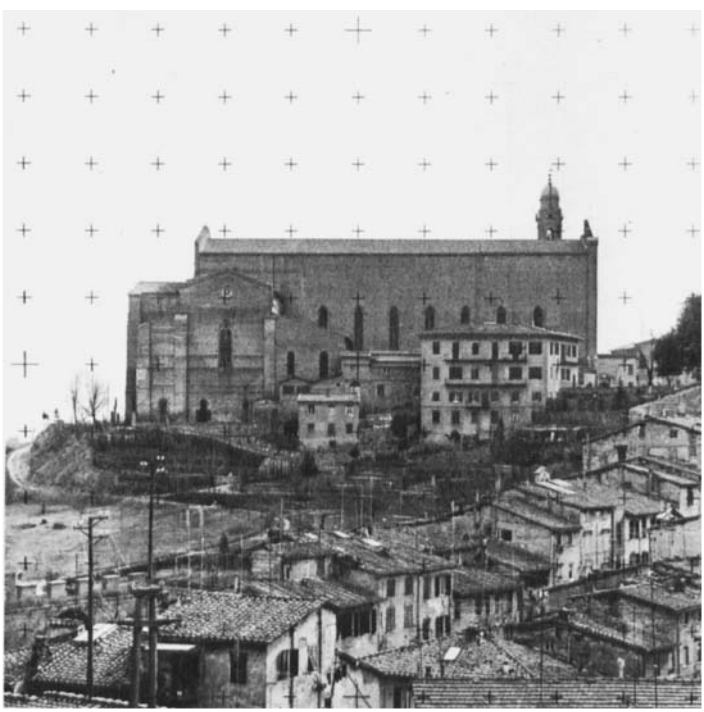

FIG. 3. Basilica of San Francesco, Siena: view of north-west façade.

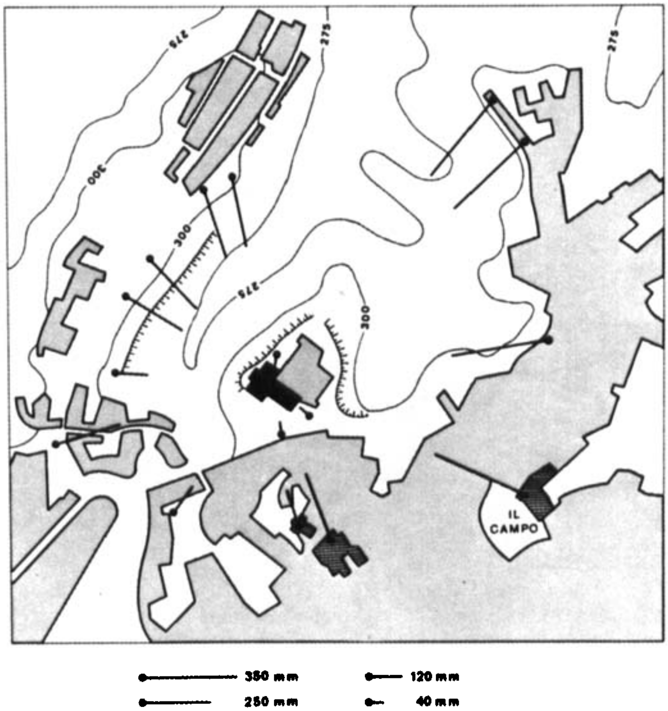

FIG. 4. Map of the site. The positions of the exposure stations around the church are shown and the various lenses used are indicated.

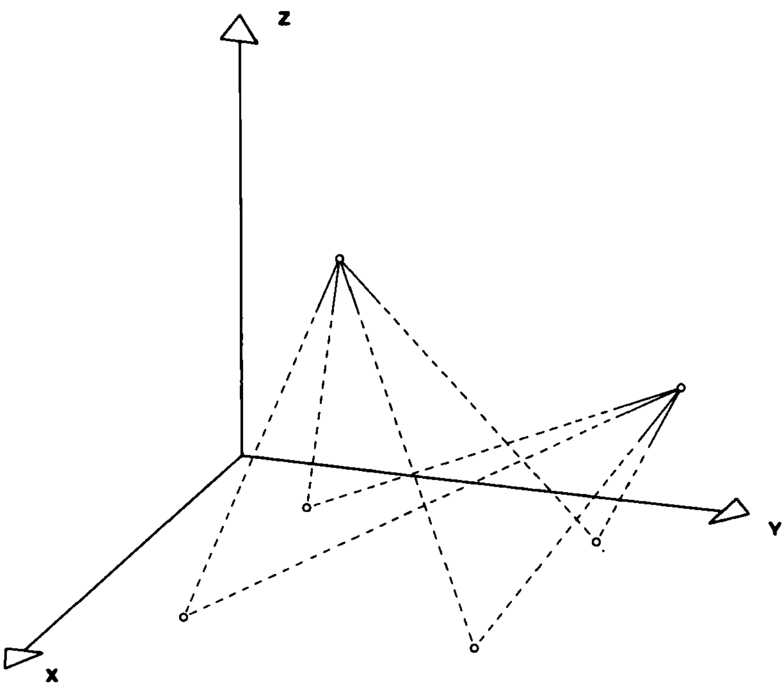

FIG. 5. Spatial point determination by the intersection of two bundles of rays.

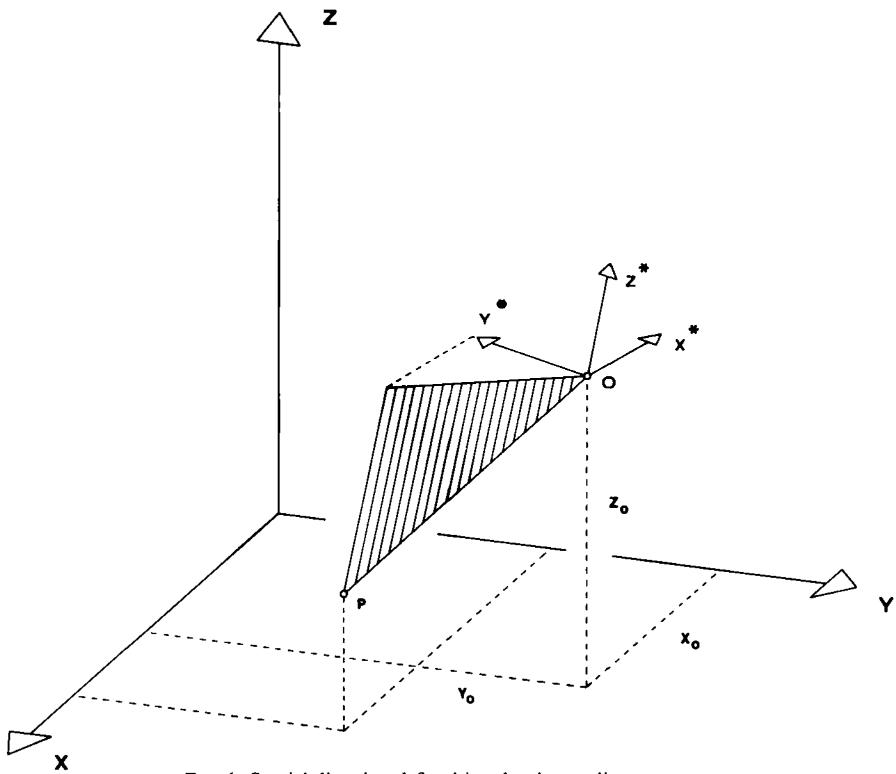

FIG. 6. Spatial direction defined in a local co-ordinate system.

reconstructed by means of the image points. The direction of rays in the local system X^*, Y^*, Z^* of the photogrammetric camera is given by the co-ordinate differences between the image points and the perspective centre (Fig. 9). Therefore the bundle can be reconstructed in image space if the image points and the perspective centre are defined in the same co-ordinate system.

The mathematical model of photogrammetric bundle triangulation assumes a plane image surface. That can be achieved mechanically by using photographic plates or by a film flattening device (Fig. 10). By incorporating a glass plate with réseau crosses into the imaging system, the geometric effect of film unflatness during exposure and any image deformation after exposure may be corrected numerically (Fig. 10).

In conventional photogrammetric cameras, the position of the perspective centre in image space, defined by the principal distance c_k and the principal point H (interior orientation shown in Fig. 9) is considered to be instrumentally fixed (metric camera) and is predetermined together with the lens distortion by laboratory or test field calibration.

A spatial photogrammetric network such as that shown in Fig. 11 allows the camera to be calibrated simultaneously within the bundle triangulation process using the constraint that homologous rays have to intersect in object space (further possibilities for simultaneous camera calibration are given in Wester-Ebbinghaus (1986)). Under these conditions it is not necessary to use metric cameras which are inflexible with regard to the photographic recording. Simultaneous camera calibration allows modern photographic technology to be used, including interchangeable lenses, a precise viewfinder, motor drive and automatic exposure. It is only necessary to ensure that the camera provides a well defined image plane with a corresponding image co-ordinate system and also that the interior orientation is constant during a series of exposures as shown in Fig. 11 (partial metric camera; Wester-Ebbinghaus (1983)). A very useful method of achieving a powerful partial

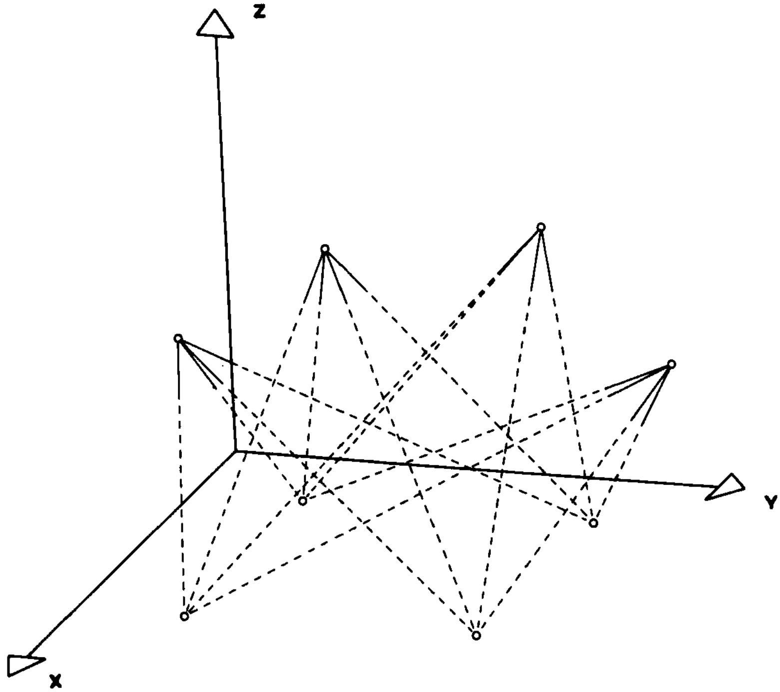

FIG. 7. Multibundle triangulation.

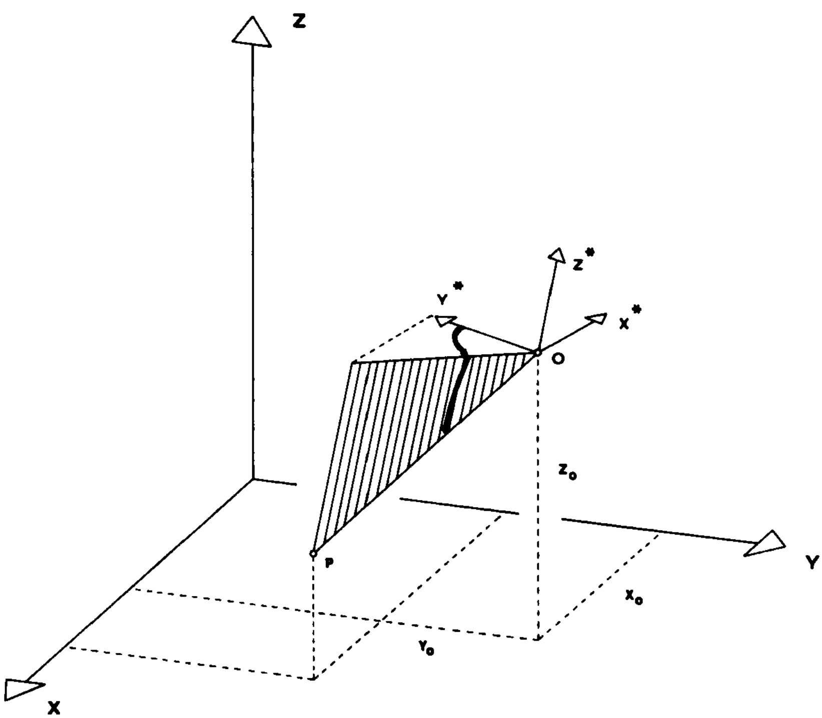

FIG. 8. Spatial direction defined in the local co-ordinate system of a theodolite.

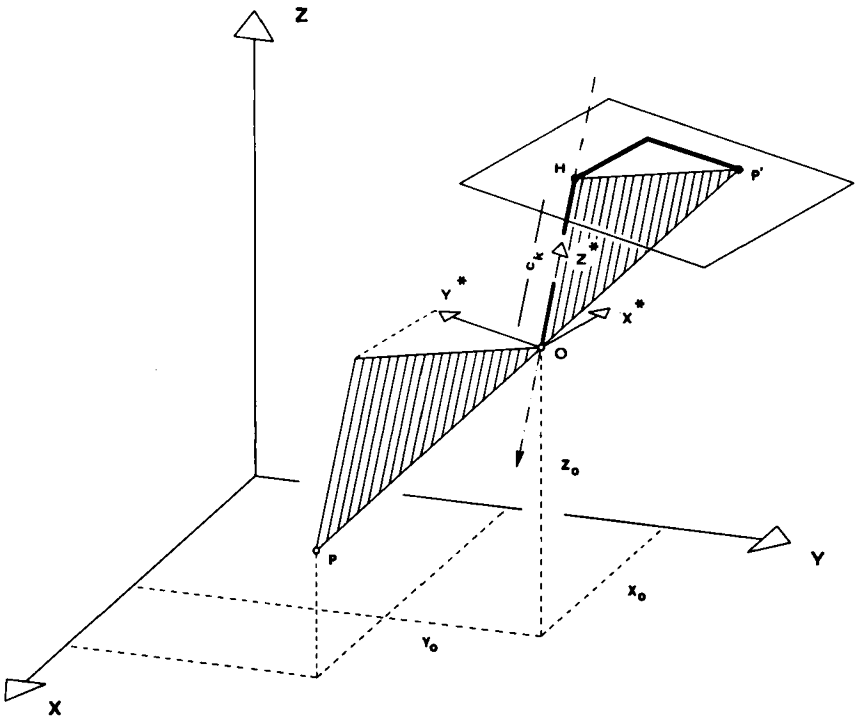

FIG. 9. Spatial direction defined in the local co-ordinate system of a photogrammetric camera.

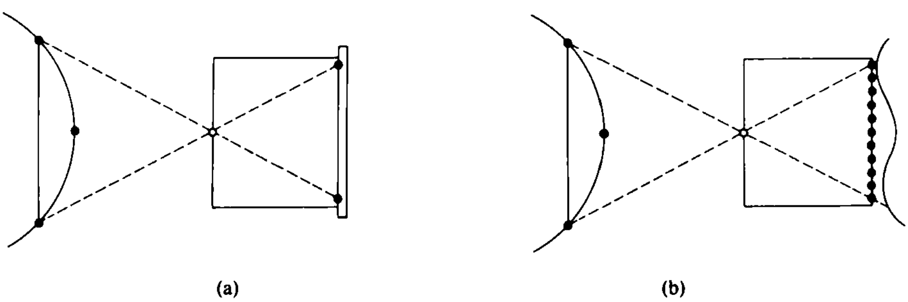

FIG. 10. Photogrammetric camera. (a) Image surface flattened mechanically. (b) Image surface transformed numerically into a réseau plane.

metric camera is to equip a professional non-metric camera system with a réseau glass plate in front of the film surface.

The ideal conditions for bundle triangulation are given in a least squares adjustment whereby all the information available in image and object space is combined in one numerical approach (bundle adjustment). Besides the image co-ordinates, additional observations can be introduced such as distances, directions, height differences and the co-ordinates of control points in order to stabilise the bundle orientation and to define the scaling, the levelling, the azimuth and the spatial translation of the photogrammetric model. Simultaneous camera calibration may be supported by using previously determined parameters of interior orientation as additional observations in the actual adjustment. (Possibilities for additional observations in bundle adjustment are described, for example, in Wester-Ebbinghaus (1985)). All the observations are included with correct weighting according to their *a priori* defined accuracy. The adjustment results in values for the spatial co-ordinates of object points and the orientation elements of all photographs.

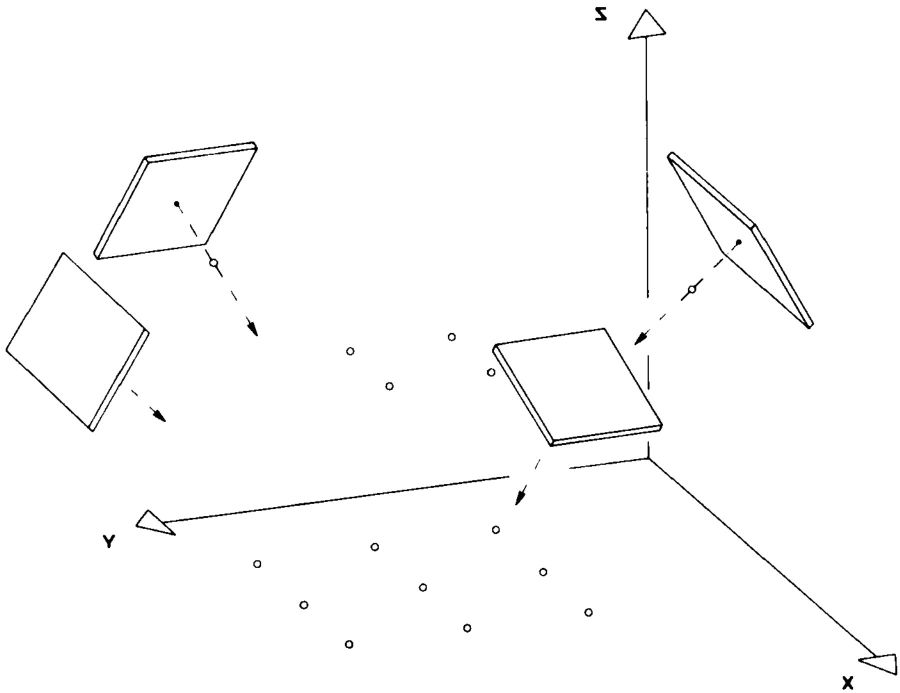

FIG. 11. Multistation phototriangulation for simultaneous camera calibration.

SURVEY CONCEPT AND PRACTICE

For the photogrammetric survey of architectural monuments, the situation *in situ* is important when carrying out the field work. The shape, position and size of the object as well as the topography have to be taken into account in order to yield an optimum network design for the particular monument. Moreover, optimisation in an economic sense is also demanded for the field work. The survey has to be carried out as rapidly as possible with a minimum of personnel and equipment. All the technical and economic requirements can be fulfilled with the sophisticated numerical methods of phototriangulation combined with flexible and convenient recording equipment. The survey of the basilica of San Francesco in Siena is an example which very effectively demonstrates the efficiency and the practicability of such a concept for architectural photogrammetry.

Measuring Equipment

The selection of an appropriate photoscale plays a decisive role when planning a photogrammetric network. A value of 1:1000 can serve as a useful standard to establish a spatial point field with an accuracy of a few centimetres by means of phototriangulation. That is adequate for many applications in architectural photogrammetry. It is assumed that well defined points and sufficient intersecting rays exist and, of course, that the image co-ordinates are precisely measured. Furthermore, the aim should be to achieve optimum utilisation of the photographic format for both geometrical and economic reasons.

These conditions restrict the range of suitable camera positions. Problems arise if only one single metric or stereometric camera with a fixed focal length is available, as is customary in architectural photogrammetry. The application of such a photogrammetric surveying system frequently leads to blind areas and disadvantageous views caused by buildings and topography. A better adaption to local conditions is possible by providing different angles of coverage. However, the expense entailed by the use of several cumbersome metric cameras cannot be justified and certainly cannot be achieved in many cases. It is consequently desirable to have a camera with interchangeable lenses and therefore the Rolleiflex SLX Réseau medium format camera (Fig. 12) produced by Rollei Fototechnic of Braunschweig, FR Germany, was selected for the photogrammetric survey of San Francesco.

FIG. 12. Rolleiflex SLX Réseau partial metric camera system.

Professional photographic technology and low weight are essential advantages of this camera system. Interchangeable lenses with focal lengths between 40 mm and 500 mm are available. In front of the film surface a glass plate with a maximum of 11 × 11 crosses is fixed to the camera body without disturbing any camera function. This calibrated réseau ensures the correction of systematic image errors caused by film shrinkage and local film deformations. In addition, it establishes an image co-ordinate system within which the position of the perspective centre in the image space can be defined. The non-metric camera thus becomes a partial metric camera (Wester-Ebbinghaus, 1983). The elements of the interior orientation (principal distance, principal point position and lens distortion) are determined by calibration. One set of interior orientation data satisfies a series of images produced with an unchanged camera body/lens combination. Over a longer period of time the position of the perspective centre can be reproduced to within ±50 μm after changing the lens, whereas the distortion can be reproduced to within ±5 μm (Wester-Ebbinghaus, 1983; Peipe, 1986).

PHOTOGRAMMETRIC AND GEODETIC FIELD SURVEY

The photogrammetric network design could be adapted to the local conditions with optimum effect by using the Rollei camera equipment. As a result of short photographic distances inside the basilica, the wide angle 40 mm Distagon lens was used exclusively. The image block consists of strips with about 60 per cent forward overlap along the façades to provide models for stereoplotting. However, this configuration shows insufficient geometrical stability. Therefore connecting images of the ceiling and views taken in a diagonal direction were added to improve the network (Figs. 13 to 15). Despite poorly illuminated areas inside the church, the orientation of the camera could be achieved without any problem because the object was clearly imaged on the screen of the precise viewfinder.

The camera equipped with the same wide angle lens was used for some views outside the church to record the main portal side and part of the chancel façade. Fig. 4 shows that the main portal side of the basilica borders directly on a built up urban district, whereas on the other sides the ground immediately drops steeply. It was, therefore, foreseeable that camera positions would be needed at a considerable distance away in order to produce a closed block. Photographs taken from a distance of some hundred metres could be accepted by using long focus lenses (Fig. 4). In this way it was possible to include elevated camera positions (for example the top of the tower of the Town Hall) which offer virtually unobstructed

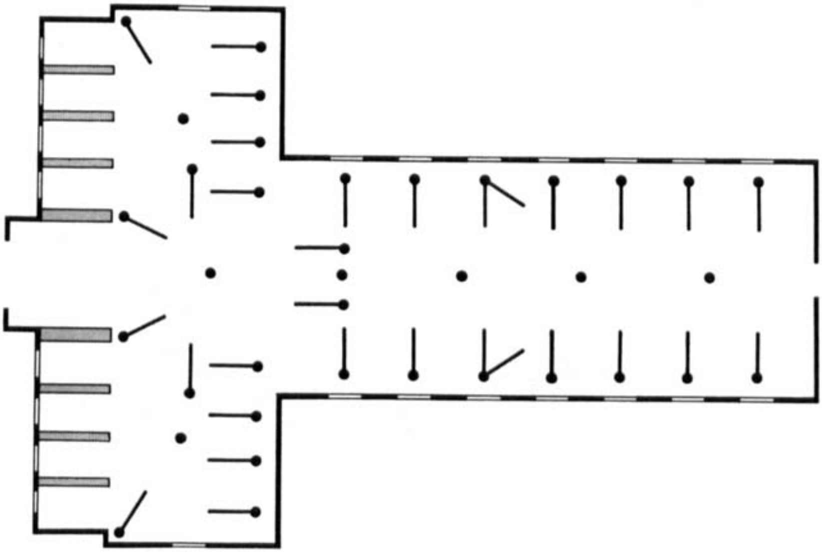

FIG. 13. Configuration of photographs taken inside the church using the 40 mm lens (the dots denote zenith photographs).

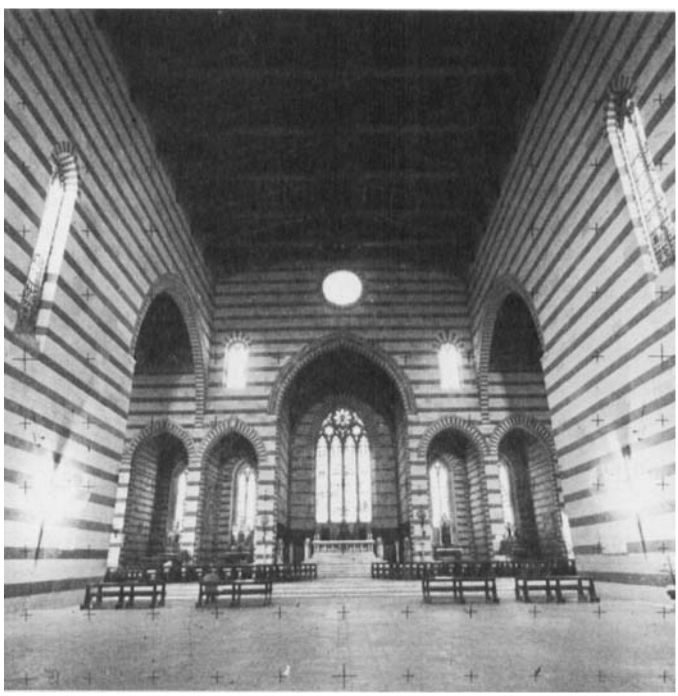

FIG. 14. Chancel façade (40 mm lens).

views of the exterior façades. Due to the various photographic distances, a total of four camera body/lens combinations with focal lengths ranging from 40 mm to 350 mm were required to close the block around the object (Figs. 1 to 3, 16 and 17).

The object information required for the absolute orientation of the image block should preferably be obtained with minimum effort. For this reason a trigonometric

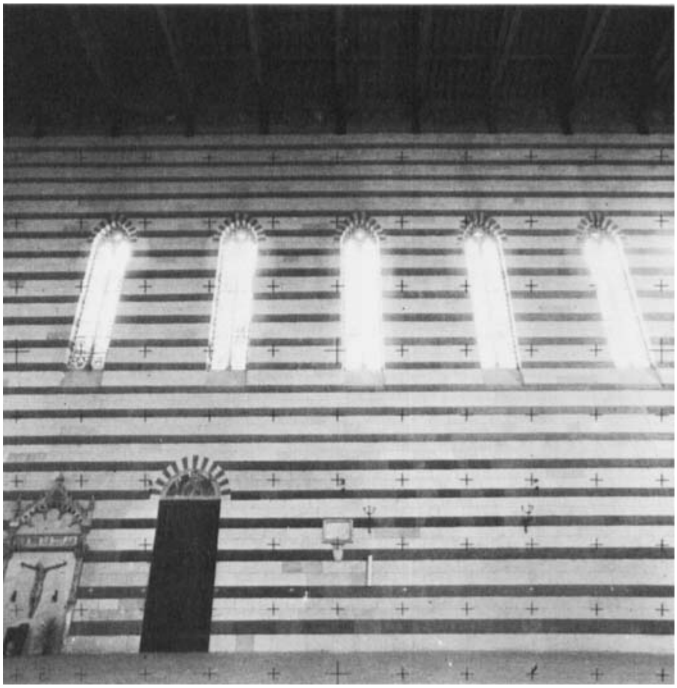

FIG. 15. Façade of the nave (40 mm lens).

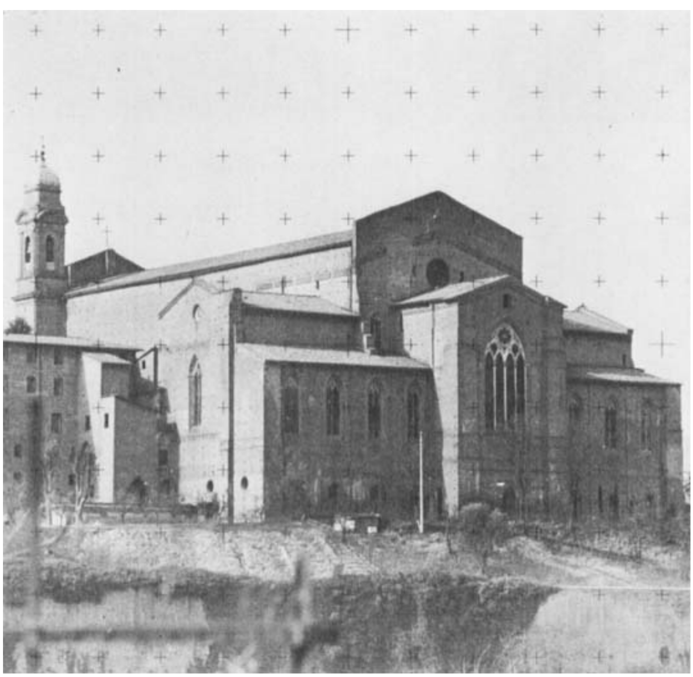

FIG. 16. Long distance exposure (250 mm lens).

point determination, as is usual in architectural photogrammetry, was dispensed with. Instead, distances for scaling and stabilising the photogrammetric network and height differences for levelling were observed inside the church (Fig. 18). The points for vertical control were targetted and were well distributed along the façades. The survey was carried out with an accuracy of ± 1 mm for the height measurement and to ± 10 mm for the distances. Diagonal distances (Fig. 18) were observed to improve the geometrical stability of the image block. The measurement of directions can serve as an alternative to the measurement of lengthy diagonal distances with ± 10 mm accuracy. A bundle of rays can be observed rapidly with an

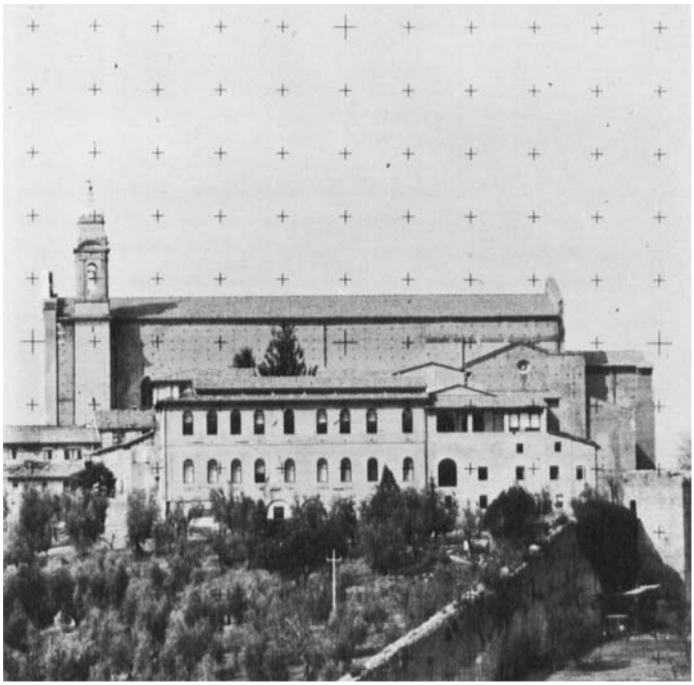

FIG. 17. Long distance exposure (350 mm lens).

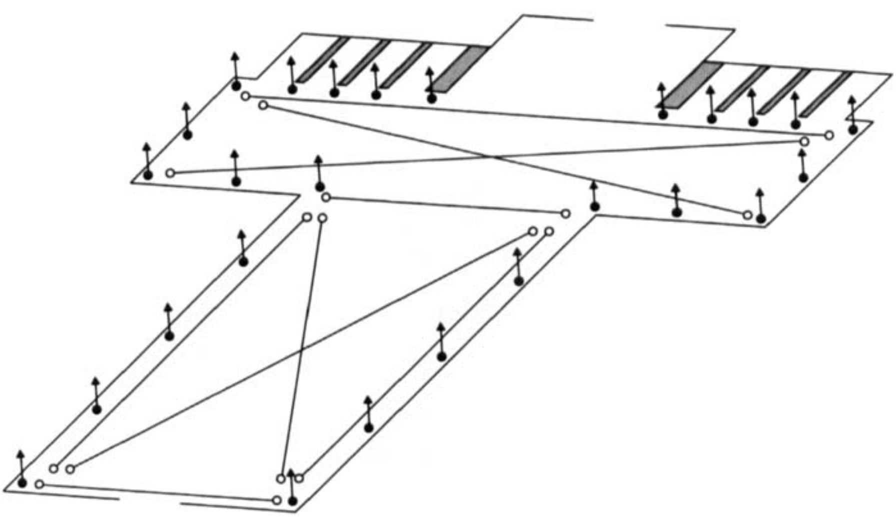

FIG. 18. Object information: distances and height differences.

accuracy of ±5 mgon by means of an engineering theodolite (Fig. 19). This instrument was also used for the height measurement, whereas the distances were obtained by a tape. The equipment was thus reduced to a minimum for the geodetic measurements as well as for the photography.

It was not necessary to carry out any geodetic observation outside the church. The information for scaling and levelling the closed block around the building could be transferred by connecting the blocks inside and outside the church *via* common points in the window corners. This is an efficient method of determining all the points in a common co-ordinate system with a minimum number of geodetic observations (Kotowski *et al.*, 1983).

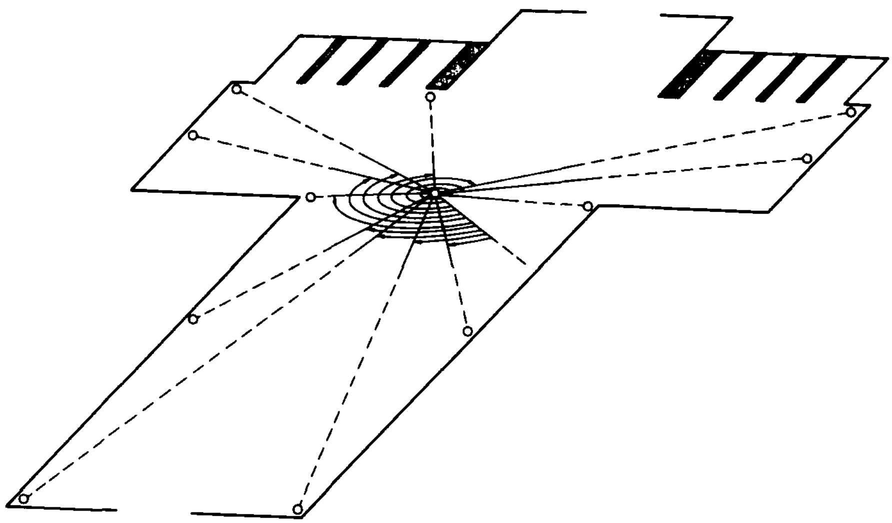

FIG. 19. Direction bundle measured by a theodolite.

Bundle Adjustment: Preparation, Results and Conclusions

Suitable tie points were selected in the photographs based on the criteria of clear identification and optimum ray intersection geometry. With the exception of the points for height and distance measurement, non-targetted points showing sufficient detail contrast were used. The measurement of image co-ordinates was carried out with a Zeiss (Oberkochen) Planicomp C100 in monocomparator mode. The image carriers simultaneously offer space for a maximum of 2×9 medium format photographs, so that the identification of homologous image points is simplified. The measured comparator co-ordinates were numerically projected into the réseau plane by a meshwise transformation (Kotowski, 1984).

Bundle adjustment is a non-linear adjustment problem. The determination of initial values for the unknown parameters (object point co-ordinates and elements of exterior orientation) is necessary. This task is an appreciable problem in phototriangulation but solutions have been formulated for several years (such as Wester-Ebbinghaus, 1978 and 1981; Kotowski *et al.*, 1983). In outline the following steps are carried out.

(1) Relative orientation of photographs with sufficient overlap.

(2) Subsequent connexion of the relatively oriented models. If necessary, auxiliary information such as the approximate direction of wall surfaces and edges may be introduced.

(3) Spatial absolute orientation of this preliminary entire photogrammetric model onto the information available in object space.

(4) Computation of the exterior orientation elements of the photographs by spatial resection.

(5) Spatial intersections made in order to calculate the object co-ordinates of points not so far considered.

(6) The last two steps are alternated until all photographs are oriented and all spatial co-ordinates are determined.

For the outlined procedure it has to be considered that both the relative and absolute orientation as well as the spatial resection are also non-linear adjustment problems and approximate values of the transformation parameters are required beforehand. Recently, however, algorithms have been developed which are distinguished by a very large convergency radius and, moreover, they are free from singularities. When applying these algorithms, initial values of the unknowns can be determined automatically (Gründig and Bühler, 1985; Hinsken, 1987). The preparation phase of phototriangulation in close range photogrammetry has thus experienced a considerable advance in practicability.

The bundle triangulation of San Francesco was carried out with the program MOR (Wester-Ebbinghaus, 1985) using version MOR-S (Hinsken, 1985) which allows for a combined adjustment of photogrammetric and non-photogrammetric observations and many of the non-photogrammetric observations. The *a priori* accuracy introduced amounted to 5 μm for the image co-ordinates, 10 mm for the distances, 1 mm for the height differences and 5 mgon for the directions. The adjustment was designed as a partially free network. The rank deficiency was reduced from seven to four as a result of the distance and height observations. The configuration of photographs as a closed block contained sufficient information for a simultaneous calibration (Fig. 11) of the four camera body/lens combinations used (Kotowski, 1985). The position of the perspective centre in image space and two parameters for the correction of radial symmetric lens distortion were calculated.

As a result of the combined adjustment, a spatial point field inside and outside the basilica could be determined relating to a common co-ordinate system. The standard deviation of the image co-ordinates amounted to $\pm 4{\cdot}3$ μm, the r.m.s.e. of a point being ± 15 mm. A maximum value of 30 mm was not exceeded. The accuracy demands are thus definitely fulfilled.

In conclusion, it can be stated that the whole project was performed economically in terms of both time and technique.

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Résumé

La triangulation par faisceaux constitue une méthode efficace pour déterminer la position de points dans l'espace en photogrammétrie architecturale.

On peut introduire toutes les données disponibles tant sur l'image que sur l'objet dans une compensation globale, fiable et précise. En recourant à des méthodes d'auto-étalonnage de la chambre photographique, simultanément à la restituition de l'objet, on peut utiliser des systèmes de traitement d'images de façon commode et souple tout en restant dans le domaine des techniques photographiques habituelles.

On peut effectuer de la sorte le relevé des monuments avec un minimum de personnel et de matériel et dans des délais très courts.

Le relevé photogrammétrique de la basilique Saint-François à Sienne fournit un exemple de mise en oeuvre de la méthode de levé présentée dans cet article. On a mené les travaux de terrain en quelques jours.

Le matériel utilisé comprenait une chambre pseudo-photogrammétrique, un théodolite d'ingénieur et un décamètre à ruban. La compensation par faisceaux a fourni les coordonnées des points dans l'espace-objet avec une erreur moyenne quadratique de ± 15 mm.

Zusammenfassung

Die Bündeltriangulation ist ein effizientes Verfahren zur Bestimmung dreidimensionaler Koordinaten von Objektpunkten in der Architekturphotogrammetrie. Die Berücksichtigung der gesamten, im Bild- und Objektraum vorhandenen Information führt zu hoher Genauigkeit und Zuverlässigkeit. Simultane Kammerkalibrierung im Rahmen der Objektrekonstruktion ermöglicht es, handliche und flexibel einsetzbare Kammersysteme zu verwenden, die professionelle Aufnahmetechnik bieten. Die Vermessung von Großbauwerken gelingt so in kurzer Zeit mit geringem instrumentellen und personellen Aufwand.

Die photogrammetrische Bauaufnahme der Basilika di San Francesco in Siena dient als Beispiel für die Anwendung der vorgestellten Verfahrensweise. Die Arbeiten vor Ort wurden in wenigen Tagen ausgeführt. Die Ausrüstung bestand aus einer Teil-Meßkammer, einem Ingenieurtheodolit und einem Bandmaß. Die Bündelausgleichung erbrachte Objektkoordinaten mit einem mittleren quadratischen Punktfehler von ± 15 mm.