

Geometric Calibration and Orientation of Digital Imaging Systems

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Contents

- 1 ABSTRACT3**
- 2 DEFINITIONS4**
 - 2.1 Camera calibration..... 4**
 - 2.2 Camera orientation 4**
 - 2.3 System calibration 4**
- 3 INFLUENCE OF INTERIOR AND EXTERIOR EFFECTS ON GEOMETRICAL PERFORMANCE5**
 - 3.1 Interior effects 5**
 - 3.1.1 Optical system 5
 - 3.1.2 Resolution-enhancing elements 5
 - 3.1.3 Sensor and signal transfer..... 6
 - 3.2 Exterior effects..... 6**
- 4 MODEL OF IMAGE FORMATION WITH THE AID OF OPTICAL SYSTEMS7**
- 5 CAMERA MODELS 8**
 - 5.1 Calibrated focal length and principal-point location..... 9**
 - 5.2 Distortion and affinity..... 9**
 - 5.2.1 Radial symmetrical distortion..... 10
 - 5.2.2 Radially asymmetrical and tangential distortion 11
 - 5.2.3 Affinity and non-orthogonality..... 12
 - 5.2.4 Additional parameters 12
- 6 CALIBRATION AND ORIENTATION TECHNIQUES..... 13**
 - 6.1 In the laboratory..... 13**
 - 6.2 Using bundle adjustment to determine camera parameters 13**
 - 6.2.1 Calibration based exclusively on image information 14
 - 6.2.2 Calibration and orientation with the aid of additional object information..... 16
 - 6.2.3 System calibration 17
- 7 BIBLIOGRAPHY..... 18**



1 Abstract

The use of digital imaging systems for metrology purposes implies the necessity to calibrate or check these systems. While simultaneous calibration of cameras during plotting is possible for many types of photogrammetric work, separate calibration and checking is useful above all in the following cases:

When information is desired about the attainable accuracy of the measurement system and thus about the measurement accuracy at the object;

- when simultaneous calibration of the measurement system is impossible during measurement for systemic reasons so that some or all other system parameters have to be predetermined;
- when complete imaging systems or components are to be tested by the manufacturer for quality-control purposes;
- when digital images free from the effects of the imaging system are to be generated in preparation of further processing steps (such as rectification).

In addition, when setting up measurement systems it will be necessary to determine the positions of cameras or other sensors in relation to a higher-order world coordinate system to allow 3D determination of objects within these systems.

The paper describes methods of calibration and orientation of imaging systems, focusing primarily on photogrammetric techniques since these permit homologous and highly accurate determination of the parameters required.



2 Definitions

2.1 Camera calibration

Calibration in photogrammetric parlance refers to the determination of the parameters of interior orientation of individual cameras. When using digital cameras, it is advisable to analyze the complete imaging system, including camera, transfer units and possibly frame grabbers. The parameters to be found by calibration depend on the type of camera used. Once the imaging system has been calibrated, measurements can be made after the cameras have been duly oriented.

2.2 Camera orientation

Camera orientation usually includes determination of the parameters of exterior orientation to define the camera station and camera axis in the higher-order object-coordinate system, frequently called the world coordinate system. This requires the determination of three rotational and three translational parameters - i.e. a total of six parameters - for each camera.

2.3 System calibration

In many applications, fixed setups of various sensors are used for measurement. Examples are online measurement systems in which, for example, several cameras, laser pointers, pattern projectors, rotary stages, etc. may be used. If the entire system is considered the measurement tool proper, then the simultaneous calibration and orientation of all the components involved may be defined as system calibration.

3 Influence of interior and exterior effects on geometrical performance

3.1 Interior effects

All components of a digital imaging system leave their marks on the image of an object and thus on the measurement results obtained from processing this image. The following is a brief description of the relevant components (Fig. 1).

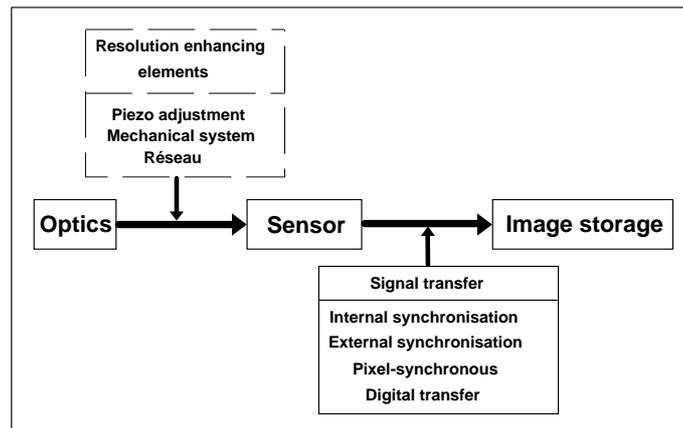


Fig. 1: Components of digital imaging systems

3.1.1 Optical system

Practically all lenses exhibit typical radially symmetrical distortion that may vary greatly in magnitude. On the one hand, the lenses used in optical measurement systems are nearly distortion-free [Godding 1993], on the other wide-angle lenses, above all, frequently exhibit distortion of several 100 µm at the edges of the field. Fisheye lenses are in a class of their own; they frequently have extreme distortion at the edges. Since radially symmetrical distortion is a function of design, it cannot be considered an aberration.

By contrast, centering errors often unavoidable in lens making cause aberrations reflected in radially asymmetrical and tangential distortion components [Brown 1966]. Additional optical elements in the light path, such as the IR barrier filter and protective filter of the sensor, also leave their mark on the image and have to be made allowance for in the calibration of a system.

3.1.2 Resolution-enhancing elements

The image size and the possible resolution of CCD sensors are limited. Presently on the market are metrology cameras like Rollei's Q16 MetricCamera with up to 4000 * 4000 sensor elements [Schafmeister 1998]. Other, less frequent approaches use techniques designed to attain higher resolution by shifting commercial sensors parallel to the image plane. Essentially, there are two different techniques.



In the case of "microscanning", the interline transfer CCD sensors are shifted by minute amounts by means of piezo adjustment so that the light-sensitive sensor elements fall within the gaps between elements typical of this type of system, where they acquire additional image information [Lenz and Lenz 1990], [Richter 1993]. Alternatively, in "macroscanning", the sensors may be shifted by a multiple of their own size, resulting in a larger image format. Individual images are then oriented with respect to the overall image either by a highly precise mechanical system [Poitz 1993] [Holdorf 1993] or opto-numerically as in the RolleiMetric Réseau Scanning Camera by measuring a glass-based reference grid in the image plane ("réseau scanning") [Riechmann 1992].

All resolution-enhancing elements affect the overall accuracy of the imaging system. In scanner systems with purely mechanical correlation of individual images, the accuracy of the stepping mechanism has a direct effect on the geometry of the high-resolution imagery. In the case of réseau scanning, the accuracy of the réseau is decisive for the attainable image measuring accuracy [Bösemann, Godding, Riechmann 1990].

3.1.3 Sensor and signal transfer

Due to their design, CCD sensors usually offer high geometrical accuracy [Lenz 1988]. When judging an imaging system, its sensor should be assessed in conjunction with the frame grabber used. Geometrical errors of different magnitude may occur during A/D conversion of the video signal, depending on the type of synchronization, above all if pixel-synchronous signal transfer from camera to image storage is not guaranteed [Beyer 1992] [Bösemann, Godding, Riechman 1990]. However, in the case of pixel-synchronous readout of data, the additional transfer of the pixel clock pulse makes sure that each sensor element will precisely match a picture element in the image storage. Very high accuracy has been proved for these types of camera [Godding 1993]. However, even with this type of transfer the square shape of individual pixels cannot be taken for granted. As with any kind of synchronization, most sensor-storage combinations make it necessary to make allowance for an affinity factor; in other words, the pixels may have different extension in the direction of lines and columns.

3.2 Exterior effects

If several cameras are used in an online metrology system, both the parameters of interior orientation and those of exterior orientation may vary, the former, for example, due to refocusing and changes of temperature, the latter due to mechanical effects or fluctuations of temperature. The resulting effects range from scale errors during object measurement right up to complex model deformation. This is why all systems of this kind should make it possible to check or redetermine all relevant parameters.

4 Model of image formation with the aid of optical systems

Image formation by an optical system can, in principle, be described by the mathematical rules of central perspective. According to these, an object is imaged in a plane so that the object points P_i and the corresponding image points P'_i are located on straight lines through the perspective center O_j (Fig. 2). The following holds under idealized conditions for the formation of a point image in the image plane

$$\begin{bmatrix} x_{ij} \\ y_{ij} \end{bmatrix} = \frac{-c}{Z^*_{ij}} \begin{bmatrix} X^*_{ij} \\ Y^*_{ij} \end{bmatrix} \quad (1)$$

with

$$\begin{bmatrix} X^*_{ij} \\ Y^*_{ij} \\ Z^*_{ij} \end{bmatrix} = D(\omega, \varphi, \kappa)_j \begin{bmatrix} X_i - Xo_j \\ Y_i - Yo_j \\ Z_i - Zo_j \end{bmatrix} \quad (2)$$

where

X_i, Y_i, Z_i are the coordinates of an object point P_i in the object-coordinate system K ,
 Xo_j, Yo_j, Zo_j the coordinates of the perspective center O_j in the object-coordinate system K ,
 $X^*_{ij}, Y^*_{ij}, Z^*_{ij}$ the coordinates of the object point P_i in the coordinate system K^*_j ,
 x_{ij}, y_{ij} the coordinates of the image point in the image-coordinate system K_B , and
 $D(\omega, \varphi, \kappa)_j$ the rotation matrix between K and K^*_j as well as
 c the distance between perspective center and image plane,
the system K^*_j being parallel to the system K_B with the origin in the perspective center O_j [Wester-Ebbinghaus 1989].

The above representation splits up the process of image formation in such a manner that in (1) it is primarily the image-space parameters and in (2) primarily the object-space parameters - i.e. the parameters of exterior orientation - that come to bear.

This ideal concept is not attained in reality where a multitude of influences are encountered due to the different components of the imaging system. These can be modeled as departures from rigorous central perspective. The following section describes various approaches to mathematical camera models.

5 Camera models

When optical systems are used for measurement, modeling the entire process of image formation is decisive for the accuracy to be attained. Basically the same ideas apply, for example, to projection systems for which models can be set up similarly to imaging systems.

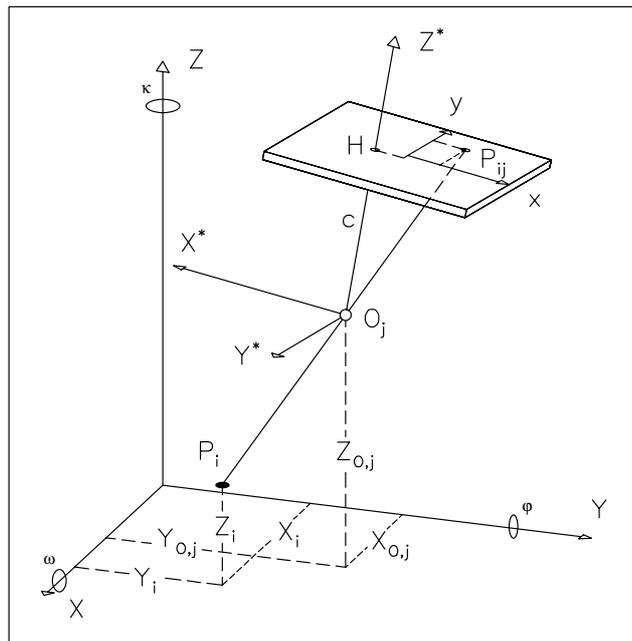


Fig. 2: Principle of central perspective [Dold 1994]

Before we continue, we have to define an image-coordinate system K_B in the image plane of the camera. In most electrooptical cameras, this image plane is defined by the sensor plane; only in special designs (e.g. in réseau scanning cameras [Riechmann 1992]), this plane is differently defined. While in the majority of analog cameras used for metrology purposes the image-coordinate system is defined by projected fiducial marks or réseau crosses, this definition is not required for digital cameras. Here it is entirely sufficient to place the origin of the image-coordinate system in the center of the digital images in the storage (Fig. 3). Since the pixel interval in column direction in the storage is equal to the interval of the corresponding sensor elements, the unit "pixel in column direction" may serve as a unit of measure in the image space. All parameters of interior orientation can be directly computed in this unit, without conversion to metric values.

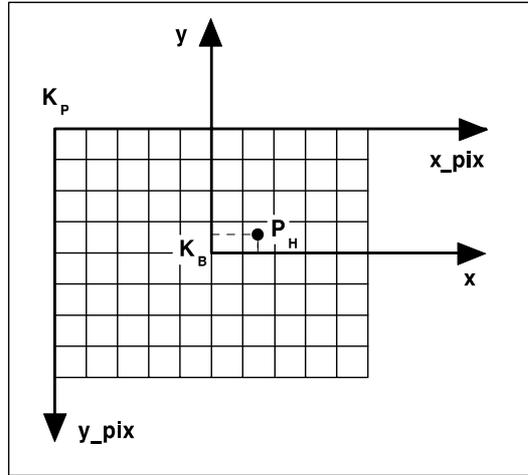


Fig. 3: Definition of image-coordinate system

5.1 Calibrated focal length and principal-point location

The reference axis for the camera model is not the optical axis in its physical sense, but a principal ray which on the object side is perpendicular to the image plane defined above and intersects the latter at the principal point $P_H (x_H, y_H)$. The perspective center O_j is located at distance c_k (also known as calibrated focal length) perpendicularly in front of the principal point [Rüger, Pietschner, Regensburger 1978].

The original formulation of Eq. (1) is thus expanded as follows:

$$\begin{bmatrix} x_{ij} \\ y_{ij} \end{bmatrix} = \frac{-c_k}{Z_{ij}^*} \begin{bmatrix} X_{ij}^* \\ Y_{ij}^* \end{bmatrix} + \begin{bmatrix} x_H \\ y_H \end{bmatrix} \quad (3)$$

5.2 Distortion and affinity

The following additional correction function can be applied to Eq. (3) for radially symmetrical, radial asymmetrical and tangential distortion.

$$\begin{bmatrix} x_{ij} \\ y_{ij} \end{bmatrix} = \frac{-c_k}{Z_{ij}^*} \begin{bmatrix} X_{ij}^* \\ Y_{ij}^* \end{bmatrix} + \begin{bmatrix} x_H \\ y_H \end{bmatrix} + \begin{bmatrix} dx(V, A) \\ dy(V, A) \end{bmatrix} \quad (4)$$

dx and dy may now be defined differently, depending on the type of camera used, and are made up of the following different components:

$$dx = dx_{sym} + dx_{asy} + dx_{aff} \quad (5)$$

$$dy = dy_{sym} + dy_{asy} + dy_{aff} \quad (6)$$

5.2.1 Radial symmetrical distortion

The radial symmetrical distortion typical of a lens can generally be expressed with sufficient accuracy by a polynomial of odd powers of the image radius (x_{ij} and y_{ij} are henceforth called x and y for the sake of simplicity):

$$dr_{sym} = A_1(r^3 - r_0^2 r) + A_2(r^5 - r_0^4 r) + A_3(r^7 - r_0^6 r) \quad (7)$$

where

dr_{sym} is the radial symmetrical distortion correction,

r the image radius from $r^2 = x^2 + y^2$,

A_1, A_2, A_3 the polynomial coefficients, and

r_0 the second zero crossing of the distortion curve,

so that we obtain

$$dx_{sym} = \frac{dr_{sym}}{r} x \quad (8)$$

$$dy_{sym} = \frac{dr_{sym}}{r} y \quad (9)$$

A polynomial with two coefficients is generally sufficient to describe radial symmetrical distortion. Expanding this distortion model, it is possible to describe even lenses with pronounced departure from perspective projection (e.g. fisheye lenses) with sufficient accuracy; in the case of very pronounced distortion it is advisable to introduce an additional point of symmetry $P_s (x_s, y_s)$. Fig. 4 shows a typical distortion curve.

For numerical stabilization and far-reaching avoidance of correlations between the coefficients of the distortion function and the calibrated focal lengths, a linear component of the distortion curve is split off by specifying a second zero crossing [Wester-Ebbinghaus 1980].

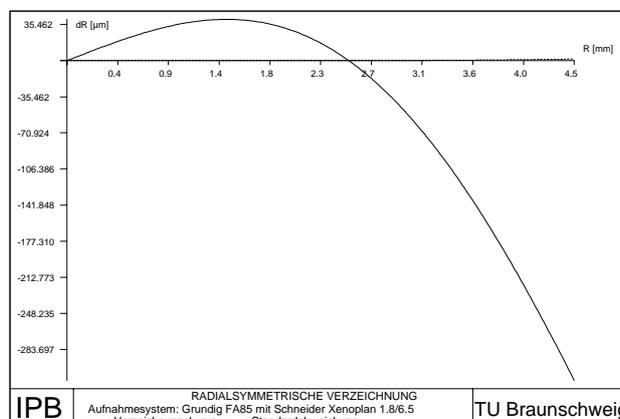


Fig. 4: Typical distortion curve of a lens



[Lenz 1987] proposes a different formulation for determining radially symmetrical distortion, which includes only one coefficient. We thus obtain the following formula:

$$dr_{sym} = r \frac{1 - \sqrt{1 - 4Kr^2}}{1 + \sqrt{1 - 4Kr^2}} \quad (10)$$

where K is the distortion coefficient to be determined.

5.2.2 Radially asymmetrical and tangential distortion

To cover radially asymmetrical and tangential distortion, various different formulations are possible. Based on [Conrady 1919], these distortion components may be formulated as follows [Brown1966]:

$$dx_{asy} = B_1(r^2 + 2x^2) + 2B_2xy \quad (11)$$

$$dy_{asy} = B_2(r^2 + 2y^2) + 2B_1xy \quad (12)$$

In other words, these effects are always described with the two additional parameters B₁ and B₂.

This formulation is expanded by [Brown 1976], who adds parameters to describe overall image deformation or the lack of image-plane flatness.

$$dx_{asy} = (D_1(x^2 - y^2) + D_2x^2y^2 + D_3(x^4 - y^4))x / c_K + E_1xy + E_2y^2 + E_3x^2y + E_4xy^2 + E_5x^2y^2 \quad (13)$$

$$dy_{asy} = (D_1(x^2 - y^2) + D_2x^2y^2 + D_3(x^4 - y^4))y / c_K + E_6xy + E_7x^2 + E_8x^2y + E_9xy^2 + E_{10}x^2y^2 \quad (14)$$

In view of the large number of coefficients, however, this formulation implies a certain risk of too many parameters. Moreover, since this model was primarily developed for large-format analog imaging systems, some of the parameters cannot be directly interpreted for applications using digital imaging systems. Equations (8) and (9) are generally sufficient to describe asymmetrical effects. Fig. 5 shows typical effects for radially symmetrical and tangential distortion.

5.2.3 Affinity and non-orthogonality

The differences in length and width of the pixels in the image storage caused by synchronization can be taken into account by an affinity factor. In addition, an affinity direction may be determined, which primarily describes the orthogonality of the axes of the image-coordinate system K_B . An example may be a line scanner that does not move perpendicular to the line direction. Allowance for these two effects can be made as follows:

$$dx_{aff} = C_1x + C_2y \quad (15)$$

$$dy_{aff} = 0 \quad (16)$$

Fig. 6 gives an example of the effect of affinity.

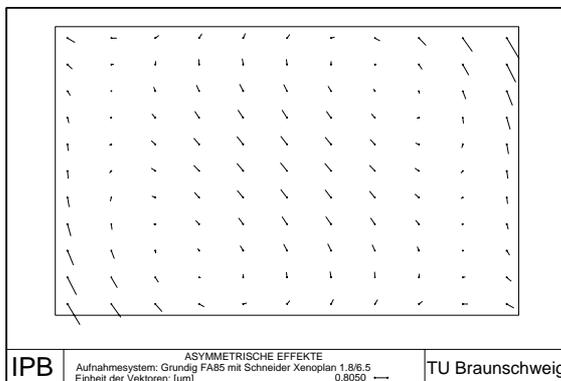


Fig. 5: Radially symmetrical and tangential distortion

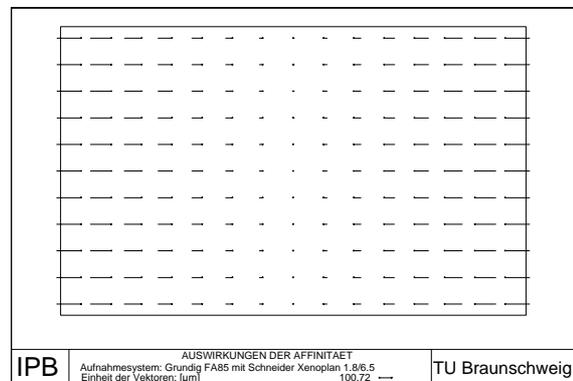
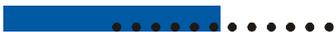


Fig. 6: Effects of affinity

5.2.4 Additional parameters

The introduction of additional parameters may be of interest for special applications. [Fryer 1989] and [Fraser and Shortis 1992] describe formulations that also make allowance for distance-related components of distortion. However, these are primarily effective with medium and large image formats and the corresponding lenses and are of only minor importance for the wide field of digital uses.

[Gerdes, Otterbach and Kammüller 1993] use a different camera model in which an additional two parameters have to be determined for the oblique position of the sensor.



6 Calibration and orientation techniques

6.1 In the laboratory

Distortion parameters can be determined in the laboratory under clearly defined conditions.

In the goniometer method, a highly precise grid plate is positioned in the image plane of a camera. Then the goniometer is used to sight the grid intersections from the object side and to determine the corresponding angles. Distortion values can then be obtained by a comparison between nominal and actual values.

In the collimator technique, test patterns are projected onto the image plane by several collimators set up at defined angles to each other. Here also, the parameters of interior orientation can be obtained by a comparison between nominal and actual values, though only for cameras focused at infinity [Rüger, Pietschner, Regensburger 1978].

Apart from this restriction, there are more reasons speaking against the use of the aforementioned laboratory techniques for calibrating digital imaging systems, including the following:

- The equipment layout is high.
- The interior orientation of the cameras used normally is not stable, requiring regular recalibration by the user.
- Interior orientation including distortion varies at different focus and aperture settings so that calibration under practical conditions appears more appropriate.

6.2 Using bundle adjustment to determine camera parameters

All the parameters required for calibration and orientation may be obtained by means of photogrammetric bundle adjustment. In bundle adjustment, two so-called observation equations are set up for each point measured in an image, based on Eqs. (2) and (4). The total of all equations for the image points of all corresponding object points results in a system that makes it possible to determine the unknown parameters [WESTER-EBBINGHAUS 1985a]. Since this is a nonlinear system of equations, no linearization is initially necessary. The computation is made iteratively by the method of least squares, the unknowns being determined in such a way that the squares of deviations are minimized at the image coordinates observed. Newer approaches are working with modern algorithms like balanced parameter estimation [Fellbaum 1996]. Bundle adjustment thus allows simultaneous determination of the unknown object coordinates, exterior orientation and interior orientation with all relevant system parameters of the imaging system. In addition, standard deviations are computed for all parameters, which give a measure of the quality of the imaging system.

6.2.1 Calibration based exclusively on image information

This method is particularly well-suited for calibrating individual imaging systems. It requires a survey of a field of points in a geometrically stable photogrammetric assembly. The points need not include any points with known object coordinates (control points); the coordinates of all points need only be known approximately [Wester- Ebbinghaus 1985a]. It is, however, necessary that the point field be stable for the duration of image acquisition. The scale of the point field likewise has no effect on the determination of the desired image-space parameters. Fig. 7 shows a point field suitable for calibration.

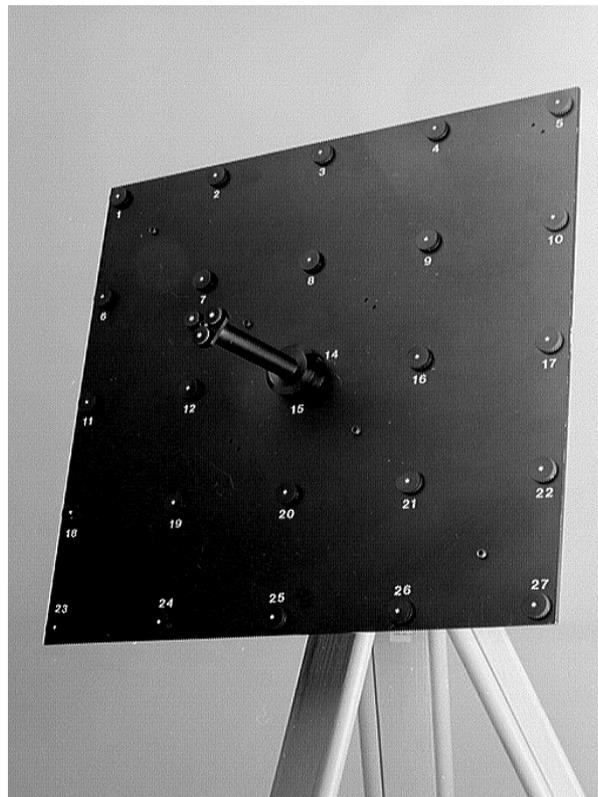


Fig. 7: Test array for camera calibration

The accuracy of the system studied can be judged from the residual mismatches of the image coordinates as well as the standard deviation of the unit of weight after adjustment (Fig. 8). The effect of synchronization errors, for example, becomes immediately apparent, for instance by larger residual mismatches of different magnitude in line and column direction.

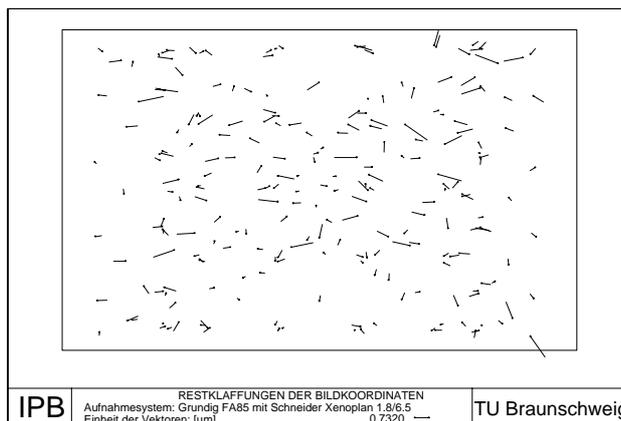


Fig. 8: Residual mismatches after bundle adjustment

Fig. 9 gives a diagrammatic view of the minimum setup for surveying a point array with which the aforementioned system parameters can be determined. The array may be a three-dimensional test field with a sufficient number of properly distributed, circular, retroreflecting targets. This test field is first recorded in three frontal images, with camera and field at an angle of 100° for determining affinity and 200° for determining the location of the principal point. In addition, four convergent images of the test field are used to give the assembly the necessary geometric stability for determination of the object coordinates and to minimize correlations with exterior orientation.

Optimum use of the image format is a precondition for the determination of distortion parameters. However, this requirement need not be satisfied for all individual images. It is sufficient if the image points of all images cover the format uniformly and completely.

If this setup is followed, seven images will be obtained roughly as shown in Fig. 10, their outer frame standing for the image format, the inner frame for the image of the square test field and the arrowhead for the position of the test field. It is generally preferable to rotate the test field with the aid of a suitable suspension in front of the camera instead of moving the camera for image acquisition. The use of retroreflecting targets and a ring light guarantee proper, high-contrast reproduction of the object points, which is indispensable for precise and reliable measurement. A complete, commercially available software package offering far-reaching automation of the process is described in [Godging 1993].

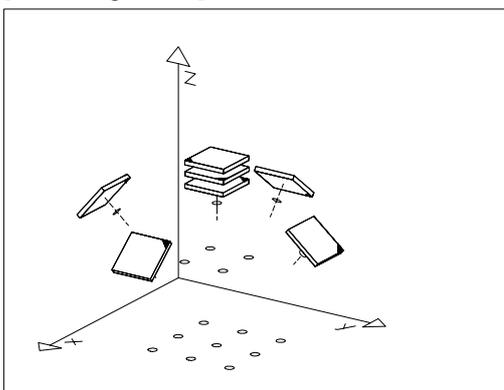


Fig. 9: Imaging setup for calibration [Godging 1993]

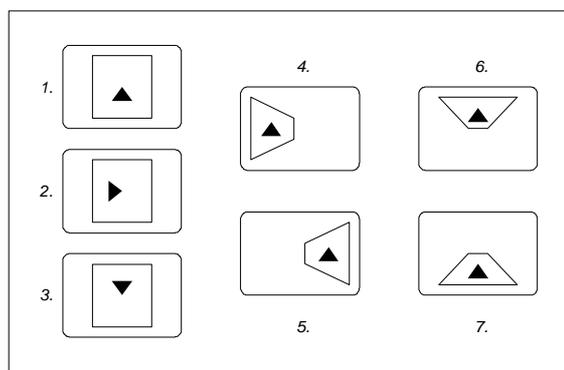


Fig. 10: Test field

6.2.2 Calibration and orientation with the aid of additional object information

Once the imaging system has been calibrated, its orientation can be found by resection in space. The latter may be seen as a special bundle adjustment in which the parameters of interior orientation and the object coordinates are known. This requires a minimum of three control points in space whose object coordinates in the world coordinate system are known and whose image points have been measured with the imaging system to be oriented.

In addition to orientation, calibration of an imaging system is also possible with a single image. However, since a single image does not allow the object coordinates to be determined, suitable information within the object has to be available in the form of a three-dimensional control-point array [Wester-Ebbinghaus, 1985b]. But constructing, maintaining and regularly checking such an array is rather costly, all the more so as it should be mobile so that it may be used for different applications. The control pattern should completely fill the measurement range of the cameras to be calibrated and oriented to ensure good agreement between calibration and measurement volumes.

The expense is considerably less if several images are available. For a two-image assembly and one camera, a spatial array of points that need to be known only approximately plus, as additional information, several known distances (scales) distributed in the object space will be sufficient, similar to section 6.2.1. In an ideal case, one scale on the camera axis, another one perpendicular to it and two oblique scales in two perpendicular planes parallel to the camera axis are required (Fig. 11). This will considerably reduce the object-side expense, since the creation and checking of scales is much simpler than that of an extensive three-dimensional array of control points.

A similar setup is possible if the double-image assembly is recorded with several cameras instead of just one. This is, in principle, the case with online measurement systems. An additional scale is then required in the foreground of the object space, bringing the total number of scales to five (Fig. 12).

If at least one of the two cameras can be rolled, the oblique scales can be dispensed with, provided that the rolled image is used for calibration [Wester-Ebbinghaus 1985b].

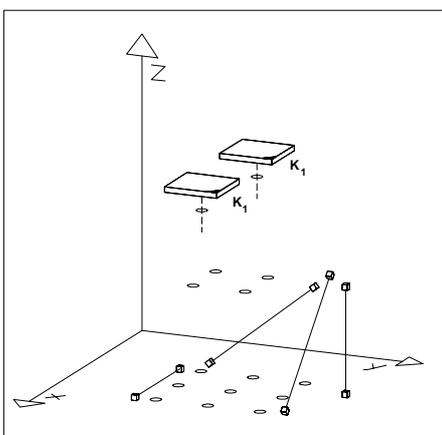


Fig. 11: Scale setup for calibrating one camera

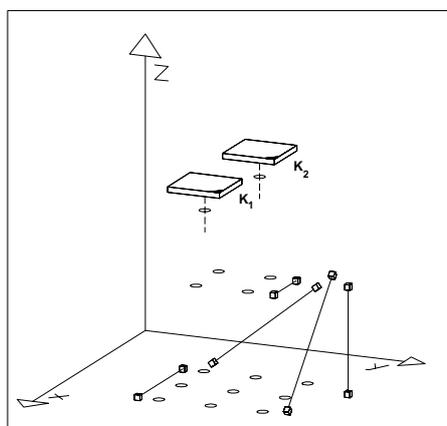


Fig. 12: Scale setup for calibrating two cameras



The setups described are, of course, applicable to more than two cameras as well. In other words, all the cameras of a measurement system can be calibrated if the above mentioned conditions are created for each of the cameras. At least two cameras have to be calibrated in common, with the scales set up as described. Simultaneous calibration of all cameras is also possible, but then the scale information must also be simultaneously available to all the cameras. If all cameras also are to be calibrated in common, this will have to be done via common points.

6.2.3 System calibration

As we have seen from sections 6.2.1 and 6.2.2, joint calibration and orientation of all cameras involved and thus calibration of the entire system are possible if certain conditions are met. With the aid of bundle adjustment, the two problems can, in principle, be solved jointly with a suitable array of control points or a spatial point array of unknown coordinates plus additional scales. The cameras then already are in measurement position during calibration. Possible correlations between the exterior and interior orientations required are thus neutralized because the calibration setup is identical to the measurement setup.

Apart from the imaging systems, other components can be calibrated and oriented within the framework of system calibration. Luhmann and Godding [1992] describe a technique in which a suitable procedure in an online measurement system allows both the interior and exterior orientation of the cameras involved as well as the orientation of a rotary stage to be determined with the aid of a spatial point array and additional scales. The calibration of a line projector within a measurement system using photogrammetric techniques was e. g. presented by Strutz [1993].



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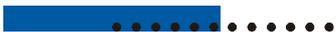
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