STATE OF THE ART OF HIGH PRECISION INDUSTRIAL PHOTOGRAMMETRY

V. Uffenkamp
Institut für Photogrammetrie und Bildverarbeitung
Technische Universität Braunschweig
Germany

1. INTRODUCTION

The requirements in industrial metrology have continuously increased during the last decades. More and more differently designed products have to be measured with a higher accuracy within a shorter time, in order to speed up the manufacturing process and to ensure the product quality. This concerns also other parts of civil engineering, where buildings, machines and industrial plants have to be observed during their stages of planning and realization.

Geodetic measuring techniques such as spatial triangulation or optical alignment and levelling can be applied to those tasks. As a non-contacting procedure with high measuring accuracy even for voluminous objects in situ, geodetic measurement is an ideal supplement to the general coordinate measurement techniques in industry.

Photogrammetry as well offers a valuable contribution. The advantages of a non-contacting three-dimensional object reconstruction by means of spatial rays are valid for the photogrammetric method, too. In addition, a short recording time on-site nearly independent from the amount of object points to be measured, and the possibility to choose the recording stations in a very flexible way, sometimes makes photogrammetry even preferable to other techniques. If a dynamic or kinematic process has to be recorded, photogrammetry seems to be the only way to measure a whole object simultaneously.

2. MULTI-IMAGE TRIANGULATION

In contrast to classical photogrammetry, where images and image evaluation instruments harmonize for the processing of stereo image-pairs, modem close-range photogrammetry relies on the reconstruction of the object simultaneously from several images of different, best possible perspective to ensure a suitable geometry of intersecting rays. With the analytical description of the imaging process and the numerical reconstruction of the object, neither for the image recording, nor for the image evaluation instrumental constraints do exist. The images can be stationed free in object space as the photogrammetric network can be reconstructed from the bundles of rays (Fig. 1). The orientation parameters of the network as well as the wanted object coordinates are estimated simultaneously in a common adjustment process [1]. This procedure is called bundle adjustment. The shape of the object can be derived from pure photogrammetric information. The object size and location yields from the insertion of additional information into the object space in the manner of known distances or given control point coordinates. The information is included to the adjustment process as additional observation.

With the common imaging equation of the central perspective the bundles of rays are described analytically. However, the assumption, that an object point is imaged on a straight-lined ray through a punctiform perspective center onto a plane sensor, is not always given directly. Instrumental expedients and the model extension of the central perspective with additional parameters are used to take into account the deviation between reality and model.

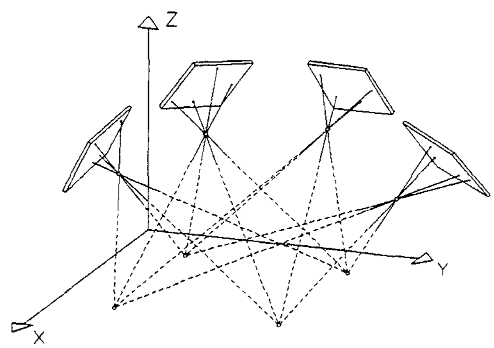

Fig. 1 Multi-image triangulation [2]

3. IMAGE RECORDING

Lens system camera body and imaging sensor build the image recording system. The resolution and the stability of the system as well as the efficiency of the realization of the central perspective is essential for the achievable accuracy of a photogrammetric system. Both, photographic image recording systems having a film as a sensor and opto-electronical systems are used for object recording. While the film has to be evaluated *off-line*, e.g. by scanning for a subsequent automized digital image analysis, digital *on-line* or even *real-time* systems provide the results directly on-site. A selection of available photographic cameras and digital sensors is shown in Tables l-2

Table 1
Photographic cameras (selection)

Manufacturer	Type	Image Size [mm] x [mm]	Réseau [mm]	Mechanical Flattening
Leica	R5	24 x 36	5	no
Rollei	35	24 x 36	5.5	no
Rollei	3003	24 x 36	5.5	no
Rollei	6006	55 x 55	5	no
Rollei	6008	55 x 55	2	no
Pentax	PAMS 645P	45 x 69	20/25	no
Hasselblad	MK 70	50 x 50	10	no
Wild	P32	90 x 65	-	no
GSI Inc.	CRC-3	60 x 90	30	no
Linhof	METRIKA 45	95 x 120	10	yes
Linhof/Rollei	R_METRIKA	95 x 120	2	yes
GSI Inc.	CRC-2	115 x 115	25	yes
Zeiss	UMK 1318	130 x 180	-	yes
GSI Inc.	CRC-1	230 x 230	50	yes
Rollei	LFC	230 x 230	2	no

Table 2
Digital sensors (selection), partly from [9]

Manufacturer	Type	Image size [mm] x [mm]	Sensor elements
Toshiba	TC 1500	35.0 x 0.007	5000 x 1
Pulnix	TM-560	8.8 x 6.6	500 x 592
Valvo	NXA 1011	6.0 x 4.5	604 x 576
Sony	XC-77 CE	8.8 x 6.6	756 x 581
Cidtec	2710	8.8 x 6.6	776 x 512
EEV	CCD05-10	22.5 x 22.5	298 x 1152
Videk	Megaplus	9.0 x 7.0	1320 x 1035
VDS	CCD-1000	13.9 x 7.8	1260 x 1152
DALSA Inc.	IA-D2	10.0 x 10.0	1024 x 1024
Hamamatsu	C 4742	12.0 x 12.2	1000 x 1018
Thomson-CSF	TH7896A	19.0 x 19.0	1024 x 1024
Tektronix	TK1024M	24.6 x 24.6	1024 x 1024
Kodak	KAF-4200	9.0 x 9.0	2048 x 2048
Ford Aerospace		30.7 x 30.7	4096 x 4096 (*)
DALSA Inc.	MEGASENSOR	12.0 x 12.0	5120 x 5120 (**)

(*) not available on the civil market
(**) announced availability last quarter 1993

3.1 Imaging sensor

Using a film as a light sensitive sensor a flat image surface is not given directly. Film flattening takes place mechanically during exposure by vacuum or opto-numerically during data processing by using réseau technique [3]. In a réseau camera a glass grid plate is used as a reference, which is projected onto the film under the same perspective conditions as the object. Film unflatness affects the imaging of the reference marks and object points indentically. The image deformation can be taken into account by numerical reprojection of the imaged grid to the nominal grid. The image points are corrected meshwise [4]. In addition, the film shrinkage after exposure will be taken into consideration at the same time. Some cameras are provided with a combination of both techniques using mechanical and numerical film flattening.

Digital image recording systems are equipped with an opto-electronical CCD sensor (Charged Coupled Device sensor), which consists of light sensitive sensor elements arranged as a single line (linear sensor) or areal (matrix sensor). CCD sensors do not need any expedient for flattening, as the elements are arranged very precisely. Within the current reachable accuracy, the sensor elements of a matrix sensor directly define the image plane of a digital photogrammetric image recording system. The geometric and radiometric characteristics of digital image recording systems have been investigated e.g. in Refs. [5] to [7]. Setting highest requirements on the accuracy, the image recording should be pixel-synchronized [8] and radiometric effects have to be minimized by individual illumination control.

3.2 Image size and resolution

Besides the network design, the resolution of the image recording system and the image size influences the accuracy of a photogrammetric system. The relation between the measurement accuracy of image points and the image size specifies a relative accuracy, which can be compared with the relation between object accuracy and object size, if a strong network and a good redundancy is considered [10]. Accuracy demands of high precision industrial applications are often 1/100000 or even better (e.g. 0.01 mm object accuracy with an object volume of 1 m^3). This requires an image size of approximately 100 mm x 100 mm assuming an image measurement accuracy of about 1 μm. Photographic large format cameras offer image sizes up to 230 x 230 mm [11,12] (Table 1), whereas commonly used digital cameras offer sensors of a few millimetres (Table 2) restricting their use to smaller object volumes or lower precision applications. The image measurement accuracy of digital sensors currently is about 0.05 pixel and better under laboratory conditions. This leads to a relative accuracy of 1/10000 . . . 1/25000 considering commonly used off-the-shelf sensors with 512 x 512 . . . 1024 x 1024 pixels. More realistic is an accuracy value of about 0.1 pixel respectively 1/5000 . . . 1/15000, as practical realizations mostly reduce the performance due to stability reasons of the camera and the camera mount [13].

The resolution of a digital system can be increased by shifting the sensor and recording the object sequentially. The partial images must be orientated to each other with high precision to build the whole image. Different recording systems have been developed (Table 3) using one of the following techniques:

Micro-scanning by shifting the sensor

(1) with high-precision piezo-controlled steps to fill the gaps between the sensor elements [14, 15].

Macro-scanning by shifting the sensor

(2) with less accurate stepping motors and high precision opto-numerical orientation of the partial images using réseau technique [16, 17].

(3) with high precision stepping motors [18-20].

(4) with servo-controlled video-theodolites [21, 22]. or a turning and tilting camera [23].

These scanning cameras, however, allow for *on-line* data acquisition of non-moving objects, whereas all *real-time* applications are excluded.

Another possibility to use low resolution cameras for high precision estimation of bigger sized objects is given, if they are arranged as individual adapted measurement systems in local networks. These local networks must be orientated to each other in a global network using a high resolution photogrammetric system. (Fig. 2). The global orientation can be done permanently or periodically. As local measurement systems also other optical methods can be applied, such as Moiré Techniques or Structured Light Techniques.

Table 3
Digital camera systems using sensor shift

Manufacturer	Type	shift	Image size [mm] x [mm]	Pixel resulting from shift
Kontron	ProgRes	(1)	8.5 x 6.4	3000 x 2300
RJM	JenScan	(1)	8.8 x 6.6	4500 x 3450
Rollei	RSC	(2)	50.0 x 50. 0	4200 x 6250
Rollei (*)	ScanPack	(3)	41.2 x 35.0	5000 x 6000
Zeiss	UMK SCAN	(3)	120.0 x 160.0	11000 x 14000
Leica	Kern SPACE	(4)	sphere	
Leica	Wild ATMS	(4)	sphere	
Leica (**)	Wild APS V/D	(4)	sphere	

(*) equipped with a linear sensor
(**) designed for single instrument applications

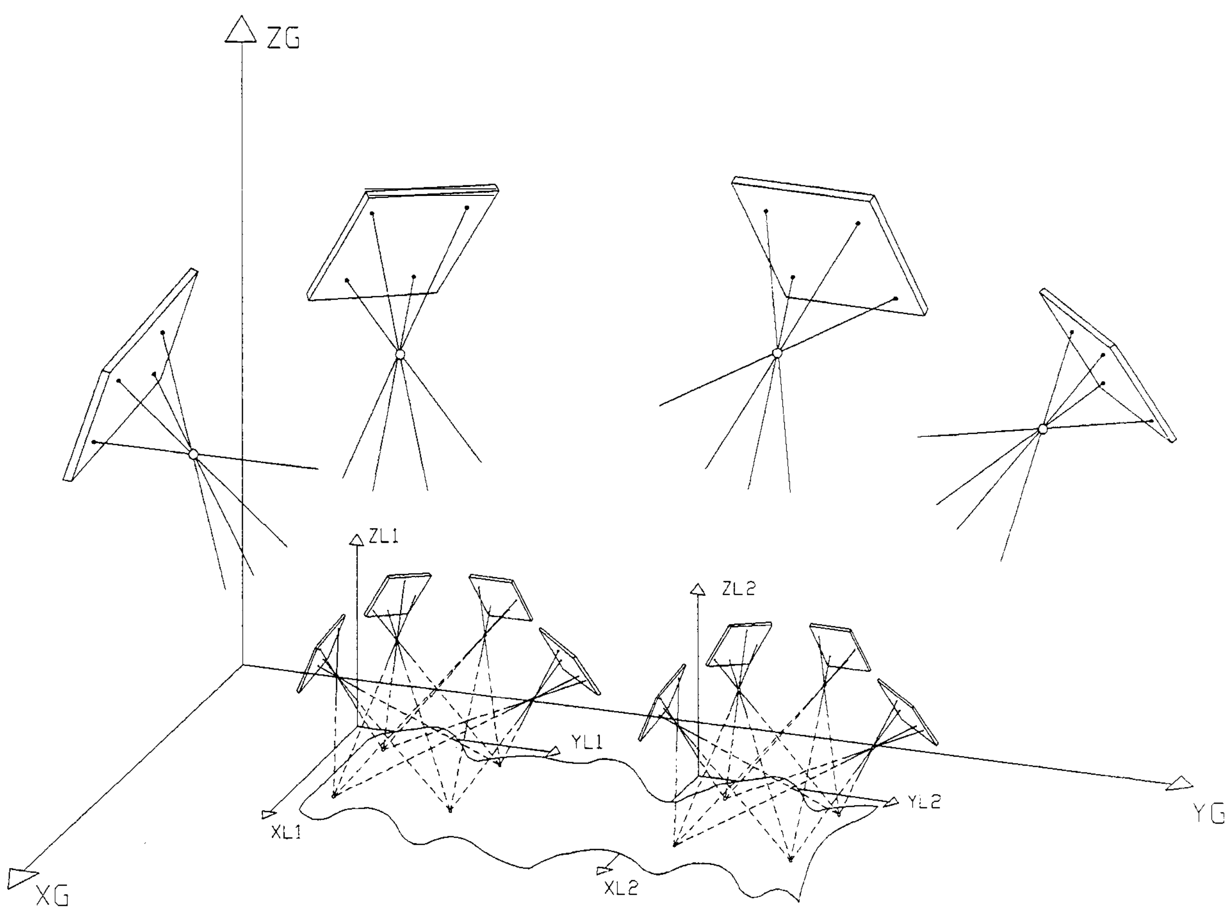

Fig. 2 Global network to orientate individual adapted local networks

3.3 Camera calibration

For the efficiency of a photogrammetric system it is important, how accurate the camera geometry is known. Depending on the strategy the system parameters may be calibrated off-site or on-site, partially or totally (Fig. 3), applying a suitable calibration procedure or an appropriate combination of procedures (Fig. 4). To meet high accuracy demands, the camera geometry should be estimated simultaneously with the orientation parameters of the network and the object coordinates by means of the bundle adjustment (simultaneous camera calibration).

The main parameters of the camera geometry are the principal point and the principal distance. The principal point is defined as point of intersection of the principal ray on the image side, normal to the image plane on the object side, with the image plane. The principal distance is the distance between the perspective center on the image side (exit pupil of the lens system) and the principal point [24].

Besides the position of the perspective center relative to the image plane the introduction of additional parameters to the imaging equation allows for the calibration of the deviation from the simple model of the central perspective and the real physical imaging [25]. Radial-symmetric and radial-asymmetric and tangential lens distortion can be estimated as well as tine deformations of a matrix sensor. Affine parameters are relevant, if the sensor elements are not quadratic (affinity scale) and the lines and columns of the matrix are not perpendicular (affinity direction). Investigations and configurations for a photogrammetric calibration of photographic or digital image recording systems with introduction of control information as well as camera self-calibration using pure photogrammetric information can be found in Ref. [7] and Refs. [26] to [32].

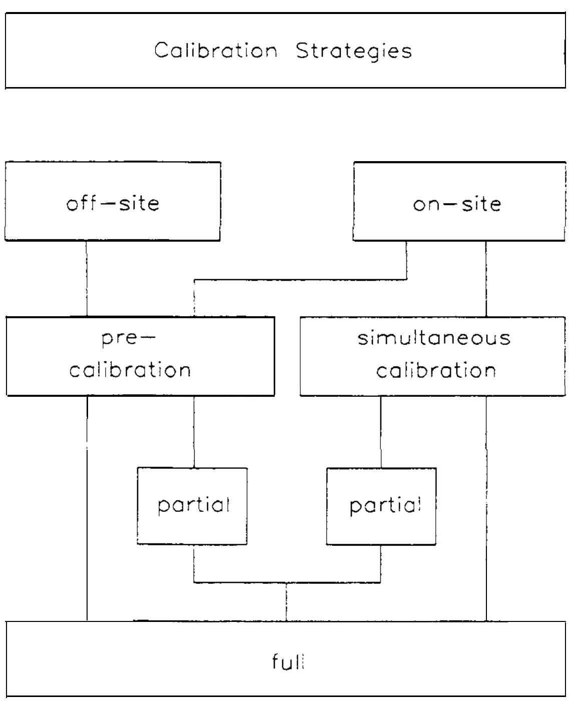

Fig. 3 Strategies for calibration of an image recording system

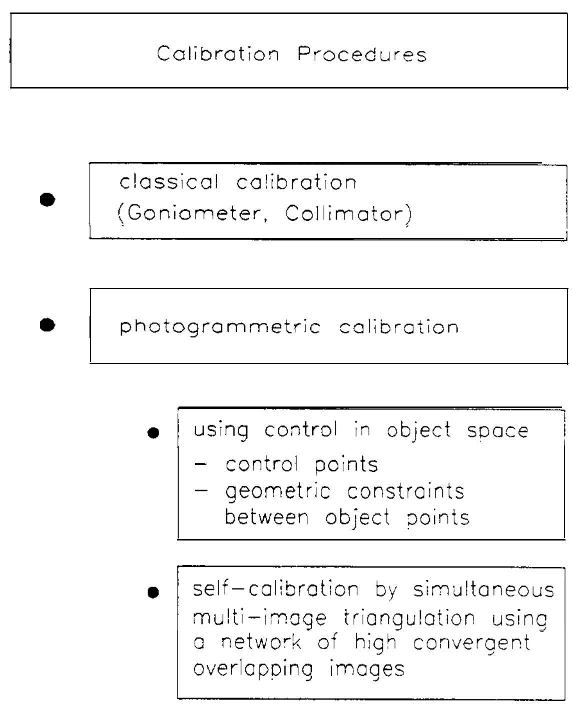

Fig. 4 Procedures for calibration of an image recording system

4. IMAGE ANALYSIS

The two-dimensional image coordinates of the projected object points make up the measured variables in photogrammetry. For industrial applications, the visual and manual measurement of image points on a film with a digitizer-table or a photogrammetric monoscopic or stereoscopic image comparator or stereo-plotter is of minor significance, as the grade of automation plays an important role. Therefore digital image processing is not only performed with digital *on-line* systems, but also with photographic systems by scanning the film partially with a CCD sensor and processing the data digitally (Fig. 5). Commonly used in industrial photogrammetry are scanners equipped with a matrix sensor, where the orientation of the partial images to the whole image is given mechanically [32] or opto-numerically using réseau technique [33]. The latter principle gives the opportunity to use less accurate moving devices. As described in Section 3.1 the imaged reference grid of the camera or a grid plate placed on the film carrier of the scanner serves for the high precision sensor orientation, if at least four grid points are imaged and measured [34]. Especially with large format images the concept of selective point digitizing is advantageous, as neither time- nor memory expended digitization of the whole image has to be done, but with minimum memory requirements partial images have to be analyzed to store just the image coordinates as digital information finally. Due to the increasing number of photogrammetric applications, modular designed digital workstations for close-range photogrammetry have been developed, allowing for data evaluation of *on-line* and *off-line* systems [35, 36].

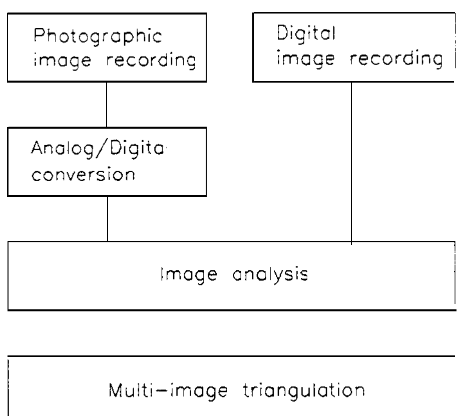

Fig. 5 Data flow of photogrammetric systems

4.1 Point and edge detection

The detection of imaged object structures given by discrete and unique points and edges is a frequent task in the photogrammetric image analysis. If the object lacks of appropriate structures, artificial signals can be attached. Retro-reflecting targets have been approved, reflecting the light best towards the source, e.g. a ring-light around the camera lens. Exposure time and aperture can be optimized for best possible point imaging while the object imaging can be suppressed, effecting a suitable contrast for the subsequent automatic image analysis.

A point, defined by a plane circle in object space with a sufficient contrast to its surroundings will be imaged perspectively as an ellipse on the sensor. Starting with an approximate value, the ellipse center can be found with tresholding techniques. For high precision requirements, the knowledge of the structure can be used to estimate the center. By analizing the grey value variation along directions perpendicular to the border of the ellipse, edge points of the ellipse can be detected. A low-pass filter to minimize the sensor noise and a high-pass filter to amplify the edges optimizes the analysis. The ellipse parameters are therewith derived by approximating the shape of the ellipse numerically using an adjustment process taking the measured edge points as input [5].

The problem of automatic point detection [37] and identification [37, 38] has been investigated to improve the productivity of the photogrammetric data processing. Point identification is especially important for retro-reflective targetting, as the object is mostly imaged diffuse and gives no visual help for the identification. Binary coded point numbering is advantageous for digital image analysis. The code is realized by concentric black and white segments surrounding the target point (Fig. 6), which ensures the correspondence between point and point number better than for example code bars fixed in the neighbourhood.

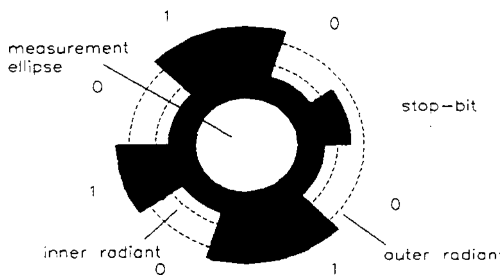

Fig. 6 Segment mark [38]

Linear object structures can be detected similar with digital edge analysis. The unique match of discrete line points within the multi-image triangulation often only is possible, if patterns of lines crossing each other are analyzed. The calculation of spatial elements without matching unique points is possible, if the elements are described analytically [39-41].

4.2 Surface reconstruction

For the acquisition of the object surface an optic signalling is preferable to the contacting signalling. A computer driven LASER may be used to project points sequentially to the object surface, which can be measured with the mentioned point algorithms. Furthermore, least square correlation procedures are used, where surface points are found as matching, if the grey values in windows of two images are fitting best possible [42, 43]. To overcome the restriction of two images, the method of multiphoto geometrically constraint matching has been developed, taking one image as a template and matching all other images to it [44]. The object coordinates can be derived simultaneously during matching.

Newer methods of object reconstruction are based on the direct description of the surface point in object space as a function of the grey values in the neighbourhood of the point. The estimation takes place in *all* images simultaneously [45-49]. The universal formulation of the method allows besides the introduction of the geometric model the consideration of radiometric influences. The parameters are estimated in an adjustment process with the aim, that the grey values measured in the images and reprojected into the object space, represent the grey values on the object best possible. This technique is known as multi-image matching. A further advantage of the formulation in object space is the possibility to measure the surface in a regular object defined grid.

If the contrast of the object surface itself is not satisfactory, an arbitrary pattern can be fixed or preferred projected optically, if the reflection is appropriate. For bigger sized objects a sequential pattern projection in combination with *on-line* scanning cameras is of particular use.

5. APPLICATIONS

The following sections shall demonstrate some examples to present some *quite different* measuring tasks, where photogrammetry was applied in a powerful and flexible way.

5.1 Inspection of big sized toolings

For the assembly of aircrafts toolings (10 x 6 x 6 m^3) are used to fix and connect the upper and lower segments of the fuselage. The mounting can take place, if the two segments are in a specified, relative position to each other by using fittings such as boreholes. The fittings have to be controlled periodically against their nominal positions. To minimize the interruption time for cost saving reasons, photogrammetry was selected to solve the task. Using a large format camera, the required standard deviation of object coordinates of 0.1 mm is reached [50].

5.2 Deformation analysis

For the development of a technique for the post-strengthening of masonry walls in seismically endangered zones through the use of fiber-based composites, tests have been carried out. To compare the efficiency of different strengthening techniques, test walls have been loaded cyclically in the plane of the wall and then perpendicular to this plane. To evaluate the selected strengthening techniques the three-dimensional deformation behaviour of the wall was determined during loading. 300 object points over the surface of 2.0 m x 3.6 m were recorded simultaneously by five synchronized large format cameras to detect deformations in the order of 0.04 mm. By means of a bundle adjustment, a spatial reconstruction of the wall shape was achieved with an average standard deviation of 0.02 mm for the object coordinates in the plane of the wall, respectively 0.03 mm for coordinates perpendicular to the wall [51].

5.3 Robot calibration

The pose repeatability of an industrial robot reaches down to some hundredth of a millimetre and is sufficient for the teach-in programming of robots, whereas the absolute pose accuracy is significant lower, especially, if the robot is loaded. For exacting applications under the use of off-line programming techniques a robot calibration is necessary. To model the kinematic behaviour of an industrial robot, long term observations of the absolute pose of the robots's tool center point was examined with a digital photogrammetric *on-line* system using three *macro-scanning* réseau cameras. The robot and the photogrammetric system were connected to measure up to 750 positions automatically without any interaction of an operator. Within an object range of 2.5 x 2.5 x 2.0 m^3 the robot positions were determined with standard deviations of approximately 0.04 mm normal to the main imaging direction of the system and 0.06 mm in the imaging direction [52].

5.4 Quality control

To avoid the conventional manual inspection using expensive, object-specific mechanical gauges, a digital photogrammetric 3-D measuring system was developed for the automobile industry. By means of digital image processing a variety of parts made of different materials, e.g. sheet-metal, rubber tubing, glass windshields, plastic objects etc. are measured. The parts are characterized by different features in shape and size, such as boreholes, points, lines, circles and cylinders. A digital rotary table serves as an object carrier and enables a flexible positioning in order to achieve good perspectives for the cameras fixed in a stable steel frame. An accuracy of 0.1 mm and better in an object space of 2.0 x 2.0 x 0.6 m^3 can be reached *on-line* [53].

6. CONCLUSION

Applying the methods of close-range photogrammetry industrial measuring tasks can be solved efficiently. The modularity of system components available on the market for image recording, image measurement and data processing enables their individual combination depending on accuracy and availability requirements of the results. Although progress is made in the development of digital sensors with bigger sized format, the photographic image recording will participate considerably in industrial metrology.

REFERENCES

[1] W. Wester-Ebbinghaus, Bündeltriangulation mit gemeinsamer Ausgleichung photogrammemetrischer und geodätischer Beobachtungen, Zeitschrift für Vermessungswesen, Heft 3/1985, p. 101-111.

[2] W. Wester Ebbinghaus, Mehrbild-Photogrammetrie - Räumliche Triangulation mit Richtungsbündeln. Symposium für Bildverarbeitung an der Technischen Akademie Esslingen 1989.

[3] W. Wester-Ebbinghaus, Das Réseau im photogrammetrischen Bildraum, Bildmessung und Luftbildwesen, Heft 3/1989, p. 64-71.

[4] R. Kotowski, Zur Reseaukorrektur von systematischen Bildfehlem, Bildmessung und Luftbildwesen, Heft 2/1984, p. 96- 101.

[5] T. Luhmann, Ein hochauflösendes automatisches Bildmeßsystem, Dissertation, Hannover 1988.

[6] R. Lenz, U. Lenz, Messung der Übertragungseigenschaften einer hochauflösenden Farbkamera mit CCD-Flächensensor, 12. DAGM-Symposium Mustererkennung, Oberkochen-Aalen 1990, p. 29-35.

[7] H.A. Beyer, Geometric and Radiometric Analysis of a CCD-Camera Based Photogrammetric Close-Range System, Dissertation, ETH Zurich 1992, Mitteilungen Nr 51.

[8] F. Schmidt, 2D-Industriemeßtechnik mit CCD-Sensoren, Zeitschrift für Photogrammetrie und Femerkundung, Heft 2/1993, p. 62-70.

[9] T. Luhmann, Bilderfassung in der Nahbereichsphotogrammetrie - Aktuelle Tendenzen, Vermessungswesen und Raumordnung, Jahrg. 54, Heft 8/1992, p. 400-410

[10] V. Uffenkamp, Photogrammetrische Verfahren zur Formprüfung, Tagungsband VIII Internationales Oberflächenkolloquium, Chemnitz 1992.

[11] D.C. Brown, A Large Format, Microprocessor Controlled Film Camera Optimized for Industrial Photogrammetry, ISPRS-Congress, Corn. V, Rio de Janiero 1984, p 29.

[12] J. Dold, A Large Format Film Camera for High Precision Object Recording, SPIE Vol. 1395, Close-Range Photogrammetry Meets Machine Vision, Zurich 1990, p. 252-255.

[13] H. Haggren, P. Pekkinen, Stability Control of Photogrammetric Stations, ISPRS-Congress, Washington D.C. 1992, IUSM session on 'Automated Control Measurments'.

[14] R. Lenz, U. Lenz, Calibration of a color CCD camera with 3000 x 2300 picture elements, SPIE Vol. 1395, Close-Range Photogrammetry Meets Machine Vision, Zurich 1990, p. 104-111.

[15] U. Richter, Hardwarekomponenten für die Bildaufhahme höchster örtlicher Auflösung, 12. Wissenschaftlich-Technische Jahrestagung der Deutschen Gesellschaft für Photogrammetrie und Femerkundung, Jena 1992, p. 367-377.

[16] W. Wester-Ebbinghaus, Opto-elektrische Festkörper-Flächensensoren im photogrammetrischen Abbildungssystem, Bildmessung und Luftbildwesen, Heft 6/1984, p. 297-301.

[17] W. Riechmann, The Réseau-Scanning Camera; Conception and first measurement results, SPIE Vol. 1395, Close-Range Photogrammetry meets Machine Vision, Zurich 1990, p. 1117-1125.

[18] H. Poitz, Die UMK SCAN von Carl Zeiss Jena - ein neues System für die digitale Industrie-Photogrammetrie, 12. Wissenschaftlich-Technische Jahrestagung der Deutschen Gesellschaft für Photogrammetrie und Femerkundung, Jena 1992, p. 327-331.

[19] R. Goldschmidt, U. Richter, Neue Hardwarekomponenten für die digitale Nahbereichsphotogrammetrie, Zeitschrift für Photogrammetrie und Femerkundung, Heft 2/1993, p. 71-75.

[20] Der Kamera-Scanner Rollei Digital ScanPack, Produktinformation Rollei fototechnic.

[21] O. Katowski, Automation of electronic angle-measuring instruments. Proc. of the second industrial and engineering survey conference, London 1987, p. 230-240.

[22] R. Gottwald, W. Bemer, Electronic theodolite-sensor-systems for real-time-photogrammetry, ISPRS-Symposium, Interlaken 1987, p. 343-349.

[23] V. Uffenkamp, Conception of a Digital Turning and Tilting Camera, Proc. of Optical 3-D Measurement Techniques, Zurich 1993.

[24] Bucholtz/Rüger, Photogrammetrie, Verfahren und Geräte. VEB Verlag für Bauwesen, Berlin 1973, pp. 43.

[25] W. Wester-Ebbinghaus, Photographisch-numerische Bestimmung der geometrischen Abbildungseigenschaften eines optischen Systems, Optik 55, No. 3, 1980, p 253-259.

[26] W. Wester-Ebbinghaus, Einzelstandpunkt-Selbstkalibrierung - Ein Beitrag zur Feldkalibrierung von Aufnahmekammem. Habilitation, Deutsche Geodätische Kommission, Reihe C, 1983, Heft Nr. 289.

[27] J. Peipe, Simultankalibrierung einer Teil-Meßkammer - Ein Anwendungsbeispiel aus dem Fahrzeugbau, Deutsche Geodätische Kommission, Reihe B, München 1985, p. 152- 158.

[28] W. Wester-Ebbinghaus, Analytische Kammerkalibrierung. ISPRS-Symposium, Corn. V, Ottawa 1986, p. 77-84.

[29] I. Hadem, K. Amdal, High-Precision Calibration of Close Range Photogrammetry Systems, ISPRS-Congress, Corn. V, Washinghton D.C. 1992, p. 568-574.

[30] J.G. Fryer, Recent Developments in Camera Calibration for Close-Range Applications, ISPRS-Congress, Corn V, Washington D.C. 1992, p. 594-599.

[31] R. Godding, Ein photogrammetrisches Verfahren zur Überprüfung und Kalibrierung digitaler Aufnahmesysteme, Zeitschrift für Photogrammetrie und Femerkundung, Heft 2/1993, p. 82-90.

[32] D.C. Brown, AutoSet, An Automated Monocomparator Optimized for Industrial Photogrammetry, Proc. Int. Conference and Workshop on Analytical Instrumentation, Phoenix, Arizona 1988, ASPRS, p. 292-307.

[33] J. Dold, G. Suilmann, Das RolleiMetric 3D-Industriemeßsystem, Zeitschrift für Photogrammetrie und Femerkundung, Heft 2/1993, p. 50-62.

[34] T. Luhrnann, W. Wester-Ebbinghaus, Digital Image Processing by Means of Réseau-Scanning, Allgemeine Vermessungsnachrichten, Int. Edition, Vol. 5, 3/1988, p. 13-18.

[35] J. Peipe, C.-T. Schneider, K. Sinnreich, DPA - Entwurfund Realisierung einer PC-basierten digitalen Arbeitsstation für die Nahbereichsphotogrammetrie, Zeitschrift für Photogrammetrie und Femerkundung, Heft 2/1993, p. 75-82.

[36] D. Woytowicz, PHAUST - A Photogrammetric System for Digital Images, Proc. of Optical 3-D Measurement Techniques, Zurich 1993.

[37] F.A. Heuvel, R.J.G.A. Kroon, Digital Close-Range Photogrammetry using Artificial Targets, ISPRS-Congress, Corn. V, Washington D.C. 1992, p. 222-229.

[38] M. Knobloch, T. Rosenthal, MIROS - A new Software for Rollei RS1 digital mono-comparator, ISPRS-Congress, Corn. V, Washington D.C. 1992, p. 35-42.

[39] H. Kager, Das interaktive Programmsystem ORIENT im Einsatz, ISPRS-Congress, Corn. V, Hamburg 1980, p. 390-401.

[40] K. Andresen, Ermittlung von Raumelementen aus Kanten im Bild, Zeitschrift für Photogrammetrie und Femerkundung, Heft 6/1991, p. 212-220.

[41] W. Bösemann, Evaluation of Threedimensional Geometric Features of Industrial Objects, ISPRS-Congress, Washington D.C. 1992, IUSM session on ‘Automated Control Measurements’.

[42] F. Ackermann, High Precision Digital Image Correlation, 39. Photogrammetrische Woche, Stuttgart 1984, p. 231-243.

[43] M. Claus, Digital Image Correlation with the PLANICOMP system, ISPRS-Symposium, Corn. V, Ottawa 1986.

[44] E.P. Baltsavias, Multiphoto Geometrically Constrained Matching, Dissertation, ETH Zürich 1991, Mitteilungen Nr. 49.

[45] H. Ebner, D. Fritsch, W. Gilessen, C. Heipke, Integration von Bildzuordnung und Objektrekonstruktion innerhalb der digitalen Photogrammetrie, Bildmessung und Lufibildwesen, Heft 5/1987, p. 194-203.

[46] B. Wrobel, Digitale Bildzuordnung durch Facetten mit Hilfe von Objektraummodellen, Bildmessung und Lufibildwesen, Heft 3/1987, p. 93-101.

[47] U.V. Helava, Object-space least-squares correlation, Photogrammetric Engineering and Remote Sensing, Vol. 54, No. 6, 1988, part 1, p. 711-714.

[48] C. Heipke, Integration von digitaler Bildzuordnung, Punktbestimmung, Oberflächenrekonstruktion und Orthoprojektion in der digitalen Photogrammetrie, Dissertation, Deutsche Geodatische Kommission, Reihe C, 1990, Heft 366.

[49] C.T. Schneider, Objektgestützte Mehr-Bild-Zuordnung, Dissertation, Deutsche Geodätische Kornmission, Reihe C, 1991, Heft 375.

[50] J. Dold, W. Riechmann, Industriephotogrammetrie höchster Genauigkeit, ein neues Meßsystem und dessen Anwendung in der Luft- und Raumfahrtindustrie, Zeitschrift für Photogrammetrie und Femerkundung, Heft 6/1991, p. 221-228.

[51] G. Schwegler, J. Dold, Simulation of earthquakes on strengthened masonry walls-Photogrammetric determination of kinematic shape changes, Proc. of Optical 3-D Measurement Techniques, Zurich 1993.

[52] B. Diewald, R. Godding, A. Henrich, Robot Calibration with a Photogrammetric On-Line System using Réseau-Scanning-Cameras, Proc. of Optical 3-D Measurement Techniques, Zurich 1993.

[53] R. Loser, T. Luhmann, The Programmable Optical 3D Measuring System POM - Applications and Performance, ISPRS-Congr., Corn. V, Washington D.C. 1992, p. 533-540.