Close Range Photogrammetry
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**Abbreviations**

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<th>Description</th>
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<tbody>
<tr>
<td>ADC</td>
<td>analogue-to-digital converter</td>
</tr>
<tr>
<td>AGC</td>
<td>automatic gain control</td>
</tr>
<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
</tr>
<tr>
<td>ASPRS</td>
<td>American Society for Photogrammetry and Remote Sensing</td>
</tr>
<tr>
<td>BRDF</td>
<td>bidirectional reflection distribution function</td>
</tr>
<tr>
<td>CAAD</td>
<td>computer aided architectural design</td>
</tr>
<tr>
<td>CAD</td>
<td>computer aided design</td>
</tr>
<tr>
<td>CAM</td>
<td>computer aided manufacturing</td>
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<tr>
<td>CCD</td>
<td>charge coupled device</td>
</tr>
<tr>
<td>CCIR</td>
<td>Comité consultatif international pour la radio (International Radio Consultative Committee)</td>
</tr>
<tr>
<td>CD-ROM</td>
<td>compact disk – read-only memory</td>
</tr>
<tr>
<td>CID</td>
<td>charge injection device</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission Internationale de l’Éclairage (International Commission on Illumination)</td>
</tr>
<tr>
<td>CIPA</td>
<td>Comité International de Photogrammétrie Architecturale (International Committee for Architectural Photogrammetry)</td>
</tr>
<tr>
<td>CMM</td>
<td>coordinate measurement machine</td>
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<tr>
<td>CMOS</td>
<td>complementary metal oxide semi-conductor</td>
</tr>
<tr>
<td>CT</td>
<td>computer tomogram, tomography</td>
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<tr>
<td>CTF</td>
<td>contrast transfer function</td>
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<tr>
<td>DAGM</td>
<td>Deutsche Arbeitsgemeinschaft für Mustererkennung (German Association for Pattern Recognition)</td>
</tr>
<tr>
<td>DCT</td>
<td>discrete cosine transform</td>
</tr>
<tr>
<td>DGPF</td>
<td>Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation (German Society for Photogrammetry, Remote Sensing and Geoinformation)</td>
</tr>
<tr>
<td>DGZfP</td>
<td>Deutsche Gesellschaft für Zerstörungsfreie Prüfung (German Society for Non-Destructive Testing)</td>
</tr>
<tr>
<td>DIN</td>
<td>Deutsches Institut für Normung (German institute for standardization)</td>
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<tr>
<td>DLT</td>
<td>direct linear transformation</td>
</tr>
<tr>
<td>DMD</td>
<td>digital mirror device</td>
</tr>
<tr>
<td>DOF</td>
<td>degree(s) of freedom</td>
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<tr>
<td>DRAM</td>
<td>dynamic random access memory</td>
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<tr>
<td>DSM</td>
<td>digital surface model</td>
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<tr>
<td>DTP</td>
<td>desktop publishing</td>
</tr>
<tr>
<td>DVD</td>
<td>digital versatile (video) disk</td>
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<tr>
<td>DXF</td>
<td>autocad data exchange format</td>
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<tr>
<td>EP</td>
<td>entrance pupil</td>
</tr>
<tr>
<td>E’P</td>
<td>exit pupil</td>
</tr>
<tr>
<td>EPS</td>
<td>encapsulated postscript</td>
</tr>
<tr>
<td>FFT</td>
<td>full frame transfer or fast Fourier transform</td>
</tr>
<tr>
<td>FMC</td>
<td>forward motion compensation</td>
</tr>
<tr>
<td>FOV</td>
<td>field of view</td>
</tr>
<tr>
<td>FPGA</td>
<td>field-programmable gate array</td>
</tr>
<tr>
<td>FT</td>
<td>frame transfer</td>
</tr>
<tr>
<td>GIF</td>
<td>graphic interchange format</td>
</tr>
<tr>
<td>GIS</td>
<td>geograph(raphic) information system</td>
</tr>
<tr>
<td>GMA</td>
<td>Gesellschaft für Meß- und Automatisierungstechnik (Society for Metrology and Automation Technology)</td>
</tr>
<tr>
<td>GPS</td>
<td>global positioning system</td>
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<tr>
<td>HDTV</td>
<td>high definition television</td>
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Abbreviations

IEEE Institute of Electrical and Electronic Engineers
IFOV instantaneous field of view
IHS intensity, hue, saturation
IL interline transfer
INS inertial navigation system
ISO International Organisation for Standardization
ISPRS International Society for Photogrammetry and Remote Sensing
JPEG Joint Photographic Expert Group
LAN local area network
LCD liquid crystal display
LED light emitting diode
LoG Laplacian of Gaussian
LSM least squares matching
LUT lookup table
L W/PH line widths per picture height
LZW Lempel-Ziv-Welch (compression)
MOS metal oxide semiconductor
MPEG Motion Picture Expert Group
MR magnetic resonance
MTF modulation transfer function
PCMCIA Personal Computer Memory Card International Association
PLL phase-locked loop or pixel-locked loop
PNG portable network graphics
PSF point spread function
REM raster electron microscope
RGB red, green, blue
RMS root mean square
RMSE root mean square error
RPV remotely piloted vehicle
RV resolution power
SCSI small computer systems interface
SLR single lens reflex (camera)
SNR signal-to-noise ratio
SPIE The International Society for Optical Engineering
TIFF tagged image file format
TTL through the lens
TV television
USB universal serial bus
VDI Verband Deutscher Ingenieure (German Association of Engineers)
VLL vertical line locus
VR virtual reality
VRML virtual reality modelling language
Image sources

ABW Automatisierung + Bildverarbeitung Dr. Wolf GmbH, Frickenhausen, Germany: 3.129cd
AICON 3D Systems GmbH, Braunschweig, Germany: 3.76c, 3.109, 3.111, 3.117c, 6.8, 6.10, 6.21, 6.25, 6.26, 6.27, 6.46a, 8.27
AXIOS 3D Services GmbH, Oldenburg, Germany: 8.37a
BrainLAB AG, Heimstetten, Germany: 8.38
Breuckmann GmbH, Meersburg, Germany: 6.34
Carl Zeiss (ZI Imaging, Intergraph), Oberkochen, Jena, Germany: 1.25, 1.26, 1.27, 1.28, 3.12, 3.48, 3.96, 3.129ab, 6.2, 6.42, 6.43, 6.44, 8.11
DaimlerChrysler, Forschungszentrum Ulm, Germany: 5.68
Dalsa Inc., Waterloo, Ontario, Canada: 3.63a, 5.35a
DMT Deutsche MontanTechnologie, German Mining Museum, Bochum, Germany: 7.22
Dresden University of Technology, Forschungsgruppe 3D Display, Germany: 6.13b
ESTEC, Noordwijk, Netherlands: 8.28
Fachhochschule Bielefeld, Abt. Minden, Fachbereich Architektur und Bauingenieurwesen, Germany: 4.59
Fachhochschule Osnabrück, Internet Site “Einführung in Multimedia”, Germany: 3.60, 3.62
Fokus GmbH Leipzig, Germany: 4.58
Frank Data International NV, Netherlands: 8.8a
Fraunhofer Institute for Applied Optics and Precision Engineering (IOF), Jena: 6.38, 6.39, Germany
Fraunhofer Institute for Factory Operation and Automation (IFF), Magdeburg, Germany: 6.16
GOM Gesellschaft mbH, Braunschweig, Germany: 6.36
GSI Geodetic Services Inc., Melbourne, Florida, USA: 1.15, 1.32, 3.54, 3.55, 3.83, 3.84, 3.117b, 3.124b, 6.3, 8.24
Hasselblad Svenska AB, Göteborg, Sweden: 3.52
HDW Howaldtswerke Deutsche Werft, Kiel, Germany: 8.31
Imetric SA, Porrentruy, Switzerland: 1.14, 1.19, 3.85, 6.20, 6.28, 7.10
Institute of Applied Photogrammetry and Geoinformatics (IAPG), FH Oldenburg, Germany: 1.1, 1.12, 1.13, 1.17, 3.28, 3.29, 3.32, 3.68, 3.71, 3.73, 3.78, 3.87, 3.88, 3.89, 3.99, 3.117a, 3.119, 3.120, 4.10, 4.52, 4.56, 4.61, 5.2b, 5.11, 5.41, 5.53, 5.66, 6.14, 6.15, 7.6b, 7.20, 7.21, 8.4, 8.7, 8.12, 8.13, 8.20, 8.21
Institute of Geodesy and Geoinformatics, Applied Photogrammetry and Cartography, TU Berlin, Germany: 1.23, 3.108
Institute of Geodesy and Photogrammetry (IGP), ETH Zürich, Switzerland: 1.21, 4.75, 7.17, 8.5, 8.6
Institute of Photogrammetry, University of Bundeswehr, Neubiberg, Germany: 7.18, 7.19
Institute of Photogrammetry (IPI), University of Stuttgart, Germany: 8.9
Institute of Photogrammetry and Geoinformatics (IPI), University of Hannover, Germany: 8.10, 8.14, 8.15, 8.16, 8.17
Institute of Photogrammetry and Image Processing, TU Braunschweig, Germany: 1.18, 7.6a, 8.31, 8.32
INVERS, Essen, Germany: 8.19, 8.22, 8.23
Jenoptik Laser-Optik-Systeme GmbH, Jena, Germany: 3.86, 3.90, 3.91
Kamera Werk Dresden, Germany: 3.98
Kodak AG, Stuttgart, Germany: 1.31
Konica Corporation, Tokyo, Japan: 3.116a
Leica Geosystems (Wild, Kern, LH Systems, Cyra), Heerbrugg, Switzerland: 3.49, 3.50, 3.105, 3.110, 3.112, 3.113, 4.68, 4.70, 4.73, 6.12, 6.14, 6.31
Landeskriminalamt Nordrhein-Westfalen, Düsseldorf, Germany: 8.34
Mapvision Ltd, Espoo, Finland: 1.30, 6.40
Messbildstelle GmbH, Dresden, Germany: 8.3
Metronor GmbH, Saarbrücken, Germany, Norway: 6.6, 6.24
NASA, Jet Propulsion Laboratory, Pasadena, Ca., USA: 6.17
Phocad Ingenieurgesellschaft mbH, Aachen, Germany: 1.33, 6.19
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany: 6.46b
Plus Orthopedics (Precision Instruments), Aarau, Switzerland: 8.37bc, 8.39
Ricoh Corporation, San Bernardino, Ca., USA: 3.118b
Rollei Fototechnic GmbH, Braunschweig, Germany: 1.16, 1.29, 3.13, 3.53, 3.56, 3.63b, 3.81, 3.82, 3.93, 3.95, 3.128, 4.44, 6.5, 6.9, 6.18, 7.8, 8.33
Sine Patterns LLC, Rochester, NY, USA: 3.34a
Sony Deutschland GmbH, Köln, Germany: 3.76b
Stadtpolizei Zürich, Switzerland: 8.34
Transmap Corporation, Columbus, Ohio, USA: 8.8b
University of Aalborg, Department of Development and Planning, Denmark: 4.59
University of Melbourne, Department of Geomatics, Parkville, Australia: 4.42, 5.2, 8.25
Volkswagen AG, Wolfsburg, Germany: 2.4, 6.45, 8.30
Weinberger Deutschland GmbH, Erlangen, Germany: 3.103, 7.15
Zoller and Fröhlich GmbH, Wangen im Allgäu, Germany: 3.105
1 Introduction

1.1 Overview

Chapter 1 provides an overview of the fundamentals of photogrammetry, with particular reference to close range measurement. After a brief discussion of the principal methods and systems, typical applications are presented. The chapter ends with a short historical review of close range photogrammetry.

Chapter 2 deals with mathematical basics. These include the definition of some important coordinate systems and the derivation of geometric transformations which are needed for a deeper understanding of topics presented later. In addition, the major aspects of least squares adjustment and statistics are summarised. Finally, a number of important geometrical elements used for object representation are discussed.

Chapter 3 is concerned with photogrammetric image acquisition for close range applications. Because of the wide variety of applications and instrumentation this chapter is extensive and wide-ranging. After an introduction to geometric basics and the principles of image acquisition, there follow discussions of analogue and digital imaging equipment as well as specialist areas of image recording. The chapter ends with a summary of targeting and illumination techniques.

Analytical methods of image orientation and object reconstruction are presented in Chapter 4. The emphasis here is on bundle triangulation. The chapter also presents methods for dealing with single, stereo and multiple image configurations based on measured image coordinates.

Chapter 5 brings together many of the relevant methods of digital photogrammetric image processing. In particular, those which are most useful to dimensional analysis and three dimensional object reconstruction are presented.

Photogrammetric measurement systems developed for close range are discussed in Chapter 6. They are classified into systems designed for single image, stereo image and multiple image processing. Interactive and automatic, mobile and stationary systems are considered, along with surface measurement systems utilising projected light patterns.

Chapter 7 discusses imaging configurations for, and solutions to, some critical close range tasks. After an introduction to network planning and optimisation the chapter concentrates on techniques for camera calibration, dynamic applications and aerial imaging from low flying heights.

Finally, Chapter 8 uses case studies and examples to demonstrate the potential for close range photogrammetry in fields such as architecture and heritage conservation, the construction industry, manufacturing industry and medicine.
1.2 Fundamental methods

1.2.1 The photogrammetric process

Photogrammetry encompasses methods of image measurement and interpretation in order to derive the shape and location of an object from one or more photographs of that object. In principle, photogrammetric methods can be applied in any situation where the object to be measured can be photographically recorded. The primary purpose of a photogrammetric measurement is the three dimensional reconstruction of an object in digital form (coordinates and derived geometric elements) or graphical form (images, drawings, maps). The photograph or image represents a store of information which can be re-accessed at any time.

Fig. 1.1 shows examples of photogrammetric images. The reduction of a three-dimensional object to a two-dimensional image implies a loss of information. Object areas which are not visible in the image cannot be reconstructed from it. This not only includes hidden parts of an object such as the rear of a building but also regions which can not be recognised due to lack of contrast or limiting size, for example individual bricks in a building façade. Whereas the position in space of each point on the object may be defined by three coordinates, there are only two coordinates available to define the position of its image. There are geometric changes caused by the shape of the object, the relative positioning of camera and object, perspective imaging and optical lens defects. Finally there are also radiometric (colour) changes since the reflected electromagnetic radiation recorded in the image is affected by the transmission media (air, glass) and the light-sensitive recording medium (film, electronic sensor).

For the reconstruction of an object from photographs or images it is therefore necessary to describe the optical process by which an image is created. This includes all elements which contribute to this process, such as light sources, properties of the surface of the object, the medium through which the light travels, sensor and camera technology, image processing, film development and further processing (Fig. 1.2).

Methods of image interpretation and measurement are then required which permit the image of an object point to be identified from its form, brightness or colour distribution. For every
image point, values in the form of radiometric data (intensity, grey value, colour value) and geometric data (position in image) can then be obtained. This requires measurement systems with the appropriate geometric and optical quality.

From these measurements and a mathematical transformation between image and object space, the object can finally be modelled.

Fig. 1.3 simplifies and summarises this sequence. The left hand side indicates the principal instrumentation used whilst the right hand side indicates the methods involved. Together with the physical and mathematical models, human knowledge, experience and skill play a significant role. They determine the extent to which the reconstructed model corresponds to the imaged object or fulfils the task objectives.

1.2.2 Aspects of photogrammetry

Because of its varied applications, close range photogrammetry has a strong interdisciplinary character. There are not only close connections with other measurement techniques but also with fundamental sciences such as mathematics, physics, information sciences or biology.

Close range photogrammetry has significant links with aspects of graphics and photographic science, for example computer graphics and computer vision, digital image processing, computer aided design (CAD), geographic information systems (GIS) and cartography.
Traditionally, there are also strong associations of close range photogrammetry with the techniques of surveying, particularly in the areas of adjustment methods and engineering surveying. With the increasing application of photogrammetry to industrial metrology and quality control, links have been created in other directions.

Fig. 1.4 gives an indication of the relationship between size of measured object, required measurement accuracy and relevant technology. Although there is no hard and fast definition, it may be said that close range photogrammetry applies to objects ranging from 1m to 200m in size, with accuracies under 0.1mm at the smaller end (manufacturing industry) and 1cm accuracy at the larger end (architecture and construction industry).

Optical methods using light as the information carrier lie at the heart of non-contact 3D measurement techniques. Measurement techniques using electromagnetic waves may be subdivided in the manner illustrated in Fig. 1.5. Techniques based on light waves are as follows:

- **Triangulation techniques**
  Photogrammetry (single, stereo and multiple imaging), angle measuring systems (theodolites), indoor GPS, structured light (light section procedures, fringe projection, phase measurement, moiré topography), focusing methods, shadow methods, etc.

- **Interferometry**
  Optically coherent time-of-flight measurement, holography, speckle interferometry, coherent radar

- **Time-of-flight measurement**
  Distance measurement by optical modulation methods, pulse modulation, etc.

---

1 Unsharp borders indicating typical fields of applications of measuring methods.
The clear structure of Fig. 1.5 is blurred in practice since multi-sensor and hybrid measurement systems utilise different principles in order to combine the advantages of each.

Photogrammetry can be categorised in a multiplicity of ways:

- By camera position and object distance
  - Satellite photogrammetry: processing of satellite images, \( h \) > ca. 200km
  - Aerial photogrammetry: processing of aerial photographs, \( h \) > ca. 300m
  - Terrestrial photogrammetry: measurements from a fixed terrestrial location
  - Close range photogrammetry: imaging distance \( h \) < ca. 300m
  - Macro photogrammetry: image scale > 1 (microscope imaging)

- By number of measurement images
  - Single image photogrammetry: single image processing, mono-plotting, rectification, orthophotographs
  - Stereophotogrammetry: dual image processing, stereoscopic measurement
  - Multi-image photogrammetry: \( n \) images where \( n \) >2, bundle triangulation

- By method of recording and processing
  - Plane table photogrammetry: graphical evaluation (until ca. 1930)
  - Analogue photogrammetry: analogue cameras, opto-mechanical measurement systems (until ca. 1980)
  - Analytical photogrammetry: analogue images, computer-controlled measurement
  - Digital photogrammetry: digital images, computer-controlled measurement
  - Videogrammetry: digital image acquisition and measurement
  - Panorama photogrammetry: panoramic imaging and processing
  - Line photogrammetry: analytical methods based on straight lines and polynomials

- By availability of measurement results
  - Real-time photogrammetry: recording and measurement completed within a specified time period particular to the application
Close range photogrammetry

- Off-line photogrammetry: sequential, digital image recording, separated in time or location from measurement
- On-line photogrammetry: simultaneous, multiple, digital image recording, immediate measurement

• By application or specialist area
  - Architectural photogrammetry: architecture, heritage conservation, archaeology
  - Engineering photogrammetry: general engineering (construction) applications
  - Industrial photogrammetry: industrial (manufacturing) applications
  - Forensic photogrammetry: applications to diverse legal problems
  - Biostereometrics: medical applications
  - Motography: recording moving target tracks
  - Multi-media photogrammetry: recording through media of different refractive indices
  - Shape from stereo: stereo image processing (computer vision)

1.2.3 Image forming model

Photogrammetry is a three-dimensional measurement technique which uses central projection imaging as its fundamental mathematical model (Fig. 1.6). Shape and position of an object are determined by reconstructing bundles of rays in which, for each camera, each image point $P'$, together with the corresponding perspective centre $O'$, defines the spatial direction of the ray to the corresponding object point $P$. Provided the imaging geometry within the camera and the location of the imaging system in object space are known, then every image ray can be defined in 3D object space.

From the intersection of at least two corresponding (homologous), spatially separated image rays, an object point can be located in three dimensions. In stereophotogrammetry two images are used to achieve this. In multi-image photogrammetry the number of images involved is, in principle, unlimited.

![Figure 1.6 Principle of photogrammetric measurement](image-url)
In normal English, the orientation of an object implies direction or angular attitude. Photogrammetric usage, deriving from German, applies the word to groups of camera parameters. Exterior orientation parameters incorporate this angular meaning but extend it to include position. Interior orientation parameters, which include a distance, two coordinates and a number of polynomial coefficients, involve no angular values; the use of the terminology here underlines the connection between two very important, basic groups of parameters.

The interior orientation parameters describe the internal geometric model of a camera. With the model of the pinhole camera as its basis (Fig. 1.7), the most important reference location is the perspective centre \( O \), through which all image rays pass. The interior orientation defines the position of the perspective centre relative to a reference system fixed in the camera (image coordinate system), as well as departures from the ideal central projection (image distortion). The most important parameter of interior orientation is the principal distance, \( c \), which defines the distance between image plane and perspective centre (see section 3.2.3).

A real and practical photogrammetric camera will differ from the pinhole camera model. The necessity of using a relatively complex objective lens, a camera housing which is not built for stability and an image recording surface which may be neither planar nor perpendicular to the optical axis of the lens gives rise to departures from the ideal imaging geometry. The interior orientation, which will include parameters defining these departures, must be determined by calibration for every camera.

A fundamental property of a photogrammetric image is the image scale or photo-scale. The photo-scale factor \( m \) defines the relationship between the object distance \( h \) and principal distance \( c \). Alternatively it is the relationship between an object distance \( X \) in the object, in a direction parallel to the image plane, and the corresponding distance in image space \( x' \):

\[
m = \frac{h}{c} = \frac{X}{x'}
\]

(1.1)

The photo-scale is in every case the deciding factor in resolving image details, as well as the photogrammetric measurement accuracy, since any measurement error in the image is multiplied in the object space by the scale factor (see section 3.2.1). Of course, when dealing with complex objects, the scale will vary throughout the image; one usually quotes a nominal or average value.

---

Footnote: In normal English, the orientation of an object implies direction or angular attitude. Photogrammetric usage, deriving from German, applies the word to groups of camera parameters. Exterior orientation parameters incorporate this angular meaning but extend it to include position. Interior orientation parameters, which include a distance, two coordinates and a number of polynomial coefficients, involve no angular values; the use of the terminology here underlines the connection between two very important, basic groups of parameters.
The exterior orientation parameters specify the spatial position and orientation of the camera in a global coordinate system. The exterior orientation is described by the coordinates of the perspective centre in the global system and three suitably defined angles expressing the rotation of the image coordinate system with respect to the global system (see section 4.2.1). The exterior orientation parameters are calculated indirectly, after measuring image coordinates of well identified object points with fixed and known global coordinates.

Every measured image point corresponds to a spatial direction from projection centre to object point. The length of the direction vector is initially unknown i.e. every object point lying on the line of this vector generates the same image point. In other words, although every three dimensional object point transforms to a unique image point for given orientation parameters, a unique reversal of the projection is not possible. The object point can be located on the image ray, and thereby absolutely determined in object space, only by intersecting the ray with an additional known geometric element such as a second spatial direction or an object plane.

Every image generates a spatial bundle of rays, defined by the imaged points and the perspective centre, in which the rays were all recorded at the same point in time. If all the bundles of rays from multiple images are intersected as described above, a dense network is created; for an appropriate imaging configuration, such a network has the potential for high geometric strength. Using the method of bundle triangulation any number of images (ray bundles) can be simultaneously oriented, together with the calculation of the associated three dimensional object point locations (Fig. 1.6, see section 4.3).

1.2.4 Photogrammetric systems

1.2.4.1 Analogue systems

Analogue photogrammetry (Fig. 1.8) is distinguished by different instrumentation components for data recording and for data processing as well as by a separation in location, time and personnel between the on-site recording of the object and the data evaluation in the laboratory or office. Preparatory work and targeting, additional (surveying) measurement and image recording with expensive analogue (film or plate) cameras take place on site. Photographic development takes place in a laboratory, so that direct, on-site control of image quality is not possible. Subsequently the photographs are measured using specialised instruments. The procedure involves firstly a determination of photo orientation followed by the actual processing of the photographic data.

The data obtained photogrammetrically are often further processed by users who do not wish to be involved in the actual measurement process since it requires complex photogrammetric knowledge, instrumentation and skills. The entire procedure, involving recording, measurement and further processing, is very time consuming using analogue systems, and many essential stages cannot be completed on site. Direct integration of analogue systems in procedures such as manufacturing processes is not possible.

1.2.4.2 Digital systems

The photogrammetric procedure has changed fundamentally with the development of digital imaging systems and processing (Fig. 1.9). By utilising appropriately targeted object points and digital on-line image recording, complex photogrammetric tasks can be executed within minutes on-site. A fully automatic analysis of the targeted points replaces the manual procedures for orientation and measurement. Special photogrammetric measuring instruments
are no longer required and are replaced by standard computing equipment. The high degree of automation also enables non-specialist users to carry out the photogrammetric recording and data evaluation.

Digital systems, since they offer automation and short processing cycles, are essential to the application of photogrammetry in complex real-time applications such as, in particular, industrial metrology and robotics. Decisions can be made directly on the basis of feedback from the photogrammetric results. If the result is delivered within a certain process-specific time period, the term real-time photogrammetry is commonly used.
**1.2.4.3 Recording and analysis procedures**

Fig. 1.10 shows the principal procedures in close range photogrammetry which are briefly summarised in the following sections.

1. **RECORDING**
   a) **Targeting:**
      Target selection and attachment to object features to improve automation and increase the accuracy of target measurement in the image
   b) **Determination of control points or scaling lengths:**
      Creation of a global object coordinate system by definition of reference (control) points and/or reference lengths (scales)
   c) **Image recording:**
      Analogue or digital image recording of the object with a photogrammetric system

2. **PRE-PROCESSING**
   a) **Computation:**
      Calculation of reference point coordinates and/or distances from survey observations (e.g. using network adjustment)

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**Figure 1.10** Recording and analysis procedures (red: can be automated in a digital system)
b) Development and printing:
Photographic laboratory work (developing film, making photographic prints)

c) Digitising:
Conversion of analogue photographs into digital images (scanning)

d) Numbering and archiving:
Assigning photo numbers to identify individual images and archiving or storing the photographs

3. ORIENTATION

a) Measurement of image points:
Identification and measurement of reference and scale points
Identification and measurement of tie points (points observed in two or more images simply to strengthen the network)

b) Approximation:
Calculation of approximate (starting) values for unknown quantities to be calculated by the bundle adjustment

c) Bundle adjustment:
Adjustment program which simultaneously calculates parameters of both interior and exterior orientation as well as the object point coordinates which are required for subsequent analysis

d) Removal of outliers:
Detection and removal of gross errors which mainly arise during (manual) measurement of image points

4. MEASUREMENT AND ANALYSIS

a) Single point measurement:
Creation of three dimensional object point coordinates for further numerical processing

b) Graphical plotting:
Production of scaled maps or plans in analogue or digital form (e.g. hard copies for maps and electronic files for CAD models or GIS)

c) Rectification/Orthophoto:
Generation of transformed images or image mosaics which remove the effects of tilt relative to a reference plane (rectification) and/or remove the effects of perspective (orthophoto)

This sequence can, to a large extent, be automated (connections in red in Fig. 1.10). Provided that the object features are suitably marked and identified using coded targets, initial values can be calculated and measurement outliers (gross errors) removed by robust estimation methods.

Digital image recording and processing can provide a self-contained and fast data flow from capture to presentation of results, so that object dimensions are available directly on site. One distinguishes between off-line photogrammetry systems (one camera, measuring result available after processing of all acquired images), and on-line photogrammetry systems (minimum of two cameras simultaneously, measuring result immediately).

1.2.5 Photogrammetric products

In general, photogrammetric systems supply three dimensional object coordinates derived from image measurements. From these, further elements and dimensions can be derived, for example
lines, distances, areas and surface definitions, as well as quality information such as comparisons against design and machine control data. The direct determination of geometric elements such as straight lines, planes and cylinders is also possible without explicit calculation of point coordinates. In addition the recorded image is an objective data store which documents the state of the object at the time of recording. The visual data can be provided as corrected camera images, orthophotos or graphical overlays (Fig. 1.11). Examples of graphical presentation are shown in Fig. 1.12 and Fig. 1.13.
1.3 Applications

Much shorter imaging ranges and alternative recording techniques differentiate close range photogrammetry from its aerial and satellite equivalents.

Writing in 1962 E. H. Thompson summarised the conditions under which photogrammetric methods of measurement would be useful:

“... first, when the object to be measured is inaccessible or difficult of access; second, when the object is not rigid and its instantaneous dimensions are required; third, when it is not certain that the measures will be required at all; fourth, when it is not certain, at the time of measurement, what measures are required; and fifth, when the object is very small ...”.

To these may be added three more: when the use of direct measurement would influence the measured object or would disturb a procedure going on around the object; when real-time results are required; and when the simultaneous recording and the measurement of a very large number of points is required.

The following applications (with examples) are among the most important in close range photogrammetry:

- **Automotive, machine and shipbuilding industries**
  - Inspection of tooling jigs
  - Reverse engineering of design models
  - Manufacturing control
  - Optical shape measurement
  - Recording and analysing car safety tests
  - Robot calibration

- **Aerospace industry**
  - Measurement of parabolic antennae
  - Control of assembly
  - Inspection of tooling jigs
  - Space simulations

- **Architecture, heritage conservation, archaeology**
  - Façade measurement
  - Historic building documentation
  - Deformation measurement
  - Reconstruction of damaged buildings
  - Mapping of excavation sites
  - 3D city models
• Engineering
  – As-built measurement of process plants
  – Measurement of large civil engineering sites
  – Deformation measurements
  – Pipework and tunnel measurement
  – Mining
  – Evidence documentation

• Medicine and physiology
  – Tooth measurement
  – Spinal deformation
  – Plastic surgery
  – Motion analysis and ergonomics
  – Microscopic analysis
  – Computer-assisted surgery

• Forensic, including police work
  – Accident recording
  – Scene-of-crime measurement
  – Legal records
  – Measurement of persons

• Information systems
  – Building information systems
  – Facility management
  – Production planning
  – Image databases

• Natural sciences
  – Liquid flow measurement
  – Wave topography
  – Crystal growth
  – etc.
In general, similar methods of recording and analysis are used for all applications of close range photogrammetry.

- powerful analogue or digital recording systems
- freely chosen imaging configuration with almost unlimited numbers of photographs
- photo orientation based on the technique of bundle triangulation
- visual and digital analysis of the images
- presentation of results in the form of 3D coordinate files, CAD data, photographs or drawings

Industrial and engineering applications make special demands of the photogrammetric technique:

- limited recording time on site (no significant interruption of industrial processes)
- delivery of results for analysis after only a brief time
- high accuracy requirements
- proof of accuracy attained

1.4 Historical development

It comes as a surprise to many that the history of photogrammetry is almost as long as that of photography itself and that, for at least the first fifty years, the predominant application of photogrammetry was to close range, architectural measurement rather than to topographical mapping. Only a few years after the invention of photography during the 1830s and 1840s by Fox Talbot in England, by Niepce and Daguerre in France, the French military officer Laussedat began experiments in 1849 on the image of a façade of the Hotel des Invalides. Admittedly Laussedat was then using a camera lucida and did not obtain photographic equipment until 1852.
(Poivilliers 1961); he is usually described as the first photogrammetrist. In fact it was not a surveyor but an architect, the German Meydenbauer, who coined the word “photogrammetry”. As early as 1858 Meydenbauer used photographs to draw plans of the cathedral of Wetzlar and by 1865 he had constructed his “great photogrammeter” (Meydenbauer 1912), a forerunner of the phototheodolite.

Meydenbauer used photography in order to avoid the conventional, often dangerous, manual method of measuring façades. He developed his own photogrammetric cameras with image formats up to 40 cm × 40 cm (see Fig. 1.23), using glass plates to carry the emulsion. Between 1885 and 1909 on behalf of the state of Prussia, Meydenbauer compiled an archive of around 16 000 metric images of the most important architectural monuments; it is still partly in existence today. The development of such archives has continued in many countries to this very day as insurance against damage or destruction of the cultural heritage (an example of Thompson’s third category: when it is not certain that the measures will be required at all, see section 1.3). Meydenbauer also developed graphical photogrammetric methods for the production of plans of building façades.

The phototheodolite, as its name suggests, represents a combination of camera and theodolite. The direct measurement of orientation angles leads to a simple photogrammetric orientation. A number of inventors, such as Porro and Paganini in Italy, in 1865 and 1884 respectively, and Koppe in Germany, 1896, developed such instruments (Fig. 1.24).

From terrestrial photographs, horizontal bundles of rays could be constructed; with two or more cameras a survey could be completed point by point using intersecting rays. By virtue of their regular and distinct features, architectural subjects lend themselves to this technique often

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1 A metric camera is defined as one with known and stable interior orientation.
referred to as plane table photogrammetry. When using terrestrial pictures in mapping, by contrast, there was a major difficulty in identifying the same point on different photographs, especially when they were taken from widely separated camera stations; but a wide separation is desirable for accuracy. It is for these reasons that so much more architectural than topographic photogrammetry was performed during the 19th century. Nonetheless, a certain amount of topographic mapping took place during the last three decades of that century; most of this fell into Thompson’s first category, “when the object to be measured is inaccessible or difficult of access” (see section 1.3), for example the mapping of the Alps by Paganini in 1884 and the mapping of vast areas of the Rockies in Canada by Deville (Thompson 1965). Jordan mapped the Dachel oasis in 1873 and Finsterwalder developed analytical solutions.

The development of stereoscopic measurement around the turn of the century was a momentous breakthrough in the history of photogrammetry. The stereoscope had already been invented between 1830 and 1832 (Wheatstone 1838) and Stolze had discovered the principle of the floating measuring mark in Germany in 1893 (Sander 1923). Two other scientists, Pulfrich in Germany and Fourcade in South Africa, working independently and almost simultaneously¹, developed instruments for the practical application of Stolze’s discovery (Meier 2002, Atkinson 2002). Their stereocomparators permitted simultaneous settings of identical measuring marks on the two photographs and the recording of image coordinates for use in subsequent numerical computations; points were fixed by numerical intersection and measurement was still made point by point (Fig. 1.25).

Photogrammetry was about to enter the era of analogue computation, a very foreign concept to surveyors with their long tradition of numerical computation: digital computation was too slow to allow the unbroken plotting of detail, in particular of contours, which stereoscopic

¹ Pulfrich’s lecture in Hamburg announcing his invention was given on 23rd September 1901, while Fourcade delivered his paper in Cape Town nine days later on 2nd October 1901.
measurement seemed to offer so tantalisingly. Only analogue computation could extend the possibility of instantaneous feedback to the observer. If many surveyors regarded analogue computation as an aberration, then it became a remarkably successful one for a large part of the 20th century.

During the latter part of the 19th century and in several countries much effort and imagination was directed towards the invention of stereoplotting instruments, necessary for the accurate and continuous plotting of topography. In Germany, Hauck proposed such an apparatus. In Canada, Deville developed “the first automatic plotting instrument in the history of photogrammetry” (Thompson 1965). Deville’s instrument had several defects, but its design inspired several subsequent workers to overcome these, including both Pulfrich, one of the greatest contributors to photogrammetric instrumentation, and Santoni, perhaps the most prolific of photogrammetric inventors.

In Germany, conceivably the most active country in the early days of photogrammetry, Pulfrich’s methods were very successfully used in mapping. This inspired von Orel in Vienna to design an instrument for the “automatic” plotting of contours, leading ultimately to the Orel-Zeiss Stereautograph which came into productive use in 1909. In England, F. V. Thompson was slightly before von Orel in the design and use of the Vivian Thompson Stereoplotter (Atkinson 1980, 2002); he went on to design the Vivian Thompson Stereoplanigraph (Thomson 1908) which was described by E. H. Thompson (Thompson 1974) as “the first design for a completely automatic and thoroughly rigorous photogrammetric plotting instrument”.

The rapid development of aviation which began shortly after this was another decisive influence on the course of photogrammetry. Not only is the Earth photographed vertically from above an almost ideal subject for the photogrammetric method, but also aircraft made almost all parts of the Earth accessible at high speed. In the first half of the 20th century these favourable circumstances allowed impressive development in photogrammetry, with tremendous economic benefit in air survey. On the other hand, while stereoscopy opened the way for the application of photogrammetry to the most complex surfaces such as might be found in close range work, the geometry in such cases was often far from ideal photogrammetrically and there was no corresponding economic advantage to promote its application.
Although there was considerable opposition from surveyors to the use of photographs and analogue instruments for mapping, the development of stereoscopic measuring instruments forged ahead remarkably in many countries during the period between the First World War and the early 1930s. Meanwhile, non-topographic use was sporadic as there were few suitable cameras and analogue plotters imposed severe restrictions on principal distance, image format and disposition and tilts of cameras. Instrumentally complex systems were being developed using optical projection (for example Multiplex), opto-mechanical principles (Zeiss Stereoplanigraph) and mechanical projection using space rods (for example Wild A5, Santoni Stereocartograph), designed for use with aerial photography. By 1930 the Stereoplanigraph C5 was in production, a sophisticated instrument able to use oblique and convergent photography—even if makeshift cameras had to be used at close range, experimenters at least had freedom in the orientation and placement of the cameras; this considerable advantage led to some noteworthy work.

As early as 1933 Wild stereometric cameras were being manufactured and were in use by Swiss police for the mapping of accident sites, using the Wild A4 Stereautograph, a plotter especially designed for this purpose. Such stereometric cameras comprise two identical metric cameras fixed to a rigid base of known length and such that their axes are coplanar, perpendicular to the base and, usually, horizontal1 (Fig. 3.2a, see section 4.4.2). Other manufacturers have also made stereometric cameras (Fig. 1.26) and associated plotters (Fig. 1.27); a great deal of close range work has been carried out with this type of equipment. Initially glass plates were used in metric cameras in order to provide a flat image surface without significant mechanical effort (see example in Fig. 1.28). From the 1950s film was increasingly used in metric cameras which were then equipped with a mechanical film-flattening device.

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1 This is sometimes referred to as the ‘normal case’ of photogrammetry.
In the 1950s we were on the verge of the period of analytical photogrammetry. The expanding use of digital, electronic computers in that decade engendered widespread interest in the purely analytical or numerical approach to photogrammetry as against the prevailing analogue methods. While analogue computation is inflexible, in regard to both input parameters and output results, and its accuracy is limited by physical properties, a numerical method allows virtually unlimited accuracy of computation and its flexibility is bounded only by the mathematical model on which it is based. Above all, it permits over-determination which may improve precision, lead to the detection of gross errors and provide valuable statistical information about the measurements and the results. The first analytical applications were to photogrammetric triangulation. As numerical methods in photogrammetry improved, the above advantages, but above all their flexibility, were to prove invaluable at close range.

Subsequently stereoplotters were equipped with devices to record model coordinates for input to electronic computers. Arising from the pioneering ideas of Helava (Helava 1957), computers were incorporated in stereoplotters themselves, resulting in analytical stereoplotters with fully numerical reconstruction of the photogrammetric models. Bendix/OMI developed the first analytical plotter, the AP/C, in 1964; during the following two decades analytical stereoplotters were produced by the major instrument companies and others. While the adaptability of such instruments has been of advantage in close range photogrammetry (Masry and Faig 1977), triangulation programs with even greater flexibility were soon to be developed, as described below, which were more suited to the requirements of close range work.

Analytical photogrammetric triangulation is a method, using numerical data, of point determination involving the simultaneous orientation of all the photographs and taking all interrelations into account. Work on this line of development had appeared before WWII, long before the development of electronic computers. Analytical triangulation demanded instruments to measure photocoordinates. The first stereocomparator designed specifically for use with aerial photographs was the Cambridge Stereocomparator designed in 1937 by E. H. Thompson (Arthur 1960). By 1955 there were five stereocomparators on the market (Harley 1963) and monocomparators designed for use with aerial photographs also appeared.
The bundle method of photogrammetric triangulation, more usually known as bundle adjustment, is of vital importance to close range photogrammetry. Seminal papers by Schmid (1956-57, 1958) and Brown (1958) laid the foundations for theoretically rigorous block adjustment. A number of bundle adjustment programs for air survey were developed and became commercially available, such as those by Ackermann et al. (1970) and Brown (1976). Programs designed specifically for close range work have appeared since the 1980s, such as STARS (Fraser and Brown 1986), BINGO (Kruck 1983), MOR (Wester-Ebbinghaus 1981) and CAP (Hinsken 1989).

The importance of bundle adjustment in close range photogrammetry can hardly be overstated. The method imposes no restrictions on the positions or the orientations of the cameras; nor is there any necessity to limit the imaging system to central projection. Of equal or greater importance, the parameters of interior orientation of all the cameras may be included as unknowns in the solution. Until the 1960s many experimenters appear to have given little attention to the calibration\(^1\) of their cameras; this may well have been because the direct calibration of cameras focused for near objects is usually much more difficult than that of cameras focused for distant objects. At the same time, the inner orientation must usually be known more accurately than is necessary for vertical aerial photographs because the geometry of non-topographical work is frequently far from ideal. In applying the standard methods of calibration in the past, difficulties arose because of the finite distance of the targets, whether real objects or virtual images. While indirect, numerical methods to overcome this difficulty were suggested by Torlegård (1967) and others, bundle adjustment now frees us from this concern. For high precision work it is no longer necessary to use metric cameras which, while having the advantage of known and constant interior orientation, are usually cumbersome and expensive. Virtually any camera can now be used. Calibration via bundle adjustment is usually known as self-calibration (see section 4.3.2.4).

The use of traditional stereophotogrammetry at close ranges has declined. As an alternative to the use of comparators, multi-photo analysis systems which use a digitizing pad as a measuring device for photo enlargements (e.g. Rollei MR2, 1986) have been widely used for architectural and accident recording. Many special cameras have been developed; for example modified professional photographic cameras which have an inbuilt réseau (an array of engraved crosses on a glass plate which appear on each image) for photogrammetric use (Wester-Ebbinghaus 1981) (Fig. 1.29).

\[^1\) In photogrammetry, unlike computer vision, calibration refers only to interior orientation. Exterior orientation is not regarded as part of calibration.\]
Since the middle of the 1980s the use of opto-electronic image sensors has increased dramatically. Advanced computer technology enables the processing of digital images, particularly for automatic recognition and measurement of image features, including pattern correlation for determining object surfaces. Procedures in which both the image and its photogrammetric processing are digital are often referred to as digital photogrammetry. Initially standard video cameras were employed generating analogue video signals which could be digitised with resolutions up to $780 \times 580$ picture elements (pixels) and processed in real time (real-time photogrammetry, videogrammetry). The first operational on-line multi-image systems became available in the late 1980s (e.g. Haggrén 1987, Fig. 1.30). Automated precision monocomparators, in combination with large format réseau cameras, were developed for high-precision, industrial applications (Fraser and Brown 1986, Luhmann and Wester-Ebbinghaus 1986). Analytical plotters were enhanced with video cameras to become analytical correlators, used for example in car body measurement (Zeiss Indusurf 1987). Closed procedures for simultaneous multi-image processing of grey level values and object data based on least squares methods were developed (e.g. Förstner 1982, Gruen 1985).

The limitations of video cameras in respect of their small image format and low resolution led to the development of scanning cameras which enabled the high resolution recording of static objects to around $6000 \times 4500$ pixels. In parallel with this development, electronic theodolites were equipped with video cameras to enable the automatic recording of directions to targets (Kern SPACE).

Digital cameras with high resolution, which can provide a digital image without analogue signal processing, have been available since the beginning of the 1990s. Resolutions range from about $1000 \times 1000$ pixels (e.g. Kodak Megaplus) to over $4000 \times 4000$ pixels. Easily portable still video cameras can store high resolution images directly in the camera (e.g. Kodak DCS 460, Fig. 1.31). They have led to a significant expansion of photogrammetric measurement technology, particularly in the industrial field. On-line photogrammetric systems (Fig. 1.32) are increasingly used, in addition to off-line systems, both as mobile systems and in stationary configurations. Coded targets allow the fully automatic identification and assignment of object

Figure 1.30 Mapvision: on-line multi-image system (1987)
features and orientation of the image sequences. Surface measurement of large objects is now possible with the development of pattern projection methods combined with photogrammetric techniques.

**Figure 1.31** Still-video camera Kodak DCS 460 (1996)

**Figure 1.32** GSI VSTARS on-line industrial measurement system
Interactive digital stereo systems (e.g. Leica/Helava DSP, Zeiss PHODIS) have existed since around 1988 (Kern DSP-1) and are in 2005 increasingly replacing analytical plotters, but they are rarely employed for close range use. Interactive, graphical multi-image processing systems are of more importance here as they offer processing of freely chosen image configurations in a CAD environment (e.g. PHIDIAS from Phocad, Fig. 1.33). Easy-to-use low-cost software packages (e.g. PhotoModeler from EOS, ImageModeler from REALVIZ, iWitness from PhotoMetrix) provide object reconstruction and creation of virtual 3D models from digital images without the need for a deep understanding of photogrammetry.

A trend in close range photogrammetry is towards the integration or embedding of photogrammetric components in application-oriented hybrid systems. This includes links to such packages as 3D CAD systems, databases and information systems, quality analysis and control systems for production, navigation systems for autonomous robots and vehicles, 3D visualization systems, internet applications, 3D animations and virtual reality. Another trend is for methods from computer vision, such as projective geometry or pattern recognition, to be increasingly used for rapid solutions without high accuracy demands.

Close range photogrammetry is today a well established, universal 3D measuring technique, routinely applied in a wide range of interdisciplinary fields; there is every reason to expect its continued development long into the future.

References


Further reading

Photogrammetry


Optics, camera and image acquisition


Digital image processing, computer vision and pattern recognition


3D computer graphics


**Least squares adjustment and statistics**


**Applications**


**Standards and guidelines**

GUM (1993) *ISO guide to the expression of uncertainty in measurement (GUM)*.

**Organisations, conferences and working groups**

ISPRS (International Society for Photogrammetry and Remote Sensing):
  Commission III: Theory and Algorithms
  Commission V: Close range Techniques and Machine Vision
  Publications: International Archives of Photogrammetry and Remote Sensing; ISPRS
  Journal of Photogrammetry and Remote Sensing
  www.isprs.org

ASPRS (The American Society for Photogrammetry and Remote Sensing):
  Publication: Photogrammetric Engineering and Remote Sensing
  www.asprs.org
The Remote Sensing and Photogrammetry Society:
Publication: The Photogrammetric Record
www.rspsoc.org

DGPF (Deutsche Gesellschaft für Photogrammetrie und Fernerkundung): Publications:
Bildmessung und Luftbildwesen (to 1989), Zeitschrift für Photo-grammetrie und
Fernerkundung (to 1997), Photogrammetrie-Fernerkundung-Geoinformation (since
1997); Publikationen der DGPF (proceedings of the annual symposia) www.dgpf.de

CIPA (Comité International de Photogrammétrie Architecturale):
Publications and conference proceedings.
http://cipa.icomos.org/

CMCS (Coordinate Metrology Systems Conference)
Publications and conference proceedings.
www.cmsc.org

SPIE (The International Society for Optical Engineering):
Publications and conference proceedings.
www.spie.org

VDI/VDE-GMA (VDI/VDE-Gesellschaft für Mess- und Automatisierungstechnik):
Publications: technical guide lines, conference proceedings.
www.vdi.de
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