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Close range photogrammetry for industrial applications

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ABSTRACT

This article summarizes recent developments and applications of digital photogrammetry in industrial measurement. Industrial photogrammetry covers a wide field of different practical challenges in terms of specified accuracy, measurement speed, automation, process integration, cost-performance ratio, sensor integration and analysis. On-line and off-line systems are available, offering general purpose systems on the one hand and specific turnkey systems for individual measurement tasks on the other. Verification of accuracy and traceability to standard units with respect to national and international standards is inevitable in industrial practice. System solutions can be divided into the measurement of discrete points, deformations and motions, 6DOF parameters, 3D contours and 3D surfaces. Recent and future developments concentrate on higher dynamic applications, integration of systems into production chains, multi-sensor solutions and still higher accuracy and lower costs.

1. Introduction

Close range photogrammetry in industry became technically and economically successful in the mid 1980s, with a first breakthrough in automated and high accurate 3D measurements (Fraser and Brown, 1986). Based on analogue large format reseau cameras, convergent multi-image configurations, digital comparators and digital image processing of the scanned imagery, close range photogrammetry offered the potential of measurement precision to 1:500,000 with respect to the largest object dimension. Especially for large volume objects (e.g. >10 m diameter) with a high number of object points, photogrammetry could exceed the performance of theodolite systems and thus became a standard method for complex 3D measurement tasks.

The availability of video and digital cameras in combination with direct access to the digital image data generated new concepts for close-range applications. So-called off-line photogrammetry systems utilizing high-resolution digital SLR cameras with (usually) wide angle lenses, retro-reflective object targets and sub-pixel image point measurement operators afforded object measurement within minutes by robust bundle adjustment, including self-calibration (e.g. Beyer, 1992; Brown and Dold, 1995). Recent systems, for example from the companies GSI, AICON and GOM, are practically fully automated, and can therefore be operated by non-specialist personnel. Data acquisition and processing can be performed at different locations, at different times and by different people (Fig. 1).

Digital off-line systems can be regarded as fully accepted 3D measurement tools that are applied in a large variety of industrial application areas, including

- automotive manufacturing, for car body deformation measurement, control of supplier parts, adjustment of tooling and rigs, establishment of control point networks, crash testing, etc.;
- the aerospace industry, for measurement and adjustment of mounting rigs, antenna measurement, part-to-part alignment, etc.;
- wind energy systems for deformation measurements and production control; and
- engineering and construction, for measurement of water dams, tanks, plant facilities, etc.

Off-line photogrammetry systems offer the highest precision and accuracy levels. The precision of image point measurement can be as high as 1/50 of a pixel, yielding typical measurement precision (RMS 1-sigma) on the object in the range of 1:100,000 to 1:200,000, the former corresponding to 0.1 mm for an object of 10 m size (Fraser et al., 2005; Parian et al., 2006). The absolute accuracy of length measurements is generally 2–3 times less (e.g. about 0.05 mm for a 2 m object) than the precision of object point coordinates, which expresses the relative accuracy of 3D shape reconstruction (Rieke-Zapp et al., 2009).

On-line photogrammetry systems provide measurements in a closed data chain, hence in real-time and with a direct link to external processes (Fig. 1). Typically, an on-line system consists of two or more calibrated and oriented cameras that observe a specific volume. Appropriate object targeting affords fully automated feature extraction in image space. 3D information about points, contours or surfaces is directly generated in order to control

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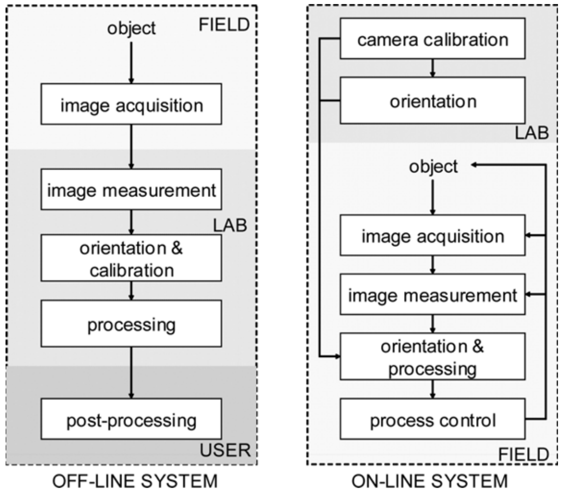


Fig. 1. Operational stages for off-line and on-line systems.

a connected process, such as on a production line or for the positioning of an object with respect to an external reference frame. Example applications of on-line systems include

- tactile probing, where a hand-held probing device with calibrated local reference points is tracked in 3D space in order to provide the coordinates of the probing tip;
- robot calibration, where a local reference body representing the robot tool centre point is observed by one or more cameras in order to determine the robot trajectory in space;
- tube measurement, where a multiple camera set-up is used to measure points and lines of arbitrarily shaped pipes or tubes in order to control a tube bending machine; and
- sensor navigation, where a 2D or 3D measurement device (e.g. a laser profile sensor) is tracked in 6DOF by a stereo camera system.

The accuracy of on-line systems is usually less than that of off-line systems due to the limited number of images, restrictions resulting in less than optimal camera calibration and orientation, and the manual operation of probes. Typical accuracy figures lie in the order of 0.2–0.5 mm over a range of 2 m (e.g. Broers and Jansing, 2007).

The successful use of photogrammetry in industry requires a number of technical components that form an efficient and economic system. The following list summarises these components and related technical issues:

- imaging sensor: resolution (number of pixels), available lenses, acquisition and data transfer speed, camera stability, synchronisation, data compression, etc;
- targeting and illumination: representation of interesting object features, target shape and size, wave length of light sources, restrictions to object access, illumination power and measurement volume;
- imaging configuration: number of camera stations, desired measurement accuracy, network design, redundancy, robustness, self-calibration ability, datum definition and object control, self-control of orientation and calibration;
- image processing: automation of target recognition and identification, sub-pixel measurement of target centre, multi-image matching approaches, feature tracking, and handling of outliers and scene artefacts;
- 3D reconstruction: methods for determination of 3D coordinates (e.g. spatial intersection, bundle adjustment) and error statistics;
- data interfaces: integration into CAD/CAM environments, machine and data interfaces, user interaction and displays, etc; and
- verification of accuracy: reference bodies, reference data, standards and guidelines, and acceptance tests.

The above listed topics illustrate that appropriate design, setup and operation of close-range industrial photogrammetry systems forms a complex task. The feasibility of a solution is not only a question of technical issues but also a function of required cost-performance ratio, system support, documentation, quality assurance and interdisciplinary skills. As a consequence, the worldwide number of system suppliers in this field is limited to probably less than 10 professional companies. However, the market for optical 3D measurements is significantly growing and offers promising prospects for the future.

In the following, the basic camera concepts, system designs and measurement tasks for industrial photogrammetry are presented. Due to the large variety of applications and system configurations, this paper can provide only an overview of recent technology and applications, rather than a comprehensive coverage. Further descriptions of technical data concerning commercial systems are provided at the listed websites of system suppliers and measurement service companies.

2. Sensor technology

Imaging sensor technology is the key feature of an industrial photogrammetry system. The selection of the appropriate sensor device is driven by requirements in accuracy, resolution, acquisition speed and frame rate, synchronisation, amount of data, spectral information, field of view, image scale, digital interfaces and cost. In general, it is desirable to use cameras with the highest resolution, imaging speed and accuracy in order to provide maximum efficiency and productivity with respect to system costs and return on investment.

Nowadays the range of available cameras and imaging sensors is huge. Based on CCD and CMOS technology, sensors are available with very high resolutions (>60 Mpixel), very high frame rates (>2000 Hz), pixel sizes varying between about 1.4 and 15 μm, and different sensor formats. An updated overview is given by Luhmann (in press), following on from earlier summaries by Luhmann and Robson (2008) and Luhmann et al. (2006).

2.1. SLR cameras

High-resolution digital SLR cameras are now available with sensors between 10 and 60 Mpixel and image formats between approximately 20 × 14 mm and 54 × 45 mm. Such cameras are designed for (semi-) professional photographic work with a range of exchangeable lenses, high-capacity storage devices and powerful batteries. Their mechanical stability is usually poor in terms of high-accuracy photogrammetric requirements, and camera calibration is therefore an important step in the complete process chain (Shortis et al., 1998). Depending upon absolute accuracy requirements, these cameras can be regarded as partially metric, with changing interior orientation, even from image to image (see Section 3.2).

SLR cameras are mainly used for off-line applications, i.e. the measurement of static objects. Suitable cameras in classical small format (35 mm SLR) are offered by companies such as Nikon, Canon and Sony, whereas medium-format cameras are available from Rollei, Hasselblad or Alpa, these being usually equipped with CCD sensor backs by PhaseOne or Leaf. Two sample cameras are shown in Fig. 2.

2.2. Digital video and high speed cameras

Dynamic processes can be observed by digital cameras with higher frame rates, e.g. video cameras or high-speed cameras.

(a) Nikon D3x (6048 × 4032 pixels). (b) Hasselblad H4D-60 (8956 × 6708 pixels).

Fig. 2. Examples of digital SLR cameras.

Fig. 3. High-speed camera PCO dimax.

Fig. 4. High-speed camera with FPGA-based target detection (AICON).

Controlled through a fast computer interface (e.g. CameraLink or Giga Ethernet), sensors with more than 1500 × 1000 pixels and frame rates of 2000 Hz are commercially available, conferring the opportunity to carry out dynamic photogrammetry of high speed events.

Video cameras with typically 1.3 Mpixel sensors and frame rates of 10–30 Hz are used in a variety of applications of photogrammetric on-line systems, examples being tube inspection (Bösemann, 2005), stereo navigation and robot guidance. Digital high speed cameras are usually equipped with CMOS sensors that enable fast data access, programmable field of view, extremely short exposure times and high dynamic range. Typical high-speed cameras provide images of about 1500 × 1000 pixels at 1000 Hz, though there are already on the market newly developed cameras with similar spatial resolutions, but with frame rates of more than 2000 Hz (Fig. 3).

A special high-speed camera for photogrammetric measurements has been developed by the AICON company. TraceCam F (Wiora et al., 2004), shown in Fig. 4, is based on a 1.3 Mpixel CMOS sensor and incorporates a camera-integrated FPGA processor able to locate and measure up to 10,000 circular white targets in real-time with a frame rate of up to 500 Hz at full sensor resolution. The camera, which stores only image coordinates and not single image frames, is designed for single camera 6DOF measurements such as recording the spatial position and rotation of spinning wheels with respect to a car body.

Synchronisation of two or more high-speed cameras remains a challenging task at high image acquisition rates, for example in the dynamic measurement of deformation in car crash testing. As an alternative to the use of multiple cameras, however, the technology of stereo beam splitting can be employed. Through the use of an optical beam splitter (Fig. 5), it is possible to acquire synchronised stereo images with only one camera (Luhmann, 2005), though the available image format is then only half of the original sensor size (Fig. 6).

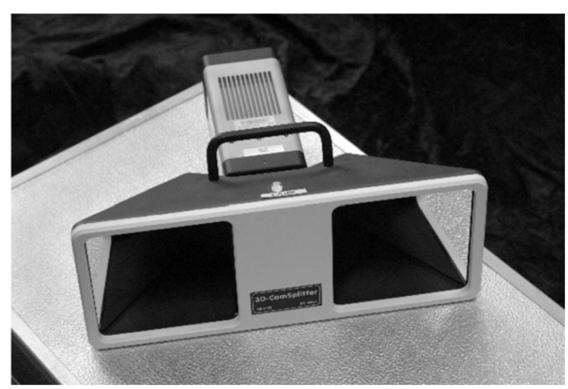


Fig. 5. High-speed camera with stereo beam splitter.

2.3. Photogrammetric cameras

There are very few cameras specifically designed for close-range photogrammetric applications. The classical 'metric camera' approach with stable interior orientation requires high additional effort in terms of optical and mechanical sensor design. The main advantage of these cameras is their assured stability and the consequent reduced need for periodic or on-the-job calibration, for example in applications where high accuracy is demanded without the technical possibility for simultaneous camera calibration.

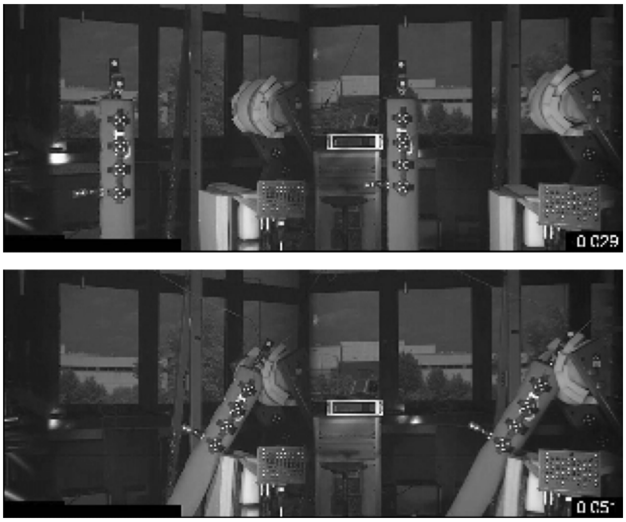


Fig. 6. Examples of stereo beam splitting image sequence.

However, the term 'metric camera' should only be used in conjunction with the desired accuracy level of the camera. Consequently, even metric cameras have to be calibrated on the job if the desired accuracy exceeds the metric tolerance of the camera.

Fig. 7(a) shows the INCA 3 photogrammetric camera from GSI, which is designed for high-accuracy industrial metrology. The fixed lens, ring flash and integrated processor enable 3D measurements in off-line (1 camera) or on-line (2 cameras) mode. The measurement of targets is performed inside the camera processor. Fig. 7(b) shows a special digital video camera AXIOS 3D SingleCam that is designed for 6DOF navigation tasks. The mechanical stability of the lens and sensor assembly is extremely high, with the camera being shock resistant up to 50 g without measurable change of the camera calibration parameters.

Multi-sensor systems comprising two or more cameras (Fig. 8) enable 3D measurements without any additional effort for calibration and orientation. Depending upon the mechanical stability of the cameras and their relative orientation, such systems can provide measurement accuracy of about 0.05 mm over a range of up to 2 m. Accuracy in absolute length measurement is closer to 0.1 mm and the overall accuracy is generally stated at around 1:20,000. These multi-camera systems are often used for navigation tasks, such as the positioning and tracking of crash dummies in car safety testing, and for medical applications.

2.4. Additional sensors

Photogrammetric sensors can be combined with additional measuring systems, as seen in fringe projection systems, laser tracking or scanning systems, tacheometers or 3D cameras. Most important are hybrid systems where the advantages of two sensor types are combined in order to form a new type of measuring system with extended functionality or performance. Examples are laser trackers equipped with a photogrammetric camera for 6DOF

(a) Metric camera GSI INCA 3 (3500 × 2350 pixels).

(b) Metric video camera AXIOS 3D SingleCam (776 × 582 pixels).

Fig. 7. Examples of photogrammetric cameras.

(a) Metric stereo camera AXIOS 3D CamBarB2 (1392 × 1040 pixels).

(b) Four-camera head AICON DPS (1300 × 1000 pixels).

Fig. 8. Examples of photogrammetric multi-camera systems.

(a) Laser tracker with camera and 6DOF probe (Leica).

(b) Surface sensor tracked by multi-camera system (Steinbichler, NDI).

Fig. 9. Examples of hybrid systems.

measurements at the object surface, offered for example by Leica (Fig. 9(a)), and the optical 3D navigation of a surface sensor through tracking with a stereo or multiple camera system, as offered by Steinbichler (Fig. 9(b)).

3. Camera calibration

3.1. Physical and mathematical models

Camera calibration is an essential part of photogrammetric systems in industrial application since measurement accuracy is usually directly related to sensor quality and correct modelling of the interior orientation. The standard models for camera calibration include the 3D position of the perspective centre in image space (principal distance and principal point), parameters for radial and decentring distortion, and possibly corrections for affinity and shear within the sensor system. These parameters are calculated through a self-calibrating bundle adjustment in a multi-station convergent network of images. Recent overviews are given in Remondino and Fraser (2006) and Luhmann et al. (2006).

Calibration becomes a more difficult task in the following cases:

- camera geometry is unstable during image acquisition (e.g. due to gravity effects);
- the number of acquired images is less than a minimum number required for self-calibration (e.g. for stereo on-line systems);
- the geometric configuration of images does not allow bundle adjustment with self-calibration (e.g. due to weak intersection angles or lack of orthogonal camera rotations about the optical axis); and
- the object does not provide enough information (e.g. points, distances) for calibration.

Photogrammetric metrology systems usually consist of integrated bundle adjustment software which is, in some cases, not accessible by normal users. Examples are systems like GSI VSTARS or AICON 3D Studio that work like black boxes in a fully automated and robust manner. In addition, bundle adjustment programs are available as stand-alone off-line packages enabling the full control of parameter selection and analysis, such as Australis (Photometrix) or Ax.Ori (AXIOS 3D).

3.2. Calibration of off-line systems

Camera calibration for off-line systems is based on a multi-image setup that is recorded either for a test field (test field calibration) or for the measured object itself (on-the-job calibration). In both cases a minimum number of tie points must be provided and these can be natural or signalised points. Optionally, given control points or distance constraints can be introduced. The datum of the object coordinate system can either be defined by three or more control points (with the risk of introducing shape constraints in the photogrammetric orientation), by minimum definition (e.g. 3-2-1 method) or by free-net adjustment.

If the mechanical instability of the camera is worse than the required accuracy level, the camera can be calibrated image-wise, i.e. each image of the bundle configuration obtains individual calibration parameters (Maas, 1999a; Tecklenburg et al., 2001). Usually the distortion values are kept constant for all images in the network, while the position of perspective centre is adjusted for each image. This method leads to significant accuracy enhancements as long as the imaging configuration consists of enough well distributed images (usually more than 30 including images rolled around the optical axis).

The precision of camera calibration can be measured by the precision of image and object points, or by standard deviations of camera parameters. A reliable and strict accuracy assessment is only possible if checks can be made against independent control points or standardised calibrated distances (see Section 5). Typical internal precision measures for digital SLR camera self-calibration can reach1:100,000 and beyond (RMS 1-sigma accuracy vs. largest object dimension), whereas accuracy values determined through length measurement are generally closer to the 1:50,000 level (Rieke-Zapp et al., 2009).

3.3. Calibration of on-line systems

Camera calibration for on-line systems with fixed or limited camera positions can only be solved by multi-image bundle adjustment if a local test or reference object can be moved through the measurement volume. In this case an appropriate multi-image configuration can be recorded which is usable for self-calibration.

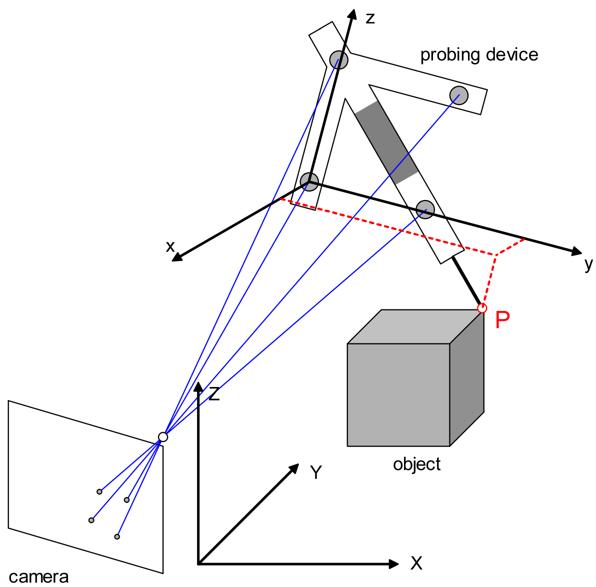


Fig. 10. Principle of a single camera system with tactile probing.

In cases where an additional calibration body is not provided cameras have to be calibrated in advance. The successful use of the system then requires stable cameras with respect to the desired accuracy level. Use of an extended space resection approach with additional parameters for interior orientation may allow for a camera-wise calibration based on given 3D control points. However, the potential of self-calibration bundle adjustment cannot be matched by single image space resection.

Calibration of on-line systems with fixed camera set-up can be performed either by observing a calibration body which is located at different positions in object space, or by measuring an additional calibrated scale-bar that is moved in front of the cameras (Amdal, 1992; Maas, 1999b). The latter method is easy to handle and provides scale information throughout the measurement volume, hence it is advantageous for accuracy assessments based on distance measurements.

4. Measurements

4.1. Single point probing

The measurement of single object points is a common task when the photogrammetric system is used as an optical coordinate measurement machine (CMM). In this case a tactile probe is employed to measure a point on an object surface while the position and orientation (6DOF) is determined by a photogrammetric system. The probe consists of local control points and a probing tip with given 3D coordinates in the same system. It can be operated manually or by a moving system, e.g. a robot.

The measurement of the 6DOF values of the probe can be performed by single cameras, by stereo cameras or by multiple camera setups. Usually the accuracy of point measurement increases with the number of cameras that observe the probe simultaneously.

Fig. 10 describes the principle of single camera probing (Amdal, 1992; Luhmann, 2009). The position of the probe is calculated by inverse space resection with respect to a minimum of four control points. Fig. 11 shows a commercial version using a probe with a linear arrangement of points, hence only 5 degrees of freedom can be determined by space resection. The typical accuracy of single-camera probing systems is in the order of 0.5 mm over a distance of about 1–2 m.

Fig. 11. Single camera system with tactile probing (Metronor).

A hand-held probe with integrated camera is offered by AICON. The camera is oriented by space resection using mobile object point panels that consist of a number of coded and uncoded control points. The 3D point accuracy is about 0.1 mm in a measuring volume that is defined by the size and number of panels.

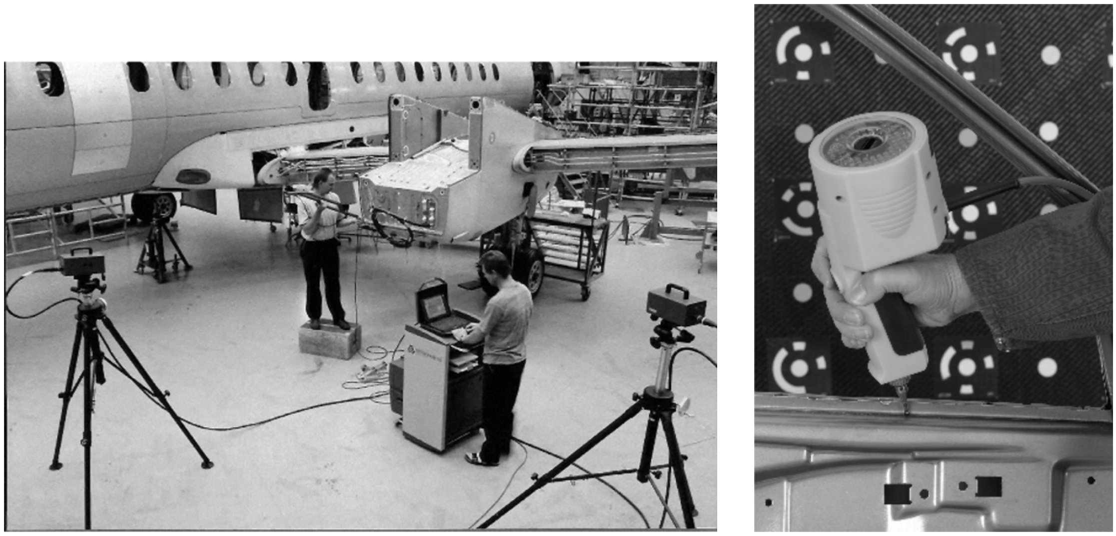
If the principle is extended to two or more cameras, the task of 6DOF measurement is solved by spatial intersection of the probe's control points. Usually the accuracy of multi-camera systems is higher than that of single cameras since the typical distance between cameras is larger than the equivalent base of control points of the probe. Commonly used systems consist of 2–4 digital video cameras (example in Fig. 8) and active or passive targets, providing measurement frequencies between 10 and 100 Hz. Systems based on linear CCD sensors, as exemplified in Fig. 9(b), work with active LED targets at frequencies of up to 1000 Hz. The typical accuracy of multi-camera probing systems by companies such as Metronor, AICON, GSI and GOM lies in the order of 0.1 mm over distances of 2–5 m, depending upon the system configuration (see Fig. 12).

Single and multi-camera systems can also be used for navigation of additional sensors (Fig. 9(b)). In this case the uncertainty of spatial orientation by the observing system is directly introduced into the measurement errors of the additional sensors.

4.2. Multiple point measurement

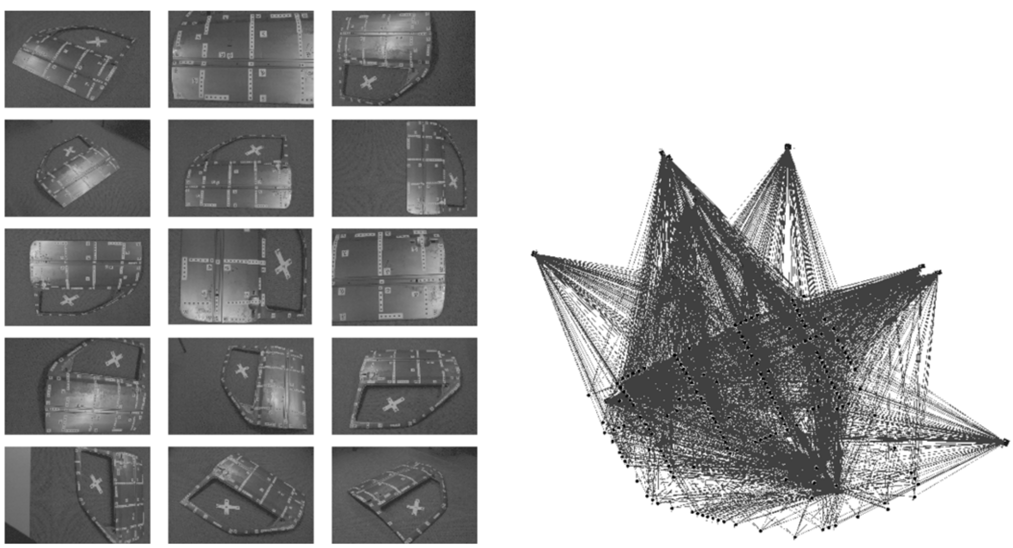
The measurement of a large number of object points is probably the application to which photogrammetry is best suited. The standard case for multi-point measurement is the off-line approach using a single high-resolution digital camera (Section 2.1), targeted object points and self-calibrating bundle adjustment. The spatial net design of images and object points can be optimised according to precision, reliability and accuracy of the measurement (Fraser, 1996).

Fig. 13 shows a partial set of images, taken with a digital SLR camera, from a multi-station bundle network used for 3D deformation analysis of a car door. Since each object point is covered by an average of 10–12 images, a high redundancy and consequently high reliability of coordinate determination, camera orientation and calibration is provided. The configuration of imaging rays illustrates that they intersect with large convergence angles yielding a homogeneous accuracy in X, Y and Z. In this example the precision in object space (RMS 1-sigma) is around 0.025 mm.



(a) Tactile probing with two-camera system (Metronor). (b) Probe with integrated camera (AICON).

Fig. 12. Tactile on-line metrology systems.



(a) Multi-image configuration. (b) 3D net configuration of rays.

Fig. 13. Multi-image set-up for car door measurement.

4.3. Surface measurement

The measurement of free-form surfaces is of increasing interest in industrial manufacturing due to the need for 3D digitisation and quality control in rapid prototyping and reverse engineering processes. Among the variety of technical solutions, the following optical methods are usually applied for surface reconstruction:

- fringe projection systems with one camera
- fringe projection systems with two or more cameras
- photogrammetry with grid projection or grid measurement
- photogrammetry with artificial or natural textures
- laser profiling and scanning with photogrammetric orientation
- hybrid solutions with combinations of the above mentioned methods.

4.3.1. Fringe projection

Fringe projection systems are applied in a large variety of industrial measurement tasks such as design, prototyping, copying of objects, roughness measurement and quality control. The typical measurement volume for a single-shot fringe projection system lies in the range of 100 × 100 × 30 mm up to 1000 × 1000 × 300 mm. The measurement volume is generally restricted by physical limitations such as reflectivity of surface material and the illumination power of the fringe projector.

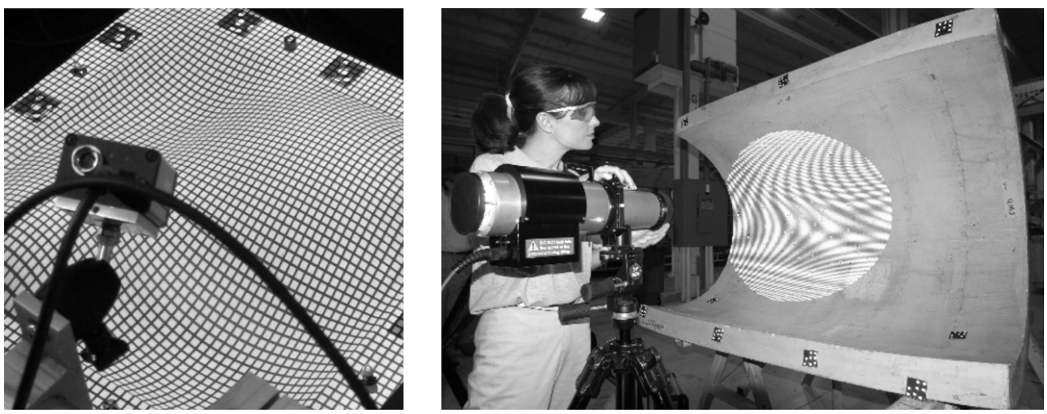
The principle of fringe projection systems is usually based on phase–shift methods (e.g. Zumbrunn, 1987) where multiple sets of shifted fringes are projected and observed by a camera under a certain triangulation angle. Since phase–shift methods are only unique in a range of $\pm\pi$ they are combined with absolute Gray code measurements or with projection of multiple sets of fringes with different wave lengths. The lateral resolution of fringe projection lies between $\lambda/20$ and $\lambda/100$ where λ is the wave length of the fringe pattern (Brenner et al., 1999). In practice fringe projection can achieve an accuracy of about 0.05–0.1 mm in a measuring volume of up to 1 × 1 × 0.3 m.

Systems based on one camera (Fig. 14(a)) require a calibrated and oriented projector that can be regarded as an inverse camera. If two cameras are used, the projector serves only as a projection device while the 3D coordinates are derived

(a) Single camera system (Vialux).

(b) Two-camera system (GOM).

Fig. 14. Industrial fringe projection systems.



(a) Grid projection system (AICON).

(b) Point projection system (GSI).

Fig. 15. Photogrammetric surface measurement systems.

from spatial intersection of the two images. The concept of phasogrammetry (Schreiber and Notni, 2000) uses measured phases as photogrammetric observations that can be introduced into the common photogrammetric algorithms such as bundle adjustment or spatial intersection. Fringe projection systems are offered by a diverse range of companies including GOM, Breuckmann, Steinbichler and Vialux.

4.3.2. Photogrammetric surface measurement

Photogrammetric methods for surface measurement use at least two images and image matching approaches for the determination of 3D coordinates of object points. As a prerequisite, the surface must provide a sufficient texture that enables the detection and matching of corresponding points. Textures can be formed by the natural surface structure, or generated by artificial patterns pasted or projected onto the surface. Usually the texture should provide enough colour or grey-level gradients at a number of different resolution scales, i.e. it should be useful for image pyramids.

The search for homologous points is either based on interest operators, followed by feature based and epipolar constraint matching, or as an alternative can involve scanning the object surface in regular or irregular grids. An early industrial surface measurement system was presented by the Zeiss Indusurf (Schewe, 1988). Recently stereo systems are offered by GOM or AICON.

If grid-like patterns are used for texturing the surface, for example by projecting regular point or line grids, well-defined discrete surface points can be detected and measured by spatial intersection, as shown in Fig. 15 for the grid-based photogrammetry systems available from AICON and GSI.

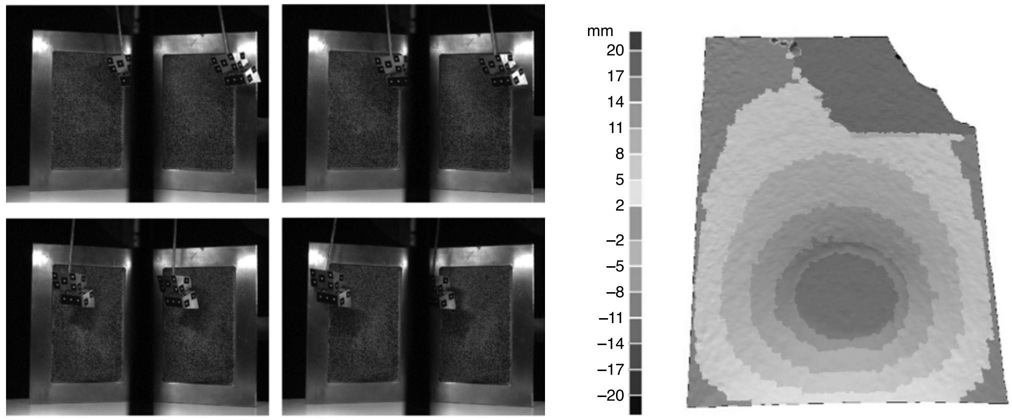
The main advantage of photogrammetric matching is the possibility of observing dynamic scenes. In the case of moving image sensors and/or moving or deforming objects, synchronised imagery can be acquired that enables the reconstruction of surfaces even under highly dynamic circumstances. Example applications are car body deformations in crash testing and the 3D measurement of airbags during instantaneous inflation. Fig. 16 shows the measurement of a deforming membrane caused by a disturbing object flying through the scene (Bethmann et al., 2009). Dynamic, shape-varying surfaces cannot be readily measured by any of the sequential or scanning methods such as fringe projection or laser scanning.

4.3.3. Photogrammetric orientation of surface sensors

In many practical cases the dimensions or structure of the object surface require more than one measurement position of the surface sensor system. Hence, the exterior orientation of the measurement system with respect to a global coordinate system must be solved for each single measurement setup, or for each local point cloud. This task can be solved using different approaches:

- optical sensor navigation by an external photogrammetric system;
- mechanical sensor navigation by robot or articulated arm;
- photogrammetric orientation by means of control or tie points; or
- point cloud matching by iterative closest point (ICP) or equivalent methods.

Fig. 9 shows two examples of hand-held sensors that are oriented in real-time either by a laser tracker with an additional camera, or by a fast multi-camera tracking system. In both cases a highly



(a) Stereo image sequence.

(b) Surface deformation map.

Fig. 16. Dynamic photogrammetric surface measurement.

(a) HandyScan 3D (Creaform).

(b) Fringe projection system oriented by control points (GOM).

Fig. 17. Surface measurement systems with photogrammetric orientation.

mobile system solution is provided, over a large measurement volume. If the tracking device is used at different stations, the measurement volume is almost unlimited. By contrast, mechanical orientation devices such as CMMs, robots or articulated arms have limited working areas and restricted mobility. Their advantage is the independence of light conditions. Compared to laser tracking or optical tracking, mechanical devices are most advantageous in small volumes of usually less than 1 m^3.

Hand-held sensors can also be navigated by tie or control points that are located on the object surface. In case of the HandyScan system from Creaform, shown along with a second system oriented by control points in Fig. 17, two cameras are used to observe targets in 3D space while a laser system is used to scan the surface. The system can be used for large objects if the distribution and accuracy of object points is sufficient. In this case the object targets are measured by a high-resolution photogrammetric off-line system and subsequently used as known control points. The concept is also able to work with unknown tie points, however with generally poor conditions for error propagation. Image-based 3D surface measurement systems can also employ exterior orientation determination by mechanical means, as exemplified by the two systems shown in Fig. 18.

The registration (orientation) of single 3D point clouds using surface features can be performed via the ICP algorithm, the applicability of the method depending strongly upon the surface structure which must provide sufficient points, corners or other features that can be matched with respect to adjacent point clouds.

4.4. Measurement of structures

In special cases the photogrammetric measurement of object structures such as edges or contours is desired. If these structures cannot be derived from discrete 3D points, they have to be extracted from image edges or contours. The measurement of regular geometric elements such as circles, spheres or cylinders based on grey-level edges is enabled by the so-called contour method of Andresen (1991). Usually three images from different positions are required to determine the element parameters in 3D space, namely the position, normal vector and radius of a circle. The method assumes that the physical object edge and the optical edge in the image are identical.

The measurement of pipe and tube structures can be performed by multi-image analysis of the contour of the tube. The TubeInspect system from AICON (Fig. 19) uses up to 16 cameras for the fully-automated measurement of arbitrary shapes of pipes and tubes. The system is directly connected to the tube bending machine, so that deviations from the nominal shape are directly processed into correction parameters for the bending machine.

5. Accuracy and verification

5.1. Standards and guidelines

The specified accuracy of an industrial measurement system and the achieved accuracy within a real project are two of the

(a) Fringe projection system mounted on robot (Steinbichler).

(b) Laser profile sensor mounted on articulated arm (API).

Fig. 18. Surface measurement systems with mechanical orientation.

most important practical considerations. Although well-accepted national and international guidelines and standards exist, the definition of accuracy performance of photogrammetric systems is still very heterogeneous. Terms like 'precision', 'relative accuracy', 'accuracy', 'measurement uncertainty', 'length measuring error', 'standard deviation', 'RMS 1-sigma' and others exist, while only a few are defined according to international standards such as ISO 10360 or GUM (1993).

In many photogrammetric applications internal precision measures from adjustment results (e.g. sigma 0, standard deviations, RMS 1-sigma values) are presented as final accuracy figures. In these cases the performance of a system can easily be manipulated simply by increasing the number of observations. It can be argued that real accuracy measures can only be generated if independent control/checkpoint data is available in object space. This verification data can be formed by 3D control points, which, however, are often not available in practice with sufficient (higher) accuracy. For tactile probing systems (e.g. CMMs and hand-held probes), diverse reference bodies are available, including ball plates or reference scales. In general, these reference bodies are relatively small, expensive, heavy and not suited for optical probing.

A rather simple way of providing calibrated and certified references is via the use of scale bars with target points that are equivalent to the type of targets used for the optical measurement system. Scale bars are very mobile, easy to calibrate and they enable traceability to national length standards.

For optical 3D point measuring systems the German guideline VDI 2634 part 1 has been available for about 10 years (VDI, 2000), and this procedure for accuracy assessment for acceptance testing and accuracy performance verification is now well accepted in industry. Indeed, larger companies may often not employ measuring systems whose performance has not been verified with respect to VDI 2634. The main idea is to arrange a number of scale bars in object space such that the principal coordinate axes are represented by a number of calibrated lengths (Fig. 20). For the accuracy test, all photogrammetrically measured distances are compared to their calibrated nominal length. The results are presented in a diagram that easily shows the length measuring error (LME) as the largest distance deviation from all measurements. In Fig. 20 the LME is equal to the parameter B.

For all-around image configurations and bundle adjustment the resulting length measuring error can be estimated from RMS 1-sigma values of object points. Assuming equal RMS values in all

Fig. 19. In-process tube inspection system (AICON).

directions and a confidence interval of 3 sigma, the estimated LME results to

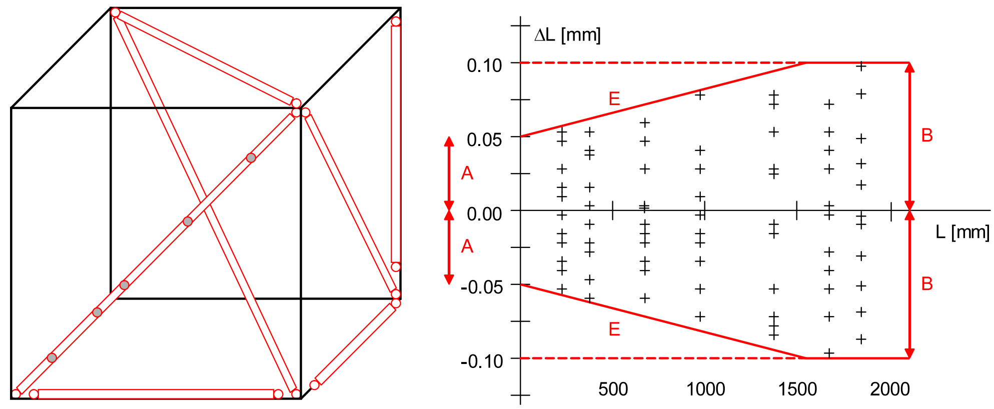
$$\mathrm{LME} = \sqrt{18} \cdot \mathrm{RMS}. \tag{1}$$

For area-based probing systems, such as fringe projection devices, VDI 2634 part 2 and 3 recommend procedures for the assessment of probing errors, plane measuring errors and sphere distance errors. Usually calibrated spherical or plane reference bodies are applied for system testing. In general, the acquired 3D points are analysed with respect to a reference surface whereby 3‰ of the measured points can be neglected due to typical outliers. Since most of the systems operate in measurement volumes of less than 1 m^3, the provision of suitable reference bodies is feasible (see Fig. 21). The use of free-form reference bodies is discussed in detail in Luhmann et al. (2008) and Bethmann et al. (2010).

5.2. Practical experiences

According to the VDI standard a number of investigations have been published during the past years. In general, the following results are reported:

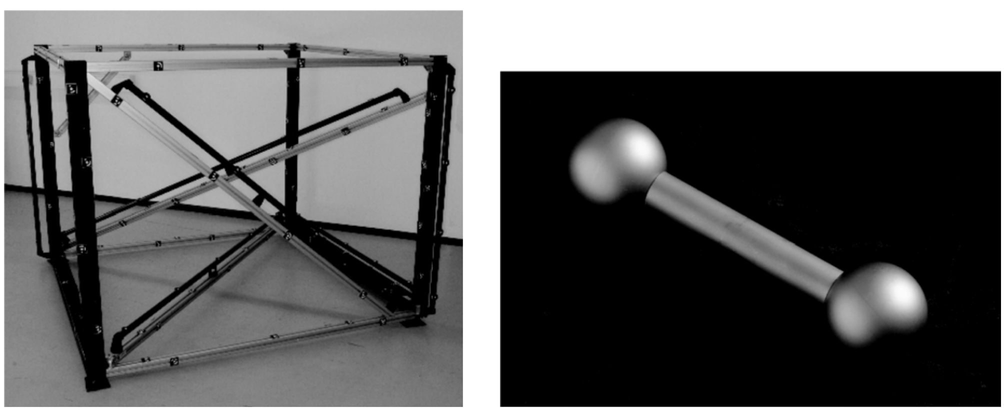
- the resulting LME is approximately 3–4 times higher than RMS 1-sigma values of object points, if gross errors have been eliminated from bundle adjustment;
- LME appears as a very strict and sensitive quality value, i.e. weakness of image configurations and incomplete camera calibration usually degrade LME values while RMS 1-sigma values do not react in the same way, at least to the same extent;



(a) Arrangement of scale bars according to VDI 2634/1.

(b) Diagram of length measuring deviations.

Fig. 20. Determination of length measuring error.



(a) VDI cube with scale bars.

(b) Sphere bar.

Fig. 21. Example reference bodies.

- LME is easy to understand for users who are not skilled in photogrammetry or adjustment techniques; and
- LME has in some respects lowered the performance indicators for photogrammetric systems in terms of the presented accuracy level, but has made photogrammetric systems more reliable and accepted.

LME ranges between 40 and 80 μm can generally be attained with high quality digital SLR cameras in a measuring volume of 2 m × 2 m × 2 m (e.g. Rieke-Zapp et al., 2009). In order to achieve high accuracy results the camera has to be calibrated on the job. Especially for off-the-shelf SLR cameras, image-variant calibration can significantly improve the results.

It is noteworthy, however, that there are circumstances, commonly encountered in single-sensor, off-line photogrammetry systems, where the LME approach is difficult to implement in practice. This occurs in the high accuracy measurement of very large objects such as aircraft body sections, ship blocks, antennas and components of wind turbines. At such large scales, checking fixtures such as those called for under VDI 2634 are not necessarily the optimal means to verify the accuracy of 3D shape reconstruction, as opposed to absolute scale accuracy alone. Here, the only recourse is often to rely on internal measures of precision, which means that care must be exercised to ensure that the network design incorporates sufficient geometric strength, high redundancy and a configuration conducive to the strong self-calibration of a sensor which exhibits a very high degree of stability and overall metric quality.

6. Summary and future prospects

This paper has provided an overview of the state-of-the-art in industrial photogrammetry. The field can be characterised by demanding requirements in accuracy, price-performance ratio, level of automation, reliability, mobility and flexibility. Photogrammetric systems compete with alternative solutions (e.g. laser trackers and CMMs), but also provide unique advantageous features for non-contact measurement of points, surfaces and structures.

Industrial photogrammetry invariably employs imaging technology based on CCD and CMOS sensors, and off-the-shelf SLR, video and high-speed cameras. For specific tasks, a limited number of specialised photogrammetric cameras exist that are optimised in terms of stability, image quality, accuracy or speed. Cameras are used in off-line and on-line applications and systems in a large number of industrial applications. While off-line systems usually form the standard case of multi-image photogrammetry, on-line systems are either configured as tactile photogrammetric coordinate measurement systems, or as special purpose systems integrated into an external process.

Calibration method and resulting accuracy are closely linked. The highest accuracies can be achieved with high-resolution sensors, multi-image configurations, targeted object points and self-calibrating bundle adjustment. A precision of 5–10 ppm is readily achievable, while some accuracy figures may well be lower, for example 20 ppm in terms of length measurement errors.

Future trends in industrial photogrammetry include an increasing integration of photogrammetric technology into process control, for example in the direct dimensional monitoring and control of production machinery and processes. Further tendencies are visible in the field of dynamic measurement tasks where fast 3D measurement of moving objects is required, with potentially moving sensors. Finally photogrammetry will be combined with other sensor types such as laser trackers, laser scanners or structured light systems.

Further developments in industrial photogrammetry are mainly initiated and driven by the suppliers of photogrammetric systems. It can be observed that only very few academic and research institutions worldwide work in the exciting and technologically challenging area of high-precision industrial close-range photogrammetry.

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