

STATE OF THE ART IN INDUSTRIAL PHOTOGRAMMETRY

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ABSTRACT

A review is given of the current state of the art in industrial photogrammetry, as represented both by photogrammetric systems in use today and by those under development. Generally speaking, systems for industrial applications fall into one of two categories: on-line and off-line. The main distinguishing feature between the two is that on-line systems utilize solely digital imagery whereas off-line systems employ principally analog photography, but can employ digital images. In the on-line category reside real- and near-real-time systems, whereas the off-line group includes traditional systems for stereo and monoscopic/convergent photogrammetry. In this latter group, automatic film mensuration and stereodigitizing are prominent recent advances. Selected systems from the two categories are discussed.

1. INTRODUCTION

In attempting to review the state of the art in industrial photogrammetry it behooves one initially to define the term. At first appearance this is simple: Industrial photogrammetry is that branch of the science of photogrammetry utilized by industry. The definition, however, manages to imply a great deal but says little in terms of specifics. For example, just what constitutes industry and what photogrammetric techniques and products do industry use? For this review the author has taken advantage of the lack of a clear definition of industrial photogrammetry to concentrate on a reasonably distinct topic, that being the growing use of non-topographic photogrammetry of moderate to high accuracy in industries involved in medium- to large-scale engineering, manufacturing, fabrication, assembly and construction. Such concerns include aerospace companies, aircraft manufacturers, automobile companies, shipbuilders, and large civil and structural engineering firms.

Having presented a scope of users who constitute 'industry', the next step is to consider the nature of the photogrammetric measurement tasks undertaken. Here, the review will concentrate on general three-dimensional coordinate determination. Thus, industrial photogrammetry will be treated in the same light as 3-axis coordinate measuring machines (CMMs) or 3-D surveying techniques utilizing triangulation and/or trilateration. Mapping applications per se will not be covered, and photogrammetry will be placed in a context more akin to digital theodolites, namely as a system for optical triangulation utilizing primarily passive sensing (i.e. non-active targets).

Objects large and small are routinely measured by industrial photogrammetry, as is evidenced by the three examples shown in Figures 1, 2 and 3. To obtain the as-built lines of the 230m container ship shown in Figure 1,



Figure 1. 230m Container Ship

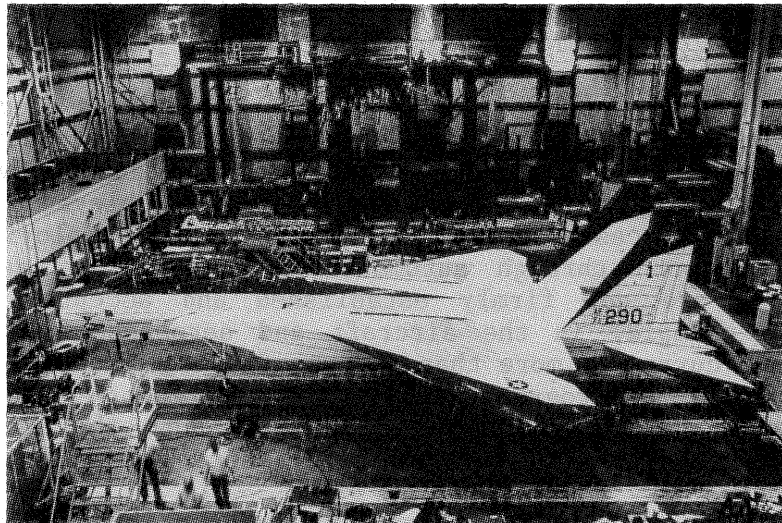


Figure 2. Fighter Aircraft

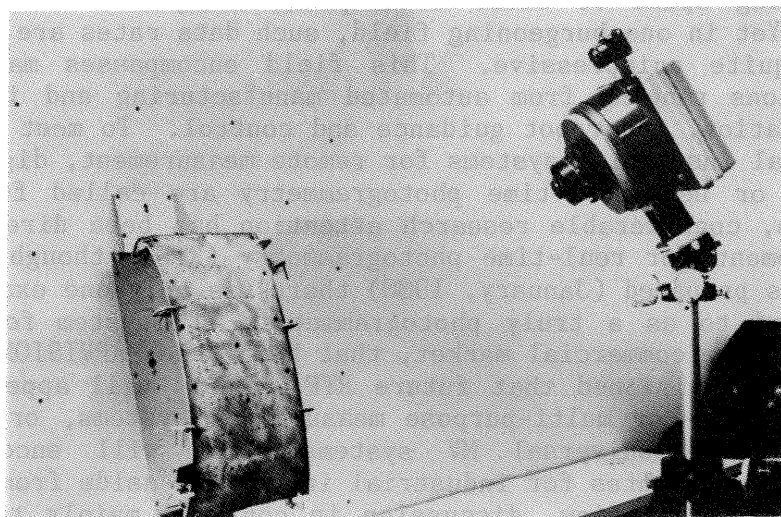


Figure 3. Small Aircraft Part

to an accuracy of better than a millimeter, a network of close to 140 photos and 1500 points were required. In measuring the fuselage, wing and stabilizer surfaces on the fighter aircraft shown in Figure 2, 38 photographs were employed for the more than 20,000 object points, which were triangulated with an accuracy of close to 0.25 mm (the final bundle adjustment exhibited in excess of 150,000 degrees of freedom). On a smaller scale still, the aircraft part shown in Figure 3 was measured to an accuracy of 0.02 mm to provide XYZ control for a robotic milling tool.

The use of non-topographic photogrammetry in industry grew steadily over the two decades leading up to the early 1980s, with the rate of growth closely paralleling advances in close-range analytics and computer technology. During this time the majority of measurement projects were carried out by a handful of photogrammetric service companies, such as Geodetic Services, Inc. (GSI), or by groups affiliated with universities or research institutes. Relatively few photogrammetric systems were employed for inhouse industrial use. Over the past few years, however, the situation has changed markedly.

Photogrammetry has traditionally been regarded as a relatively skill-intensive measuring tool characterized by a rapid data acquisition phase followed by a lengthy film measurement and data processing stage. In considering industry it is also natural to think of production and productivity. The slow turnaround time of photogrammetric systems employing manual film measurement is not always tolerable from a productivity point of view and this tends to inhibit commercial acceptance. Over the past 3-4 years, however, significant advances have been achieved in automating the photogrammetric process. So-called turnkey systems employing automated film measurement, both through automatic monocomparators and automatic stereodigitizing, are now firmly established and accepted in selected industries. For example, in the aircraft and aerospace sector in North America there are currently more than a dozen firms employing high-accuracy monoscopic/convergent photogrammetry, while in Europe the automobile industry is perhaps the most prominent user of both the medium-accuracy monoscopic/convergent technique and automated stereodigitizing.

As compared to CMMs and digital theodolite systems, the measurement rate exhibited by automated photogrammetric systems such as STARS from GSI (photo measurement at one point per second) and InduSURF from Zeiss (stereodigitizing speed of close to a point every two seconds) is very competitive. Yet in one burgeoning field, such data rates are for numerous applications quite unimpressive. This field encompasses machine vision (MV) applications ranging from automated manufacturing and inspection to part identification, and robot guidance and control. To meet the needs of automated visual inspection systems for remote measurement, digital cameras and real-time or near-real-time photogrammetry are called for. Over the past few years, considerable research attention has been directed towards system development for real-time photogrammetry (RTP), though at the time this review was prepared (January, 1988) there was only one example of what may be referred to as a truly photogrammetric RTP system for industrial applications on the commercial market, that being the MAPVISION system from Finland. It is envisioned that future RTP systems will appear either as stand-alone, single- or multi-purpose measurement systems, or as integral components of more universal MV systems which will encompass other knowledge-based attributes for industrial inspection aside from optical 3-D measurement. In this review, discussion is confined mainly to the former category and to the metric aspects of RTP.

Generally speaking, photogrammetric systems for industrial measurement fall into one of two broad categories: on-line or off-line. The major distinguishing feature between the two is that on-line systems imply real-time or near-real-time sensing capability and therefore utilize solely digital cameras. Off-line systems, on the other hand, exhibit the traditional separation of the data acquisition phase from the image mensuration and data processing stages, and may employ either analog or digital photography. A breakdown by category of systems for industrial photogrammetry is shown in Figure 4.

Here, the discussion will commence with some remarks on measurement accuracy, and this is followed by an outline firstly of systems constituting the off-line category, and secondly of the somewhat smaller on-line group. Emphasis is placed on discussing systems that represent, in the author's view, the present state of the art in industrial photogrammetry. Thus, not all systems currently in use are referred to specifically, and those that are briefly discussed have been selected on the basis that they represent significant recent developments. Consequently, one area of Figure 4 which will attract only a cursory overview is that involving off-line systems which utilize manual film mensuration, since these are the traditional systems of non-topographic photogrammetry which are both well-known and comprehensively covered in the literature. Film and plate cameras utilized or being developed for industrial photogrammetry will not be separately discussed, principally because there has been only modest development in this area since the last ISPRS Congress in 1984. The systems reviewed embody in most cases results of research conducted by a number of individual researchers or groups. Unfortunately, it is not practical in a paper of this type to cite all references to relevant literature and references have been kept to a minimum.

2. ACCURACY CONSIDERATIONS

In North America, the adoption of photogrammetry by industry followed to some extent the widespread acceptance of another non-contact measurement method based on optical triangulation, that being dual- and multiple-head digital theodolite systems. The accuracy of these systems was often simply expressed by the angular resolution of the theodolites, and in the early days at least the role played by network geometry in determining triangulation accuracy was not sufficiently appreciated by many users. Thus, 'one-second theodolites' implied an angular resolution of 1:200,000 of object distance and this figure was tacitly taken as representative of the accuracy of measured XYZ coordinates. Notwithstanding this somewhat incomplete picture, the adoption of angular resolution as a measure of relative system accuracy capability is logical both for theodolites and photogrammetry.

An approximate formula relating the RMS value of the standard errors of measured XYZ coordinates, $\bar{\sigma}_C$, to the scale of photography, 1:S, and the precision of image coordinate measurements, σ , is given as:

$$\bar{\sigma}_C = q S \sigma \quad (1)$$

where q is a factor whose value ranges from an optimum of close to 0.4 for multi-station convergent geometries to in excess of 2.5 for weaker 'normal' geometries employed in stereodigitizing (e.g. Fraser, 1984). For example, in the InduSURF system discussed in the next section, the q -value relating to just the precision in depth, σ_z , is around 3. Equation 1 can be recast

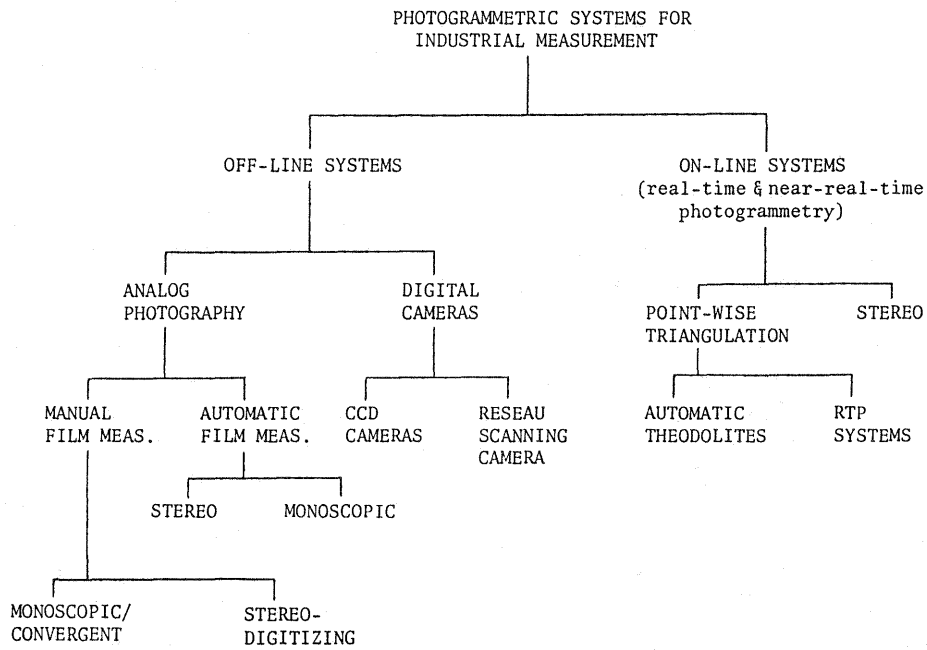


Figure 4.

TABLE 1. Angular measurement precision for different combinations of camera focal length and image coordinate precision.

Camera Focal Length (mm)	Format (mm)	Std. Error of Image Coords. σ (μm)	Angular Std. Error σ_a (")	Representative Camera/Comparator Combination or Digital Camera
240	230x230	0.5	0.4	CRC-1 with AutoSet automatic monocomparator
200	130x180	1.5	1.5	UMK 20/1318 with 1st order analytical plotter
120	230x230	0.5	0.9	CRC-1 with AutoSet
100	130x180	1.0	2.0	UMK 10/1318 with Rollei RS comparator
100	130x180	2.0	4.1	UMK 10/1318 or P-31 with analytical plotter
80	60x60	2.5	6.4	Hasselblad MK70 or Rollei 6006 Reseau with analytical plotter
40	60x60	1.0	5.2	Rollei RSC reseau-scanning camera
40	60x60	4.0	21.0	70mm semi-metric camera with 2nd order analytical plotter
20	9x7	0.3	3.1	Videk Megaplus CCD camera at 1/20th pixel image measurement accuracy
12.5	8.8x6.6	1.0	16.0	CCD camera with approx. 20 μm pixels and 1/20th pixel accuracy

into the following form which relates XYZ coordinate precision directly to angular precision:

$$\bar{\sigma}_C = q d \sigma_a \quad (2)$$

where d is the average object distance and σ_a the standard error of angle measurement. Equations 1 and 2 have been employed to compile Table 1 which gives representative angular accuracy figures for common combinations of photogrammetric cameras and image coordinate measurement devices, as well as for a few digital cameras. It should be mentioned that in the table, angular precision figures have been determined simply as $\sigma_a = \sigma/\text{focal length}$, which implicitly assumes that all systematic errors (e.g. film unflatness and deformation) have been fully compensated for.

Relative system accuracies can be compared through the σ_a -values in Table 1, and for the remainder of the paper angular precision will be used for this purpose. Proportional attainable accuracies in object space, i.e. $\bar{\sigma}_C/\text{object dimension}$, have not been entered in the table since they are partly a function of both geometry and camera field of view. They will, however, be addressed in the discussion of individual systems.

3. OFF-LINE SYSTEMS FOR INDUSTRIAL PHOTOGRAMMETRY

Off-line photogrammetric systems, which are characterized by the fact that image mensuration and data reduction occurs off-line from photography, may employ analog or digital cameras. Systems utilizing digital cameras, however, which do not yield near-real-time results, may indeed be technically on-line when comprised of a solid state camera interfaced to a personal computer. For the purpose of this discussion, off-line is taken to mean, in essence, non-near-real-time. Thus, a system for 3-D measurement which comprises a single digital camera will be regarded as belonging to the off-line group.

As indicated in Figure 4, systems belonging in the off-line category can be distinguished by imaging device: those comprising analog cameras versus those utilizing digital cameras. At the present time, virtually all photogrammetric systems employed in industry incorporate film (or plate) cameras. Measurement of the film may proceed either manually as with traditional monocomparators and analytical plotters, or automatically via video scanning of the analog image. Manual film measurement in turn can follow one of two approaches: stereodigitizing as opposed to monoscopic measurement followed by analytical restitution, typically with a bundle adjustment approach. Analogous to manual film reading, automatic image measurement can be via digital correlation in a stereomodel, such as with the InduSURF system, or involve monoscopic measurement by, for example, either the video scanning monocomparator AutoSet from GSI or the Rolleimetric RS comparator which utilizes a technique termed reseau scanning.

3.1 Manual Measurement of Analog Images

Up until quite recently, system configurations of metric or semi-metric cameras coupled with manually operated comparators or analytical plotters were exclusively used for industrial photogrammetry in various parts of the world. Such systems gained a foothold in many industrial sectors and are still prominent in selected areas of application, though the use of photogrammetry in particular industries is by no means universal. For example,

photogrammetry is widely applied in the energy sector (coal mining and electric power generation) in West Germany, but seemingly not too much elsewhere. Similarly, early applications of manual photogrammetric systems (now largely superseded by automated operations) by U.S. aerospace and aircraft manufacturers have not been matched to any great extent in Europe or elsewhere. A number of other examples of geographically localized fields in which manual systems for industrial photogrammetry have found significant usage can also be identified; for instance, measurement of storage tank volumes in the U.S. and Japan, the monitoring of large engineering undertakings such as dams and excavations in Australia, application to shipbuilding in the U.S. and Europe, underwater structural monitoring in the North Sea oil fields, and precision measurements in support of building construction, renovation or restoration in Western Europe.

Systems can be configured from a host of different photogrammetric cameras, film measurement devices and software packages for data reduction. Also, they may be either single-source or involve equipment from different manufacturers. As indicated in Table 1, system accuracies can vary dramatically depending on the camera/comparator combination selected. Accuracies can also differ as a result of the photogrammetric procedure adopted; e.g. stereo versus monoscopic/convergent, self-calibrating bundle adjustment versus direct linear transformation (DLT), targeted or non-targeted object, provision of object space control versus no control, etc.

Identifiable trends in industrial photogrammetric systems employing manual film mensuration include the following:

- . The use of reasonably low-cost analytical plotters (e.g. the ADAM Technology MPS) coupled with semi-metric 70mm and 35mm cameras to form systems with angular accuracies of say 10-20 seconds of arc (").
- . The re-emergence of film in preference to glass plates.
- . The widespread use of self-calibration to fully exploit the versatility of semi- and non-metric cameras.
- . A move away from the use of independently surveyed object space control. For stereo work, for example, control can be provided via combined monoscopic/convergent and stereo nets. The role of control reverts to providing a means to effect coordinate transformation of the photogrammetric data.
- . Direct interfacing of digital mapping techniques and/or CAD with stereo-restitution (e.g. computer assisted 'mapping' of refinery pipeline networks).
- . The provision of user-friendly network design and simulation software as well as data reduction subsystems designed for use by non-photogrammetrists. The aim here is to render photogrammetric measurement less skill intensive, though this will always be a problem for manually operated stereo systems.
- . The complete dominance of analytical plotters and computer controlled monocomparators over purely manual comparators. Within the confines of their manual operation, film measurement devices will stress maximum computer assistance to improve measurement throughput.

- . The use of special targeting such as retroreflective targets and laser scanning.

3.2 Automatic Film Measurement

Under this heading both automated stereomodel restitution and automatic monocomparators employing digital imaging of analog photography are considered. In military mapping, fully automated stereocompilation has been a reality for some time and the first automatic, computer controlled monocomparator was developed well over a decade ago. Automated systems for industrial photogrammetry, however, had to await the development of new technologies such as solid-state digital cameras and powerful, mini and personal computers before automation became an economical proposition.

Automated Stereodigitizing

The installation in October, 1986 of a photogrammetric system for surface measurement at Volkswagen AG in West Germany represented the first commercial example of automated stereodigitizing in industrial photogrammetry. This system, which was developed by Ackermann and colleagues at INPHO GmbH, Stuttgart in co-operation with the Zeiss Company, is currently used for the measurement of gridded surface points and shape lines on car bodies, and specifically on design models. Marketed under the name Zeiss InduSURF this system employs digital image processing and matching of stereomodels set up in a Planicomp C100 analytical plotter fitted with Hamamatsu CCD cameras (Schewe, 1987).

In the configuration used for automobile surface measurement, InduSURF typically employs a Zeiss SMK stereometric camera at an object distance of about 1.5m, which gives rise to an image scale of 1:15. Once a stereomodel is imaged it is relatively and absolutely oriented on the analytical plotter (by a human operator) following which the SURF software takes over to perform the automatic point measurement at a rate of around one point every two seconds. For shape-line digitizing, retroreflective target tape is used, whereas for measuring the surface along grid lines no targetting is required, only the presence of sufficient surface texture which can be projected if required.

Both feature-based and least-squares correlation are employed to yield x-parallax matching accuracies of about 1/20 of a pixel. Coupled with the resolution of the xy table on the planicomp of 1-2 μm , overall image coordinate measurement accuracy is close to 2 μm . For the SMK camera this corresponds to an angular precision of about 4 ". A base/distance ratio of 0.4 is used, giving rise to standard errors of $\sigma_z = 0.1\text{mm}$ in depth and $\sigma_{xy} = 0.02\text{mm}$. The disparity between σ_{xy} and σ_z is a consequence of the relatively weak 'normal' geometry, the small base doubtless enhancing the accuracy of image correlation.

For many surface measurement tasks in industry conventional stereophotogrammetry can be economically supplanted by the monoscopic/convergent technique employing special targetting strategies and automatic film mensuration. This, however, is unlikely to be the case for the car body measurement for which InduSURF was designed, for at least one good reason. The surface profiles to be digitized are delineated by intersections with parallel planes and are defined mathematically. Thus, within the absolutely oriented stereomodel the measuring mark can be set at the required surface point, whereas there would be no practical means by which a target could be correctly placed in position prior to photography. One

can surmise that the success of InduSURF is more attributable to the intelligence embodied in the SURF software than to simple automation of the stereorestitution procedure.

Automatic Monocomparators

Of the automated film mensuration systems currently available on the commercial market, two have been designed primarily with industrial photogrammetric applications in mind. These are the AutoSet-1 automatic monocomparator from GSI (Brown, 1987), and the Rolleimetric RS1 reseau-scanner from Rollei Fototechnic (Luhmann & Wester-Ebbinghaus, 1987).

AutoSet can essentially be thought of as a traditional computer controlled monocomparator in which digital image processing has replaced human judgement in the determination of centroids of images. The adoption of video-scanning technology, coupled with an xy table of very high accuracy (0.1 μ m resolution) results in an instrument which is some five to ten times faster and more accurate than traditional photogrammetric monocomparators (and analytical plotters). Accuracies (RMS) of 0.4 μ m are obtained on AutoSet, and when driven by a COMPAQ 386 PC, the unit can measure at a rate of one point every 0.8 seconds in fully automatic mode. Of the current STARS system installations in industry, all those utilizing AutoSet also employ the CRC-1 camera. This combination yields an optical triangulation system with an angular resolution of better than half a second of arc for the CRC-1 with 240mm lens and under a second for the 120mm lens. Moreover, by virtue of the camera's large format (23 x 23 cm), the CRC-1/AutoSet combination routinely yields accuracies of 1:250,000 of the extent of the object in the field of view, and in a number of projects object point precision of better than 1:400,000 has been achieved when using the medium-angle lens (50° x 50° field of view).

The RS reseau-scanning comparator operates on a very different principle from AutoSet. Embodied in the AutoSet design is high mechanical and optical stability, as well as the requirement for the xy table to hold its digitizing accuracy over a 23 x 23 cm area of travel. To circumvent the need for a precise measuring table, the Rolleimetric RS utilizes a reseau plate, such that the position of any image point can be determined relative to adjacent reseau marks. The unit employs a CCD camera which can be used to scan the image plane. The spacing of the reseau grid is designed to correspond to the CCD sensor size at the selected projection scale. Thus, in the recording of any partial scene on the photograph four reseau crosses will also be recorded. The reseaus are imaged separately to ensure they are recorded irrespective of photographic background. Digital image processing is then used to determine the sensor coordinates of the four reseau marks and the targets in the partial frame, and these local coordinates are transformed into the reseau datum via perspective transformation.

With a 2mm reseau grid spacing, the RS comparator can yield accuracies of 1 μ m for optimal targets. This accuracy requires detection of target centroids to about 0.1 pixel in the CCD image. When coupled with the Rolleiflex 6006 70mm semi-metric camera with 40mm lens, an angular resolution of the Rolleimetric system is about 5 ". The design measuring rate for the RS is around one point every 6-7 seconds.

In comparing AutoSet and the RS comparator it can be seen that AutoSet is both more accurate and considerably faster, and the higher performance is reflected in its higher cost. In the Rolleimetric unit the quest for low mechanical effort has been achieved at the expense of increased image

processing effort. With AutoSet, only one target is captured with each setting of the instrument, in a directly analogous way to human setting. With the reseau-scanning technique, on the other hand, each CCD frame may contain any number of targets, as well as the four reseau crosses. Even in cases where approximate image coordinates can be determined a priori, the digital image processing effort may have to include the detection, correct labelling and centroid determination of multiple targets.

3.3 Digital Cameras

In this group, systems comprising CCD cameras and so-called reseau scanning cameras are considered. Such systems represent the digital equivalent of traditional configurations for industrial photogrammetry, and specifically those designed for the monoscopic/convergent approach. The monocomparator is, of course, no longer required, but aside from film mensuration the steps involved for the digital approach match those of the analog counterpart. Here, a two-stage operation is involved. Initially, all images are acquired, with the necessary image preprocessing, target recognition and xy coordinate extraction ideally occurring concurrently with the capture of each image. Following this phase, object point positioning via triangulation is performed, invariably on the on-line computer for the digital sensor(s).

Before proceeding, it should again be mentioned that this 'on-line' feature does not contradict the heading of the present section in that 'off-line' digital systems are understood here to be those that do not yield near-real-time positioning information. That is, there will be a finite time delay of perhaps many seconds or minutes between the image acquisition and triangulation phases, the latter being in a sense off-line to the former.

At the present time there are a number of practical limitations and difficulties which must be overcome before a photogrammetric system employing digital cameras could be released for commercial use in routine industrial measurement applications requiring moderately high accuracies. Firstly, there are the familiar limitations of presently available digital cameras, namely the small size and limited resolution of CCD area-array sensors. These features result in narrow fields of view and therefore dictate the use of small imaging scale. Solutions to the problem of small image format are being offered both through the introduction of large format, high resolution sensors (e.g. the sensor of 55 x 55 mm and 2K x 2K pixel format being developed by Tektronix, Inc.) and through the recording of large format images by the use of mosaiced arrays or partial frame capture. The recording of a scene by sequentially capturing and processing partial frames is of particular interest in the photogrammetric context since this approach is embodied in a reseau-scanning camera, which is discussed later.

A second difficulty with digital camera usage in a multistation photogrammetric network is target recognition and detection, and the matching of conjugate image points in the multiple scenes. Special targeting schemes (e.g. active targets or the use of retroreflective targets) can be employed to greatly simplify recognition and detection, but labelling and matching is a very pronounced problem, especially for convergent imaging geometries where each image may display a very different perspective view of the object. It is hard to envision the successful introduction of a 'turnkey', general purpose digital photogrammetric system for 3-D industrial measurement before practical solutions are found for this problem. For systems dedicated to a single, repeatable measurement task, this concern may not be

so evident, since approximate image coordinates can be computed and search windows determined based on known camera position and orientation.

CCD Cameras

One limitation familiar to all CCD camera systems that is most pertinent to accuracy capabilities is the degree to which the camera can be geometrically calibrated, and the stability of this calibration in the presence of electronic and environmental disturbances. In analog photogrammetry film unflatness remains as an insidious problem whose effects evade successful modelling by practical means in a self-calibration adjustment. It seems only fitting then that in a digital camera the calibration concern should again center on the focal plane. But here attention is paid to such aspects as determining the frequency differences between the CCD pixel clock and that in the A/D converter, warm-up effects, and the problem of line synchronization or jitter (e.g. Gruen, 1987).

At this point the author will take the opportunity to relate some of his own recent experiences with CCD cameras. Recently, an experiment was conducted at GSI to examine accuracy aspects of utilizing a CCD camera for industrial measurement. The aims of the project were quite modest and centered on evaluating the photogrammetric triangulation accuracy which could be attained with a Sony XC-37 CCD camera utilized in a multi-station convergent network. A planar control field covering an area of 1 x 1m and comprising 37 evenly distributed targets was to be measured, the triangulation being performed via a self-calibrating bundle adjustment. The additional parameter model chosen accounted for radial and decentering distortion, principal distance and principal point offset, and affinity and non-orthogonality in the xy image coordinate system. The inclusion of the affinity term was to account for an x-scale factor which would arise from any frequency difference between the clock of the Datacube frame grabber and that of the CCD pixel shift clock.

For each combination of CCD camera and A/D converter a different level of electronic disturbances on geometric calibration can be anticipated. As is shown by Beyer (1987), these influences, while invariably sub-pixel in magnitude, can significantly degrade triangulation accuracy. Moreover, effects such as line jitter vary from image to image. The approach adopted to both minimize electronic effects and yield some compensation for the limited resolution of the CCD sensor was to provide greater data redundancy through the 'grabbing' of many additional images. The Sony camera has a 384 H x 490 V sensor with a pixel spacing of 23 μm in x (horizontal) and 14 μm in y (vertical). With a lens of 8.5mm focal length and assuming target centroiding to say 0.05 pixel, the equivalent angular resolution of the system would be around 25 ".

The photogrammetric network established comprised 10 camera stations in a convergent imaging geometry (max. convergence angle of 70°), with each station being at a distance of close to 1.7m from the center of the target point array. This yielded an image scale of 1:200. At each station two images were taken, though not from precisely the same position. Virtually all target points appeared in all 20 images. Circular retroreflective targets of 11mm diameter were used, thus giving rise to images of around 55 μm diameter, or about 3 x 5 pixels. A simple, weighted pixel averaging was used to determine target centroids. Although a somewhat larger target would have been preferable a size limit was imposed by the need to accurately calibrate the control field via traditional

photogrammetric means. The XYZ coordinates of each target were measured with a CRC-1 camera to an accuracy of better than 0.02mm.

Table 2 gives a summary of the results of the photogrammetric measurement with the Sony XC-37. The 1 μm RMSE of image coordinates confirms an angular resolution of about 25 " for the camera. This figure could no doubt be improved upon by enlarging the targets or, possibly, by employing template matching. The degree of improvement, however, may be limited by the influence of electronic effects which have been assumed here to be effectively 'randomized' by taking multiple exposures. The discrepancies between the measures of precision (σ) and accuracy (s) in the table certainly confirm the presence of unmodelled systematic error, thus showing a few shortcomings in the randomization idea.

TABLE 2. Results of Photogrammetric Measurement with SONY XC-37 Camera.

RMSE of Image Coordinates (μm)			RMS Value of Standard Errors (mm)			RMSE of Object Point Coordinates (mm)			
s_x	s_y	s_{xy}	$\bar{\sigma}_{xy}$	$\bar{\sigma}_z$	$\bar{\sigma}_c$	s_x	s_y	s_z	s_{xyz}
1.1	0.9	1.0	0.058	0.086	0.069	0.089	0.094	0.074	0.086
(0.04 pixel)	(0.07 pixel)		(1:24,400)	(1:16,400)	(1:20,500)	(1:15,900)	(1:15,000)	(1:19,100)	(1:16,400)

In spite of the less than optimum accuracies attained, the results are nevertheless encouraging, and from them it is possible to extrapolate to array sensors of larger format. Take for example the 2K x 2K device from Tektronix which has 27 x 27 μm pixels. This 70 mm format sensor could yield an angular resolution of under 4 " , assuming image measurement accuracies of 0.05 pixels and a camera lens of 80mm focal length (approx. 40° x 40° field of view). Such a combination could potentially yield triangulation accuracies routinely surpassing 1:50,000, and so open the door to further measurement applications in industry. The calibration of large format sensors is, however, potentially complicated by unflatness of the image surface. The Tektronix sensor, for example, can display a bowing which may amount to $\pm 50 \mu\text{m}$ (Blouke et al, 1986).

The Reseau-Scanning Camera

The reseau-scanning concept employed in the Rolleimetric RS comparator can also be applied to cameras. Here, a reseau plate mounted in the focal plane is scanned by a CCD sensor. Thus, through the recording of successive partial images the entire photographic format can be covered. The first commercially available reseau-scanning camera for industrial photogrammetry, the 70mm Rolleimetric RSC, was developed by Rollei Fototechnic in cooperation with researchers at the Universities of Hannover and Braunschweig (Luhmann & Wester-Ebbinghaus, 1987).

Operationally, the reseau-scanning in the RSC differs from that in the RS comparator in that it is not performed grid-wise. Rather than positioning the CCD sensor centrally over grid squares bordered in the corners by four reseau crosses, the sensor is positioned directly over the target to be measured. With the 1mm reseau spacing, this arrangement ensures that between four and nine reseau crosses will be imaged with each target, the reseau being separately recorded from the target image. The positioning of the sensor is under either program control where approximate image

coordinates are available or joystick control by an operator who views the entire photographic scene via a video viewfinder. Upon capturing each successive partial image the RSC determines the pixel coordinates of both the target(s) of interest and the reseau and then performs a perspective transformation to yield image coordinates in the reseau system. The camera is also configured such that each partial image can be separately focussed, while maintaining a constant interior orientation of the camera.

The great potential of the RSC lies in its ability to digitally extract targets from photographic scenes of medium format to the resolution necessary for a host of photogrammetric measurement tasks in industry. To fully exploit the accuracy capability of the camera, self-calibration is mandatory to account for any changes in the geometric relationship between the perspective centers of the camera lens and reseau illumination system (Luhmann & Wester-Ebbinghaus, 1987). Under ideal circumstances, and assuming an image measurement accuracy of 1 μm , the angular resolution of the RSC with 40mm lens is close to 5 ".

For monoscopic/convergent photogrammetry, the RSC displays essentially all but one of the benefits of a high-resolution, large-area CCD sensor of 70mm format. The deficiency is obviously the time involved to mechanically scan the scene, and record and process the individual digital images. In its automatic measurement mode the camera is designed to measure at a rate of around 10 points per minute. As a fully digital system, the RSC could yield on-site measurement results for sufficiently stable objects. Moreover, with multiple reseau-scanning cameras measurement operations in what may be generously said to be near real time become feasible, albeit at a lower accuracy than could be anticipated with a single camera employing self-calibration. In these situations, long term stability of the exterior orientation of the camera setup must be ensured, as with theodolites.

4. ON-LINE SYSTEMS

Machine Vision can be defined as "automated non-contact sensing of images of objects to provide adequate information for process decisions and actions". Functional objectives of MV center on improving product quality through the substitution of inconsistent human judgement by consistent machines; increasing productivity, again through the use of vision engines to speed up manufacturing, grading, sorting and inspection processes previously limited by human endurance; and decreasing costs. Among the basic functions of MV are the measurement of objects or parts thereof to locate defects, the determination of the presence or absence of an object, locating and orientating a workpiece, and identifying, verifying and possibly matching imaged objects. With its broad definition, MV encompasses a number of disciplines, and one of these is RTP.

Only a decade ago there were by some estimates less than a dozen companies worldwide doing significant work in MV; now there are more than 200. Most of the MV systems thus far developed have been designed as one-of-a-kind with very limited application, e.g. there is a vision system for measuring the area and roundness of pizza crusts. Of the single-purpose systems designed for automated visual inspection and gauging, only a handful concern themselves with reasonably accurate 3-D measurement. In the context of industrial photogrammetry, MV systems employing precision 3-D sensing via passive triangulation are of interest for this review. Such units constitute the on-line category of photogrammetric systems for industrial measurement.

Two approaches to RTP (including near-real-time systems) can be distinguished and these follow the traditional breakdown of either the stereo or monoscopic/convergent technique. Here, however, stereo does not necessarily imply 'normal' geometry, but more the automatic restitution of two or more images to yield a 3-D digital model of the scene being imaged, as is envisioned by the STEREOPSIS system (Hobrough & Hobrough, 1985). The realities and constraints of image matching, however, will doubtless mean that stereo RTP systems will primarily utilize 'normal' imaging geometry. In accordance with Figure 4, the alternative RTP technique is based on point-wise triangulation. Here, full image to image correlation per se may not need to be employed, instead target detection and measurement techniques (e.g. feature extraction followed by simple centroiding or template matching) are used to capture all object points of interest in a scene. If only one target per frame is imaged, as in the single-point tracking mode employed by MAPVISION, there is no image matching problem. However, if multiple targets are captured a practical means of matching must be adopted. For relatively oriented 'near-normal' geometries epipolar line searching can be applied (e.g. El Hakim, 1986), whereas with imaging configurations of known exterior orientation, search windows can be established in the frame based on an a priori knowledge of the object space coordinates of each target.

Gruen (1987) provides a review of 'truly photogrammetric real-time systems' which have been either recently developed or are currently under development. Of these RTP systems, really only three have demonstrated potential utility for industrial photogrammetry. These are MAPVISION, which was developed at the Technical Research Center of Finland (Haggrén, 1987) and is commercially available through the Leitz Company, the Digital Photogrammetric Station (DIPS) under ongoing development at the Institute of Geodesy and Photogrammetry, ETH Zurich (Gruen & Beyer, 1987), and a two-camera RTP system reported by El Hakim (1986) which employed a commercial vision system. All three systems incorporate CCD cameras and are capable of producing relative point positioning accuracies in the range of 1:2500 to 1:10,000, with 1:5000 and better being routinely attainable by DIPS and MAPVISION. Beyer (1987) has reported image measurement to 0.04 pixels for the Aqua CCD cameras employed in DIPS (with self-calibration). This indicates an angular accuracy of the system of close to 5 ". As with off-line systems employing CCD cameras, the accuracy attainable with RTP is currently limited by image resolution.

MAPVISION

As a system developed specifically for industrial inspection and assembly control applications, the stand-alone Machine Automatic Photogrammetric Vision system MAPVISION merits further discussion. As mentioned, MAPVISION is commercially available and to the author's knowledge there are four units now in use, one of which is employed for periodic monitoring of structural deformation of aircraft (Haggrén, 1987).

In its current system configuration, MAPVISION employs four (expandable in cases to eight) 512 x 512 pixel Hitachi CCD cameras with focal lengths in the range of 7.5 to 12 mm. The cameras are both synchronized in pairs and synchronized to the Matrox frame grabbers in the image processing system via an external clock. The system is capable of both single- and multi-point tracking and at the present time 99 points can be measured at a time. Target detection is greatly enhanced through the use of image subtraction whereby an actual image of say a laser illuminated spot or retroreflective target is subtracted from a reference image of the background.

MAPVISION operates on a resection/intersection basis. Once the camera configuration for the particular measurement task is established, the system is put through a calibration routine in which the DLT formulation is employed to establish both the exterior and interior orientation parameters (including lens distortion) for the cameras. Some 15-25 independently surveyed control points are utilized in this process, which typically takes less than an hour. Following the resection phase, the system is set up to triangulate object points with a frequency of anywhere from about 1-1/2 to 5 seconds depending on whether image averaging and/or convolution are employed.

From a photogrammetric standpoint, one desirable enhancement to MAPVISION would be the removal of the need for independently surveyed control, which in industry nowadays is most often set in with electronic theodolites. Under the assumption that the interior orientation of each camera is sufficiently stable, the DLT coupled with the need for control in the resection phase could give way to a bundle adjustment which would require either minimal or in some cases no control. It is hard to imagine that the additional computation time would measurably extend the calibration procedure, which itself comes after a warm-up period that may amount to an hour. Similarly the iterative least-squares triangulation for each point can be carried out in a fraction of the 1.5 second minimum measurement time. At accuracy levels of 1:10,000, the benefits of the mathematical rigor of the bundle adjustment may not be significant, but what will be apparent is that the RTP system will truly stand alone without the requirement for additional and often costly surveying work.

Automated Theodolite Systems

Some license has been taken here in selecting systems as so-called real-time. Now similar license will be taken with the term photogrammetry so that automated electronic theodolite systems can be considered under the RTP umbrella. In basic terms, an automatic theodolite is simply a digital camera which yields image coordinate data (sequentially) in the form of angles rather than xy coordinates. Automated theodolite systems belong to the on-line group which employs single-point tracking. Once the exterior orientation of two or more automatic theodolites has been established, triangulation can proceed in a single-point mode very much akin to the approach employed in MAPVISION.

Theodolites demonstrate considerable accuracy advantages over conventional RTP systems by virtue of the fact that their angular precision is mainly a function of the resolution of the horizontal and vertical circle encoders and not that of the CCD camera integrated into the telescope. For example the SPACE system from Kern is designed to yield angular standard errors of better than 1 " (Gottwald & Berner, 1987). Weighed against the high accuracy of automatic theodolites is their relatively slow speed in comparison to camera-based RTP systems. SPACE displays a measuring rate of around one point every seven seconds in its automatic mode.

5. CONCLUDING REMARKS

If one were to select a common thread binding the significant recent developments in industrial photogrammetry it would be digital image processing. In the off-line systems employing film cameras, digital image acquisition and processing has made possible the commercial introduction of automatic film reading and stereodigitizing, whereas with on-line systems

it is central to all current and future developments in RTP. With this in mind, it seems reasonable to surmise that the future pace of development and indeed commercial acceptance of industrial photogrammetry, and especially of the on-line category of systems, will parallel advances in digital image processing and developments in the broad field of machine vision.

There is no reason to suspect that the future for industrial photogrammetry will not be bright; but there is also little evidence to suggest that dramatic developments will occur overnight. It is perhaps a little frustrating to many photogrammetrists to realize that in a number of respects the vexing problems with on-line systems of the future are no longer confined to the traditional areas of sensor geometry modelling and the analytics of restitution. Instead, the first part of the following definition of photogrammetry comes again to the fore: "Photogrammetry is the science of image understanding and image metrology."

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