# RESULTS OF THE GERMAN COMPARISON TEST FOR DIGITAL POINT OPERATORS

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**KEY WORDS:** Close-Range Photogrammetry, Digital Point Measurement, Sub-Pixel Accuracy, Simulation

## ABSTRACT:

A test procedure has been developed in order to compare different digital point measurement techniques. For this test a number of synthetic and real images with various circular point patterns have been generated and submitted to 20 different institutions throughout Germany, Switzerland and Austria (universities and system developers). One goal of this test is to compare the suitability of different point operators under equal conditions. A second goal is to verify the current limits of sub-pixel point positioning which, by numerous authors, have been reported down to a few thousands of a pixel. The investigation of the image test material is based on a 2-D (image space) and 3-D (object space) analysis.
The comparison study reports of the results of the following point operators: structural edge-based ellipse operators, center-of-gravity operators, template matching operators and least-squares matching operators.
Using synthetic images the results show that a sub-pixel accuracy of 1/100 of a pixel size can be achieved by edge-based ellipse operators. With real images taken from a fully-digital high-resolution CCD camera the mean accuracy in image space is limited to 2/100 of a pixel (under laboratory conditions). These results are obtained from test field calibration using self-calibrating bundle adjustment. They correspond to a relative accuracy of about 1:140.000 with respect to the largest object dimension.

## KURZFASSUNG:

Dieser Bericht faßt die wesentlichen Ergebnisse einer Vergleichsstudie zusammen, die die Leistungsfähigkeit verschiedener digitaler Punktmeßalgorithmen untersucht. Dazu wurden diverse synthetische und reale Bilder erzeugt, in denen verschiedene kreisförmige Punktmuster abgebildet sind. Dieses Testmaterial wurde an 20 wissenschaftliche und kommerzielle Institutionen in Deutschland, Österreich und der Schweiz verteilt, die die abgebildeten Punkte mit ihren eigenen Verfahren gemessen haben. Zum einen sollte in der Studie ein Vergleich verschiedener Punktmeßverfahren unter identischen Bedingungen durchgeführt werden. Zum anderen sollte die Grenze der Subpixel-Meßgenauigkeit evaluiert werden, die in verschiedenen Publikationen bereits auf wenige tausendstel Pixel definiert wurde. Der Vergleichstest stützt seine Ergebnisse sowohl auf eine 2D- (Bildraum) als auch eine 3D- (Objektraum) Analyse.
Folgende Algorithmen konnten untersucht werden: strukturierte kantenbasierte Ellipsenoperatoren, Schwerpunkt-Operatoren, Template-Matching-Verfahren und Kleinste-Quadrate-Verfahren.
Mit synthetischen Bildern werden Genauigkeiten von bis zu 1/100 Pixel erreicht (Ellipsenoperator). In den mit einer volldigitalen, hochauflösenden CCD-Kamera aufgenommenen realen Bildern werden Bildmeßgenauigkeiten von 2/100 Pixeln erreicht (Laborbedingungen). Diese Ergebnisse wurden im Rahmen einer Testfeldkalibrierung erreicht. Sie entsprechen einer Relativgenauigkeit von ca. 1:140.000, wenn die größte Objektausdehnung zugrunde gelegt wird.

## 1 OBJECTIVES

In recent years great progess in development and application of digital close-range systems can be recognized. These systems are mostly used in industrial application, especially in the fields of quality assurance, production process control and research and development. Most systems are using high-resolution digital cameras, artificial point targeting, precise digital image measuring algorithms and bundle adjustment techniques. Recent publications show that digital photogrammetric systems are meanwhile accepted in industry where they compete with classical measuring devices such as coordinate measurement machines (CMM) (Luhmann 1995).

In this environment it is essential not only to achieve high accuracies but, to have a proven kind of system and accuracy acceptance test procedure. In the world of CMM applications these tests have been developed and they are used permanently. In industrial photogrammetry there is not only a lack of such a common acceptance test, or but also a standard of common language in terms of accuracy and system performance.

In this context one objective is the investigation of sub-pixel accuracy of digital point measurement methods. Image acquisition and processing are fundamental steps in digital close-range photogrammetry that basically affect the resulting system accuracy. Object information lost in image space cannot be reconstructed afterwards.

In 1995 the author initiated a comparison test for the evaluation of different digital point measurement techniques. For this test a number of synthetic and real images with various point patterns were generated and submitted to different institutions. One goal of this test is to compare the suitability of different point operators under equal conditions. A second goal is to verify the current limits of sub-pixel point positioning which, by numerous authors, have been reported down to a few thousands of a pixel.

Up to now the comparison study reports of the results of the following point operators: structural edge-based ellipse operators, center-of-gravity operators, template matching operators and least-squares matching operators. After a first project stage it is planned to deliver the test material to a wider group of experts on an international basis. The test is strictly non-commercial and results shall be handled confidentially if required.

The investigation of the image test material is based on a 2-D (image space) and 3-D (object space) analysis. In 2-D analysis the measured image coordinates of point centers will be compared to their (assumed) nominal values given by a program for the generation of synthetic point patterns.

The 3-D investigation is based on a set of real test field images taken with a fully-digital CCD-camera. The test field was prepared with a number of retro-reflective targets which are widely used in practice. The accuracy analysis includes a comparison of RMS values of image coordinates as well as the RMS values of adjusted object coordinates given by a bundle adjustment with self-calibration.

The test does not cover an independent comparison with given object coordinates measured by a system of higher accuracy, e.g. a theodolite measuring device. This will be done at a later stage of the investigation.

## 2 PARTICIPANTS

Approx. 20 scientific and commercial institutions throughout Germany, Switzerland and Austria received the test material. Up to now (March 1996) a total of 10 participants have returned their results.

| | Submitted | Returned |
|---|---|---|
| Scientific institutes | 10 | 7 |
| System developers | 7 | 3 |
| Industrial users | 2 | 1 |
| Total | 20 | 11 |

All participants used their own implementation of different point operators. Some members of the test returned more than one result, for instance, if they wanted to compare different algorithms. Although all results have been handled confidentially and published without names and affiliations, the number of system developers in the test is rather poor.

## 3 IMAGE MATERIAL

### 3.1 Synthetic Images

In order to test the performance of point operators under controlled conditions a number of images with artificial targets have been created. These targets can be overlayed in any type of background image. Each pattern can be varied in terms of sub-pixel center coordinates, size, orientation angle, contrast and noise. In addition it is possible to simulate occlusions or other point disturbances.

The mathematical model of point generation is not claimed to be totally error-free. The program is able to calculate the greylevel function of circular targets based on the rigorous ellipse model and a bilinear greylevel interpolation. Figure 1 shows an example of a synthetic ellipse pattern compared with a patch from a real retro-reflective target (Broers & Hemken 1996). Slight differences occur at the edge of the point.

Using this program a set of five test images (500 x 500 Pixel, 8 bits per pixel ) has been created (Table 1, Figure 2). Each image contains a total of 25 targets with different properties.

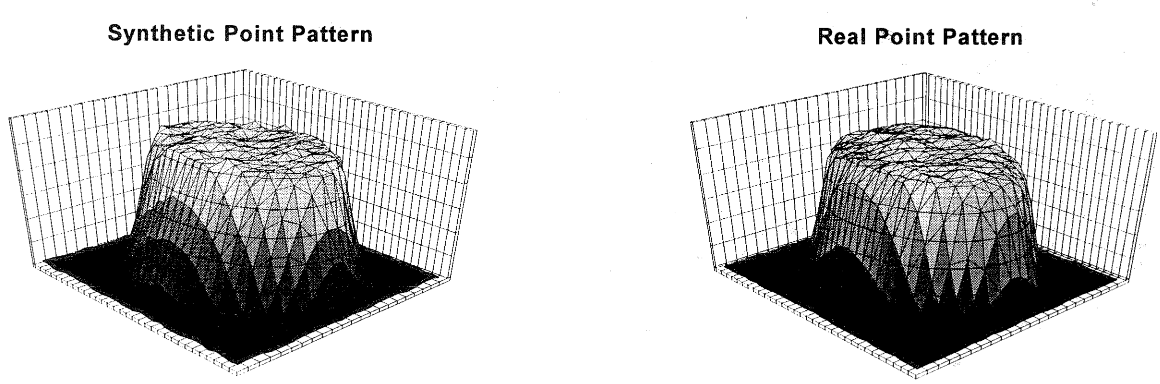


*Figure 1a: Synthetic and real point patterns*

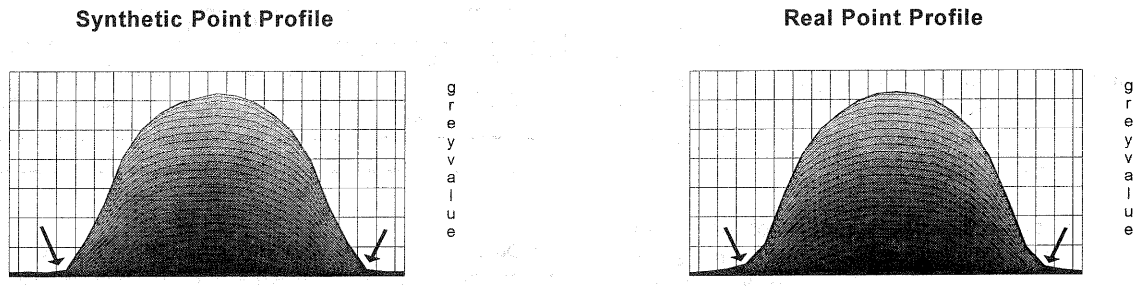


*Figure 1b: Synthetic and real point profiles*

While IMAGE1 to IMAGE3 show very realistic features, IMAGE4 and IMAGE5 demonstrate the effect of occlusions, point disturbances and varying backgrounds as they may occur only in very few practical cases.

| | VARIATIONS | | | | | | |
|---|---|---|---|---|---|---|---|
| IMAGE | position | size | shape | rotation | noise | backgr | occlusion |
| 1 | | + | + | + | | | |
| 2 | + | + | + | + | + | | |
| 3 | + | + | | + | | | |
| 4 | + | + | + | + | + | | + |
| 5 | + | + | + | + | + | + | + |

*Table 1: Description of synthetic images*

### 3.2 Testfield Images

In cooperation with Rollei Fototechnic, Germany, a set of 8 digital images showing a photogrammetric test field with approx. 45 object points has been taken. For this purpose a fully-digital high-resolution CCD camera Rollei 6008 / ChipPack has been used.

By default this testfield is used for standard camera calibrations in the factory. It is prepared with 55 retro-reflective targets on a plane black surface, and additional 3 points in spatial positions. The object has been imaged from eight different locations according to the standards of testfield calibration network design (Wester-Ebbinghaus 1986). This configuration allows for the complete determination of all parameters of interior orientation without knowledge of control points.

The ChipPack camera consists of a 2K x 2K CCD frame transfer imaging device. Image signals are digitized directly within the camera electronics in order to avoid analog video transfer and processing. The CCD sensor produces greylevels of 10 bit resolution which are later transformed to 8 bit (256 greylevels). Camera control and image transfer is performed by a SCSI interface. The camera is equipped with a ring flash device which gives a shadow-free illumination onto the retro-targets (Godding & Woytowicz 1995).

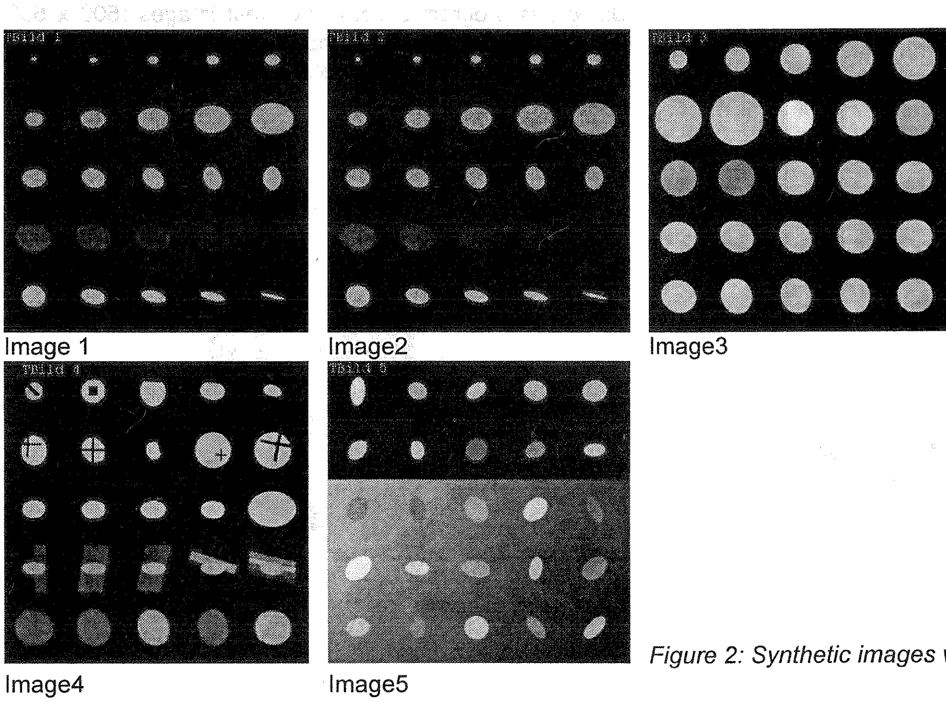


*Figure 2: Synthetic images with artificial test patterns*

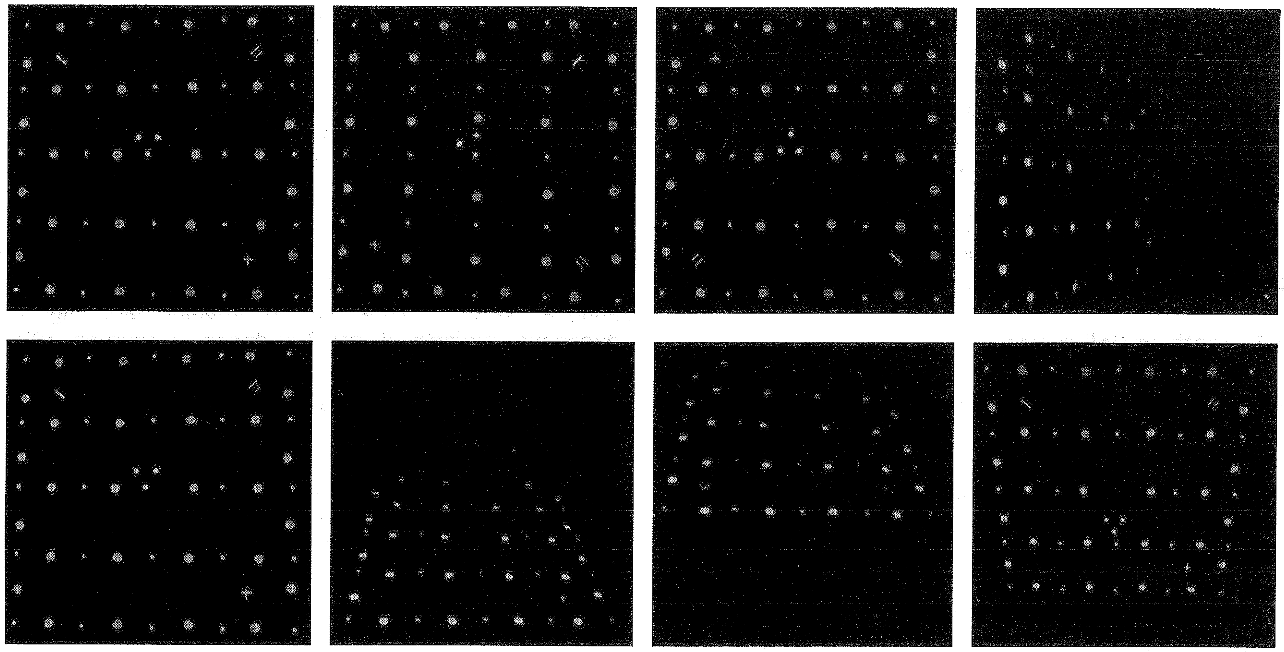

*Figure 3: Images for testfield calibration*

The technical description of the acquired images is as follows:

| | |
|---|---|
| Camera | Rollei 6008 / ChipPack |
| Imaging device | 2048 x 2048 pixels |
| Sensor elements | 15µm x 15µm |
| Image format | 30mm x 30mm |
| Lens | Distagon 40mm |
| Size of testfield | 80cm x 80cm |
| Mean image scale | 1:25 |

Figure 3 displays the set of 8 testfield images.

## 4 RESULTS

### 4.1 Synthetic Point Patterns

Theoretical investigations and practical experiments have shown that the position of a circular target can be determined with an maximum accuracy of 1/1000 pixel. Basically the resulting accuracy *d* depends on the size of the target *s* and the contrast *k* between target area and background. The precision has been determined emperically to

$$d = \frac{4}{s \cdot k} \tag{1}$$

This equation shows that accuracy improves with increasing size and/or contrast. The factor 4 results from differences between synthetic and real image data (Broers & Hemken 1996). Theoretical investigations by FÖRSTNER have shown similar results (Förstner 1984).

Figure 4 shows some of the results obtained by the test participants on the delivered imagery. In the case of IMAGE1 the best results have been achieved by method A, B and G (all ellipse operators). These methods show mean differences to the nominal values between 0.003 and 0.009 pixels. The results of center-of-gravity operators (F,I) and the line following approach (D) are between 0.015 and 0.03 pixels. Even better results (0.002 pixels) have been produced with IMAGE3 (ideal patterns).

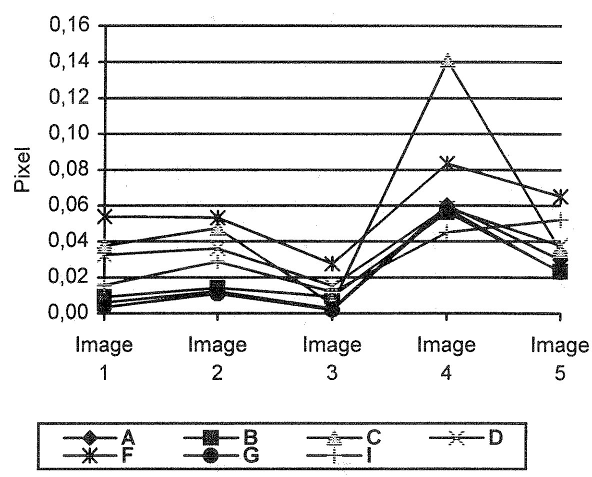


*Figure 4: Results on synthetic images*

IMAGE2 shows slightly worse results caused by noise added to the image greyvalues. Additive noise of 3 greylevels leads to reduced accuracy if ellipse edge operators have been applied.

IMAGE4 (additional occlusions) show equal results for the best operators in the range of 0.05 pixels. Although occlusions should be handled easier by structural approaches (i.e. ellipse methods) a higher number of points could not be measured.

In IMAGE5 a variation of the background greylevel has been simulated. This effect leads to a decreased accuracy by factor 2 compared with the results of IMAGE1.

As a conclusion of this part of the test one can state that the theoretical precision of 1/1000 pixel can be nearly reached for perfect, undisturbed targets (0.002 pixels). More realistic features can determined with an mean accuracy of about 0.02 to 0.005 pixels. In addition these results have proved the mathematical model used for the generation of artificial patterns.

### 4.2 Testfield Calibration

All test participants have delivered their measured image coordinates of the testfield images. These values have been used as observations in a free net bundle adjustment program with self-calibration facility (MOR). All testfield points have been used as datum points. The parameters of interior orientation include:

| | |
|---|---|
| principal distance (focal length): | $c$ |
| principal point: | $x'_0$, $y'_0$ |
| radial distortion: | $a_1$, $a_2$ |
| asymetric distortion: | $b_1$, $b_2$ |
| affinity and sheering: | $c_1$, $c_2$ |

In order to compare the image accuracy the RMS values of image coordinates have been evaluated. These values can be used as an estimation of point measurement accuracy.

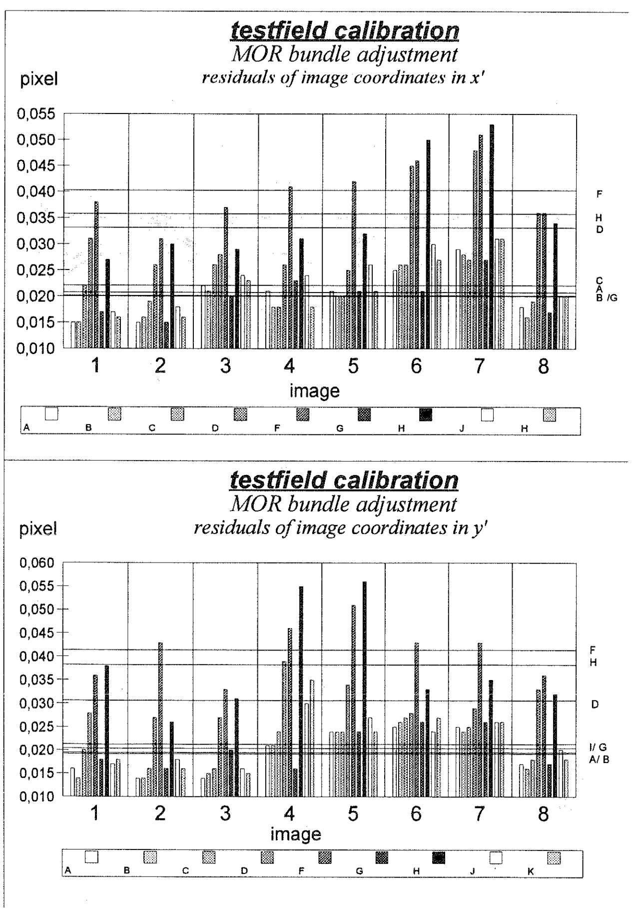


*Figure 5: Residuals of image coordinates*

Figure 5 shows the residuals of image coordinates in x- and y-direction as obtained by the test participants. Again the best results have been achieved with edge-based ellipse operators showing a mean accuracy in image space of about 0.02 pixels. It has also been confirmed that center-of-gravity operators lead to worse results (0.05 pixels).

The analysis of the RMS of image coordinates gives an indication of the potential of image accuracy for real images. Due to variations in imaging and lighting directions, artifacts of target surfaces (Zumbrunn 1995) and noise (by camera electronics) a lack of accuracy of factor 2 compared to synthetic images has to be expected. A closer look to the bundle adjustment results shows that the number of gross errors (which are automatically rejected) varies with the type of operator. Therefore the pure RMS value of image coordinates or the sigma 0 of least-squares adjustment should not be used in order to evaluate the accuracy of a complete system.

The adjusted 3-D coordinates have not been investigated in detail. Due to the free net adjustment process it is not possible to compare object coordinate values. An improved test procedure should therefore be performed with a testfield with precisely measured object coordinates or distances. They were not available at the time of the test period.

Figure 6 shows the standard deviation of object coordinates. In the best case the RMS of adjusted object points is estimated to ±8µm in object space. This compares to an image accuracy of about 0.02 pixel if the mean image scale of 1:25 is taken into account. With respect to the largest object diameter (1.1m) a relative accuracy of 1:140.000 has been obtained.

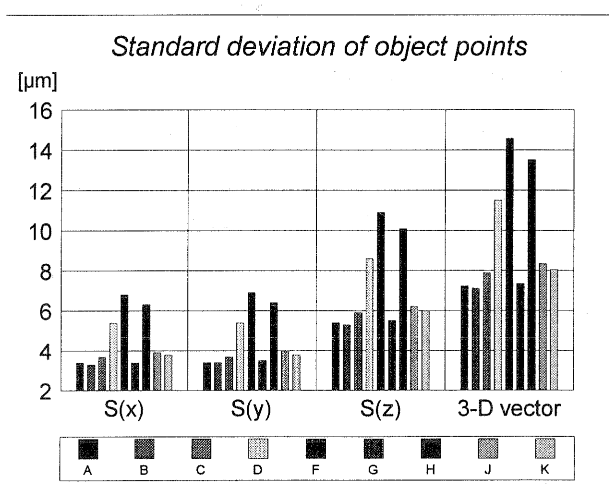


*Figure 6: Standard deviation of object points*

It must be pointed out that these results have been achieved under laboratory conditions and that they display mean accuracies. For practical applications the number of gross errors as well as the maximum residuals have to be considered.

## 5 SUMMARY

In the first run the presented test on digital point measurement accuracy was restricted to members of the Working Group *Industrial and Engineering Photogrammetry* of the *German Society for Photogrammery and Remote Sensing (DGPF)*. Although there were only 10 different results returned, the test has clearly shown that there is a significant need for users to investigate their measuring operators and systems. This test can therefore be regarded as one step to a standardized acceptance test for digital photogrammetric systems tha has already been required (Dold 1995, Wendt 1995). In order to move forward a joint working group of DGPF and VDI (German Association of Engineers) has meanwhile been established which will work out criteria and rules for the testing of photogrammetric systems (based on similar guidelines for CMMs).

The generated test images were almost suitable for the determination of sub-pixel accuracy. A second generation of test images should include very small points which are often used in practical applications.

Theoretical and practical investigations have demonstrated that the limit of sub-pixel resolution is about 1/100 of a pixel. In order to achieve even higher accuracies the number of processed bits per pixels must be increased to 10 or 12 which is already the performance of state-of-the-art CCD imagers.

This very high accuracy can only be obtained if perfectly shaped and imaged targets can be used and if the whole imaging process (illumination, optics, sensor, analog-to-digital conversion, data transfer) could be handled with equivalent precision. Noise, disturbed targets or changing backgrounds will decrease accuracy significantly.

The methods used in this test include: edge-based ellipse operators, center-of-gravity operators, template matching and least-squares matching. Ellipse operators seem to produce best results (1/100 pixel) but, due to the algorithm, are restricted to points larger than 4-5 pixels in diameter. Gross errors in point shape can be handled very well by ellipse operators and robust adjustment algorithms.

Adaptive center-of-gravity methods can operate on small targets and they offer short processing times. The achieved accuracy is slightly poorer than for ellipse operators (2/100-3/100 pixel). However, they can hardly recognize point disturbances nor background variations due to the non-structural approach of the method.

Least-squares matching is an acceptable tool for point measurement if suitable templates can be generated. Like center-of-gravity it cannot handle point artifacts unless they are combined with geometric constraints such as epipolar geometry. However, this is only possible if orientation values are available. Geometric accuracy seems to be limited to 2/100 of a pixel.

The testfield image series has shown that there is a decrease of accuracy of about factor 2-3 compared to ideal synthetic imagery. The images have been acquired under laboratory conditions with a brand-new Rollei digital camera where several control parameters still have to be optimized. The mean accuracy of 0.04 pixels confirms the potential of other modern digital cameras (Peipe 1995). Under practical environmental circumstances in industry it is likely that further accuracy decreases may occur.

The main goal of this test has been achieved successfully. The theoretical and practical limit of point measurement accuracy has been investigated. Image measuring accuracy can be interpreted as the probing uncertainty known from CMM technology. It is not a measure of object or system performance because additional criterias like object targeting, network design or processing time have to be taken into account.

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