

# AUTOMATED DIMENSIONAL INSPECTION WITH REAL-TIME PHOTOGRAMMETRY

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Commission V

## ABSTRACT

Real-Time Photogrammetry, in the sense of on-line Digital Close-Range Photogrammetry, has reached a high-level of performance. It has evolved from a research topic to a viable technology for a large number of applications. In order to gain acceptance by potential users the performance must be proven under practical conditions. This paper reports on a pilot study for the deformation analysis of car bodies in crash tests successfully performed in cooperation with a car manufacturer. The performance of a prototype Real-Time Photogrammetric System (RTPS) was verified under factory floor conditions. An accuracy of better than 1 mm in each coordinate axis was attained within a  $5 \times 2 \times 2 \text{ m}^3$  measurement volume with off-the-shelf CCTV-type solid-state cameras. The measurement task and the requirements of the pilot study are outlined. The measurement configuration, the hardware, and the software used in the test are addressed. The measurement procedure, pre-calibration of the CCD-cameras, the accuracy, the measurement speed, and problems encountered in the study are discussed.

**KEY WORDS:** Industrial, Real-Time, Machine Vision, Performance, Close-Range

## 1 INTRODUCTION

Significant advances in a number of areas have led to a vast increase in the performance of Real-Time Photogrammetric Systems (RTPS). The resolution, i.e. number of sensor elements, of CCTV-type (Closed Circuit Television) solid-state cameras has been improved, pixelsynchronous frame grabbers are widely available, and the storage and processing capabilities of computers have made dramatic progress. Advances in the radiometric and geometric characterization and calibration of CCD-cameras made it possible to attain very high accuracies (Gustafson, 1991; Shortis et al. 1991, Beyer, 1992). A number of systems with high accuracies and a significant level of flexibility have been developed for various applications and are either in a prototype stage or even installed on the factory floor (e.g. El-Hakim, 1986; Schneider and Sinnreich, 1990; Bruhn, 1991; Haggren, 1991).

The analysis of deformations incurred by vehicles due to impact in crash tests is typical for a number of measurement tasks. It requires the determination of the object space coordinates of 50 to 400 signalized points both before and after the crash. Depending on the measurement method between 1 and 3 days are needed currently for each of the two measurement phases. A RTPS allows to improve the measurement speed and thus reduce costs. It can measure the object coordinates of a much larger number of points as well as of non-signalized but identifiable features. A pilot study was performed in cooperation between Volkswagen AG and the Institute of Geodesy and Photogrammetry to verify the performance of a RTPS system for this task.

## 2 PROBLEM

The pilot study required the determination of the object coordinates of 73 targeted points on a station wagon (Volkswagen Passat). Only low-cost CCTV-type CCD-cameras were to be used. An accuracy of 1 mm had to be attained within a measurement volume spanning  $5 \times 2 \times 2 \text{ m}^3$ . The object coordinates of 44 points were measured by Volkswagen AG with an industrial theodolite system for a verification of the accuracy.

Figure 1 shows the measurement configuration. The car was placed on a turntable and rotated around the Z-axis by  $30^\circ$  increments. Images were acquired from all sides with 3 cameras in fixed positions. The targets on the car were located on the exterior, the motor block, and the door area (58 targets) and in the interior of the car (15 targets). Cameras 1 and 2 were placed such that targets on the exterior and most targets in the interior of the car could be imaged. Due to the distribution of targets on the vehicle only three images acquired in the  $30^\circ$  rotational positions with camera 3 were used. Another 4 images were acquired with that camera at positions providing better views of the interior.

The points were marked with retroreflective targets having diameters of 20 and 30 mm (60 and 13 targets respectively) with a small dot in the middle. The targets were suitable for both the theodolite measurement system and the CCD-cameras. Three SONY-XC77CE cameras equipped with 9 mm Fujinon lenses and illuminations for the retroreflective targets were used. The imagery of these cameras was pixel-synchronously acquired via a multiplexer by a MAX-SCAN frame grabber (Datacube).

The image format was set to 726 x 568 pixel with a pixel spacing of 11 x 11  $\mu\text{m}$ .

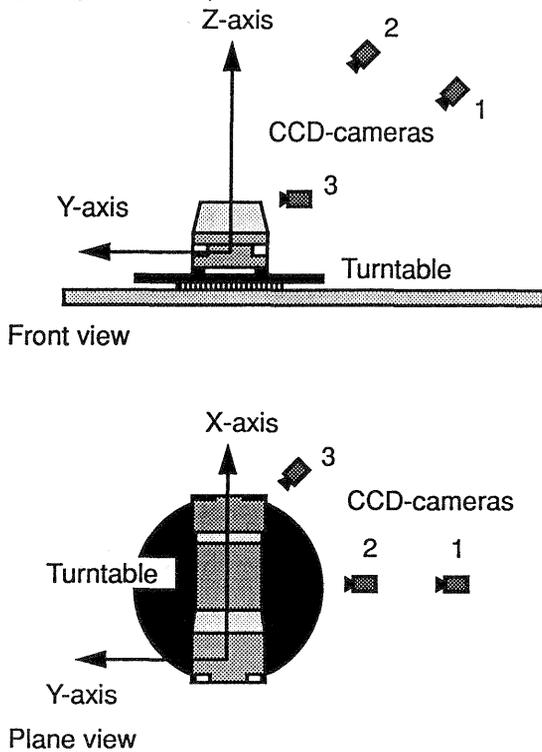


Figure 1 Measurement configuration of pilot test.

### 3 PRE-CALIBRATION

Precise values for the elements of the interior orientation, the parameters of the pixel-to-image coordinate transformation, and the additional parameters were determined before the test via a system calibration using a three-dimensional testfield. The accuracy requirements of the test correspond to approximately  $1/10^{\text{th}}$  of the pixel spacing. The calibration of the cameras was thus not designed for utmost accuracy but to fulfil the requirements.

Four cameras were calibrated with their lenses focused at infinity. Initial values for the interior orientation and the parameters of the pixel-to-image coordinate transformation were derived from the data sheets of camera and frame grabber. These values were improved via the following additional parameters:

- location of the principal point in x and y
- camera constant
- scale factor in x
- first two parameters for radial symmetric distortion

The pixel-to-image coordinate transformation is defined as (Beyer, 1992):

$$x = (x' - x'_p) \times \text{psx} \quad (1)$$

$$y = (y'_p - y') \times \text{psy} \quad (2)$$

with:

- x, y .....image coordinates
- x', y' .....pixel coordinates
- x'\_p, y'\_p .....location of principal point in pixel
- psx, psy .....pixel spacing in x and y

A testfield spanning  $4.2 \times 2.0 \times 1.1 \text{ m}^3$  with 186 targets was used (see Figure 2). Latter were black circles with a diameter of 20 mm on white background. Images were acquired with 0 and 90 degree roll at each of a 6 station network. The image coordinates were measured with Least Squares Matching (LSM, Gruen, 1985). The image scale varies from 1:460 to 1:760. The targets are thus imaged onto 2.4 to 4.0 pixel in diameter. The inner precision for these targets is 0.02 to better than 0.01 pixel. The ideal diameter of these targets in the imagery was determined to be at least 6 pixels (Beyer, 1992).

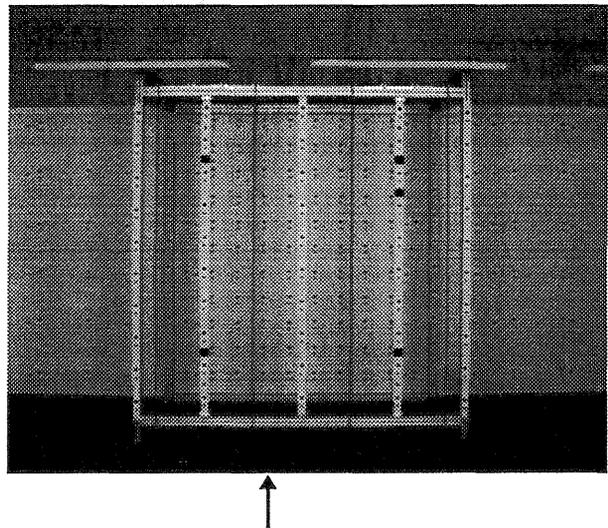


Figure 2 Testfield used in pre-calibration of CCD-cameras.

The pre-calibration was performed with separate bundle adjustments for each of the four cameras. Thirty control and 124 check points on the wall of the testfield (the front structure was displaced shortly before the test and no reference coordinates were available) were used. The accuracy in image space is between  $1/10^{\text{th}}$  and  $1/20^{\text{th}}$  of the pixel spacing. In a re-evaluation of the imagery all image coordinates were re-measured and the data was introduced into one combined bundle adjustment. The geometry is very strong with every object point imaged in 9 to 48 images with 33.5 images on average. The accuracy in object space is (after a spatial similarity transformation) 0.22, 0.10 and 0.56 mm in X, Y and Z respectively (X and Y within the plane of the wall, Z towards the cameras). The accuracy in image space corresponds to  $1/30^{\text{th}}$  of the pixel spacing. The accuracy is severely degraded by local illumination gradients across the targets due to shadows. Figure 4 shows a plot of the differences to reference coordinates for the points on the wall of the testfield. The horizontal displacement for points in a number of columns is apparent. Figure 2 b shows a part

of an image with a grayvalue profile indicating the (horizontal) illumination gradient across the area of the targets in a column. These were created by the vertical rods of the testfield and three 1.5 m long horizontally placed fluorescent lights. The arrows in Figures 2, 3 and 4 indicate one column with displacements. Local illumination gradients were found to be an important limiting factor even after much greater efforts have been undertaken to generate a uniform illumination. These tests have also shown that an accuracy of at least  $1/50^{\text{th}}$  of the pixel spacing can be attained with high redundancy and more extensive modelling of systematic errors (Beyer, 1992).

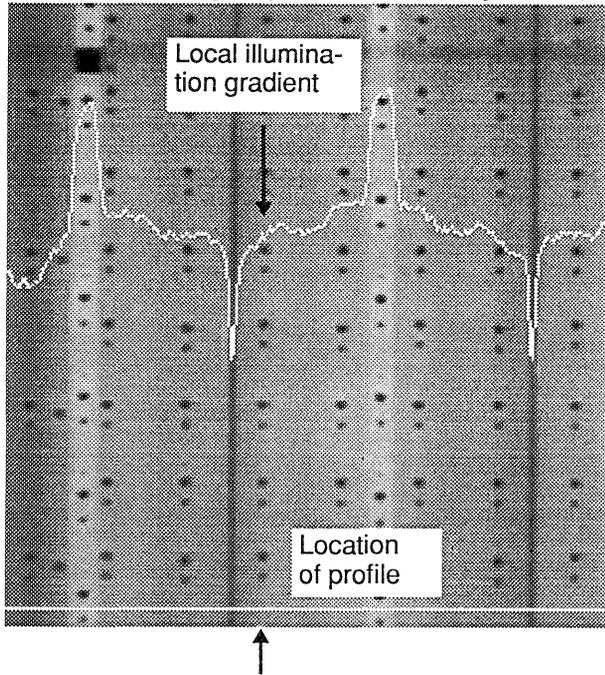
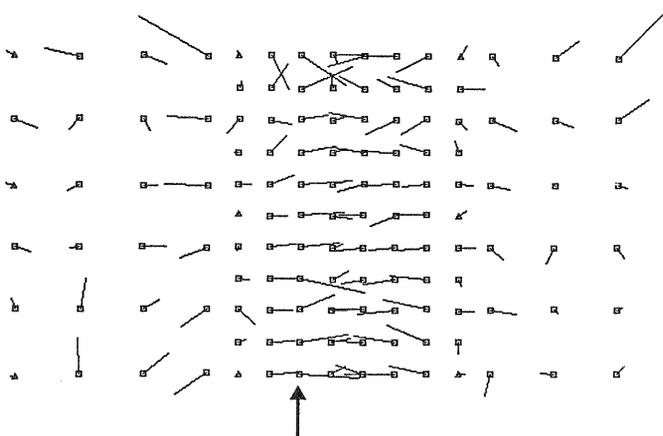


Figure 3 Subpart of testfield with local illumination gradients due to shadows.

Scale for Points ——— 800.000 [mm]  
 Scale for Vectors — 100.000 [micron]



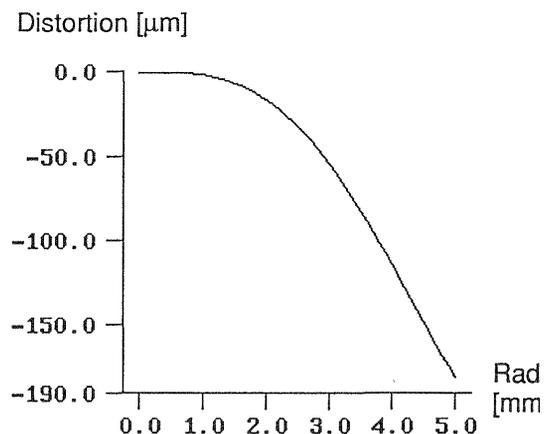
a) Differences to reference coordinates showing systematic displacements due to shadows.

Typical CCTV-type lenses with short focal length exhibit large radial symmetric distortions. The large distortion of the 9 mm lens is apparent as a bending of the testfield structure in Figure 2. The distortion profile (first two parameters of radial symmetric distortion) for one lens used in the pilot study is shown in Figure 4. It reaches  $182 \mu\text{m}$  at the corner of the 6 by 8 mm image format, corresponding to a displacement of 16 pixel.

#### 4 MEASUREMENT OF CAR

The image coordinates of all targeted points were determined with a semi-automated procedure. First some targets (typically 4 to 6) were identified manually in each image and the exterior orientation was computed. Targets without approximate object coordinates were measured interactively in two images to derive object coordinates. Thereafter targets with object coordinates (approximations) were projected into the image and their coordinates were measured automatically. A correct identification of the targets in the interior of the car was very difficult as the structure of the car was not discernible due to the dark imagery. The measurement of the targets in the interior was thus only performed after the targets on the exterior of the car were measured.

The precise determination of the image coordinates was performed by Least Squares Matching. Targets covering only a few to over 12 pixel in diameter (inflection points of grayvalue profile) were successfully measured. The measurement speed for a 7 by 7 template is approximately 8 points per second on a SPARCstation 1 (SUN Microsystems). This could be vastly improved by eliminating overhead for research purposes (e.g. zooming and display of the patch in each iteration and writing a huge output file). The measurement speed is nevertheless



b) Distortion profile of a 9 mm lens.

Figure 4 Differences to reference coordinates and distortion profile.

sufficient as only 96 seconds are required to measure the image coordinates of the 770 image points on that workstation.

Reference coordinates as well as the stability of the car during the rotations of the turning table were determined by Volkswagen AG with an industrial theodolite measurement system. Reference coordinates were determined for 44 of the 73 targeted points. The stability of the car body was assessed by measuring the coordinates of 8 points in another rotational position of the turntable. The RMS discrepancy of the two data sets was found to be 0.3 mm (after a spatial similarity transformation). The stability of the car can thus be considered acceptable with respect to the accuracy requirements of this pilot study, but will place a limit for attaining higher accuracies.

the pre-calibration were used for the pixel-to-image coordinate transformation, the interior orientation elements, and the additional parameters (the first and second parameter of radial symmetric distortion were used as constraints). Furthermore all images of the third camera were eliminated. Only 3 points in the interior could not be determined as they were only imaged once by cameras 1 and 2. The results show that a significant improvement was attained. The accuracy specifications are now easily attained and the accuracy in image space is better than 1/10<sup>th</sup> of the pixel spacing. When performing a spatial similarity transformation onto the reference points and accuracy of 0.42, 0.30 and 0.76 mm is attained in X, Y and Z respectively. The corresponding accuracy in image space is 1/20<sup>th</sup> of the pixel spacing (0.52 and 0.57  $\mu\text{m}$  in x and y respectively). The RMS misclosures

Version	AP	Co	Ch	r	$\hat{\sigma}_0$	$\hat{\sigma}_X$ [mm]	$\hat{\sigma}_Y$ [mm]	$\hat{\sigma}_Z$ [mm]	$\mu_X$ [mm]	$\mu_Y$ [mm]	$\mu_Z$ [mm]	$\mu_x$ [ $\mu\text{m}$ ]	$\mu_y$ [ $\mu\text{m}$ ]
1	0	8	36	1144	4.28	1.60	1.48	1.94	5.51	4.19	11.10	10.3	19.1
2	18	8	36	1144	1.01	0.38	0.35	0.46	0.64	0.53	1.12	1.1	1.8
<i>Improvement factor 1 / 2</i>					4.2	4.2	4.2	4.2	8.3	7.9	9.6	9.4	10.6
3	12	8	36	807	0.64	0.30	0.25	0.36	0.58	0.44	0.90	0.87	0.93
<i>Improvement factor 2 / 3</i>					1.6	1.3	1.4	1.3	1.1	1.2	1.2	1.3	1.9

Table 1 Results of bundle adjustment and accuracy verification.

- AP.....Number of additional parameters
- Co.....Number of control points
- Ch.....Number of check points
- r.....Redundancy
- $\hat{\sigma}_0$ ..... Variance of unit weight a posteriori
- $\hat{\sigma}_X, \hat{\sigma}_Y, \hat{\sigma}_Z$ .....Theoretical precision of check point coordinates
- $\mu_X, \mu_Y, \mu_Z$ .....Root Mean Square Error of check point coordinates in object space
- $\mu_x, \mu_y$ .....Root Mean Square Error of check point coordinates in image space

Table 1 gives the results of some versions of the bundle adjustment and the comparison to the reference coordinates. All versions were calculated with 8 control points leaving 36 check points for the verification of the accuracy. No additional parameters were used in version 1. The results show that the accuracy requirements cannot be met without appropriate modelling of systematic errors. The accuracy in image space corresponds to less than a pixel. Version 2 was computed with the values for the additional parameters from the first testfield calibration. The empirical accuracy measures show that the specifications were met. The accuracy in image space corresponds to 1/10<sup>th</sup> of the pixel spacing.

Version 3 was computed after the pilot test. The image coordinates were re-measured with an improved version of the algorithm (detection and elimination of oscillations, Beyer, 1992). The values of the re-evaluation of

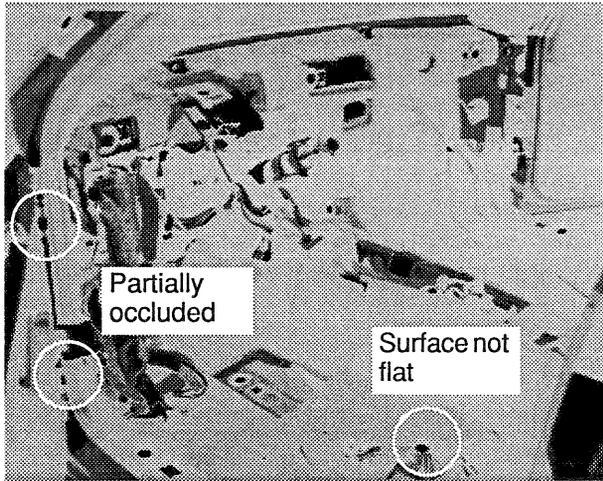
from the bundle adjustment of version 3 are 0.69 and 0.48  $\mu\text{m}$  in x and y respectively. This indicates that a significantly higher level of accuracy is attainable when an improved network configuration and algorithms can be used.

The discrepancy between the theoretical precision measures and the accuracy estimates of all versions is attributable to a number of problems and limitations, some of which are discussed in the following.

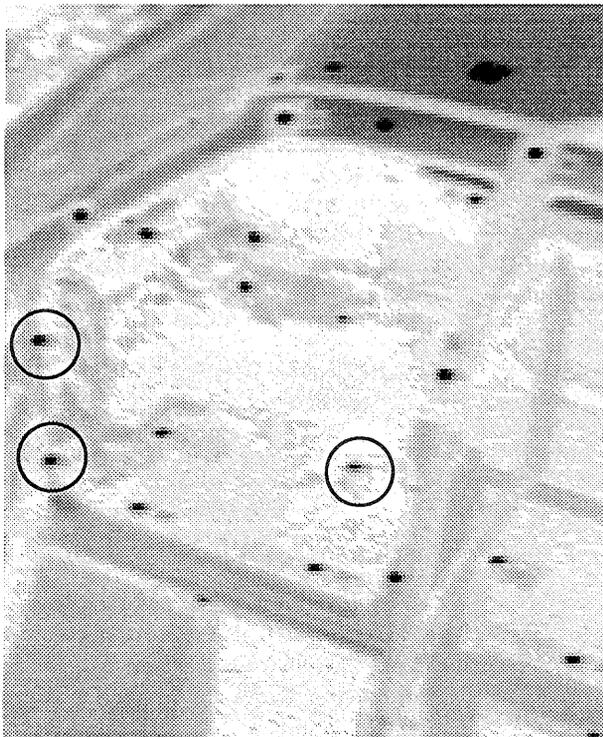
The geometry of the network was not optimal as it had to be adapted to hardware and space constraints. The connection between the targets on the exterior and interior proved geometrically weak as there was an insufficient number and poor distribution of targets around the doors. The distribution of the targets on the vehicle led to a poor use of the image format for a number of frames.

The network was designed such that all object points should be imaged at least in 6 frames. This was aimed at to assure both the required accuracy and a high degree of redundancy. This was nevertheless not attained in the pilot study. The differing surface orientations of targets resulted often in too oblique illumination and imaging conditions. A number of targets was thus imaged in 2 to 4 frames. Investigations showed that the reliability of these targets was poor and that comparably larger discrepancies to the reference coordinates occurred at them. This factor can be improved for points on the outside of the car but is hardly to be enhanced for targets inside the car which can often only be seen from a few positions due to occlusions.

Numerous targets were poorly imaged due to a number of reasons. The lighting was not properly adjusted, leading to slight blooming. This is evidenced by the slight horizontal extension to the right for the targets shown in Figure 4 b. Figure 4 shows two views of the door and the



a) Digitised 24 x 36 mm slide.



b) Part of inverted frame of camera 1

Figure 5 Images indicating some imaging problems.

interior of the car. The image in Figure 4a was digitized from a slide print taken with a 24 x 26 mm film camera. The one in Figure 4b was grabbed from camera 1. Both were inverted for visualization purposes. Although the two images are taken from slightly different positions they show similar areas. Comparing the two images one can see for example that the targets in the door area are actually partially occluded (see the left circled targets). This cannot be detected due to the small number of pix-

els on which they are imaged. Furthermore some targets are not on flat surfaces, which cannot be detected as well. Complete flatness of the targets will hardly be attainable in such an application as deformations of the targets during impact cannot be circumvented. These problems could be alleviated to some degree with "high-resolution" cameras, i.e. cameras delivering over 1024 x 1024 pixel, as occlusions might be detectable.

The known difficulties indicate that the accuracy and reliability can be improved. The measurement speed with the semi-automated procedure is already quite fast. The complete pilot test was conducted within 3 days. This included the set up of the test arrangement and the measurement of reference coordinates. This clearly shows that the integrated software package DEDIP is very powerful and flexible.

## 5 CONCLUSIONS

It was shown that the accuracy attainable with low-cost CCTV-type CCD-cameras is sufficient for many industrial and other applications. The limited "resolution" of the cameras requires relative large targets on one hand, but a much larger number of images can be acquired and processed. This provides for a large enhancement of the reliability. Precise target location methods and positioning algorithms with suitable calibration techniques are a prerequisite for meeting the accuracy requirements. Fully integrated software allows to meet the time critical processing demands.

The test has thus clearly shown that Real-Time Photogrammetry is able to meet a number of requirements for industrial and other measurement tasks. Important considerations to be addressed in future are the automation of the measurement process including the verification of the stability of calibration values and/or the exterior orientation elements.

## 6. ACKNOWLEDGMENTS

The author would like to thank all members of the department "Konzernforschung - Vermessungstechnik" of Volkswagen AG for their fine cooperation and support in the pilot test. Acknowledgments are also extended to staff of the Institute of Geodesy and Photogrammetry for the realization of special camera and lighting fixtures required for the project.

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