COMPARISON AND VERIFICATION OF OPTICAL 3-D SURFACE MEASUREMENT SYSTEMS

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ABSTRACT:

The following paper is a summary and comparison of different optical measuring systems for free-form surface measurement according to their achieved accuracy. The investigation includes three fringe projection systems, two stereo image-based matching methods and one object-based multi-image matching method. The accuracy is assessed by use of a 3D surface reference body consisting of a double sine curved surface. The reference body has been calibrated by a coordinate measuring machine whereby the measured 3D points are used to calculate a NURB splines surface model. The resulting CAD model is used as a reference for the optical measurements. The surface has Lambertian reflectance properties, thus fringe projection systems can be used without object preparation. For photogrammetric matching the reference body is pasted by a very thin texture foil.

1. INTRODUCTION

The 3D measurement of nearly arbitrary free form surface can be carried out by different optical methods. In most cases fringe projection based systems are used that rely on stationary sensor positions and object scenes during the scanning process. Although these systems become faster over the last years, e.g. Höfling (2008) reports on the recently fasted fringe projection systems with up to 50 complete measurements per second, very fast deformations or moving objects are usually not measured with fringes.

Our research focuses on very fast dynamic processes as they occur in car safety testing where area-based object deformations shall be measured in frame rates of 1000 Hz or even more. Therefore photogrammetric matching procedures are further developed to be used for the sequential processing of high-speed cameras image sequences. The software system PISA enables image matching in image sequences based on correlation and enhanced least squares matching (LSM).

Accuracy is one of the most important criteria for performance evaluation of a measuring system. This paper discusses possibilities of accuracy comparisons by means of a calibrated 3D reference body. Our investigations include fringe projection systems and photogrammetric matching methods as well. The achieved results are analysed and compared to each other.

2. CALIBRATED SURFACE REFERENCE OBJECT

For the comparison and verification of the accuracy of optical 3D measurement systems a calibrated surface reference object is used. The reference body is made of the industrial plastic material Ureol and has been milled by a CNC machine. The reference object provides a free form surface in form of a double sine curve of 400 mm x 400 mm x 100 mm that is surrounded by a plane plateau of 50 mm width. Altogether the reference has a size of 500 mm x 500 mm x 200 mm. The plane plateau consists of four drilled reference holes which are located in the corners, eight Hubbs targets (four spherical targets and four cylindrical targets) and twelve flat retro-reflective control points (Figure 1).

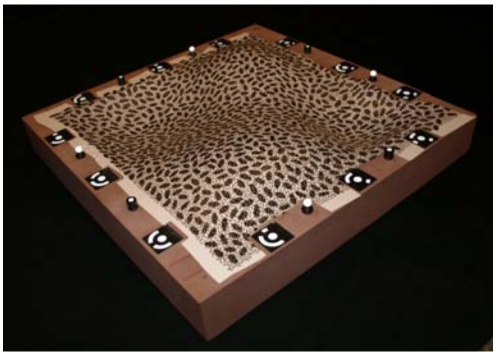

Figure 1. Reference object with texture

The reference data about the surface geometry and coordinates of holes and spherical control targets have been measured by a precision Leitz PMM 12106 coordinate measurement machine (CMM). According to VDI/VDE 2617 (ISO 10360) the accuracy of the CMM is specified to

$$0.8[\mu m] + l[\mu m] / 400[mm] \qquad (1)$$

Based on eq. 1 the reference body is measured with a theoretical accuracy of about 2 µm. In order to be realistic we expect an accuracy of less than 10 µm for the CMM data. The

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reference coordinate system is defined by minimum datum definition using the 3-2-1 method by two sides and the plane plateau.

The subsequent accuracy assessment of measured point clouds is based on reverse engineering using NURBS (Farin, 1995).

The retro-reflective points have been measured by photogrammetry (AICON 3D Studio) and transformed in the reference coordinate system using the four spherical control targets as reference points.

The reference body surface of brown colour without any texture, and provides diffuse reflection characteristics. It can be measured by fringe projection systems without any preparation. Image matching methods can only be used if an artificial is either projected or pasted onto the surface. In this case a thin and flexible foil is used. The foil can be printed with arbitrary patterns that provide appropriate texture for the specific task.

3. COMPARISON OF OPTICAL 3-D SURFACE MEASUREMENT SYSTEMS

In the following different optical 3D systems for free form surfaces measurement are analysed according to their accuracy with respect to the reference object. Accuracy evaluation is based on the differences between the measured point cloud and the reference data from the CMM measurement. In each case the measured point cloud is transformed by a best-fit adjustment onto the reference surface in order to avoid systematic errors that may caused by orientation problems. After eliminating outliers the root mean square error of all deviation vectors is calculated as a global accuracy estimate of surface measurement.

3.1 Test environment

For stereo image acquisition two Weinberger SpeedCam MiniVis high-speed cameras are used. The cameras provide 1280 x 1024 pixels of 12 µm each. They are equipped with a 12.5mm lens by Pentax. The frame rate reaches 500 Hz in full resolution, or higher rates with smaller image sizes. The cameras can be synchronised by an external trigger signal. Two 500 W studio light sources are used to provide enough light for the extreme short exposure times.

For image matching the surface texture should consist of a random pattern with high contrasts and high spatial resolution. We are using a random pattern of ellipses that provide both high image contrasts and gradients in all directions (Luhmann et al., 2006b). The texture results from two superimposed patterns with different sized ellipses in various grey levels. Hence the texture is suitable for multi-scale processing in image pyramids.

For the experimental set-up the imaging configuration is designed such that an appropriate base-to-height ratio is achieved. The object is observed in a distance of about 700 mm under a stereo base of about 600 mm. The convergence between both cameras results to about 10° (Figure 2).

The expected accuracy can be estimated by error propagation of the equations for spatial intersection. As a result, an accuracy of 0.05 mm can be expected in X and Y while in Z the accuracy is estimated to about 0.15 mm based on 1/10 pixel image measuring accuracy.

The images are acquired with full camera resolution of 1280 x 1024 pixels. The pixel size in object space is about 0.7 mm x 0.7 mm according to an imaging scale number of m = 56.

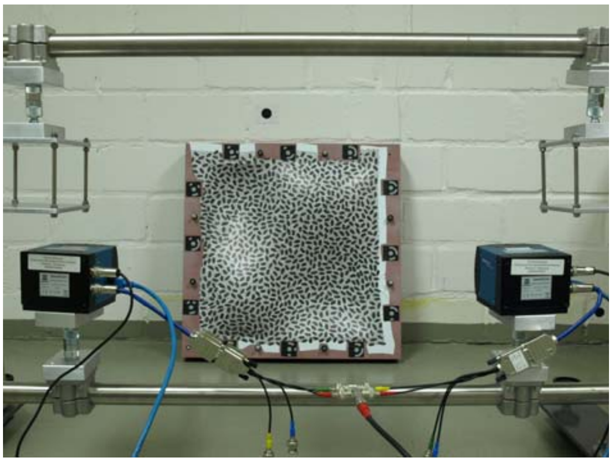

Figure 2. Experimental setup

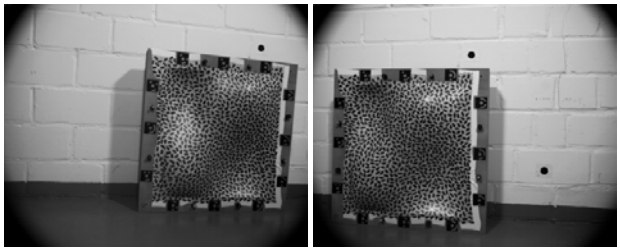

Figure 3. Stereo image pair

3.2 Image matching

3.2.1 Stereo image matching: We are investigating two systems based on area-based matching, i.e. normalised cross-correlation and LSM. Introductions to matching methods are given, as examples, by Gruen (1985) or in textbooks like Luhmann et al. (2006a).

System A is designed for aerial imagery. The software for DTM generation uses cross-correlation in epipolar lines. The two images of a stereo pair are resampled into normal images in order to speed up calculation times. The similarity measure between left and right image (reference and search image) does not compensate for affine or perspective distortions. The following investigations use a grid spacing of 3 mm in X and Y, a correlation window of 21 x 21 pixels and a correlation threshold of 0.4.

A comparison to the reference model yields a standard deviation of 0.593 mm. A number of outliers can be observed especially at the borders of the model where larger depth changes exist. In addition larger deviations of up to +1.5 mm occur in the valley areas of the sine model (Figure 4).

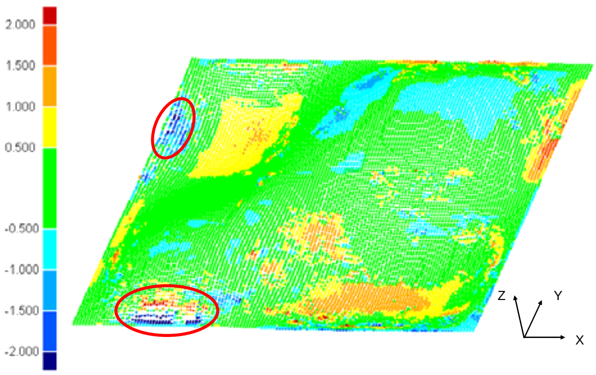

Figure 4. Stereo image matching – System A

System B is called PISA (Photogrammetric Image Sequence Analysis) and was developed at the IAPG Oldenburg for dynamic photogrammetric deformation analysis. PISA allows for image matching in stereo images sequences (Godding et al., 2006). Again images are resampled into normal stereo images in order to include epipolar constraints and to reduce computation times. In addition to cross-correlation an advanced least-squares matching algorithm has been implemented. Optionally the usual affine transformation in LSM can be replaced by a plane projective transformation with 8 parameters. The enhancement to projective transformation provides a better matching between patches with larger perspective distortions as they often appear in very steep surface areas, or when large convergence angles between cameras exist (example in section 4.1). Since the reference object is quite smooth the standard parameters (6 geometric and 2 radiometric) are applied. The size of the reference patch is defined to 21 x 21 pixels.

The surface measurement of the reference body is again performed with a grid spacing of 3 mm in X and Y. Initial values for LSM are derived from the previous cross-correlation process with a correlation threshold of 0.2. Figure 5 shows the result of a matched point cloud.

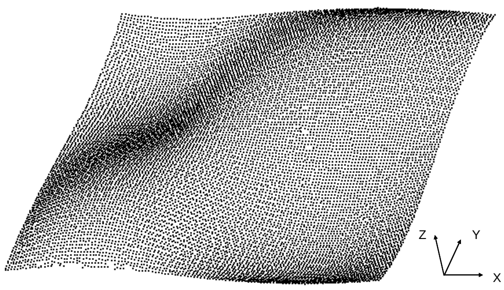

Figure 5. Point cloud of reference body measured by LSM (System B1)

A comparison with the nominal values of the reference object yields to a standard deviation of 0.080 mm with maximum deviations in the order of 0.9 mm (Table 1). Figure 6 shows the difference model between measured point cloud and reference data. It looks quite homogeneous with very little mismatches. Isolated outliers are eliminated by median filtering.

The histogram of deviations in Figure 7 indicates that about 86% of all points lie within an interval of ±0.1 mm. We can assume that the accuracy potential with this method of about 0.12 pixels can be reached for realistic cases.

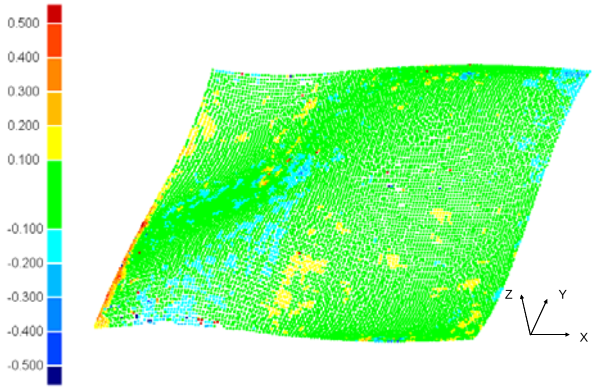

Figure 6. Stereo image matching – System B1

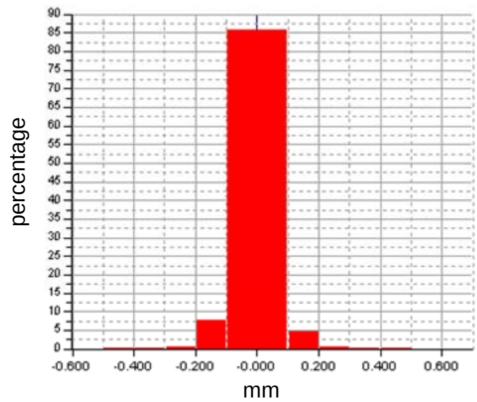

Figure 7. Histogram of point deviations (System B1)

If the grid spacing is reduced to 1 mm the accuracy can be enhanced to 0.076 mm (Table 1). The higher point density yields to a reduction of bad matches as they may occur from poor initial values.

A measurement with projective LSM (Table 1, system C) yields slightly worse standard deviations for both point densities (1 mm und 3 mm) compared to affine LSM. In specific areas the number of outliers is higher for projective LSM. We assume that the functional model is overdetermined with surfaces that are almost flat. Additional investigations will be carried out for this topic.

Compared to system A (cross-correlation), LSM with 6 geometric parameters increases accuracy by a factor of about 7.

3.2.2 Object-based multi-image matching

The following matching system uses an object-based multi-image matching approach as proposed by Wrobel (1987) and Weisensee (1992) under the synonym FAST vision (facet stereo vision). Using more than two images allows for higher redundancy and better handling of surface artefacts. The matching process is based on back-projection of object points into the images and iterative minimisation of grey value differences. A geometric surface model and a radiometric model of reflectance properties are calculated simultaneously by least squares adjustment (Schlüter and Wrobel, 1998).

The approach works successful with good approximate values of the surface geometry. Therefore the results from LSM have been introduced as initial values into the FASTvision system. However, the calculated point cloud shows a number of outliers, namely in areas of steep slopes (as depicted in Figure 8). The comparison to the reference data yields a standard deviation of 0.773 mm with maximum deviations of ±5 mm (Table 1).

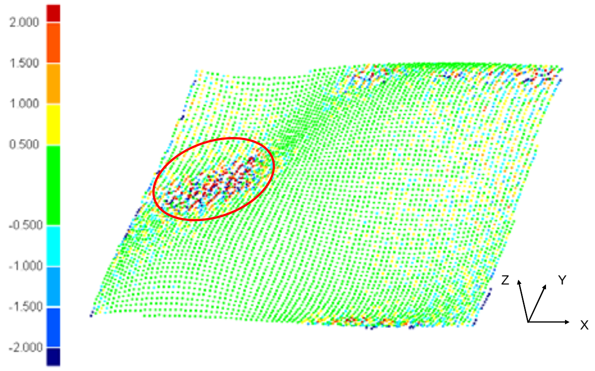

Figure 8. Object-based multi image matching – System D

3.3 Fringe projection based on phase measurements

Fringe projections systems are widely used for the measurement of free-form surfaces. Based on triangulation the fringe pattern of a projector is imaged by at least one camera. The phase difference of fringe wave patterns yields the height information for every pixel of the camera (Luhmann et al., 2006a).

Three different fringe projection systems have been tested. One of the systems is based on a two camera setup (system F) and the others on a one camera setup (systems E and G). At the current stage of the investigation these systems are described anonymously. For the measurements each system has been set up optimally for the desired measuring task, namely the reference object. Since a measuring accuracy of less than 1/10 mm shall be achieved with all products, system G has to observe the surface in four independent patches, thus yielding a high density of points. It is not documented whether the systems apply filtering of the point cloud. Numbers of outliers and maximum errors can not be compared directly since no raw data is available.

The measurement results of all three fringe projection systems are summarised in Table 1. They report standard deviations between 0.055 mm and 0.085 mm with maximum deviations of about 0.3 mm. However, when analysing the spatial distribution of deviations it becomes obvious that systematic errors are present. For every system local areas can be identified where either positive or negative deviations with respect to nominal surface can be observed. In addition, it is not clear to which extend point filtering is applied in the software. Hence, some results look quite smooth while systematic behaviour is still visible.

Figure 9Figure 9 and Figure 10 show results where larger deviations exist for areas of steep slope or local minima/maxima. In Figure 11 the above mentioned measurements in four quarters is clearly visible by systematic errors of point cloud registration (arrow symbols). In general all fringe projection systems have confirmed the level of accuracy that can be expected with that technology. With respect to object size a relative accuracy of about 1:5,000 to 1:10,000 seems to be realistic.

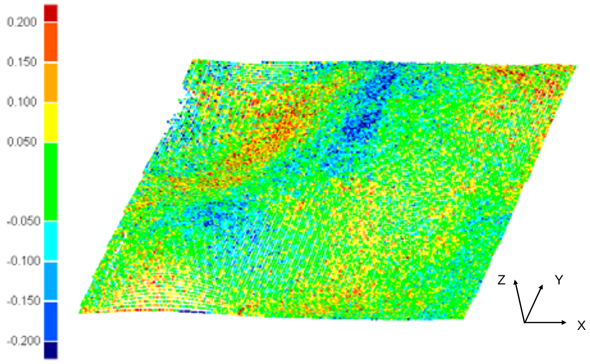

Figure 9. Fringe projection – System E

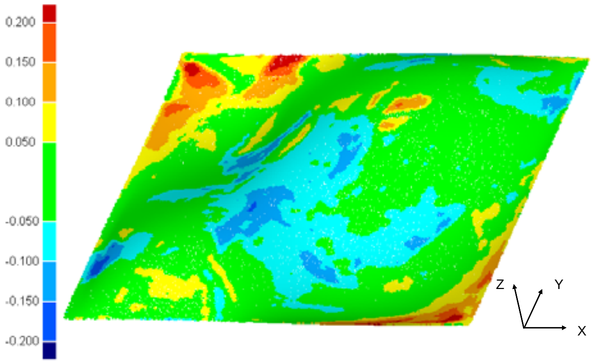

Figure 10. Fringe projection – System F

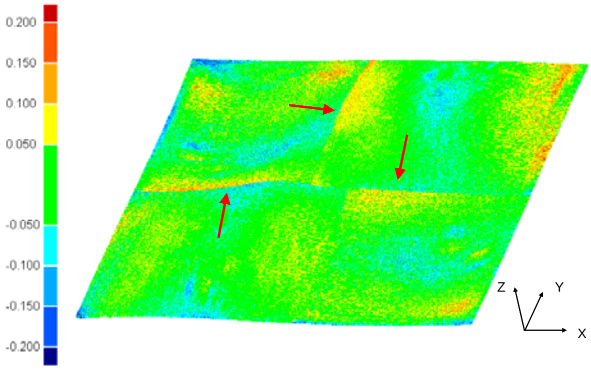

Figure 11. Fringe projection – System G

3.4 Multi-camera grid measurement

A multi-camera grid measuring system is also used for testing (system H). The system consists of 4 – 12 digital video cameras and a slide projector. The slide consists of a grid that is projected onto the surface (Figure 12). In object space the grid points have a spacing of about 7 mm – 9 mm. The grid points are detected automatically and calculated to object coordinates by space intersection.

The point cloud illustrated in Figure 13 corresponds to a standard deviation of 0.071 mm. Again systematic errors can be observed on hills and valleys of the surface. In valleys positive deviations can be observed while they are negative for hills.

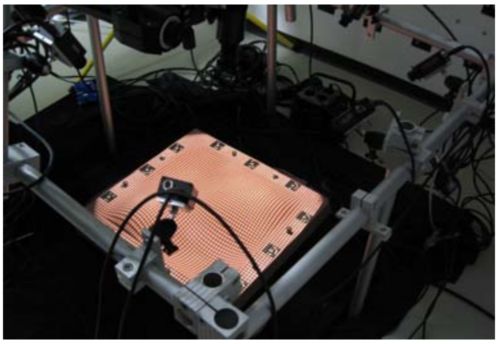

Figure 12. Experimental setup – System H

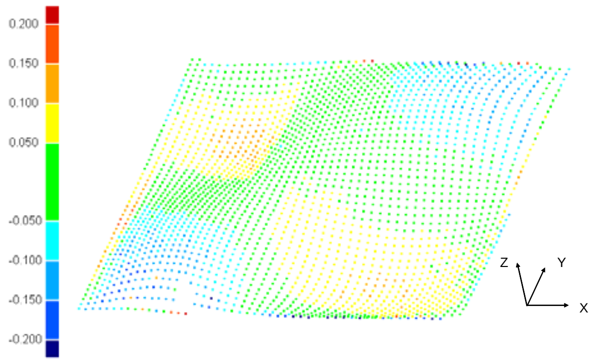

Figure 13. Multi-camera grid measurement – System H

3.5 Comparison

The following table shows the result of different optical 3D surface measurement systems.

system	method	number of points	3D deviation	
			Max +/- [mm]	standard deviation [mm]
A	stereo image matching	18 200	3.023 / -3.947	0.593
B1		15 230	0.892 / -0.910	0.080
B2		134 150	0.919 / -0.783	0.076
C1		15 210	1.204 / -1.087	0.102
C2		133 960	1.039 / -1.008	0.086
D	object based matching	5 785	5.802 / -5.088	0.773
E	fringe projection	25 250	0.370 / -0.411	0.085
F		62 300	0.270 / -0.184	0.065
G		620 000	0.259 / -0.297	0.055
H	multi-camera grid	2 480	0.332 / -0.433	0.071

Table 1. Comparison of measurements

The systems differ significantly in the number of measured points. Fringe projection systems usually provide higher point densities. Image-based matching methods (section 3.2) allow for the individual selection of point spacings. With smaller grid spacings the accuracy of LSM measurements is enhanced, probably due to better initial values derived from adjacent points (Table 1, system B2 and C2). Fringe projection system delivers the highest accuracy when the measuring volume corresponds to recommendations of the manufacturer. Minimum and maximum deviations are also smaller, and less outliers can be observed as well.

4. PRACTICAL APPLICATION

4.1 Automotive industry

One application of dynamic surface measurement is deformation analysis during car crash tests (Raguse et al., 2004), for example the monitoring of the footwell. Fringe projection systems can not be applied due to limited mounting space, extremely fast deformations and mechanical stress during the test. In this case a matching based solution is designed using an artificial texture with random pattern.

The experimental setup considers specification from automotive industry and given conditions of the real environment of the footwell. Two Weinberger cameras (see section 3.1) are used to record the scene according to Figure 14. The surface was prepared with high-contrast ransom pattern is used to provide enough texture for matching.

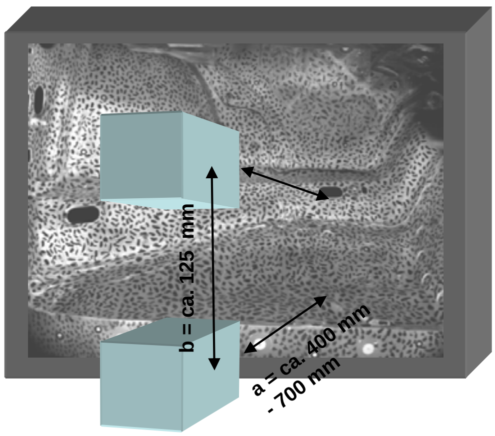

Figure 14. Experimental setup for footwell measurement

The expected accuracy was estimated to 0.05 mm in X and Y and 0.53 mm in Z, both based on 1/10 pixel of image accuracy. After optimisation of input parameters the following point cloud (Figure 15) has been measured completely in one step.

In this application LSM with 8 geometric parameters generates better results because the footwell surface shows large slopes with respect to the viewing directions of the cameras. It can be shown that the resulting point cloud fits better to the reference surface model.

The red ellipses in Figure 15 indicate areas of outliers that result from reflections, hot spots or lack of texture. In some regions of high curvature or steep slopes not enough correspondences could be detected. Outliers are removed for the subsequent accuracy statement.

Firstly, the point cloud is transformed into the CAD model by a best-fit transformation with 6 parameters (fixed scale). The comparison to the nominal geometry based on shortest distance evaluation yields to a standard deviation of 0.753 mm (Figure 16). The histogram of deviations in Figure 17 indicates that about 64% of all points lie within an interval of ±0.5 mm and 98% of all points lie within an interval of ±2 mm. Due to the complex surface structure the resulting accuracy is worse compared to the reference body. However, the specifications of the automotive partner are fulfilled.

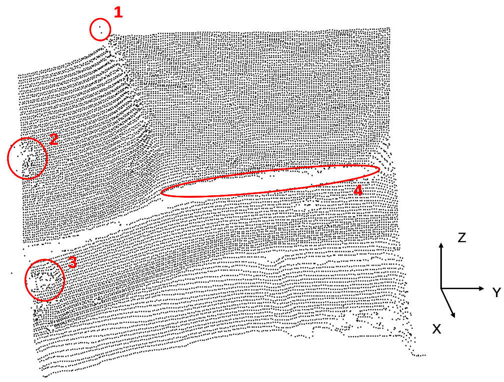

Figure 15. Measured point cloud – footwell

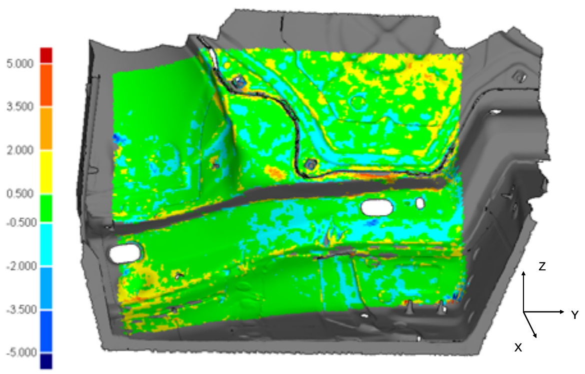

Figure 16. 3D analysis – footwell

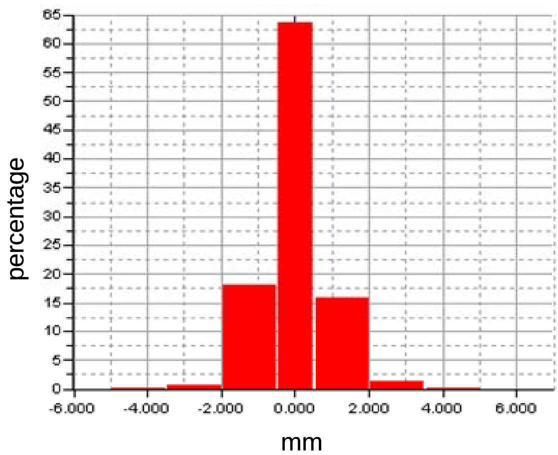

Figure 17. Histogram of point deviations

5. CONCLUSION

The paper deals with the comparison and verification of optical 3D surface measurement systems. Several systems and methods have been tested: fringe projection systems based on phase measurements, photogrammetric image matching methods (correlation, least squares matching), object-based multi-image matching and a multi-camera grid measurement system.

The measuring results of all systems have been verified with respect to a CMM reference measurement. Fringe projection systems yield highest accuracy and completeness of the data. The best image-based matching result is obtained by least squares matching that optionally can be enhanced by projective transformation for more complex surfaces.

Photogrammetric multi-camera measurement of grid points leads to an accuracy that is equivalent to fringe projection. However, the number of points is much smaller.

A practical project for dynamic object deformation analysis has been presented. Due to the practical conditions only image-based matching is suitable for this task. Recent results are promising in terms of accuracy and degree of automation.

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