EXPERIENCES WITH 3D REFERENCE BODIES FOR QUALITY ASSESMENT OF FREEFORM SURFACE MEASUREMENTS

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ABSTRACT:
The following paper discusses the use of 3D reference bodies for the assessment of measurement accuracy of free-form surface measurement systems. Reference bodies are mechanical structures with calibrated values in terms of given coordinates, distances or surfaces. Standardised guidelines exist for the determination of limited performance characteristics such as probing error or sphere distance error, that are basically used for fringe projection systems. Since free-form surfaces usually consist of a variety of surface shapes and structures of different size and curvature, it is worthwhile to discuss the use of free-form reference bodies for performance evaluation. Two different reference objects have been designed and tested with different surface measurement methods: fringe projection, laser tracking, laser scanning with articulated arm and least squares stereo matching. The first reference object is designed for static measurement purposes, the second one is used for the verification of dynamic surface deformations. Both objects provide local reference points and can be calibrated by different techniques. In particular, the references are used to check the ability of area-based matching methods, both in static and dynamic scenes. In the recent implementation of the PISA system different geometric models and matching strategies can be selected. It can be proven that least squares matching with polynomial transformation of second order yield best results.

1. INTRODUCTION

For industrial purposes the comparison of real measurement data with calibrated and certified references is a standard procedure yielding figures about measurement uncertainty under consideration of retraceability to the standard unit metre. Standardised guidelines define characteristics test values and propose procedures for measurement, acceptance test and reverification.

The German guideline VDI/VDE 2634 part 1 recommends characteristics and procedures for accuracy assessment of area-based optical 3D measuring systems. In general, this guideline has been developed for fringe projection systems that are able to measure a large number of 3D surface points with one single measurement. However, the guideline can also be used for other surface measuring techniques such as photogrammetric matching methods or laser scanning devices.

VDI/VDE 2634/1 defines basically three characteristics: the probing error is determined by measuring a sphere and calculating the span of deviation from a least-squares best-fit sphere. The plane measurement error is defined by the span of deviations of surface points measured on a calibrated plane reference body. Finally the sphere distance error is defined as the deviation of the measured distance between two spheres with respect to the calibrated length. If probing error and sphere distance error are determined, the ISO conform length measurement error can be derived.

Part 3 of VDI/VDE 2634 specifies methods for optical 3D measuring systems based on area scanning for several single views. Typically these systems are composed of several components, e.g one or several imaging sensors and one or several projection systems which project structures onto the object surface. The 3D point clouds are acquired in several shots, i.e. they must be transformed into one common coordinate system. The task can be solved either by photogrammetric orientation methods (e.g. tie points, optical navigation) or by measuring devices (e.g. articulated arm, CMM, robot). Examples of such sensors are measuring systems based on fringe projection, photogrammetric and/or scanning systems with area-based measuring capabilities.

Figure 1. Sphere bar reference object

The proposed reference bodies are planes, spheres and sphere bars made of steel, ceramic or other suitable materials (example in Figure 1). The surface coating of the spheres scatters light diffusely, thus optimised for active projection of structured light. As a drawback these objects can hardly be measured by passive photogrammetry since they do not provide any texture.

Usually the standardised reference bodies provide simple quality numbers. However, testing against calibrated surfaces is not supported. For this purpose the IAPG has developed two different types of surface reference bodies that are suited for photogrammetric matching methods. In addition, these parts can

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also be measured by alternative methods, e.g. fringe projection, CMM scanning, laser tracker or laser scanning.

Using these reference bodies the IAPG image matching system PISA (Photogrammetric Image Sequence Analysis) for dynamic surface measurement has been investigated and verified in terms of measuring accuracy (Luhmann et al., 2008a).

2. SURFACE REFERENCE BODIES

2.1 Requirements and specifications

The general requirements of surface reference bodies can be summarised as follows:

- surface with representative shapes and curvatures
- surface with different structural resolutions
- surface with suitable reflectance properties
- variable texture for different imaging resolutions
- physical definition of the object coordinate system
- control points that can be probed by different measuring techniques
- calibrated with higher accuracy with given measuring uncertainty under consideration of retraceability
- constant in terms of geometric stability
- mobile (optional)
- provision of different deformation stages (optional)
- cost-effective

For accuracy assessment two different reference bodies have been designed that fulfil most of the above mentioned specifications. Test body 1 is used for the measurement of a static (non-deformed) surface, test body 2 provides different deformation stages for dynamic surface measurements.

Both surface reference bodies consist of a redundant number of control points that represent the workpiece coordinate system. The control points are made of plane circular targets and spheres, hence can be probed by different tactile and non-contact systems.

Figure 2. Static reference object with texture

2.2 Static Reference Body

The static 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. The reference has a size of 500 mm x 500 mm x 200 mm. The surrounded 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 2). The surface geometry has been measured by a

precision coordinate measurement machine (CMM) with a theoretical accuracy of about 2 μm (Luhmann et al., 2008b).

2.3 Dynamic Reference Body

A second test body has been designed that allows for dynamic free-form surface measurement. It can be deformed by mechanical forces under controlled conditions, hence it is possible to obtain reference data of each deformation stage by an alternative measuring method.

The reference body is made of a stable aluminium plate where a corrugated or other metal sheet is mounted in a solid fixture. A corrugated metal sheet has been used for the following tests since it easily provides a surface with high curvatures.

The test object consists of 16 coded targets, four of them in an off-plane position. In addition, five fixtures are provided that can hold photogrammetric targets or a reflector of a laser tracker. These control points permit the a posteriori transformation of measured point clouds into the reference coordinate system in order to avoid best-fit transformations of one point cloud to the other.

The surface of the reference body does not consist of natural texture. Hence an artificial texture has to be created in order to identify homologous points for multi-image matching. For this purpose a flexible foil of less than 0.1 mm thickness can be pasted on the surface. The foil can be printed with any type of pattern. Figure 3 shows the dynamic test body with pasted texture foil.
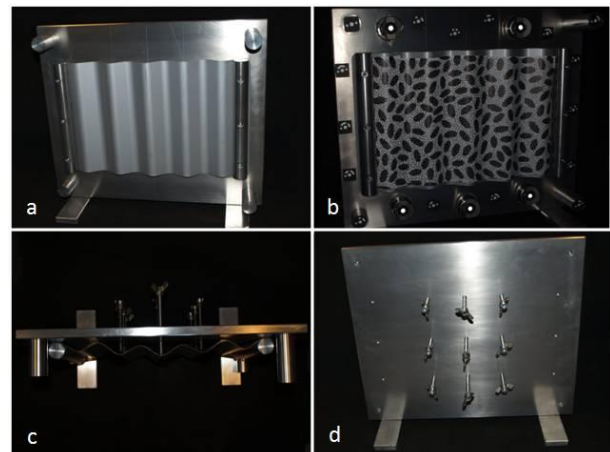

Figure 3. Dynamic reference body (a: front view, b: with texture, c: top view, d: rear view)

A texture used for image matching should provide high contrast and arbitrary or unique patterns. For this purpose different types of texture patterns have been developed, ranging from artificial random noise structures to ellipse shape textures. The ellipse pattern (Figure 3b) is most suited for high speed video sequences due to the extremely short exposure times. It provides high contrast and gradients in all directions (Luhmann et al., 2006). In addition the texture is useful for image pyramids since two patterns in different resolutions are combined.

In order to apply deformations to the test surface nine bolts can be screwed through the aluminium plate and press against the surface. In this manner a variable deformation can be created while the test sheet remains relatively stable, hence can be measured by, for instance, tactile probing.

3. STATIC ANALYSIS

The software package PISA allows for the photogrammetric compilation of stereo image sequences for three-dimensional reconstruction of high-dynamic object deformations. The implemented approach supports pre-processing steps such as Wallis filtering or resampling of normal stereo images. Image matching is based on normalized cross-correlation and least-squares matching (LSM). The conventional LSM method (e.g. Gruen, 1987) uses an affine transformation for geometric adjustment while PISA is extended by alternative geometric models such as projective and polynomial transformation (Bethmann et al., 2009).

A comparison of different optical measurement techniques using the reference object of Figure 2 have been published in Luhmann et al. (2008b). It has been shown that least squares stereo matching with projective transformation leads to an average measuring precision of about 0.08 mm (1 sigma) in object space. Alternative measuring methods such as fringe projection or grid projection yield precision figures in the order of 0.06 to 0.1 mm in comparison to the CMM reference measurement. In all cases a best-fit surface analysis has been calculated using the Geomagic software package.

The same data sets have recently been used for an advanced geometric LSM model where a polynomial transformation of second order is applied. The results show a significant improvement of surface accuracy (Bethmann & Luhmann, 2010).

For a comparison of the different geometric transformations of LSM we use the same parameters for all tests in PISA. For this texture we choose a grid spacing of 3 mm in X and Y, a correlation window of 21 x 21 pixels and a correlation threshold of 0.5. The patch size of the LSM transformation is 31 x 31 pixels. The following table shows the resulting standard deviations calculated from the differences to the NURBS model.

	standard deviation [mm]
cross correlation	0.444
LSM affine	0.205
LSM projective	0.165
LSM polynomial	0.077

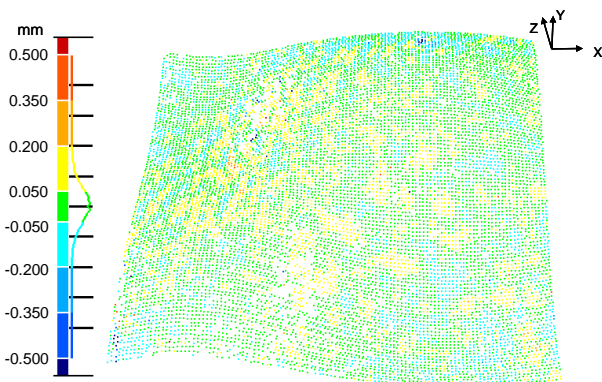Table 1. Accuracy of LSM surface measurement

Figure 4. Surface deviations by LSM with polynomial transformation

The best result is achieved by the polynomial transformation. If the patch size for projective transformation is changed to 21 x 21 pixels, a standard deviation of 0.1 mm for this approach is obtained. As expected the resulting precision depends on the choice of the patch size.

Figure 4 shows the deviation of the point cloud measured by the polynomial transformation with respect to the reference model.

In contrast Figure 5 shows the deviation of the point cloud measured by the projective transformation with respect to the reference model. It is obvious that systematic errors occur at the hills and valleys of the reference body according to the restricted modeling of larger surface curvatures by plane transformations. Further on, the distribution of the deviations in Figure 4 is more similar to normal distribution than the distribution in Figure 5.
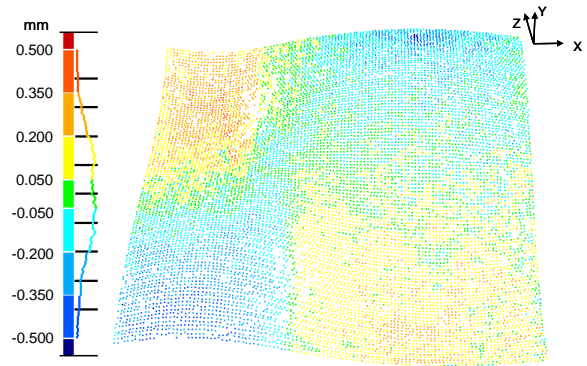

Figure 5. Surface deviations by LSM with projective transformation

4. DYNAMIC ANALYSIS

Using the dynamic reference body (Figure 3) the PISA implementation is tested with respect to accuracy and performance in the case of dynamic deformations.

In the first investigation an API laser tracker is used to probe the reference surface in different deformation stages in order to achieve reference data of higher accuracy. The absolute accuracy of the laser tracker is reported to 25 μm in a distance of 5 m (API, 2010a).

In addition the laser tracker measurement, each deformation epoch is also measured by a digital SLR camera Nikon D2X (4288 x 2848 pixels, pixel size 5 μm, focal length 24 mm). Here two different imaging configurations have been applied. Firstly, the camera stations have been chosen such that sufficient ray intersection geometry is achieved. For this case the cameras are mounted in a distance of 600 mm with a base length of 400 mm. A convergence angle of about 10° between both images ensures a full format view of the complete reference object.

Due to the steep surface slopes of the corrugated metal sheet a second configuration with 200 mm base line has also been tested.

Based on simple statistical error propagation the expected precision of object coordinates measured by spatial intersection can be estimated. For a base line of 400 mm and an image measuring accuracy of 1/10 pixel an estimated precision of 0.01 mm in XY and 0.03 mm in Z can be expected. For a reduced bas line of 200 mm the precision in Z will drop to about 0.07 mm. However, due to the shorter base line a better similarity between both images in areas of high curvature can be expected, hence a higher matching precision is likely. For this error estimation it is assumed that errors in calibration and orientation do not exist.

In a second investigation each deformation epoch is measured by an articulated arm with an adapted laser scan device (AxxisScan). According to the system supplier specifications the accuracy of the scanning arm is about 90 μm (API, 2010b). With respect to the accuracy potential of the PISA approach of about 80 μm the measurements with the articulated arm can only be used for comparison purposes and not as reference data of higher accuracy. Again each deformation stage is also recorded by photogrammetric stereo images as performed for the previous test.

4.1 Stereo matching vs. laser tracker

For this test the reference body was prepared with a printed texture foil (Figure 3b). For each deformation epoch reference data was measured with the API laser tracker by tactile probing with a reflector ball. For each measured 3D point cloud a reverse engineering process was calculated in Geomagic whereby the probing offset of the reflector ball (0.5 inch) was considered.

Due to the manual probing of the surface the resulting point cloud was partly inhomogeneous. Since tactile measurement is a time consuming process (about 30 minutes per epoch) only three epochs have been measured.

Reverse engineering in Geomagic generates a NURBS description of the surface (Farin, 1995). The precision of surface reconstrcution is estimated by a comparison of the measured point cloud with respect to the NURBS model. In this test the achieved precision results to 0.028 mm for epochs 00 and 01, and 0.037 mm for epoch 02. Figure 6 illustrates the deviations of the measured laser tracker point cloud with respect to the NURBS surface for epoch 00.
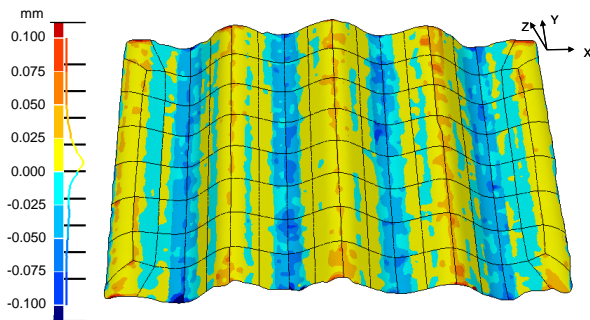

Figure 6. Deviations of original laser tracker data with respect to NURBS surface

4.1.1 Accuracy assessment: Using the stereo image pair with 400 mm base line and base-to-height ratio of 1:1.5 the images show severe perspective distortions in areas of steep surface slopes (Figure 7).

The PISA implementation for cross-correlation and LSM is controlled by a number of variable parameters such as patch size, grid width, correlation thresholds and others. Although a number of different parameter settings have been tested, the perspective distortions cause problems with area-based matching. Figure 8 shows one representative result where the areas of mismatches are clearly visible.
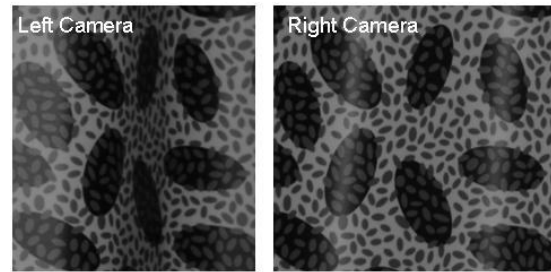

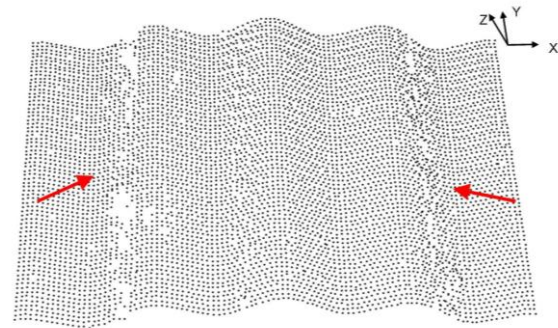Figure 7. Perspective distortions at 400 mm base line

Figure 8. Resulting point cloud with outliers (base line 400 mm)

Changing the base line to 200 mm results in point clouds that are more smooth and homogeneous. The shorter base yields reduced perspective distortions, thus better matching quality.

The reference body consists of five reference fixtures (nests) for the laser tracker reflector in order to transform the laser tracker data into the reference coordinate system.

Figure 9 shows the comparison of the measured point cloud (base line 200 mm, LSM polynomial) with respect to the laser tracker measurement. The shortest distance between each point of the point cloud to the nominal reference surface is calculated that leads to a standard deviation of 0.222 mm. The largest deviations occur in areas of hills and valleys.
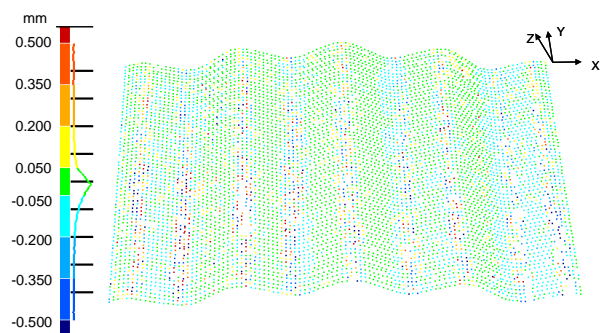

Figure 9. Deviations of LSM data with respect to laser tracker NURBS surface

The reason for these deviations can be found by analysing the stereo images in these areas. By using the foil reflecting hot spots occur at valleys and hills of the surface. Although Wallis filtering is applied, mismatches still exist that affect the overall accuracy. Figure 10 shows an example where the differences between both images are obvious. As a consequence, this test does not allow for a significant evaluation of the achieved accuracy.
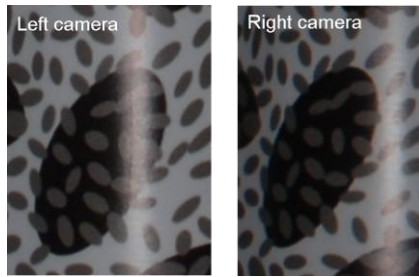
Figure 10. Reflections on surface

4.2 Stereo matching vs. articulated arm scanner

For this test an articulated arm with laser line scanner will be used to generate reference data of the surface. Due to the scan technology it is not useful so measure a surface with high contrast textures as it exists for the texture foil. The scanned 3D data will be affected by absorbing surface colours or bright reflections (Kern, 2003). Consequently, first scanning test result in higher noise for surface data in darker texture areas.

Since the matching approach requires sufficient textures the experimental setup has been changed. Instead of texture foil white powder was applied to the raw metal surface. The laser scanning device is now able to measure homogenous surface data. For the stereo measurements a video beamer was used to project an ellipse type structure onto the surface (Figure 11).
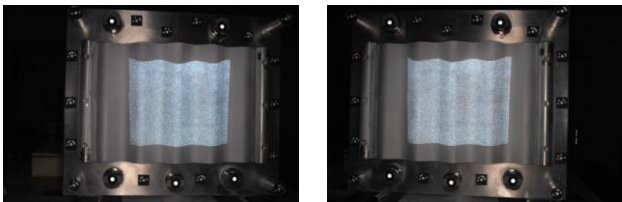

Figure 11. Stereo image pair with projected texture

The reference body was deformed in nine stages (epochs). For each epoch the surface was scanned by the articulated arm scanner, and measured by stereo photogrammetry as well.

Reverse engineering was again performed in Geomagic. Originally more than three million surface points per epoch have been scanned by the arm (Figure 12). In order to generate a NURBS model the point cloud has been reduced to a point spacing of 1 mm.
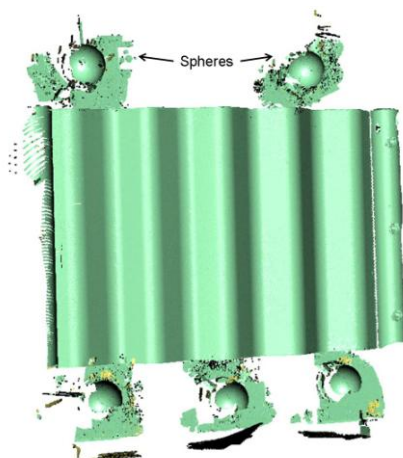

Figure 12. Raw point cloud measured by scan arm

Table 2 summarises the resulting standard deviations of reverse engineering and the coordinate transformation errors for each deformation epoch.

epoch	standard deviation of NURBS modelling [mm]	transformation error [mm]
00	0.043	0.037
01	0.040	0.062
02	0.194	0.097
03	0.125	0.066
04	0.078	0.038
05	0.074	0.184
06	0.082	0.031
07	0.085	0.066
08	0.088	0.045

Table 2. Standard deviations of reverse engineering and transformation errors

The quality of surface reconstruction is limited by the noise of the measured point cloud. In this test the epochs 02 and 03 show the highest noise levels, and hence standard deviation are at maximum The reason for the large standard deviations is not clear for the time being, and will be investigated in the near future.

In order to transform the scan arm measurements into the reference body coordinate system, a ball of 1.5 inch diameter was placed in to each of five reference fixtures. After scanning of the ball surface a best fit sphere has been calculated. After 3D similarity transformation to the nominal coordinates of the ball centres epoch 05 shows the worst results (

Table 2). Since the other epochs could be transformed with sufficient precision, it can be assumed that the control point measurement of epoch 05 consists of gross errors. In order avoid any affect by false coordinate system transformation the following evaluations are based on a best-fit of matching results to scan arm measurement.

Stereo matching was again performed by LSM with polynomial transformation. Due to the field of view of the video beamer only an inner part of the test body has been measured. The surface was measured with a point spacing of 3 mm, hence about 3000 points are measured in each epoch. Figure 13 illustrates the measured point clouds shown in the XZ plane for each epoch. The deformation of each epoch can clearly be detected.
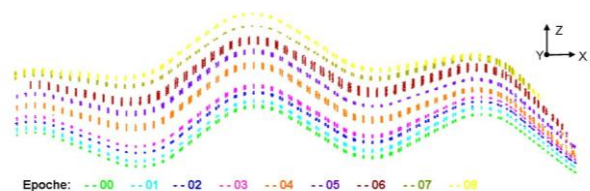

Figure 13. Deformation of the dynamic reference body

Table 3 summarises the resulting standard deviations after comparison with the NURBS reference data. All values lie between 43 μm and 78 μm. It is obvious that both measuring systems provide precisions of the same order.

epoch	standard deviation [mm]
00	0.048
01	0.058
02	0.059
03	0.073
04	0.054
05	0.078
06	0.072
07	0.043
08	0.048

Table 3. Standard deviation of 3D analysis

As one example Figure 14 shows the result of a comparison of the stereo matching point cloud vs. the scan arm measurement of epoch 00. The visible deviations are normally distributed and do not show any systematic behavior.
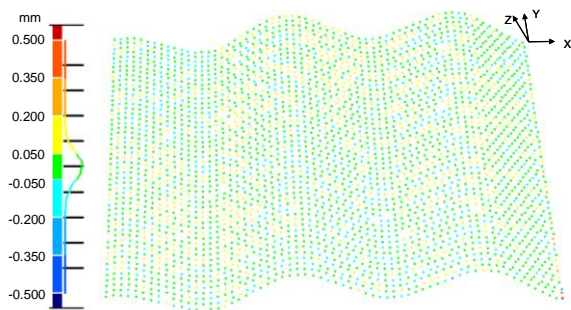

Figure 14. Deviations of LSM data with respect to scan arm NURBS surface (epoch 00)

5. CONCLUSIONS

The paper reports on experiences with free-form surface reference bodies that can be used for accuracy assessment of photogrammetric stereo matching systems and other systems for free-form measuring e.g. fringe projection systems. Providing calibrated reference objects with higher accuracy is not trivial since photogrammetric stereo matching provides an accuracy level that is equal to other well proven techniques, e.g. fringe projection or laser scan devices. In our implementation of stereo least squares matching an accuracy of about 80 µm in an object volume of about 500 mm x 500 mm x 150 mm is obtainable. Using tactile measurements for surface calibration is either too time consuming (and expensive) or the manual probing inflicts additional uncertainties to the result.

The measurement of dynamic changes of a surface is even more complicated since the reference body must provide a flexible object material that permits mechanical deformations while a high accurate reference measurement must be able at the same time.

Different measurements systems have been tested to check their ability for serving as a higher accurate reference system. Neither laser tracker probing nor articulated arm scanning could provide reliable and homogeneous surface data with higher accuracy than achieved with LSM. The fringe projection systems available at IAPG could not be used for this investigation since they do not offer a measuring volume large enough to measure the test body with one single shot.

Concerning the potential of least squares matching the tests have proven that LSM with advanced geometric models

(polynomial transformation) is able to match even such surfaces that consist of large curvatures and steep slopes.

For future developments the characteristics of surface measurement system should be enhanced to figures that describe structural resolution of a system. Here the smallest object details shall be addressed that can be measured by a system under defined circumstances.

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