## SURFACE DETERMINATION WITH AN ACCURACY OF FEW MICRONS

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**Abstract**

In manufacturing the fine structure of the surface of different objects traditionaly will be determined by mechanical profiling instruments with direct contact to the object. The needle for touching the surface has at least a diameter of 5μm and is influenced by the inertia and vibrations. In addition some objects with a soft surface and for example abrasive wheels cannot be surveyed by this method. With photos taken by a stereo microscope, Rolleimetric cameras and CCD-cameras the surface determination has been done by photogrammetric solution. The geometric problems and the method of solution is described. Accuracies of ±5μm in the object space can be reached.

**Key Words:** Macro Photogrammetry, Microscope, Bundle Orientation

### 1. Introduction

The progress in industrial manufacturing with the requirement for an exact handling of the different steps, without empirical tests, the progress in medicine and other areas is causing a growing demand also for an accurate information about the threedimensional shape of the handled objects. For many purposes there is a request for information about the fine structure of the surface. By tradition in the manufacturing mechanical profiling instruments are used. But they are limited to profiles, they are sensitive about vibrations and it is not possible to examine soft surfaces or objects like abrasive wheels. In addition the needle for touching the surface has a diameter of at least 5μm and is influenced by the inertia.

As alternative solution the surface determination by photogrammetry can be used. Corresponding to the required fine structure, a large photo scale has to be used. The handling of images with a scale between 8 : 1 and 1 : 10 will be descriped. Photos or digital images (CCD-cameras) can be used.

### 2. Camera Systems

The imaging has been done with different optical systems. Metric cameras are not availble for the extreme close range - the macro photogrammetry, so nonmetric or partial metric cameras had to be used.

### 2.1 Stereo Microscope

Stereo microscopes are often used in medicine. The handling is very simple, a direct stereoscopic view to small objects is possible and after fast changing of the lenses against camera tube, stereoscopic photos can be made. The image scale and the focus can be changed.

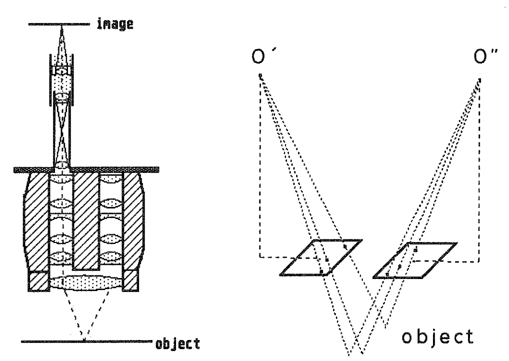



**Fig. 1:** stereo microscope - geometric situation

A standard film for images 36mm * 24mm will be used. For 3.5-times enlargement the calibrated focal length will be f=384mm. If the usual configuration of the normal case of photogrammetry would be used, with 60% endlap the base in the photo would be 14.4mm - corresponding to a base to distance relation of 1:27. With such a relation the stereo view would be very poor. By this reason, the principal point is shifted 50mm in the direction of a base enlargement. Together with a 100% overlap of the photos, the base has a size of 100mm in the image plane, that means, the base to distance relation will be 1:3.8.

### 2.2 Partial Metric Cameras

Alternatively to the stereo microscope cameras with macro lenses, adapter rings and teleconverters can be used. For a sufficiant photo scale the Rolleimetric 6006 and 3003 have been used with a calibrated focal length between 50mm and 600mm. The base to distance relation for the normal case is not sufficiant, by this reason the cameras have been used oblique.

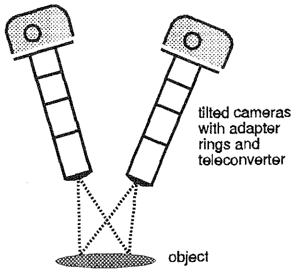



**Fig. 2:** camera configuration

The camera system very often is larger than the object itself. In addition the combination of the different optical components is not very stable. So it was more convenient to rotate the object infront of the camera than to rotate the camera.

### 2.3 Video cameras

Solid state cameras exceeding the standard tv-size of 768 * 512 pixels are very expensive. For economic reasons the standard CCD-cameras Phillips LDH 0460/21 with the Valvo chip NXA 1011 have been used. The pixel size of 10μm * 8μm leads to 6.1mm * 4.1mm chip size.

The same configuration as shown in fig. 2 had to be used for getting a sufficiant base to distance relation. The necessary distance between the object and the lenses required a focal length in the range of 40mm to 120mm.

| camera | size [$mm^2$] | accuracy in image | relative accuracy | resolution [lp] |
|---|---|---|---|---|
| Rollei 6006 | 60*60 | ±2μm | $\pm 0.3 * 10^{-4}$ | 4200 |
| Rollei 3003 | 36*24 | ±2μm | $\pm 0.6 * 10^{-4}$ | 2100 |
| Phillips CCD | 6.1*4.1 | ±1μm | $\pm 1.7 * 10^{-4}$ | 380 |

**Table 1:** comparison of the used cameras

The cameras operating with film do have a much better resolution like the CCD-cameras, in addition also the accuracy in relation to the film format or sensor size is better up to 5 times (see table 1). But the CCD-cameras can be used on-line which is necessary for example in applications for industrial manufacturing. If the cameras are used for quality control, the result has to be available within a very short time. That means, the whole process has to be done automatical with image correlation and/or automatic object identification. The listed accuracy (table 1) may not be reached in any case, especially in macro applications there are large problems with the image quality caused by the very small depth of focus.

## 3. Calibration

The photogrammetric solution is based on the reconstruction of the bundle of rays by means of the image coordinates and the inner orientation including radial symmetric distortion and systematic image errors. Calibration certificates have not been available for the used systems. For the stereo microscope the basic relations of the geometry have not been known in advance. A calibration and examination of the geometric stability was necessary.

A complete calibration is only possible with a threedimensional testfield. The accuracy of such a testfield has to be at least in the range of the aspired object point accuracy. After several tests copies of reseaus mounted on u-shaped metalic plates have been used. The reseau itself is defining points in one plane, the lower part of the bevel of the metalic plate has been used instead of height control points (see fig. 2).

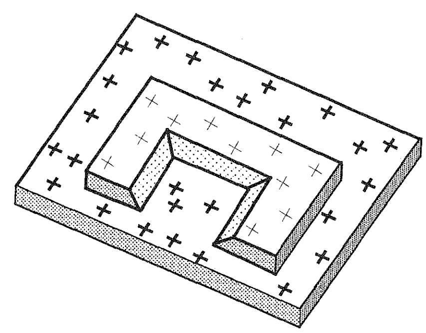


**Fig. 3:** threedimensional testfield

The thickness of the metalic plate is depending upon the depth of focus. Plates with a thickness between 1 and 3mm have been used. The depth of focus together with the tilted view was the limiting factor. Unsharp points cannot be used, at first the pointing accuracy is limited and outside of the depth of focus the optical relations are different.

Caused by the very small view angles the unknowns of the inner orientation are strongly correlated and the accuracy of the required elements are limited. The calibration and also the computation of the photo orientation is only possible by bundle adjustment. The Hannover program BUNOR, belonging to the program system BLUH has been used. Caused by the correlations it was not possible to determine the inner orientation together with systematic image errors. But this was not a problem because of the large area of tolerance of the inner orientation parameters. The systematic image errors determined in a second step are related to the fixed inner orientation of the same images.

| camera in used configuration | | | |
|---|---|---|---|
| focal length | principal point xp | principal point yp | scale |
| 6006 + 2-fold converter + 34mm adapter ring | | | |
| 218 ± 0,4 | 0.73 ± 0.4 | 1.01 ± 0.8 | 1:1.19 |
| 6006 + 2-fold converter + 68mm adapter ring | | | |
| 275 ± 0.3 | 0.40 ± 0.2 | -.62 ± 0.4 | 1.7:1 |
| 6006 + 2-fold converter + 102mm adapter ring | | | |
| 337 ± 0.3 | 0.75 ± 0.5 | -1.18 ± 1.7 | 2.5:1 |
| 3003 + 2-fold converter + 2 adapter rings | | | |
| 260 ± 0.3 | 0.34 ± 0.9 | 0.32 ± 0.6 | 2.6:1 |
| 3003 + 3 adapter rings | | | |
| 138 ± 0.1 | 0.92 ± 0.5 | 1.38 ± 0.8 | 1.5:1 |

**Table 2:** results of calibration [mm] Rolleimetric 6006 and 3003

After the first test, the camera configuration has been dismounted and mounted again to check the possibility of restoring the camera system. The differences of the second calibration against the first have been just at the significant limit. Especially the location of the principal point also changed the sign. As final result, the fiducial center was used as principal point.

With the fixed parameters of the inner orientation the systematic image errors have been determined by bundle adjustment with self calibration by additional parameters. The systematic image errors of both Rolleimetric cameras are quite different depending upon the number of the used optical elements. The structure and also the size is changing. Also after dismounting and mounting the systematic image errors are changing. That means, the selfcalibration has to be included into the standard solution of orientation determination and model handling.

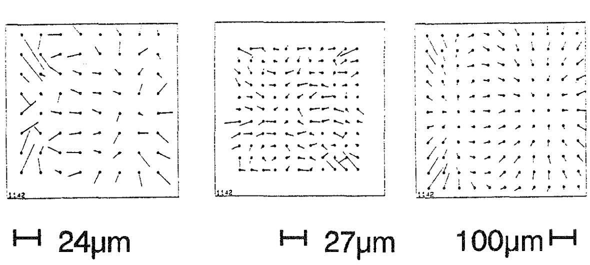



**Fig. 4:** systematic image errors of the different configurations of the Rolleimetric 6006

Similar results like with the Rolleimetric with the stereomicroscope have been achived. The systematic image errors have reached 50µm and have not been stable. In the case of the stereo-microscope the zoom seams not to be very stable, in the case of the Rolleimetric the mounting of the different optical elements cannot be repeated accurate enough.

The attributes of the optical systems used for the CCD-cameras are different. The systematic image errors were below 0.3 pixels and not significant. It is necessary to use only cameras, switched on since a longer time to avoid the well known drift of the CCD-values during warm up.

The examination of zoom lenses, the Vivitar with a C-mount for CCD-cameras and the HFT Rolleinar for the Rolleimetric, have demonstrated the problems of zoom systems. The reproduction of the inner orientation based on marked setting points was not possible within the aspired accuracy. A selfcalibration for every new setting is required. Also the strong dependency of the radial symmetric lens distortion from the focal length has to be investigated every time.

## 4. Geometric conditions during practical applications

As result of the above mentioned investigations, the different systems were used also for practical applications with a threedimensional control field like shown in figure 3. Without such a test field the camera orientation cannot be determined accurate enough. The traditional orientation procedure with relative and absolute orientation is not possible. The correlations of the elements of the relative orientations are listed with the values 1.000. But the the bundle solution can be used without problems.

The principal point and the calibrated focal length were fixed and the bundle orientation has been done with selfcalibration by additional parameters. In the case of the use of photos, analytical plotters are used for the model handling. The orientation parameters of the bundle solution have been used also for the orientation of the analytical plotters. In addition an on-line correction of the fiducial mark position based on the systematic image errors was used.

In the case of on-line photogrammetry with CCD-cameras, the exterior orientation was fixed. With such a configuration it is not necessary to determine every orientation element and a two-dimensional control field is sufficiant (Jacobsen et al 1990), (Husen et al 1992).

## 5. Applications

The trend in close range photogrammetry is going to on-line applications. The major disadvantage of this is the limited resolution and accuracy in relation to the image size (see table 1). The procedure has to respect these limitations. A typical example of on-line application of the macro photogrammetry is the determination of profiles of a toothed wheel. With 2 CCD-cameras in a convergent solution the object has been imaged. Based on correlation the profiles were determined. For a good correlation the ilumination is very important for getting a sufficiant contrast. A second example is the survey of tools with an accuracy of few microns. Such an accuracy cannot be achieved in imaging the whole object. By this reason only a small area has been used at the time and the orientation of the combination of 2 convergent CCD-cameras was determined in relation to a reseau used as control point pattern (Jacobsen et al 1990, Husen et al 1992).

For every on-line solution specialized software is required. As first test and as independent check manual measurements by "traditional" photogrammetry can be used, but very often it is not economic to write specialized programs and a usual model handling is sufficiant. Digital stereo plotters are only available in a limited number and mainly not operational. With displayed digital images or with photos taken with the above mentioned systems analytical plotters can be used. A lot of different applications have been handled in the University of Hannover. The wide range of applications is typical in this area. Only some examples are shown.

### 5.1 Abrasive wheels

Abrasive wheels cannot be surveyed by mechanical profiling. The fine structure is very detailed so it was not a problem to get images with good contrast. Based on photos taken with the Rolleimetric 6006 in convergent arrangement (the camera was fixed and the object has been rotated) profiles and digital height models (DHM) were measured. As a surprise the DHM (fig. 5) is indicating very clearly the direction of manufacturing.

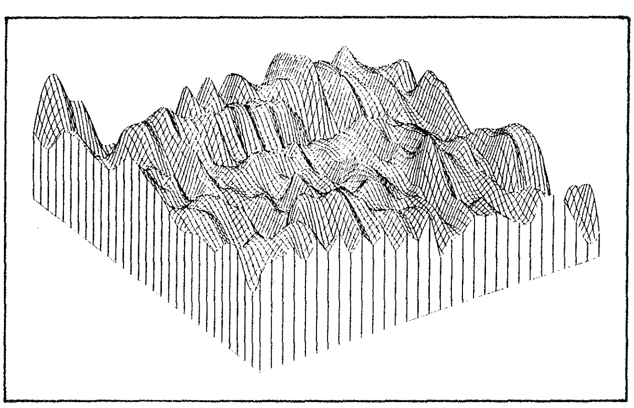
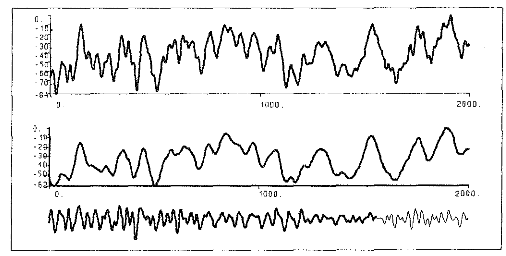


**Fig. 5:** smoothed digital height model of an abrasive wheel size: 2mm * 2mm, height differences 80µm

The obtained standard deviation of ±5µm for the individual points was sufficiant. Typical for an application like this is the requirement for additional figures about the surface like figures about the roughness.




abrasive wheel [microns]
original profile, low pass and hight pass filtering
length of profile: 2mm 2000 points
accuracy +/- 5 microns

**Fig. 6:** profile of an abrasive wheel

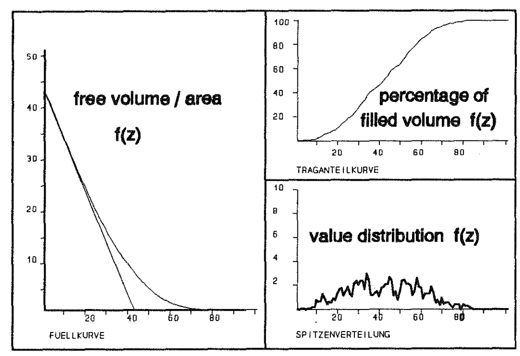



**Fig. 7:** profile analysis of an abrasive wheel

### 5.2 Metalic surface

The information about the roughness of metalic surfaces is important for the deformation of sheet iron in car manufacturing. The roughness is changing from sheet to sheet also if it is coming from the same charge. As first test for a later on-line solution, investigations were made with Rolleimetric 6006-images. Over approximately 8mm * 8mm an accuracy of ±5µm has been reached.

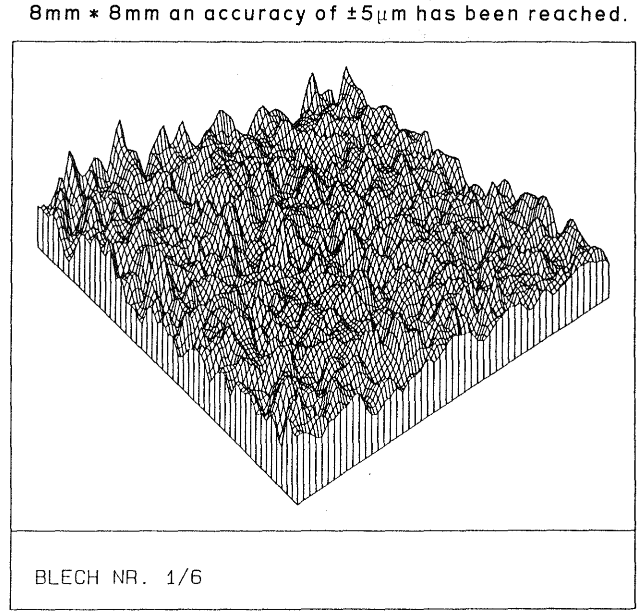



**Fig. 8.:** height model of a metalic surface
0.8mm * 0.8mm
maximal difference in height 60 microns

### 5.3 Exhaust catalyst

The effective area of an exhaust catalyst is depending upon the variations in height. The surface is not solid enought for mechanical profiling. The needle of a profiling device would engrave the sufrace. By photogrammetric means without contact to the object, this problem does not exist. Figure 9 shows a profile crossing the catalyst. Also this object has been determined with an accuracy of ±5µm.

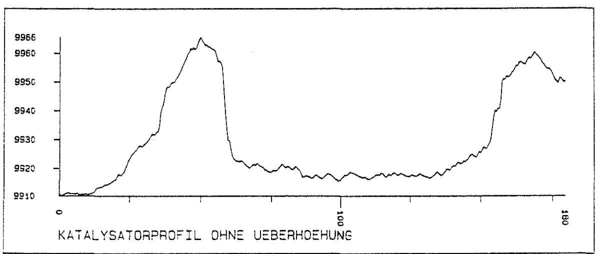



**Fig. 9:** catalyst profile, length: 1.8mm
height with same scale like position

### 5.4 Examination of human bones

The fine structure of human bones is changing over the years. The size of the tiny plates and bars will be reduced. Such a complicate three-dimensional object can only be measured by means of photogrammetry.

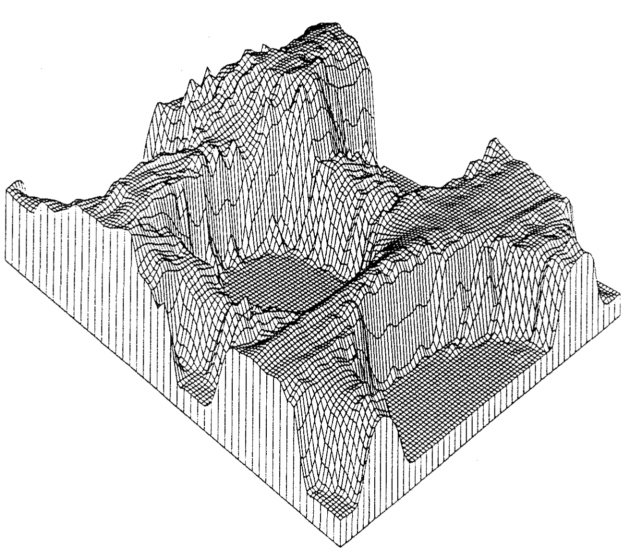


**Fig. 10:** height model of the finestructure of a human bone, size: 1.25mm * 1.25mm

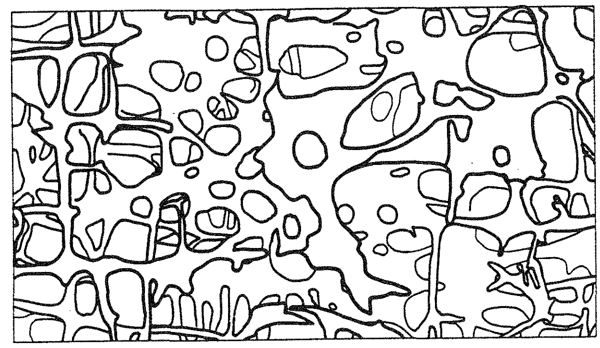


**Fig. 11:** finestructure of a human bone
size: 5mm * 9mm * 2.5mm
thickness of lines = f(z)

### 6. Conclusion

An accuracy of few microns in the object space can be reached by macro photogrammetry. The geometric stability of the used imaging systems is limited. The orientation parameters have to be calculated by the bundle method with selfcalibration based on a threedimensional control point body. The evaluation can be done on-line with digital images and specialized software or off-line with photos in analytical stereo plotters. Totaly new areas of applications have been opened.

### Refrences

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