

Robust Automatic Surface Reconstruction with Structured Light

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Abstract:

For the measurement of surfaces of close range objects, which do not show sufficient surface texture, an automatic system based on the projection of structured light has been developed. An off-the-shelf slide projector projects chromium slides with a regular dot pattern of 800 ... 8000 dots and perfectly binary transparency characteristics onto a surface. For robust point determination the object is imaged by three or four CCD cameras, which allows to reduce the number of ambiguities in the establishment of correspondences drastically by the method of intersection of epipolar lines. The advantage of the method is the fact that it does not require any approximate values nor an initial match given by a human operator and does though offer the advantages of a photogrammetric system like redundancy, accuracy and compatibility with triangulation methods.

The paper will give an overview of the hardware of the system and the chain of data processing, discuss reliability, accuracy and applicability and give a comparison with competitive methods. Results will be shown from the measurement of a model car surface and from a carbon panel put under load in a deformation analysis.

Introduction:

The automatic, non-contact measurement of object surfaces in e.g. industrial, medical or archaeological applications is one of the most important applications of digital close-range photogrammetry. A wide variety of methods has been developed within the last 10 - 20 years (see Strand, 1985 or Tiziani, 1989 for overviews), which differ considerably in their performance and applicability.

As surfaces do often not show sufficient texture, many methods work with structured light, the information of which is being used either in an active or in a passive manner. A simple method of surface measurement is the scanning of a surface with a light spot, which is usually generated by a laser and recorded by some kind of location-sensitive photoelectric detector (e.g. Seitz et al., 1986). If the geometry of projection device and recording device is known, coordinates of surface points can be computed. More efficient than the projection of a single dot is the projection of a dot raster, a line (lightsheet sectioning, e.g. Kramer et al., 1990) or a grid, from which efficient surface measurement techniques like Moiré techniques (e.g. Seib/Höfler, 1990 or Zumbrunn, 1987) or the coded light approach (Stahs, Wahl, 1990) can be developed.

Another possibility of the (passive) use of structured light is the texturing of a surface with a projected random pattern and the evaluation by correlation techniques (e.g. Zeiss InduSURF - Claus, 1988). While the projection of single dots or lines cannot be called a simultaneous method and coded light approach or the very accurate phase-shift Moiré techniques can be seen as quasi-simultaneous methods (they require the recording of a few consecutive frames), passive surface texturing methods are usually truly simultaneous methods, which are also suited for objects that are moving or changing shape rapidly.

The aim of the approach described here was the development of a versatile method for automatic simultaneous surface measurements, which should be based on relatively simple hardware and fast algorithms. For this reason the projected pattern was chosen a regular dot raster.

Method:

The dot rasters with densities of 800 ... 8000 dots were projected onto the object by a slide projector (consumer slide projector or special projector with iris and macro-optics) and recorded by standard CCD cameras. The pattern was etched into a chromium

layer on a glass plate (Maas, 1991a); as opposed to film-based patterns this way a perfectly binary transparency characteristics was achieved. In order to avoid the cumbersome calibration of a projector the information of the projected pattern was not used actively (Regensburger, 1990), but only passively. Image coordinates on the pattern slide and projector orientation- and calibration data need not to be known.

This way the surface gets marked with a large number of dots, which are of elliptical shape in the general case. The marked surface can be recorded simultaneously with two or more CCD cameras or (non-simultaneously) with one camera from two or more positions. If good approximate values of the surface are given, two cameras resp. two camera positions are sufficient; if good approximate values are missing or if the surface shows strong modulations or discontinuities, three or four cameras may become necessary. A configuration with one projector and four cameras is shown in Figure 1.

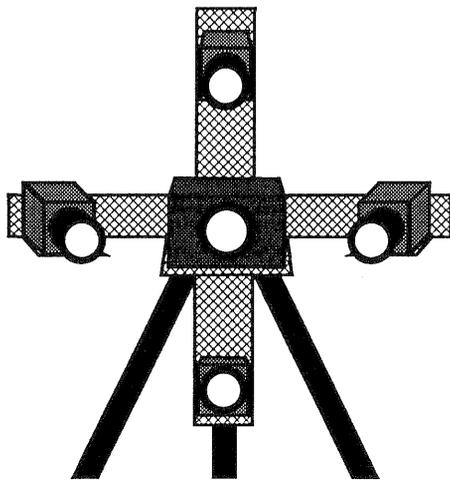


Figure 1: Four camera configuration

The data processing from the raw digitized images to the surface description can be divided into the major steps:

- image preprocessing
- image analysis and image coordinate determination
- establishment of correspondences between images using epipolar line information
- 3D coordinate computation
- interpolation and surface description

The whole procedure can be set up to work completely automatically for single surface measurements or for sequences of surface measurements e.g. in deformation analysis processes. For a detailed

description see (Maas, 1991a).

The same procedure has basically been installed and analysed thoroughly for the determination of 3D-coordinates of particles visualizing turbulent flows (Maas, 1991b, Maas, 1992a). Unlike the recording of moving particles in water the targets are situated on a mostly continuous and relatively static surface here, by which some of the problems occurring there are discarded and the targets can be called relatively well-behaved. Their image coordinates can be determined at an accuracy of $1/20$ of a pixel or better by simple thresholding and computation of the centre of gravity. The problem of ambiguities in the establishment of stereoscopic correspondences, extensively discussed in (Maas, 1992b), has to be solved here as well. Only if the surface is relatively plane and if good approximate values are available, or when the number of projected dots is small, the correspondence problem can be solved reliably with a system based on only two camera positions. In practical applications with problematic surface properties like reflecting or dull black regions, non-perfect projection and image quality (e.g. depth of focus in projection and imaging), occlusions, strong modulations or surface discontinuities three or four cameras (resp. camera positions) will be necessary to solve ambiguities and obtain unambiguous correspondences by the method of intersection of epipolar lines or similar methods (Maas, 1992b). Having established consistent triplets (resp. quadruplets) of corresponding image points in the image coordinate datasets the spatial coordinates can be computed by spatial intersection or together with the camera calibration data in a one-step bundle solution. The resulting object coordinates can be interpolated to a regular grid or rendered to derive CAD structures.

The method is a truly simultaneous technique, but the number of projectable points is limited to about $1/50$ of the number of image pixels due to the projection of discrete dots, which have to cover at least 2×2 pixels in the digitized image to allow for a coordinate determination with subpixel accuracy. To increase the spatial resolution several exposures can be made from every camera station with the projected pattern phase-shifted by fractions of the dot raster width; however, the method cannot be called a strictly simultaneous method then.

The camera orientation and calibration is a crucial step as deficiencies in the calibration will make the epipolar lines miss the correctly matching points; thus large errors in the calibration will not only influence the accuracy but may make the whole method fail if

correspondences cannot be established reliably.

Examples of applications:

To show the potential of the method some applications on different, more or less complex objects will be given in the following. The applications shall basically show the versatility of the method independently from the fact that are competing methods for certain applications.

A relatively simple application is a deformation measurement of a carbon wing panel (Figure 2). This 500 x 300 mm² panel is put under load and deformations are to be measured on a regular grid and compared with finite elements computations at multiple load steps. The panel surface was marked by ~5000 projected dots, the coordinates of which were determined by a three-camera system and interpolated to the grid. Repeated measurements in unloaded estate yielded a standard deviation of about 25 µm for deformations in depth coordinate direction.

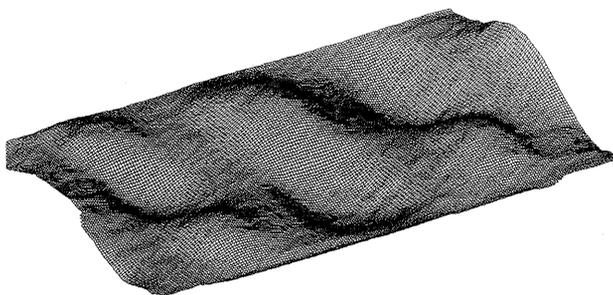


Figure 2: Carbon wing panel put under load (10 times enhanced)

As the projected pattern is moving relative to the surface during deformations it does well mark the surface, but it allows only for the determination of deformations in depth coordinate direction but not for the computation of local strains and shears. For this purpose a dot raster has to be directly applied to the surface with the advantages that also strains and shears can be computed and that the projection density and dot size can be adapted locally; however, the method can no longer be called a non-contact measurement method then.

A significantly more complex object is given by the model car shown in Figure 3. The surface modulations of the car are significantly larger than those of the carbon wing panel, the surface shows discontinuities and the metallic paint leads to strong local reflections. Moreover, occlusions or steep modulations do often cause dots being detected only in one image but missed in other views.

In this application the method failed completely when

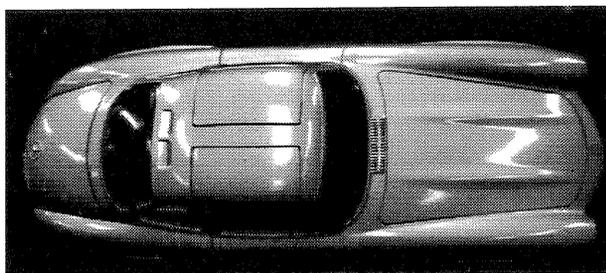


Figure 3: Model car with reflecting surface

only two cameras were used. With three cameras and ~1000 projected dots the failure rate in the establishment of correspondences was about 1%, with four cameras it was decreased to less than 0.1%. In general wrong matches cause gross errors and can easily be detected in the surface coordinates dataset and filtered out as they appear as large peaks on the surface. To increase the spatial resolution and to be able to comprehend edges in a better way several exposures with the pattern phase-shifted were taken from each camera.

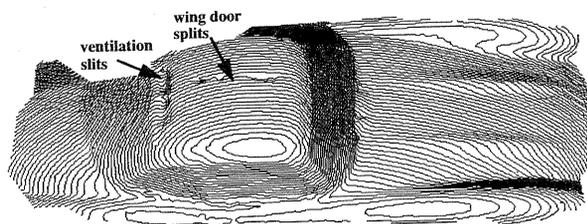


Figure 4: Model car - 0.5 mm isoline plot

The result of the surface measurement with 6800 projected dots in total is shown in Figure 4. The model is incomplete in some regions because only one projector position was chosen. The discontinuities on the roof visible in the isoline plot show the ventilation slits and wing door splits.

To be able to measure the surface of a complete object from all sides in one common coordinate system the method has to be combined with photogrammetric bundle triangulation methods. This has been done in a diploma thesis with the task to generate a surface model of a bust of Ludwig van Beethoven (Zanini, 1991).

The surface properties were well-behaved for the pattern projection (dull white gypsum material), the shape, however, can be seen as relatively complex. In total 12 projector positions with 4 camera positions each and some additional exposures for the connection in the photogrammetric bundle triangulation were necessary. To be able to perform the method in a strictly non-contact manner connection points were signaled on a frame posed around the object.

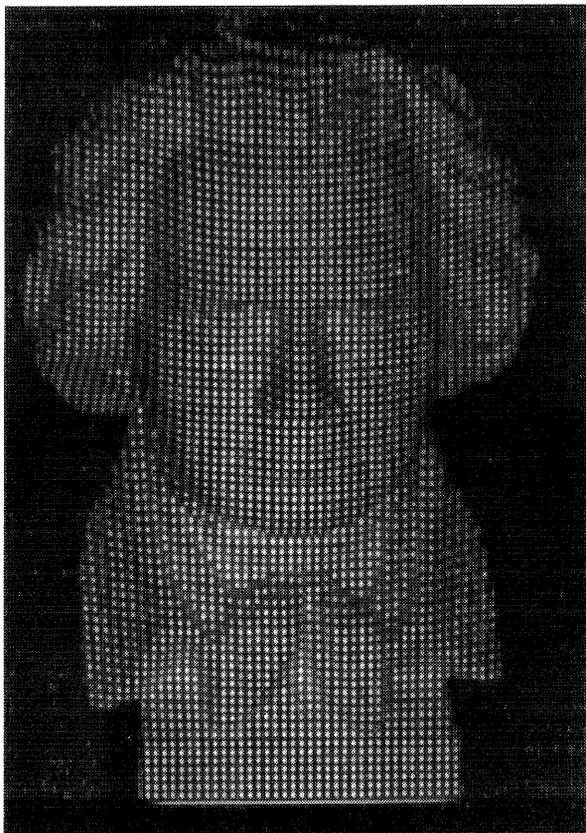


Figure 5: Beethoven bust with projected dot pattern

Including exposures with phase-shifted pattern the complete surface dataset consists of 43,000 projected dots. Results of a subset of about 18,000 dots are shown in Figure 6 - Figure 8. Figure 8 shows a photorealistic visualization of the dataset, which has been generated from the photogrammetrically determined object surface data by a raytracer program.

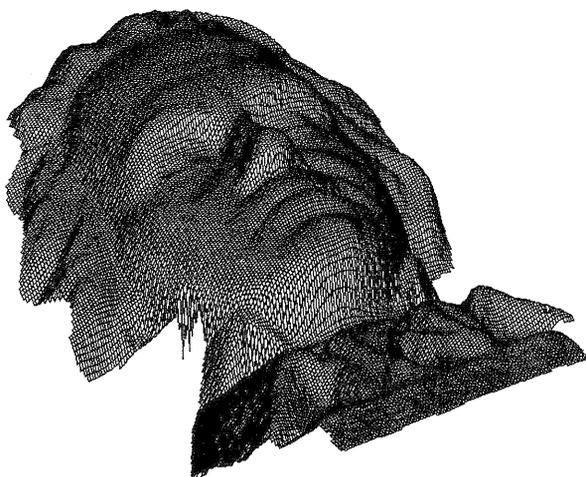


Figure 6: Beethoven - grid Model



Figure 7: Beethoven - isoline plot

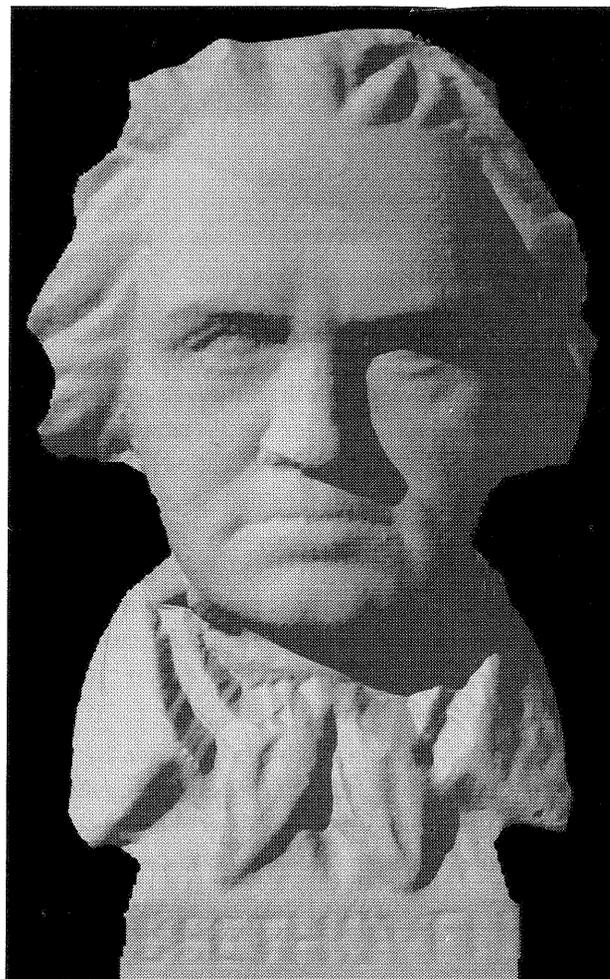


Figure 8: Beethoven - Photorealistic visualisation

Conclusion:

Although the projection of a simple dot raster is definitely not the ideal method for all kinds of applications of surface measurements in close-range photogrammetry (Moiré methods show the advantage of directly visualizing deformations, the coded light approach is very suited for fast robotics applications, sharply contoured objects require edge based methods), the versatile potential of the method could be shown in some very different applications. The method can be seen a good compromise between the requirements of accuracy, speed and versatility with a relatively inexpensive hardware configuration.

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