EXPERIENCE WITH InduSURF IN 3D MEASUREMENT OF INDUSTRIAL SURFACES

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ABSTRACT

InduSURF from Carl Zeiss, Oberkochen, is a system for 3D measurement of surface shapes using wire models. A very large number of points in digitized stereo photos is measured automatically by a correlation procedure. The stereo photos are digitized in sections by CCD cameras in the Planicomp analytical plotter. Then the x and y parallaxes in the digitized photos are determined by high-precision digital correlation in the host computer. If good contrast exists, the measuring accuracy of the automatic procedure is at least equivalent to that achieved by the operator. The report deals with the measurement of styling models, the measuring strategy and further processing of the photogrammetrically determined wire model in the user's CAD system.

1. INTRODUCTION

Optical measuring techniques are now being increasingly used in industrial measurement for geometry and shape inspection. Photogrammetry has recently presented itself as a method in this field, especially if the digitization of photogrammetric photo pairs is involved. The conversion into digital images and the use of a complex image processing software permit the virtually automatic 3D measurement of shapes, e.g of inner and outer car body surfaces.

For this purpose, the photographic and plotting system InduSURF (standing for industrial surface measurement) has been developed by Carl Zeiss Oberkochen and INPHO in Stuttgart in close cooperation with the Volkswagen AG in Wolfsburg where the system has been successfully used since 1986 for the measurement of all styling models. During the development of a new model in the car industry, the manually shaped styling model has to be remeasured whenever a change has been made in the shape of the car body or any functional parts. Such measurements may be required more than 100 times during the development stage of a new model.

The 3D coordinates of the surface are determined along cross sections. They are converted using the VDA format into the user's CAD system (in this case VWSURF), where they are filtered and interpolated. The surface structure is approximated by socalled patches (see chapter 6) until the final shape of the car body has been found. The data set defining this final shape then serves as a basis for production and various quality assurance procedures.

The measurement of styling models for the determination of the outer car body surface is usually performed with coordinate measuring machines. A complete measuring process of this type with a coordinate measuring machine may take up to 32 hours. During this time the styling model is no longer available to the designer. This down time can be reduced considerably - by approx. 75% - by the application of the photogrammetric method thanks to the enormous potential it offers to accelerate the procedure.

2. PHOTOGRAMMETRIC TAKING SYSTEM

Photos of the car body to be measured are taken with photogrammetric cameras. To enable automatic measurement, the object is specially prepared for correlation by applying a texture (Fig. 1). The texture can either be sprayed on or projected. Application of the texture by spraying, however, may lead to unacceptable changes in the object, e.g. due to the thickness of the sprayed-on particles. Preference should therefore be given to the projected texture where the object remains unchanged. This, however, requries a darkened room to ensure that the projected texture displays sufficient contrast with the object.
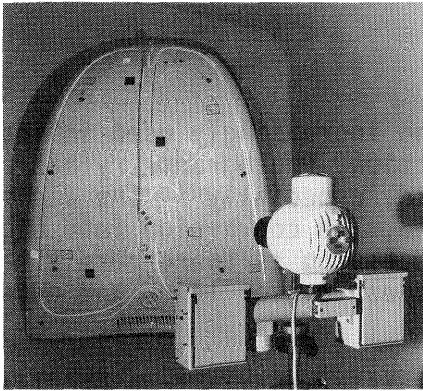
Fig. 1: Texture projector with SMK cameras in front of a test object with affixed character lines and projected texture

Fig. 2: InduSURF plotting system, comprising C100 Planicomp, HP 1000 host computer, A 900 and CCD module

If projected texture is used, it is essential that the texture remains unchanged. Hence the texture projector should not be moved, at least not during the exposure of a stereo photo pair. It is therefore advisable in this case to use two cameras which are triggered simultaneously to obtain photographs of the car body together with the texture.

Metric or réseau cameras can be used for this type of photography. The stereo photos can be taken either in the normal configuration or convergently, and can then be plotted. Suitable media for the photographs are glass plates or roll film. Roll films on a polyester basis, e.g. Aviophot PAN 150, are particularly suitable due to their high stability.

The texture projector (Fig. 1) which has been specially developed for this application by Carl Zeiss Oberkochen is very powerful. It features a considerable depth of focus and uses a special texture slide suited for correlation /2/. The texture slide was produced on the HP 1000 as a digital random pattern and was output on film on the Optronics P 1700.

For the measurement of character lines, some car makers apply thin adhesive tape to the car body. One edge of the tape runs along the character line and guides the probe of the coordinate measuring machine. If retroreflective adhesive tape is used with additional illumination, then the edges of this tape will appear with sufficient contrast in the photographs and can be measured automatically using a line-following algorithm. Contrast increases the closer the additional illumination is located to the center of the camera lens.

The control points on the car body are required for the transformation of the photogrammetric measuring data into the object coordinate system. For the 3D measurement of these control points with a high-precision geodetic surveying system, Carl Zeiss offers the economy-priced IMS Industrial Measuring System based on the ETh 3 theodolite. This means that a taking and measuring system which can easily be transported in a car is available for the measurement of medium-sized and large objects. The measurement of the control points by coordinate measuring machines is no longer necessary. Instead, the complete measuring system is portable and allows the measuring object to be left in its place.

3. HARDWARE COMPONENTS (CCD MODULE) AND IMAGE MATCHING

Automatic plotting is only made possible by the digitization of the image information. For this, the C 100 Planicomp is equipped with a CCD module comprising 2 CCD cameras, 2 camera control units for A/D conversion and 2 DMA interfaces for the digital data transmission to the HP 1000 host computer /5/. Fig. 2 shows the InduSURF plotting system. The major technical data of the CCD module are listed in table 1.

Camera	Hamamatsu C1000-35M
Sensor type	Hitachi He97211 MOS
Usable sensor area	256 (H) x 243 (V) pixels
Pixel size of one sensor element	27 x 27 μm
Pixel size in the image plane	20 x 20 μm
Scanning area in the image plane	5.1 x 4.8 mm^2
Radiometric resolution range	256 steps (grey levels)
Density dynamic range	1.4
Resolution	Horizontal 240 lines (at center)
	Vertical 190 lines (at center)
Geometric camera distortion	Less than ± 1%
Signal-to-noise ratio	46 dB
Spectral range	400 nm to 1050 nm
Time required to digitize, transfer and correlate the 2 images	1 sec

Table 1: System specifications for CCD components and correlation time

The digitization of the two photographs is performed in segments. In this process a window with the dimensions 5.1 x 4.8 mm^2 is defined around the image point whose 3D coordinates are to be determined in the object space. Then this window is quantized with a pixel size of 20 x 20 lm and digitized with 8 bits.

The image matrices resulting from the analog-digital conversion are transferred to the EMA (extended memory area) of the HP 1000 via DMA interfaces. For the matching procedure, however, only a section of the digital image with a maximum size of 32 x 32 pixels is used. This demarcation is necessary, on the one hand, to ensure that the surface to be measured is optimally approximated to a plane and, on the other hand, to keep the computation time to a minimum.

To enable the correlation of the image matrices, the image coordinates of the point to be correlated must be known to the nearest + 3 pixels in both digital images. The matrices are then displaced relative to each other in x and z in such a way that maximum coincidence is obtained. After successful matching and determination of the 3D coordinates, the two image segments are displaced for the computation of a new point. There have been no problems so far in fulfilling the requirement that the approximation address of the image coordinates of a corresponding point should be determined with an accuracy of + 3 pixels. In case it should not be possible to determine the approximation address with the required accuracy, a feature-based matching algorithm has been developed which automatically determines the approximation address with an accuracy of about 1 pixel /3/.

The high-precision matching of the two digital image matrices is imperative for automatic plotting. This transformation of one image segment into another is performed by adaptive least-square correlation /1/.

4. SOFTWARE MODULES

The software consists of two main groups, the general photogrammetric software of the Planicomp and the special organizational and mathematical software for the InduSURF application.

The photogrammetric software package for the <u>Planicomp</u>, which has existed for more than 10 years now, permits central-perspective imaging, manual photo plotting with high coordinate accuracy and the numerical and graphical output of the plotting results.

The digital image processing software was developed for Carl Zeiss at the INPHO GmbH, Stuttgart under the direction of Professor F. Ackermann of the University of Stuttgart. The software package is called SURF (for surface measurement) and includes modules for sensor calibration, cross sections and character line measurement.

The necessary software comprises several modules subdivided into interactive preparation programs and automatic measuring programs.

BINGO

This bundle adjustment program for engineering objects is used for linking and adjusting photo blocks. It optimally matches the individual photograms in the block to known control elements. BINGO provides precise information on the matching accuracy and reliability in the object coordinate system and permits the presimulation of the taking geometry beforehand for planning purposes.

Sensor Calibration

Before automatic plotting is started, the CCD sensor must be calibrated geometrically, i.e. its position in the higher-level coordinate system of the <u>Planicomp</u> must be determined by affine transformation. This transformation allows the correlated coordinates to be transferred from the sensor system to the <u>Planicomp</u> instrument system. This calibration can be automatically repeated in specified time intervals with an accuracy of approx. 0.03 pixel /4/.

Input of the Control Parameters

To prepare the automatic plotting process, the operator has to enter the control parameters into the system. When the program is started, the terminal displays either the data already entered or default values for the control parameters which can then be altered through menu control. Essential control parameters are, for example, step widths, profile spacing, thresholds for the correlation coefficient and the point transfer accuracy, the window size and at least one starting point for the correlation, to mention only a few.

Character Line Measurement

A further module is used for the measurement of character lines along the edge of a retroreflective adhesive tape affixed to the car body.
The following parameters are entered for the automatic 3D measurement of a character line: the starting and end points, the maximum distance between the measuring points and whether the left or right edge of the tape is to be measured. The automatically measured path of the edge is stored and taken into account automatically in the cross section measurement, e.g. for break lines.

Cross Section Measurement

The shape of surfaces is determined along cross-sections with x = const, y = const , z = const. The cross sections are specified in the interactive mode in the coordinate system of the measuring object.
The spacing of the cross sections and measuring points is freely selectable for each coordinate direction. The actual distance between the measuring points is controlled automatically as a function of curvature by a tolerance tube. The program is able, for example, to measure contour lines. In addition, the operator can enter any cross section along which an automatic measurement is to be performed.

Before the automatic profile measurement is started, the operator must place the floating mark once on the object surface. Areas to be measured and cut-out areas on the object surface can be specified by 2D and 3D polygons. These areas are either measured manually or received automatically from the character line measurement.

VDA/FS Format

The VDA format was defined by the CAD/CAM team of the German Car Makers' Association. It is particulary suitable for the exchange of surface data among various CAD systems and was specially developed for data exchange between car manufacturers and their suppliers.

The correlated 3D coordinates (wire model) can easily be converted into the VDA format and transmitted on-line or off-line to the user's CAD system.
The measuring procedure is shown schematically in table 2.:

- insertion of the photos, orientation measurement and bundle adjustment with BINGO
- geometric sensor calibration by affine transformation
- menu-controlled entry of the control parameters
- manual or automatic 3D measurement of the character lines
- definition of the measuring and cut-out areas using 2D or 3D polygons
- definition of the starting point by placing the floating mark once on the object surface
- automatic measurement of all profiles
- automatic storage of areas where correlation is not possible
- optional manual remeasurement of correlation failures
- data conversion into the VDA format
- VDA data transmission into the CAD system

Table 2: Schematic sequence of automatic plotting with InduSURF

After the operator has oriented the models and entered the control parameters, the system runs fully automatically until all profiles have been measured. This permits unattended plotting, e.g. in nighttime operation.

Another important aspect is the ease with which all C series Planicomp plotters can be retrofitted with the CCD module. In a retrofitted Planicomp, all programs are also available to the operator without any restriction.

Fig. 3 shows the section of a VW Rabbit car body.

The wire model of the lower half of the door measured with InduSURF is shown in Fig. 4.
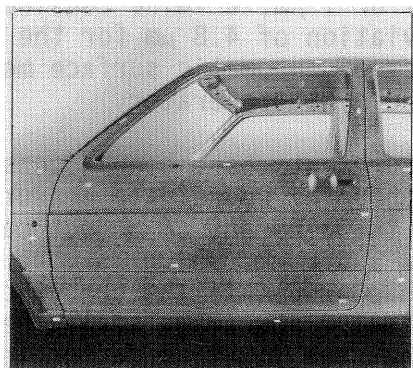
**Fig. 3:** Raw car body of a VW Rabbit with stuck-on character lines
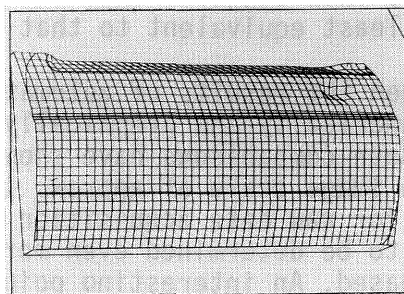
Fig. 4: Wire model of the lower half of the door plotted with InduSURF

5. TEST RESULTS

In the following I would like to give a rundown on some test plottings that have been performed so far.

More than 10 different test objects have been photographed and measured photogrammetrically. The photographs used for plotting were taken with UMK and SMK cameras and with the réseau cameras Hasselblad MK 70 and Rolleiflex 6006 Metric. A representative example for the procedures involved is the measurement of the long side of a car body. Fig. 5 shows the front part of the side wall, of which a total of 7 stereo models have been taken with the SMK. The IMS industrial measuring system (see chapter 2) was used to derive the 3D coordinates of the photogrammetric control points from the reference points located, for example, in the wheel boxes. The bundle block adjustment of the 7 models with BINGO resulted in a standard deviation of 4.8 lm for the image coordinate measurement. The average residuals of the 12 control points are sx = ± 72 μm, sy = ± 102 μm and sz = ± 71 μm on the object. The greater inaccuracy of the y coordinate is due to the less precisely defined y coordinate of the reference point on the car.
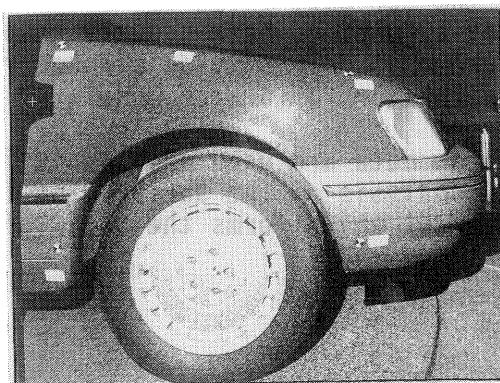
Fig. 5: Section of a car body side wall measured with InduSURF

The image coordinates of homologous points were determined along profiles using the least square matching algorithm. In the good contrast and texture conditions obtained by the use of the texture projector, the homologous image coordinates can be determined with accuracies in the subpixel range. The typical matching accuracy is 0.05 pixel or 1 μm, a value considerably lower than the above-mentioned standard deviation of 4.8 μm for the image coordinates. This suggests that the accuracy of automatic surface measurement is at least equivalent to that achieved by the operator.

At Volkswagen the results of automatic measurements have been assessed and compared numerically and graphically with those of coordinate measuring machines. Both comparisons have shown that the accuracy of object coordinates at an image scale of approx. 1:15 was ± 0.2 mm, which is more than sufficient for raw data acquisition (see chapter 6). If the object coordinates need to be determined even more precisely, the image scales have to be increased. An interesting point is that the limiting factor for an increased accuracy in the object coordinates is not found in the matching procedure but, for example, in the accuracy of control point measuring and setting.

Another major feature of the system is the measuring speed which is currently 1 sec for each successfully correlated point. In even surfaces without break lines only a minimal number of iterations is required, and the correlation time therefore is approx. 0.8 sec.

As a result of the measuring strategy used /6/, the rate of correlation failures is very low. It is less than 3% and is output at the end of the program together with the number of successfully correlated points.

6. FURTHER PROCESSING OF THE MEASURED DATA IN THE CAD SYSTEM

For the asthetic assessment of the car body shape and its styling information, the car industry always needs the physical 1:1 design model. This means that - unlike the aricraft industry - the new shape of a car body cannot yet be generated in the CAD system but has to be modelled manually. The design model is scanned in profiles with x, y, z = const.; approx. 20,000 points are measured and transmitted to the CAD system for the definition of the outer car surface.

At the Volkswagen AG in Wolfsburg the profile measurements obtained by scanning are called raw data. They are not yet suited to provide an adequate description of the car body shape but have to be scaled down to give the impression of a genuine, harmoniously shaped car body. The actual profile measurements only provide a rough representation of the outer car surface in the form of a wire model.

In the CAD system these raw data are used as a basis for the definition, smoothing and functional analysis of the surface and finally for the generation of the 3D data set which forms the basis of production and quality assurance.

It can therefore be stated in this special case that, surprisingly, the decisive factor for the quality of the surface description is in fact the CAD system rather than the measuring process.

As a result, the smoothing of the measured profiles in the CAD system is of paramount importance. It is performed by parametric curves called Bezier elements (Fig. 6). Polynomials of the 2nd to 10th order are used for the iterative smoothing process which is performed by the operator on the raster display terminal. After completion of the smoothing, the surface is covered with an easily changeable network of polyhedrons /8/. Fig. 7 shows the final result of CAD processing: the definition of the car body by patches.
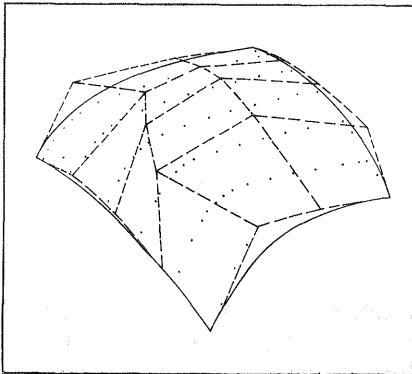
Fig. 6: Raw data measuring profiles, surface description through Bezier elements (VW photo material)
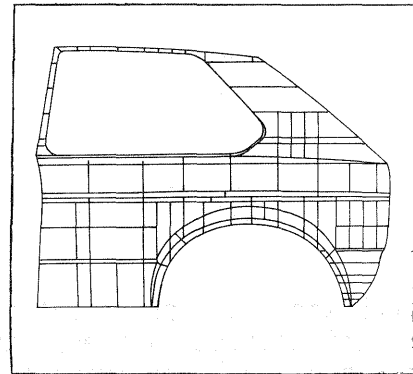
Fig. 7: Description of a rear part using patches (VW photo material)

If any changes are made on the styling model by the designer, the model has to be rescanned and processed in the CAD system. The great importance of geometric data acquisition in car development can be fully appreciated when we consider that the time required for measurement increases proportionally to the changes on the model. After release of the CAD data, they are transferred for further processing to the production planning department where the data sets are used as a basis for NC programming and the manufacturing of the moulding and deep-drawing tools.

InduSURF is particulary suitable for the determination of raw data in car development, due to its high cost-efffectiveness as compared with coordinate measuring machines. This results from the fact that photographing the styling model takes only half a day, that the model is no longer needed afterwards and can be returned to the designer.

7. OUTLOOK

The measurement of the inner and outer surfaces of styling models is one field of application for InduSURF. Further possible applications include aircraft and ship building and the measurement of large and small objects such as turbine blades and dentures. Measurements can also be performed for quality assurance purposes in industrial production if time is not a critical factor. As a result, the use of InduSURF is recommended whenever

- no-contact measurement is required,

- the object cannot be transported to the measuring system

- instantaneous documentation of the current object condition is required

- documentation of the object condition is required and a decision on the scope of measurement is not to be taken until later on,

- repeated or supplementary measurements need to be performed although the measuring object is no longer available.

InduSURF employs sophisticated 3D image processing software which has been substantiated by theory and tested in practical use. The reliable three-dimensional determination of geometric elements is therefore also of great interest for other fields of industrial measurement confronted with similar tasks.

The surface shape of the object to be measured is currently derived from a given regular grid. Should further development be required towards a more intelligent measuring strategy, it can be implemented by the replacement of individual subprograms in the modular software. It would be conceivable, for example, to measure the patch limit (see chapter 6) directly, instead of interpolating it from profile measurements in the CAD system.

InduSURF also offers the possibility of being upgraded into a real-time system. The major hardware and software components of such a system already exist.

The CCD module, the software package and the computer can be grouped together into an optical measuring head which, in turn, can be combined with an industrial robot of high positioning accuracy. This combination constitutes a new type of coordinate measuring machine, a 3D measuring robot /7/.

InduSURF also lays the foundations for reliable high-precision plotting of aerial photographs by the use of image processing techniques.

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