OBJECT SURFACE MEASUREMENT AND REPLICATION BY PHOTOGRAMMETRY AND COMPUTER AIDED DESIGN

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Abstract

A description is given in which way the analytical plotter is used as a subsystem of a Cad- and reproduction system. To be able to work with the Cad-system the photogrammetrically measured data must have a certain structure. To get the required structure and to reduce the measuring time a computer program has been written, which is used on-line with an analytical plotter. When using the program, the measuring mark moves in a certain prescribed pattern through the stereo model. With the Cad-system the photogrammetrically measured object data are manipulated in such a way that shaded coloured images of the object are produced and 3D line drawings can be made. Output data of the Cad-system is used as input for a milling machine to reproduce the object at a certain scale in hard foam. With some worked-out examples in the field of medical technology and auto industry it will be shown in which way the whole system operates.

1. Introduction

Two faculties of Delft University of Technology have combined their knowledge and available hard- and software systems in order to perform some experimental projects in the field of medical engineering and car-industry. Within these disciplines observation and study of object surfaces occupy a significant place. For object surface representation 3D interactive graphical systems (e.g. CAD) can be used. With these systems shaded images of objects may be displayed by using any type of projection and from any point of view.
A second method of 3D representation is the production of an object replica at a certain scale by means of a computer driven milling machine. Both ways of representation are used in our experiments.
The object surface is described by a mathematical surface modeller. The chosen modeller needs structured object data in the form of X, Y, Z coordinates. From existing objects, with a complex form these coordinates can be gathered very efficiently by photogrammetry.
In the following part of our paper a description is given of:
- the applied measuring and reproduction systems;
- the mathematical surface modeller;
- the data structure;
- the measuring technique;
- the determination of the precision of surface replication.

Results are presented of measurements and representations of the human face and a part of a car body. The advantages and limitations of the method are discussed.

2. The measuring- and reproduction system

An overview of the system is given in figure 1. For object photography are used either a non-metric Hasselblatt camera or a metric U.M.K. Zeiss Jena camera. With a Zeiss C100 Analytical Plotter the objects are measured. The photogrammetric output is sent via a computer network to the Computer Aided Design And Model Production (CADAMP) system. This system has been developed at the Faculty of Industrial Design Engineering. After mathematical processing of the measured object data by CADAMP the object can be presented in colour on a terminal screen. It can as well be reproduced in hard foam by N.C. (Numerically Controlled) milling. In the next chapter the CADAMP system will be described.

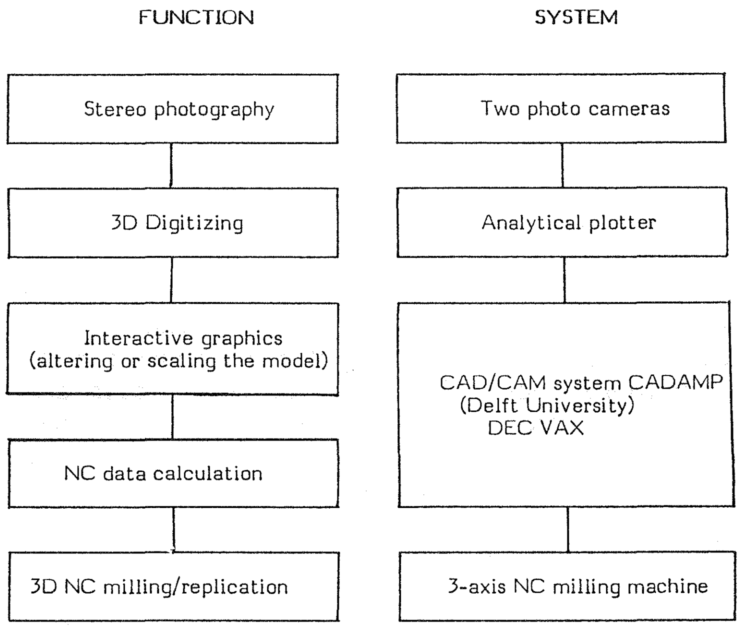


Fig. 1. Overview of the production system and the apparatus and software used.

3. The CADAMP system

Based on the measured coordinates of the object we have to define mathematically a surface that corresponds as much as possible to the digitized shape. This is a well known problem in Computer Aided Design (CAD). We have applied our CAD system CADAMP (Computer Aided Design And Model Production) (Broek, 1984) for the surface representation. Normally CADAMP is used by designers to develop shapes of (industrial) products. The user typically inputs a number of 3D point coordinates to the system, which then calculates and graphically displays a smooth surface which approximates the 3D points. CADAMP provides the user with several tools for optimizing the shape of his design. CADAMP is currently implemented on a VAX computer from Digital Equipment Corporation. A version on the IBM Personal Computer is called SIPSURF and is commercially available from Delft Spline Systems Inc., Delft, The Netherlands.
The mathematical surface description is made by B-spline functions $N^m(u)$ of degree m. Such a B-spline function is non-zero over only a limited part of the parameter (u) range, and consists of polynomial functions of u of degree m (or less) that are smoothly pieced together. Essentially each data point $\mathbf{r}_i$ is assigned its 'own' B-spline $N_i^m(u)$ such that when parameter u increases from minimum to maximum,

$$\mathbf{r}(u) = \sum_i \mathbf{r}_i N_i^m(u)$$

is a smooth 3D curve running close to each of the $\mathbf{r}_i$ locations. $\mathbf{r}(u)$ is called a B-spline curve.
Similarly, if a network of points, r_{ij}, is obtained from the stereophoto digitizer, CADAMP calculates the surface

$$\mathbf{r}(u, v) = \sum_j \sum_i \mathbf{r}_{ij} N_i^m(u) N_j^{m'}(v)$$

$\mathbf{r}(u, v)$ is called a B-spline surface of degree (m, m'), and the computer can calculate the complete shape by varying the parameters u and v over their full range. $\mathbf{r}(u, v)$ is a smooth surface that passes close to each of the locations (control points) $\mathbf{r}_{ij}$.
The user has direct control over the surface smoothness and over the approximating power by the values m and m'. If m = m' = 1 then the B-spline surface reduces to an exact bilinear interpolation of the data points, which is generally not smooth. If m = m'= 3 (cubic B-splines) a good balance is usually obtained between smoothness and exact reproduction of the measured shape. CADAMP allows degrees up to 20.

Once the data has been converted into the surface representation, there are many applications available with the CAD system.
3D line drawings can be quickly generated. Thus the shape can be viewed from any direction, isometrically or in perspective view. Details can be studied by zooming in.
The user is able to modify the shape by displacing control points or by deleting or adding new ones.
For our photogrammetric application, the graphics may well be used to check the measuring results.
Shaded colour images can also be produced by CADAMP; these images have turned out to be very reliable for the detection of errors in the measuring procedure.

CADAMP allows fully automatic NC milling of any B-spline surface. The user may, however, specify the size of the final model by a scale factor.

NC milling of CADAMP shapes is done by a three-axis milling machine. This apparatus was constructed at Delft University, at the end of the 1970s, although currently such devices are commercially available. However, most of the present milling machines are very large and expensive, and they are slow as they must be very accurate and able to mill metal. A milling machine specialized to light materials (such as polyurethane) is absolutely favourable for applications as described in this article. The milling machine we used can reach a speed of half a metre per second, and production of foam models typically takes about 20 minutes. The maximum milling range is 685x490x371 mm (length, width, depth).
Currently CADAMP plans to replace the milling machine by a robot with many degrees of freedom to perform the replication operation.

4. Required structure and format of the input data for CADAMP

As has been described in the previous chapter, the geometric models of CADAMP are based on B-spline surfaces. For the definition of a B-spline surface the most significant part of the data is the network of control points $\mathbf{r}_{ij}$. It means that there must be a number of rows, each containing a number of data points, with the requirement that each row has exactly the same number of points.

During the earliest experiments when interfacing the measuring system and CADAMP, the digitized points were directly taken as control points for the B-spline surfaces.

This implied that in some way the measuring sequence has to produce points in a network arrangement. This was achieved either by the measuring methodology itself or by specially developed software at the controlling computer or by both (see next chapter). In any case, the CADAMP system was offered an ordinary ASCII file containing the network points in a sequential order in a free format. The only remaining essential input was the B-spline degree for both parametric directions (m and m'). The advantage of this type of interfacing is its directness. Once the data points are in a network structure, the CADAMP system can immediately use them for line drawing, picture shading and automatic milling.

There are, however, two important draw backs. First, some effort must be taken at the 3D digitizer to actually produce the network structure (see next chapter). Secondly, there is a systematic deviation between the measured points (control points) and the B-spline surface calculated from them. This difference is large at locations where the object curvature is strong. The effect will be demonstrated in chapter 6, where B-spline surfaces are compared with straight bilinear interpolation.

On both these issues, improvements have been made by applying surface fitting techniques. This will be described in chapter 8.

5. Object measurement

Depending on the geometrical and topological complexity of the object it may turn out that the object cannot be described by one single B-spline surface.
In order to still describe the object in an accurate way by B-splines the object has to be divided into parts (patches), each of which can be associated with one B-spline surface. The patch division depends on the object form. A more complex form needs more patches. For example a car roof can be measured as one patch but a wheel house of a car has to be divided in more patches.

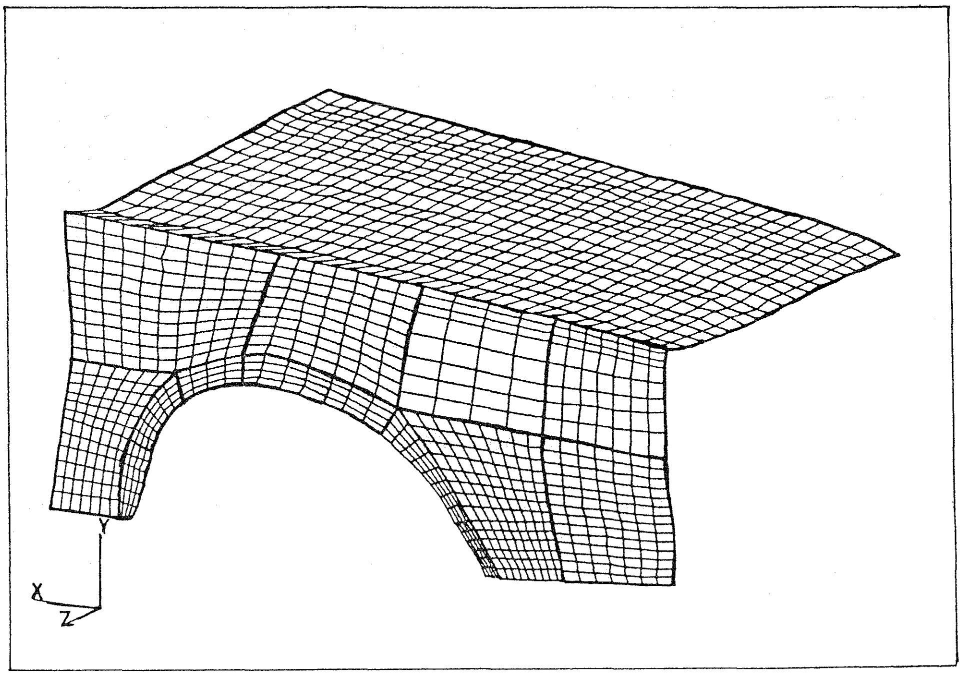


Fig. 2. Patch division and patch networks of car hood part and wheel housing.

Each patch has to be covered by (preferably) a regular (but not necessarily rectangular) network of points. X, Y, Z coordinates of the network points are determined by digitizing the stereo model of the object. To speed up the measuring work a program has been developed for the Zeiss Planicomp C100. In the program subroutines are applied, which belong to the Planicomp software. When using the program in each patch a number of profiles is measured. Each profile is measured from left to right. The profiles in the patch have the same number of points. The measuring mark is moved automatically to the points, which have to be measured. The operator only places the measuring mark on the object and records X, Y, Z coordinates.

A 3D line drawing (isometric view) of a part of the hood and the wheel housing of a car is given in figure 2. The drawing has been built up by twelve patches. Each patch has a different network of measured points.

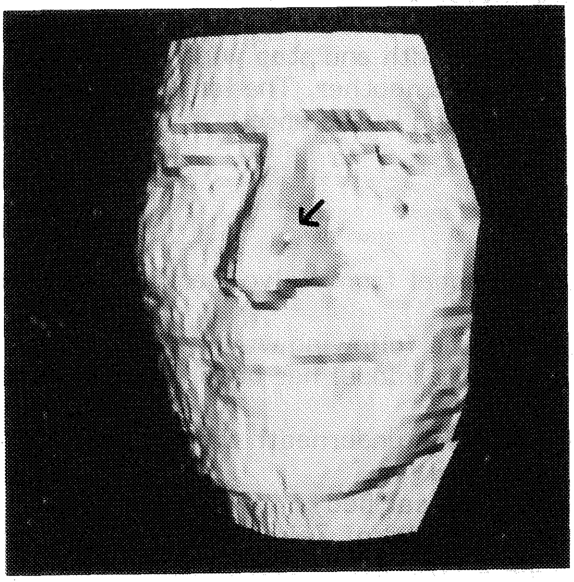
6. Experiments and results

6.1. Introduction

Two experiments will be described. The first one concerns the measurement and 3D reproduction of the human face. This experiment has been described in detail in (Vergeest et al, 1987). Therefore only a summary of this experiment is given. The second experiment concerns the measurement and 3D representation of a part of a car model from Volvo Car B.V., The Netherlands. Applications of photogrammetry in the automotive industry are described in for example (Wahl, 1983).

6.2. Face measuring and replication experiment

Two faces are photographed with a Hasselblatt camera.
The photographic data are: b/h = 0.25, c = 100 mm, photo scale 1:10.
As control points for the absolute orientation are used the outer eye corners (x, y, z) and a point on the chin (z).



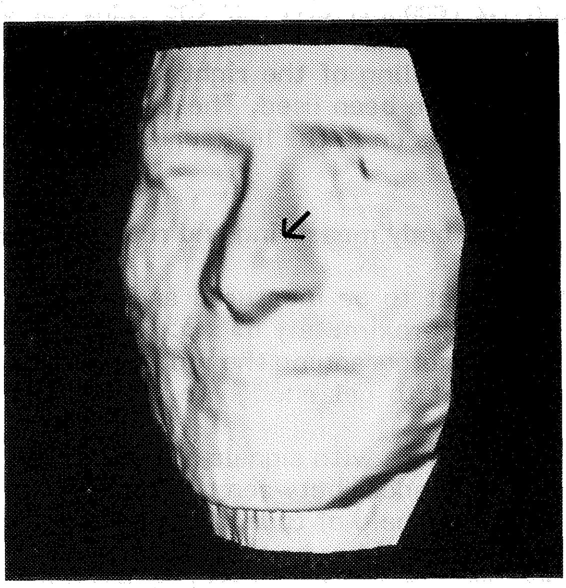


Fig. 3. Shaded images of a human face.
Left: B-spline surface of degree 1.
Right: B-spline surface of degree 3.

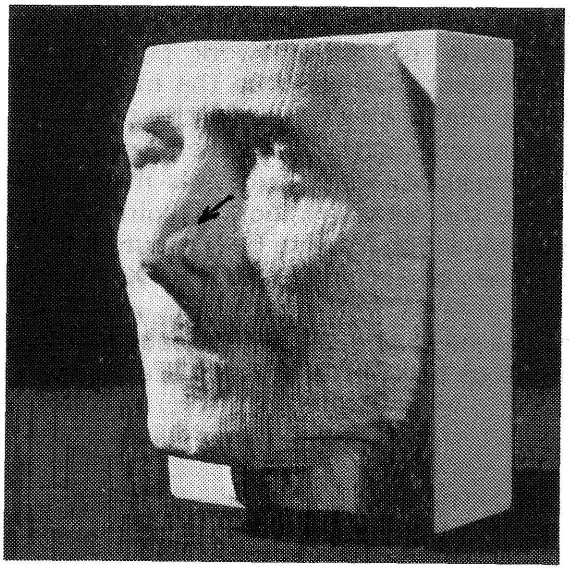
 

Fig. 4. N.C. milled surfaces of a face.
Left: scale 1:1, B-spline surface of degree 3, hard foam.
Right: scale 1:2, B-spline surface of degree 3, soft foam.

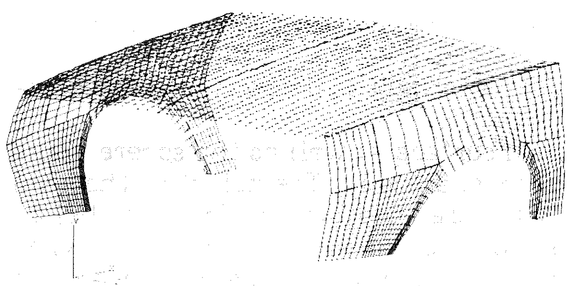
Each face has been measured from 1 stereo pair and as one patch (50 x 50 points). 3D line drawings, colour shaded images and replicas of the faces have been produced. Figure 3 shows two different representations of the same face. The pictures have been produced by photographing a terminal screen at which the faces have been generated as colour shaded images.The surfaces are generated by using B-splines of degree 1 and degree 3 respectively.. From the figure it can be concluded that when the degree of the B-spline is increased a smoothing effect takes place. Large measuring errors show up in the images: see arrows pointing to the nose.
The face surfaces of fig. 3 are also shown in fig. 4, but in this case they have been produced by N.C. milling. For both surfaces a third degree B-spline has been used for the generation of the N.C. milling data. The milling scales for left and right are 1:1 and 1:2 respectively. For the right surface more measurements have been made than for the left one.
For the milling of the right surface a smaller profile width and step width within the profile have been used. Therefore this surface is much smoother. The large measuring error shows up in the left surface only. See arrow pointing to the nose.

6.3. Car body measuring and replication experiment

The object to be measured and replicated is a car model from Volvo Car B.V. with a size of approximately 85 x 35 x 29 cm.
Before photographing the model has been prepared in the following way:
- In order to get enough texture in the photographs the model has been sprayed with powder.
- Steel strips with signals at the end points were clamped underneath the car body. The distances between the signals have been measured.
- With the help of tape, signals have been placed on the car body.

The car model has been photographed with a U.M.K. camera of Zeiss Jena.
The photography data are: C = 100 mm; photo scale = 1:14; B/H = 0.6; overlap 60%.
Two stereo models have been used to digitise a part of the car model. The first stereo model contains the car roof and the car hood. In the second model the wheel housing

and the car doors can be measured.
The absolute orientation of the first model has been carried out by using the signals on the steel strips. After the orientation the y-axis of the chosen coordinate system is perpendicular to the car bottom and the x-axis coincides with the centre line of the car roof.
Signals measured in the first model have been used as control points for the absolute orientation of the second model. The standard deviations computed from the residuals after absolute orientation are for x, y and z: 0.15 mm, 0.30 mm, 0.21 mm.
The car model surface points are measured as described in chapter 5. The total number of points is 1600. The point location is given in fig. 2.
For the representation of the whole car in 3D only half of the car needs to be digitised. This is made possible by the favourable choice of the coordinate system. To get the coordinates of the other half, only the sign of the z-coordinate has to be changed.
Figure 5 shows at the left side a 3D-line drawing of the measured part of the car hood and the wheel house. At the right sight the same surface is shown as shaded image.



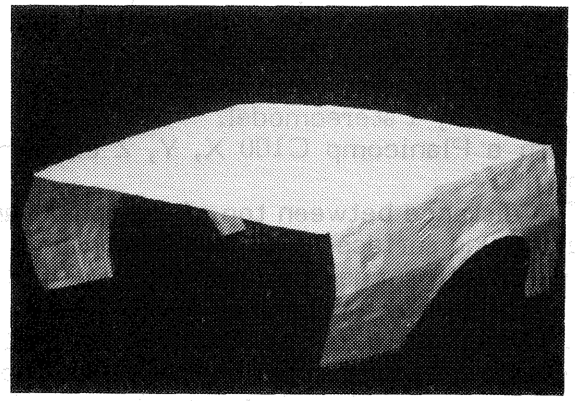


Fig. 5. Measured car model part
Left: Line drawing. B-spline surface of degree 1.
Right: Picture of colour shaded image. B-spline surface of degree 1.

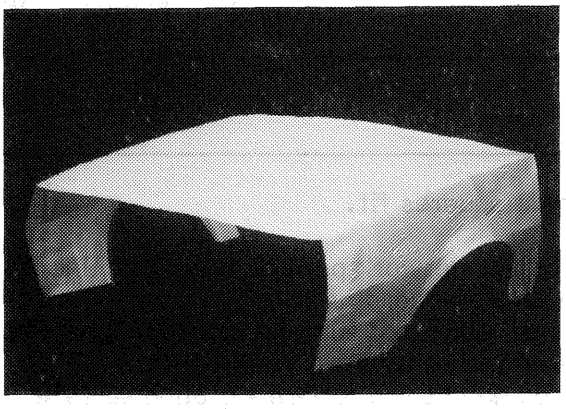


Fig. 5. Measured car model part
B-spline surface of degree 3.

The surfaces are here represented by B-spline surfaces of degree 1, which results in a bilinear interpolation of the measured data. From the shaded image it can be derived that measuring errors perpendicular to the surface cause surface irregularities.
The same surface as in fig. 5 is shown in fig. 6. But in this case the surface is described by a B-spline surface of degree 3.
From figures 5 and 6 it can be concluded that, incrementing the B-spline degree smoothes away part of the random errors, without changing the shape characteristics.

7. Precision of surface replication by CADAMP

To evaluate the precision of surface representation by CADAMP the following method has been applied. With a networks of 24 points a semi sphere with a radius of 83.33 mm has been defined. By the CADAMP software the spherical surface is described by a cubic B-spline surface.
The surface has been milled in hard foam by using a profile width of 1 mm and steps of 1mm in each profile. The diameter of the drill is 10 mm. The drill has a spherical cutter head. With a pen rows of points have been marked on the milled surface.
The sphere has been photographed together with a grid at the background with a U.M.K. camera of Zeiss Jena.
The photography data are: C = 100 mm, B/Z = 0.3, photoscale 1:14. The sphere is covered by 1 stereomodel.
With a Planicomp C100 X, Y, Z coordinates are determined of the marked surface points.
The distance between top of the sphere and ground surface as well as the sphere width at ground surface level have been measured also mechanically. The height of the semi sphere determined by photogrammetry differs not more than 0.2 mm from the height determined by mechanical measurement. In order to determine how accurate the X, Y, Z coordinate data set produced by photogrammetry, describe a true sphere a least squares fit program has been applied. The unknown X_0, Y_0 Z_0 centre point coordinates and radius r of the sphere are computed by the program. Also the residuals
$dr = (sgrt\ (X-X_0)^2 + (Y-Y_0)^2 + (Z-Z_0)^2) - r$ and the standard deviation of the radius sr are part of the output.
In table 1 the results of the computations are summarized.

N	R(mm)	n	r(mm)	h(mm)	Wm(mm)	sr(mm)
24	83.33	50	83.69	83.1	83.4	0.27

Table 1. Results of the least squares fit.

In table 1: N = number of network points of the B-spline surface.
R = sphere radius according to input
n = number of measured surface points by photogrammetry
r = computed radius by least squares fit
h = measured height top sphere - ground surface
Wm = mechanically measured width
sr = standard deviation of the radius of the milled sphere

The following conclusions are drawn from table 1:

The following conclusions are drawn from table 1:
- The difference between the theoretical radius R and the radius r determined by the least squares fit is 0.4 mm or 0.5% R.
- The differences between the measured height and width of the milled sphere and the theoretical radius R are respectively 0.2 and 0.1 mm.
- The standard deviation sr of the computed radius r is 0.27 mm or 0.33% R.

The following error sources contribute to the standard deviation sr:
1. Surface representation by B-splines. B-splines can only approximate a sphere. The approximation depends on the chosen network configuration. In this case only the distance between top sphere and ground surface, derived from the network coordinates will be exactly reproduced.
2. Milling errors. The diameter of the drill is 10 mm, which causes milling errors at sudden surface changes. Comparable with orthophoto production also profile width (1 mm) and point steps in the profile (1 mm) cause milling errors.
3. Photogrammetric measuring errors. According to experience a standard deviation of 10 microns at photo scale can be used. This means that if only photogrammetric measuring errors are assumed the standard deviation of the computed radius would be equal to 0.14 mm.
   This implies, by the Law of Error Propagation, that the errors caused by the B-spline surface representation and by milling cause a standard deviation for the radius equal to 0.23 mm or 0.27%.

8. Further research

On several points, improvements of the measuring replication system are imaginable. In this chapter we indicate some possibilities of smoothing the data points, of which is known that their precision is finite. This we achieved with the program SURFIT, developed for use in connection with CADAMP. SURFIT essentially produces from a set of measured profiles a B-spline surface (patch), which approximates every measured point better than a tolerance distance, given by the user in advance. Each B-spline surface thus found is treated further in the same way as described in previous chapters. This method offers in principle the following benefits:
- The systematic deviation between B-spline control points and B-spline surface disappear. Only a deviation less than the specified tolerance remains.
- It is no longer required that each profile contains the same number of data points. Depending on the local surface complexity any number of measured points between 2 and 99 may be chosen, for each profile independently.
- SURFIT searches for the B-spline surface with the smallest number of network points under the constraint set by the tolerance value. This sometimes results in a representation with fewer data than the original amount of measured data.
- In many cases measurement inaccuracies are partly smoothed away.

During tests with SURFIT, one of the results was that the car motor hood digitized at 666 points could be approximated within 2.5 mm by a cubic B-spline surface with a network of only 132 points. At the same time irregularities in the shape were decreased. Further investigations will be made on more advanced parametric surface fitting including 3D high frequency surface curvature reduction.

9. Conclusions

We have demonstrated that a photogrammetric measuring system can be well coupled to a CAD system (CADAMP). The combination thus created offers valuable graphical presentation and physical reproduction possibilities. The measuring methodology and digitizing control software have been optimized for fast acquisition of the data in a suited structure. The CADAMP system can display either directly the measured data, or smooth B-spline surfaces generated from it. The measured 3D shapes can be replicated in hard foam automatically by NC milling. The overal accuracy of the reproduction system has been determined to be better than 0.3%. If the measured object has a relatively flat shape characteristic, the CADAMP software is able to smooth away a part of the random measurement errors.

10. Acknowledgement

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