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NEW SURFACE FITTING APPROACH IN REVERSE ENGINEERING OF SHEET METAL PARTS

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1. Introduction

The industry's need for accurate object acquisition to be used both in product design and manufacturing has widely increased the development of 3D shape measurement systems. They are necessary for digital restitution to be applied in reverse engineering process whenever product optimisation or benchmark is required, and may allow in line inspection for quality monitoring.
Among them optical techniques in comparison with other systems like co-ordinates measurement machines (CMMs) present the advantages of higher speed, good accuracy and low cost [Chen 2000]. For these reasons they are becoming more and more popular, achieving large field of applications related to geometrical feature recognition for robot control, obstacle detection sensor and cinematic problem assessment.
A successful adoption of optical shape measurement concerns with sheet metal stamping quality control for in line monitoring of panel shape. In this kind of application different types of defects may arise both during forming phase and during assembling. Generally speaking we can distinguish between structural and aesthetic defects. The first group is related to the forming strain path and affects the structural functions of the component (necking may lead to rupture, flat to low resistance in case of denting, wrinkles to assembling problems). The second one consist of "cosmetic faults" of the final expected shape that influence the appearance of visible parts [Altan 97].
Wrinkles together with a large part of aesthetic defects are included in the shape problem category. Among them main differences are related to the amplitude of the surface deviation and to its positioning on the component. So on a stamped component very small regular waves can be found, typically in corners with small radius, or buckles with a less linear trajectory, identified by a single curvature with higher amplitude (it could be 3 mm up to 10 mm). Another kind of shape defect may be depressions or embossments, called *teddy bear ears,* with a depth of less than 1 mm (generally in the order of 1/10 mm), and puckers. They produce undesirable corrugations on the wall of a drawn shape which has passed over a radius of the die. It is clear that the painting may increase part of the aesthetic impact of these defects so, to reduce the amount of scrap and the economic loss, their detection is recommended in the early production chain.
At present, the state-of-the-art in stamping quality monitoring is typically committed to human eye inspection, so automated solutions started to be discussed both in research and industrial community. One of them has been proposed and developed within an EU BRITE research project, known as DIGIMAN. To fulfil several requirements regarding shape complexity, surface reflectance and the specific environmental conditions of the press shop, such as lighting and vibrations, the optical device has been based on the structural light approach. To orient this device towards in line monitoring the output measure represents the shape deviation of the current panel in the respect of the target shape of a faultless one. To get an immediate evidence of the deviation it is projected in terms of contour plot

directly on the analyzed part [Broggiato 2001].
With this statement it seems clear that the absolute shape evaluation did not represent the final goal of the DIGIMAN project, nevertheless the developed system is able to evaluate it and with further research activities, in particular on the data manipulation, its capability and use may be improved. More in detail it may be enhanced to become a powerful tool for die design and set up by means of integration the cloud analysis with RE systems, allowing CAD/real part comparison.
This paper aims to present some new results related to the adoption of the optical device previously mentioned. More in detail it is focused on the discussion of surface reconstruction techniques, developed to enhance the system capability.
The object representation in many RE commercial software (see e.g. Geomagic Studio® by Raindrop Geomagic, Points2Polys® by Paraform or Cocone® by Yjamiti) is usually performed fitting a triangular mesh to point cloud using the 3D position of points. Then, the mesh may be converted in parametric surface patches (Bezier, B-Spline or NURBS) to get a smooth surface representation of the part.
The authors present an alternative technique to quickly get accurate results in the shape reconstruction and investigate the surface in terms of maximum deviation, curvature, smoothing. The geometric typology to be analysed and the matrix-like structured range data allow performing surface reconstruction using specific routines optimised also for large set of data defined on a rectangular domain.
In the next paragraph a brief overview of the experimental device is given focusing its actual status, then in the next section the fitting process is presented and discussed in the respect of sheet metal stamping components.

2. Shape acquisition device

The shape acquisition device built up for panel quality analysis is an optical system based on the structure light approach, joining together *gray coding* and *phase shift* methods. The first one allows a rough but speed measure of the shape while the second is able to improve the final accuracy that has been estimated of about 1/25000.
The hardware consists of a 1280×1024 pixel CCD camera, a LCD projector and a personal computer equipped with a Matrox Meteor II® frame grabber to convert the camera analog output into digital black and white images. The camera is mounted about one meter far from the support with its CCD plane parallel to the reference. The projector is inclined with respect of the direction between the camera and the part. The acquired area can be set to 400×300 mm or 520×390 mm by changing the lenses. A support frame for the component has been built onto the reference plane to allow repetitive positioning. The PC simultaneously drives the camera grabs and the LCD projection on the part.
During the gray code phase different images of the part are taken projecting black and white fringes with halved pitches. Because of the angle that exists between the LCD projector and the camera, a generic point of the shape (or pixel of the camera) will be black or white according to its position on the part. Analyzing the pixel status (black or white) of each image a binary code is obtained, by an *ad hoc* calibration procedure this code may be translated into a 3D position of the point.
The results are then improved according to the phase shift procedure: the fringes change from stripes to sinusoidal pattern, with amplitude equals to the half of the last one used in the gray code projection. This projection is then repeated varying the fringe phase so they appear shifting on the part. In this case a generic pixel of the images, saved during these projections, presents a sinusoidal pattern of gray values with a frequency equals to that one of the fringes and a phase angle that is a function of the space position that is associated to the pixel.
Iterating the procedure for each pixel of the CCD a point cloud is obtained. It is referred to CCD dimensions and to fringe pitch and projection angle. This means that x and y are given in pixel, while the elevation values, z, are evaluated in terms of phase angle. Nevertheless, after an accurate calibration, the shape geometry profile could be correctly measured. In particular, the z scale factor can be easily evaluated moving the reference plane a few millimeters toward the camera and computing the phase angle difference for each pixel; this approach has been used to quantify the shape deviation between two components. Applying more accurate calibration procedures to the whole

measurement volume, the co-ordinates of each surface point may be evaluated in an orthonormal reference system.

3. Mathematical background

As the proposed approach uses NURBS curves and surfaces to reconstruct the shape of the part by fitting approximation methods, in the following a brief overview of the main aspects of the NURBS and fitting criteria will be presented to understand the underlying theory. For brevity and simplicity, we restrict our discussion to curves, but similar statements and algorithms hold for surfaces. For more details see [Farin 1990, Dierckx 1996, Hoschek 1993, Piegl 1997].

3.1 About NURBS

A *NURBS* (**N**on-**U**niform **R**ational **B**-**S**pline) geometric entity is mathematically defined by parametric ratios of *B-Spline polynomials*. Given n+1 *control points* P_i, the general form of a NURBS curve is [Piegl 1997]:

$$f(t) = \frac{\sum_{i=0}^{n} w_i N_{i,k}(t) P_i}{\sum_{i=0}^{n} w_i N_{i,k}(t)} \qquad a \leq t \leq b \qquad (1)$$

where the points P_i define the *control polygon* of the curve, w_i are *weights* associated to each control points and $N_{i,k}$ are the k*th*-degree *B-Spline basis functions* defined using the recurrence formula:

$$N_{i,0}(t) = \begin{cases} 1 & if\ t_i \leq t \leq t_{i+1} \\ 0 & otherwise \end{cases}$$

$$N_{i,k} = \frac{t - t_i}{t_{i+k} - t_i} N_{i+k+1}(t) + \frac{t_{i+k+1} - t}{t_{i+k+1} - t_{i+1}} N_{i+1,k-1}(t) \ . \qquad t_i \leq t \leq t_{i+k+1} \qquad (2)$$

$N_{i,k}$ has the general polynomial form:

$$a_1 + a_2 t + a_3 t^2 + \ldots + a_{k+1} t^k$$

then it has C^{k-1} continuity at each t_i. Moreover, $N_{i,k}$ is zero outside the interval (t_i, t_{i+k+1}) and is so normalized that

$$\sum_{i=0}^{n} N_{i,k}(t) = 1\ . \qquad t_k \leq t \leq t_{n+1} \qquad (3)$$

NURBS are, therefore, represented as polynomials pieced together at some breakpoints with some level of continuity between them. The breakpoints t_i are real numbers, named *knots*, and their non-decreasing sequence is the *knot vector* of the function *f*(t). NURBS have several advantages with respect to other polynomial entities, such as the local control of the curve (moving a control point will affect only a limited region of the geometry) and the possibility to introduce new control points without increasing the polynomial degree k, in such a way to have more degrees of freedom.

The scalars w_i have an important role when local changes have to be applied to the curve: by varying the weights the curve will be pulled toward or pushed away the corresponding control point. Control points together with the knot vector define the shape of the curve. For an open curve a *non-uniform knot vector*, with m+1 knots and m = n+k+1, has the form:

$$T = (\underbrace{a, a, \dots, a}_{k+1}, t_{k+1}, t_{k+2}, \dots, t_{m-k-2}, t_{m-k-1}, \underbrace{b, \dots, b, b}_{k+1}) \quad (4)$$

with the first and last k+1 knots equal to the end values of the parametric interval [a,b], usually set to [0,1], and the *interior knots* are not equally-spaced. The first condition assures that the curve passes through the first and last control point, while the second condition gives more degrees of freedom to the curve, i.e. it is possible to change the shape of the curve by moving the interior knots. More knots will be localized where more complex shape occurs. This allows the NURBS to represent a wide set of geometric entities, including conics. An *uniform knot vector* means that the interior knots are uniformly spaced. If all the weights are equal to 1, then, for the property (3), the equation (1) represents a *B-spline* curve:

$$f(t) = \sum_{i=0}^{n} N_{i,k}(t) P_i \, . \quad (5)$$

3.2 Curve and surface fitting

Fitting problems generally consist in the construction of curves and surfaces which fit a given set of points, with eventually additional geometric data, such as derivatives or curvatures in some points. There are two different types of fitting: interpolation and approximation. Interpolation requires to find a curve/surface passing "through" the given points, while approximation requires to find curve/surface passing "near" the given points and minimizing a prescribed error, e.g. the minimum distance between points and curve/surface. Approximation should be used when the data to be fit comes from measurement devices, because in this case a large number of points are available and some noise in the data occurs due to the device limits. Therefore, it is important in such a case to capture the shape of the curve or surface. When spline entities, such as B-Spline or NURBS (for brevity, simply spline in the following), are used to fit data, the parametric approximation problem is usually posed as a *least squares problem* [Hoschek 1993]: given p+1 points Q_i to be approximated, with associated parameters $\bar{t}_i$, find a function *c*(t), e.g. in the form (1) or (5) for spline curves, which minimizes the overall error:

$$d = \sum_{i=0}^{p} \left(c(\bar{t}_i) - Q_i \right)^2 \omega_i \quad (6)$$

with ω_i positive weight assigned or to be assigned to each given point Q_i.

The inputs to the approximation problem are usually points, the error bound and the degree of the curve. The outputs will be a set of control points, the knot vector and weights. The user can enter the latter two sets of parameters or the algorithm must calculate them. The solution is obtained with an iterative method, because is not known in advance how many control points are required to reach the desired accuracy.

The choice of parameterisation of the given points Q_i and the number and distribution of the knots in the knot vector are two critical aspects, and in the literature no criteria is available to decide in advance which approach will yield the "best" fit for a particular data set [Hoschek 1993]. Among the common methods of choosing the parameterisation of the points, the *centripetal* method gives generally best results [Lee 1989] and it has been used in the proposed approach. Assuming (4) as the form of the knot vector and starting from the set of parameters assigned to the given points, the choice of the interior knots of (4) may be done considering the mean values of the entered parameterisation. This method gives good results in the interpolation fitting, but it can be used also in approximation fitting if not too many points are to be fit. More strategies are available in [Dierckx 1996] to choice the internal knots as first guess. If the desired accuracy is not met, a new distribution is adopted moving knots toward the zones where the fit is particularly poor, and the resolution of the equations (1)-(6), or (5)-(6), is repeated. When the weights ω_i in (6) have to be calculated by the algorithm, some statistical information on the data distribution may be used to assign a value to each ω_i. More often they are set to 1.

The least squares criterion in (6) does not guarantee that, due to the noise in the data set, the obtained solution will not have an unexpected local shape, such as wiggles. To avoid this inconvenient a smoothing factor must be taken into account to smooth the spline especially where more noise occurs. The approximation fit problem may be then posed as a *smoothing problem* [Dierckx 1996]: given p+1 points (x_i, y_i), i=0…p, find a spline *s*(t) which minimize

$$\eta := \int_{x_0}^{x_p} \left[D^l s(t) \right]^2 dt \qquad (7)$$

subject to the condition

$$\delta := \sum_{i=0}^{p} \left(s(x_i) - y_i \right)^2 \omega_i \leq S \qquad (8)$$

with S *smoothing factor* specified by the user. In (7) l is usually set to 2 or 3 for cubic or quintic spline respectively. Therefore, the problem is to find a compromise between a *smooth behaviour* (given by η) and an enough *closeness to fit* (given by δ).

4. Fitting of sheet metal components

In sheet metal part reconstruction from point acquisition an high accuracy of the fitting process is required to capture the real shape of the component and its defects, considering that some errors occur for the intrinsic limitation of the measurement device. This means that the interpolation fitting approach is not appropriate for this analysis to avoid unwanted wiggles. Moreover, the least squares criterion alone could not result in the natural shape of the part. In such a case the smothing criterion should be adopted so that the reconstruced surface looks smooth enough.

Several approximation techniques could be used to fit curves/surfaces to a data set but the final results will be strongly affecetd by the adopted algorithm.

This section concerns with the application of an efficient technique to get accurate results in the shape reconstruction using some of the algorithms introduced previously.

In fact, the matrix-like structure of the acquired point cloud, with points equally spaced in x and y directions, offers the possibility to reconstruct the surface patches following two different approaches. (I) Fit curves to the sets of aligned points and then blend a surface onto that curves (blending or lofting surface); (II) Fit a surfaces on the whole point data set. Both fitting approximations have been carried out in the (7)-(8) fashion.

Generally speaking, the first approach is easier to perform because of the wide diffusion of many robust routines for 2D curve fitting that work also in automatic way, and also because of the availability, in the most of CAD systems, of blending or lofting functions able to create a surface interpolating a set of curves with an imposed high global accuracy. It also permits to fit tight curves to the point data where feature variations occur. The main drawbacks consist in long working time, especially when a very dense point cloud is given, and in the limit of the number of curves to be blended in a single surfacing task. When several blending patches are used, more work is needed to guarantee the C^2 condition along the common edges.

The second approach requires a more complex algorithm to surface the 3D point cloud directly. In general it does not give as the same high global accuracy as in case of curve fitting, especially in the approximation problems, but allows to take into account a smoothing factor on the whole data set. This is very useful when more noise is expected on the acquired data.

To perform this analysis the Spline Toolbox of Matlab® [de Boor 1999] along with the FITPACK free software package by Dierckx [Dierckx 1996] have been adopted to get a detailed control of the shape and check the maximum approximation error. In particular, CURFIT and REGRID routines in FITPACK have been used in curve fitting and mesh data fitting respectively.

The proposed approach has been applied to the sheet metal component shown in Figure 1 in terms of

point cloud. The exaggerated scale adopted in the figure shows better the main features to be investigated through the reconstruction of the surface. The scattered points around the flanges correspond to the bad data acquired by the optical device that must be deleted. The original data set consists in 125440 points then filtered to 7840 points to make the calculation easier.
The CURFIT software gives the possibility to create a curve with different smoothing factor S, including the interpolating curve when S=0, as well as the curve with η=0 (see (7)), i.e. the weighted least squares polynomial of degree k when S is very large. This approach is conduit in a *trial and error* way until the expected shape is returned. To make this step faster and the results more accurate, the CURFIT routine has been integrated in the Matlab environment with Spline Toolbox, which offers several commands to graphically change knots and weights, as well as the possibility to compare different solutions in terms of local and global returned accuracy. Cubic entities (k=3) have been adopted in the reconstruction of curves and surfaces.

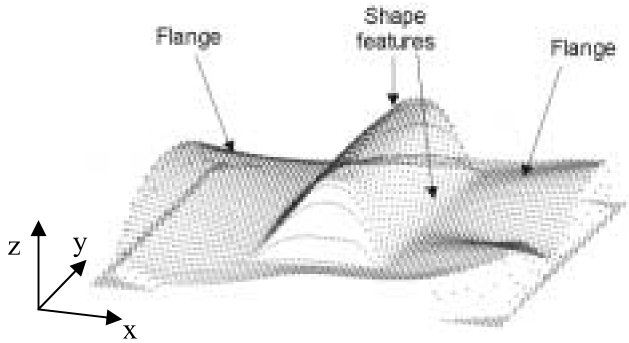

Figure 1. Acquired point cloud of the analysed sheet metal part

Figure 2 shows a detail of curves, for two sets of points, taken out from the zx section plane, obtained with different S values. As some noise occurs in the point data, the interpolating fitting does not return the expected shape.

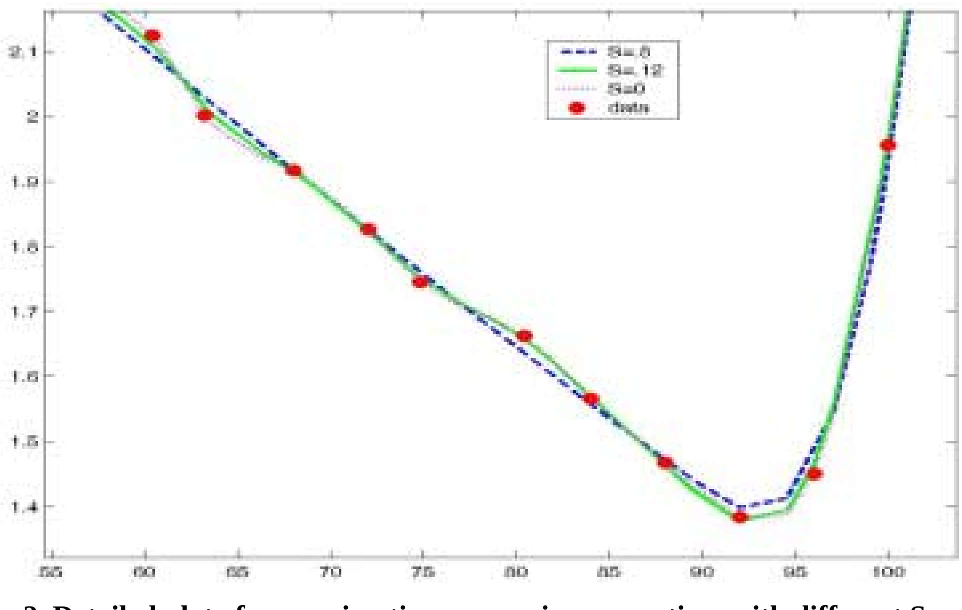

Figure 2. Detailed plot of approximation curves, in a zx section, with different S values

On the other hand, a small smoothing factor has been found to be good enough for all the curves because of the global pretty good accuracy of the scanned data.
Some changes have been made in CURFIT to allow the parameterisation of the given points with *centripetal* method, which gives better results than the commonly used *chord length* method, especially when the data takes very sharp turns [Piegl 1997]. Regarding the strategy for locating the knots of the spline, the original algorithm used in CURFIT has been adopted. It starts calculating the

weighted least squares polynomial of degree k without interior knots. Then more knots will be added in those intervals where the fit is poor, until the condition on S is satisfied. Once a spline is calculated, with a given number of knots, a different (sometime better) distribution of them has been reached with the Matlab command *newknt*.
To reconstruct the whole part geometry a lofting surface through 70 curves has been created in Rhino3D® CAD system and the final result is shown in Figure 3 in terms of two-color zebra strip plot, giving an idea of the curvature.

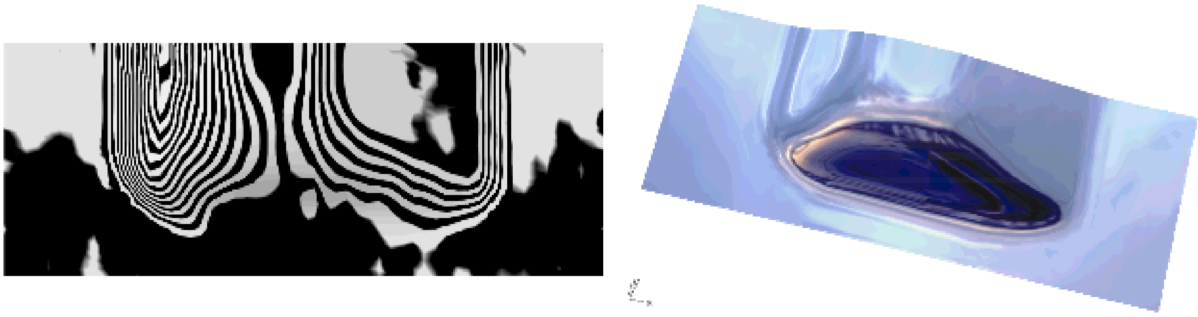

Figure 3. Zebra-strip plot and shaded view of a part of the loft surface in Rhino3D

The same considerations made for curves hold for surfaces. Here a bi-cubic NURBS surface has been created on the whole data set by means of REGRID routine. Some results are shown as contour plot in Figures 4. The comparison of the result obtained with the two approaches shows that the quality of the final surfaces is almost equal, even though the loft surface appears to be a little less smoothed. This strongly depends on the blending function that, in case of many curves to blend, may add inaccuracy.

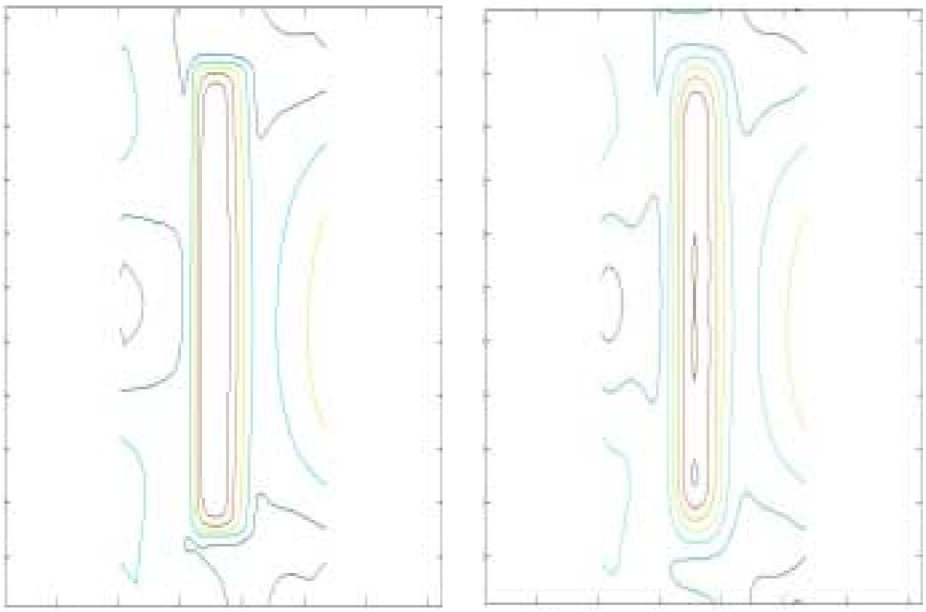

Figure 4. Contour plot of the whole NURBS surfaces, respectively for S=0 and S=.8

5. Conclusions

This paper is aimed to discuss some fitting strategies to surface reconstruction from a point cloud obtained by an optical shape measurement system. More in detail it assesses a NURBS based procedure to smooth the experimental data with higher accuracy, with the aim of guarantee a clear evaluation of panel defects that may occur during sheet metal forming.
Both suggested methods allow to reconstruct the whole surface reflecting the real shape of the acquired object. For the used measurement optical system a small smoothing factor has been found to

be adeguate to reach a compromise between the closeness to fit and the smoothing behaviour of the surface. Moreover, this procedure, offering the mathematical definition of the curves and surfaces, gives a total control of the shape allowing to investigate any geometric characteristic such as the global or local error, the first and second derivatives as well as the gaussian and mean curvatures.
The main drawback of the surface fitting approach on mesh data is that it is always defined on a rectangular domain. When a non-rectangular domain B is specified, it is possible to define a rectangle A containing B and then determine a spline approximation on A. To complete the region A the unknown points closer to the boundary of the region B can be obtained based on the discrete first derivative of border points of the region B. This approach is useful when relatively a few points have to be added to the given region. Otherwise, a specific more complex and time consuming algorithm for scattered data approximation, such as the one proposed by Dierckx, must be used.

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