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Free-form Surface Generation from Measuring Points using Laser Scanner

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ABSTRACT

With the development of a laser scanner of high precision and increased speed, reverse engineering becomes a key approach to reduce the time for the development of new products. But the modeling process is not so automated enough until now. Modeling in real workshops is usually performed by the experienced operators and it requires a skillful technique to get the resultant surface of high quality and precision.

In this paper, a systematic solution is proposed to automate the free-form surface generation from the measured point data. Compatibility is imposed to the measured point data during input curve generation. And the compatibility of cross-sectional curve is also considered for the loft surface generation. The data in each step is produced in IGES file format to make an easy interface to other CAD/CAM software without any further data manipulation.

Keywords : Reverse Engineering, Laser Scanner, Compatibility, Input Curve, Polygonal Chain, B-Spline Curve, B-Spline Surface, IGES

1. Introduction

Reverse engineering produced CAD data for manufacturing after measuring a real part. To reduce the time for the development of new products and the manufacturing process efficiently, this technique is important these days in real workshops. Ordinary objects in reverse engineering appear as raw parts without any CAD data or prototypes made from clay, wood, and plasters. And 3 dimensional CAD data are generated through the measurement and modeling process.

CMM (Coordinate Measuring Machine), laser scanner, and CT (Computer Tomography) have been used for measurement, and a laser scanner, a non-contact measuring machine, is currently used a lot. It has a great advantage in fast measuring speed and high precision, and line-typed point data make it easy to model surface with cross-sectional curves.

But there are some defects. First of all, additional sampling process is needed to represent the feature exactly with reasonable number of data because too many measuring data cause some problems during modelling process. And the registration process is needed to put together all the local coordinates in each direction when it is impossible to scan an object only in one direction. Polylines which are not perfectly merged are found in some regions according to the characteristics of a laser scanner.

Most of researches in reverse engineering has been focused on the development of measuring machine, data acquisition, the surface generation, and the improvement of surface quality.

Data acquisition in reverse engineering by contact and non-contact measuring machine was compared and the real problems during measurement were examined [1]. And some issues on creating B-rep models were described through characterization of geometric models, segmentation and surface fitting.

Kruth[2] generated surfaces by putting together several surfaces from CMM point data subject to boundary conditions. The boundary conditions for NURBS curves and surfaces to join with positional, tangential and curvature continuity were described, and the conditions were imposed in the surface fitting process.

Piegl[3] introduced an algorithm to impose the compatibility of cross-sectional curve during NURBS skinning and eliminated the problem of lots of control points when users specify tolerances in approximation.

Werner[4] presented the whole processes of the free-form surface in reverse engineering. An integrated solution for measurement and geometric modeling of free-form surfaces was introduced, and the machining errors in CNC milling machine were compensated by the comparison of the error between the machined surface and the theoretically-determined surface.

Vision system and its technique has been used to divide scan data into several regions. The edge operators in computer vision technique were used to detect a change in shape and surfaces were generated in each divided regions[5]. Vision system was also used to obtain geometric data for boundary detection and surface segmentation[6]. These data were combined with the data from CMM and surfaces were generated according to the sectional curve.

Some artificial intelligence techniques have been applied to generation of surfaces. Genetic algorithm was used for the triangulation of scan data for the optimized STL data[7]. A weighting scheme was used to arrange all triangles in a priority order and a user can specify the amount of triangles to be removed. Neural network was used to reconstruct and repair an existing freeform surface[8]. The points from networks were compared with the points on the known surface, and the points generated by the trained network were used to generate toolpaths for machining the surface.

Previous researches on CT image have been focused on the shape reconstruction[9,10].

In this paper, a method is proposed to generate a loft surface efficiently and rapidly. Point data are measured from a laser scanner, and cross-sectional curves and the resultant surface are generated from the data. The compatibility algorithm is presented to generate input curves and surfaces efficiently.

To verify modeling error, prototypes are machined in NC machines and built from RP equipment, and compared with an original model. And the input data and the generated surface are represented in IGES format, thus they can be supplied to other CAD/CAM software without any data manipulation. Fig. 1 shows the overall flowchart proposed in this paper for the generation of the free-form surface.

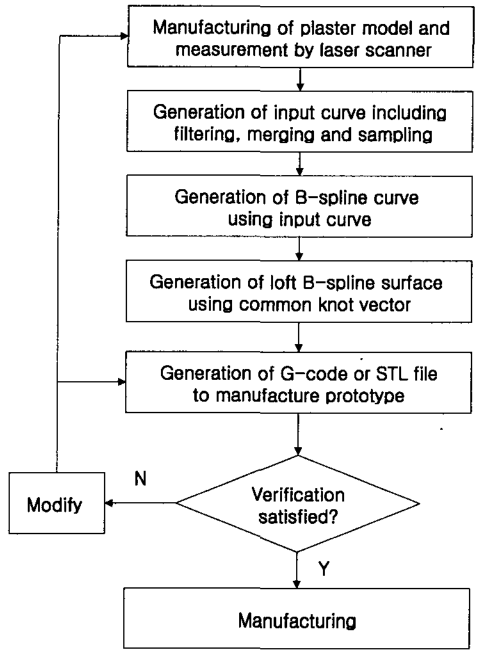


Fig. 1 Overall flowchart

2. Compatibility of measured point data

The process to maintain the compatibility of measured point data includes noise removal, smoothing and filtering of scanned data. The next step includes polyline generation, search and removal of polygonal chain, and sampling with reasonable number of points which represent the feature exactly.

2.1 Preprocessing

Data from a laser scanner are composed of a number of point data where some noise components are globally distributed which comes from surface quality and laser dispersion. Noise removal, smoothing and filtering of scanned data should be done to prevent any problem in the next steps. And point data are connected to form a polyline following Y direction in Fig. 2 which is perpendicular to the main movement of scanning probes in Surveyor 1200. This preprocessing is a difficult and tedious job for a user to implement, but most laser scanning systems support a software to deal with it. So the preprocessing can be implemented according to users's purpose.

Fig. 2 Laser scanning and X,Y,Z axes

2.2 Generation of connected polyline

To form fully-connected polylines, each scanning line should be installed in the same position following Y direction during scanning process, which is essential for loft surface generation from cross-sectional curves. But some regions where point data are not connected automatically as shown in Fig. 3 can exist due to the characteristics of a Cartesian-typed laser scanner.

Polylines with the same X coordinate should be searched and put together to connect at regular intervals. Sequential connection of polylines generates one fully-connected polyline in which no point data are overlapped, thus the troubles of manual connection can be reduced.

Point data can be overlapped in the region where several polylines along the Y axis exist. If they are not overlapped as shown in Fig. 3, the merging process is just to link them sequentially.

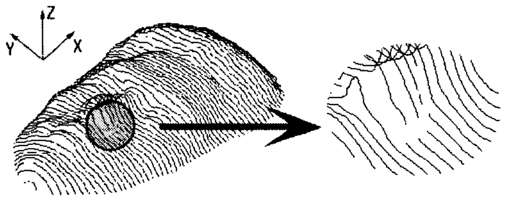


Fig. 3 Polylines which are not perfectly merged

If point data are overlapped in the region where several polylines with the same X coordinate exist as shown in Fig. 4, the merging process in Fig. 5 is needed to represent all overlapped region.

To connect two overlapped polylines, the first overlapped point(P5) moves to the centroid (P5') of a triangle of P2, P3, P5. And the next point(P3) moves to the centroid(p3') of a triangle of P5', P3, P6. This process is repeated to the last overlapped point(P4), so one polyline(P1, P2, P5', P3', P6', P4', P7, P8) is generated.

This process is performed correctly when many point data exist in the overlapped region. In the case of a few point data, some edges to represent characteristic feature can be distorted. In this paper, a polyline is composed of lots of pont data which are sufficient for the measuring process.

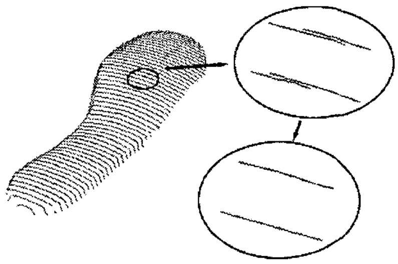


Fig. 4 Overlapped polylines

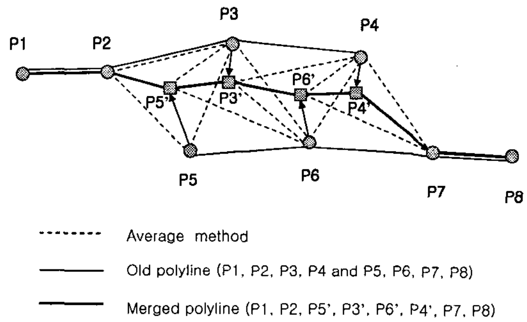


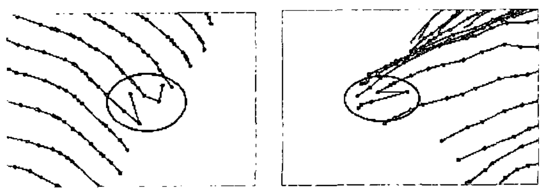
Fig. 5 Merge algorithm

2.3 Removal of polygonal chain of point data

Polygonal chain of point data makes a bad effect on surface modeling because unbalanced coordinates and parameters can cause a wiggle on cross-sectional curves.

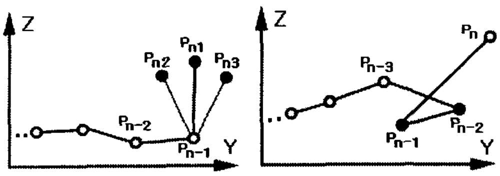
Polygonal chain can be found by searching all point data sequentially and checking a region where the sign of a curvature along Y axis changes. That region means the place where the Y coordinate of a point decreases while other Y coordinates show a tendency to increase. After finding polygonal chain, some points for removal should be decided the relation between points around polygonal chain.

Unskillful operation of a laser scanner and bad surface quality cause the polygonal chain especially at the end edge of surface. Polygonal chain from real measurement appears near the end edge of surface where the last point is projected abnormally or somewhat chained as shown in Fig. 6 (a), (b).



(a) (b)

Fig. 6 Intersected polygonal chain on scan data



(a) (b)

Fig. 7 Cases of intersected polygonal chain

The type of data distribution of polygonal chain proposed in this paper is shown in Fig. 7. Polygonal chain rarely happens in the middle of a polyline, so it is supposed to happen at the end of a polyline in this paper. Pn1 in Fig. 7 (a) is almost right-angle perpendicular to previous point. P_{n2} and P_{n3} show the case of acute-angle and obtuse-angle respectively.

In the case of right-angle and acute-angle, the point is considered to form polygonal chain and should be removed. In the case of obtuse-angle, a point which forms less angle than predetermined value should be removed. Three different cases are classified in Eq. (1) with the angle between points. Y is a constant and its value is 3 approximately according to the previous experiments. Some points around the top and bottom of a polyline are searched and, if the points meet Eq. (1), then they are removed.

The case in Fig. 7 (b) can be judged by fluctuation of Y coordinate between points. If some points meet the Eq. (2), the points are considered to form polygonal chain and should be removed.

$$(|\alpha_{n-2} - \alpha_{n-1}| \le \gamma |\alpha_{n-1} - \alpha_n| \quad (1)$$

where α_n is the angle of n-th point.

$$(y_n - y_{n-1}) \cdot (y_{n-1} - y_{n-2}) < 0 \quad (2)$$

where y_n is y coordinate of n-th point.

2.4 Characteristic point sampling

To generate input curves, the points of a polyline should be reduced to reasonable number of points which represents the feature of a model. Input curves are preliminary curves for surface generation and they are composed of as many points as are enough for the feature representation. Priority in sampling process should be given to the precision, not to the number of points.

For precise sampling, characteristic points which represent the feature of a model are obtained. These points have a close relation with the angle and the distance between points. A point which makes a large angle with the previous and the next point is considered as a characteristic point and Fig. 8 (c) shows a problem when only considering angle. That is to say, distance also makes an effect on the sampling and the parameterization in curve generation.

The result of curve fitting of sampled point data in Fig. 8 is as follows:

Fig. 8 (a) shows the point data to be sampled. Fig. 8 (b) shows the curve fitting with use of all point data without sampling. Fig. 8 (c) shows the sampled point according to angle. Fig. 8 (d) shows the sampled point according to angle and distance. The curve in Fig. 8 (c), (d) is generated with use of sampled point data and this curve is used for input curve, so the sampling according to angle and distance should be adopted to represent a feature well as can be seen in Fig. 8 (d).

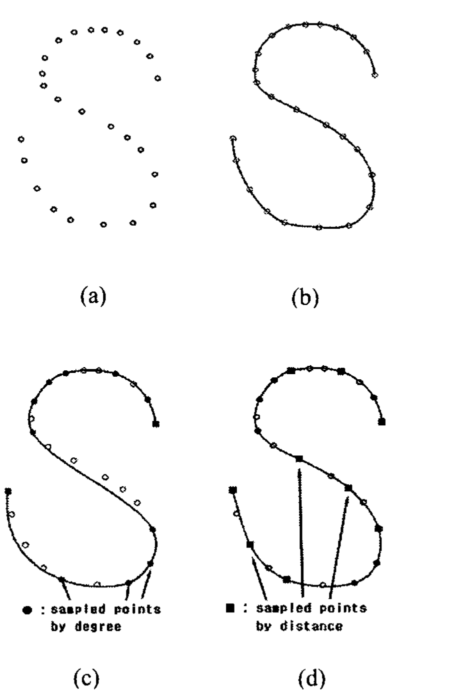


Fig. 8 Comparison of fitting result
(a) Data to be sampled,
(b)Fitting using all data,
(c) Fitting with angle,
(d) Fitting with angle and distance

3. Compatible cross-sectional curve and surface generation

Input curves are B-spline curves and are generated to pass all the characteristic points using interpolation. And the curves are changed to cross-sectional curves for surface generation if the compatibility is added. This process includes the sampling of input curves with reasonable number of points, and knot insertion and deletion for knot distribution at regular intervals. And the same degree and common knot vector are required to all cross-sectional curves for surface generation.

3.1 B-spline curve and surface

B-spline curve is a well-known form to represent a free-form curve as represented in Eq. (3) because local modification is possible and nonperiodic knot vectors represent the feature better than any other method. And control points can be added without increasing the curve degree. The B-spline basis function of p-degree is defined by Eq. (4).

P-degree B-spline curve (*C(u)*) is represented with the linear combination of the blending functions, so the control points can be obtained if a set of points, parameter value, and knot value are given.

Three common methods for choosing parameter values from input points are uniform, chord length, and centripetal. Chord length method is employed in this paper because it produces better result than uniform method in general cases and the resultant parameter values depend on the distribution of input points. Knots are defined by Eq. (6) with the average of parameters to reflect the distribution of them.

B-spline surface of degree is defined by Eq. (7) which is the linear combination of blending functions like B-spline curve.

$$C(u) = \sum_{i=0}^{n} N_{i,p}(u) P_i \ , \quad a \le u \le b \tag{3}$$

$$N_{i,p}(u) = \frac{(u-u_i)N_{i,p-1}(u)}{u_{i+p}-u_i} + \frac{(u_{i+p+1}-u)N_{i+1,p-1}(u)}{u_{i+p+1}-u_{i+1}}$$

$$N_{i,0}(u) = \begin{cases} 1, & \text{if } u_i \le u \le u_{i+1} \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$\begin{aligned} & d = \sum_{k=1}^{n} |Q_k - Q_{k-1}| \\ & \bar{u}_0 = 0 \ , \quad \bar{u}_n = 1 \\ & \bar{u}_k = \bar{u}_{k-1} + \frac{|Q_k - Q_{k-1}|}{d} \qquad 1 \le k \le n-1 \end{aligned} \tag{5}$$

$$\begin{aligned} & u_i = 0 && (0 \le i \le p) \\ & u_i = 1 && (n+1 \le i \le n+p+1) \\ & u_{j+p} = \frac{1}{p} \sum_{i=j}^{j+p-1} \bar{u}_i && (1 \le j \le n-p) \end{aligned} \tag{6}$$

$$S(u, v) = \sum_{i=0}^{m} \sum_{j=0}^{n} P_{i,j} N_{i,p}(u) \ M_{j,q}(v) \tag{7}$$

3.2 Cross-sectional curve generation

The previous input curve simply interpolates the sampled points so that as many control points as the sampled points are generated. Re-sampling of the curve which is generated from the sampled points decreases the number of control points. Thus uniform control points are obtained with improved parameterization by distributing more than one point at regular intervals.

A sampling method according to chord height is employed in this paper. Fig. 9 shows the sampled points considering chord height.

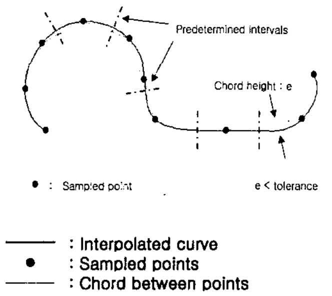


Fig. 9 Sampled points according to chord height

3.3 Compatibility of cross-sectional curve

Each cross-sectional curve must have the same degree and common knot vector for loft surface generation[9,11]. Common knot vector can be defined by getting the same number of knots and calculating their average in Eq. (6). But if the parameterization of the curve is bad, the common knot vector becomes very different from its original value so that the resultant surface has bad quality. Insertion and deletion of knot to distribute one knot at regular intervals as shown in Fig. 10 makes the knot value of each cross-section even, and the avcrage of the knot value in Eq. (8) produces good surface.

$$(u_{common})_i = \frac{1}{n+1} \sum_{k=0}^{n} (u_i)_k \quad 0 \le i \le m+p+1$$
$$(v_{common})_j = \frac{1}{m+1} \sum_{l=0}^{m} (v_j)_l \quad 0 \le j \le n+q+1 \quad (8)$$

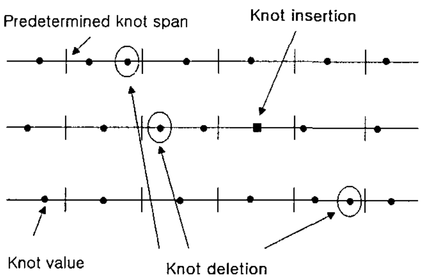


Fig. 10 Knot deletion and insertion

3.4 Loft surface generation

Surface is generated by interpolation of compatible cross-sectional curves. B-spline surface is generated by repeating the B-spline curve generation with the control points of each cross-sectional curve as input points. Eq. (9) shows the cross-sectional surface when fixing in Eq. (7). $R_{k,i}$ is the control points of B-spline surface and it is calculated by the linear combination as the same way in the calculation of control points of B-spline curve.

$$C_k(u) = S(u, \overline{v_k}) = \sum_{i=0}^{m} \left(\sum_{j=0}^{n} P_{i,j} M_{j,q}(v) \right) N_{i,p}(u) \quad (9)$$
$$= \sum_{i=0}^{m} R_{k,i} N_{i,p}(u) \qquad (k = 0, 1, \cdots, n)$$

3.5 IGES file format

IGES file format, as a neutral format, is used in most CAD/CAM systems. All input data from a laser scanner are IGES file format. The generated curve and surface are also represented in IGES file format to supply to other CAD/CAM software without any data manipulation.

Input points, entity type 106, are composed of X, Y, Z coordinates, and B-spline curve, entity type 126, is composed of degree, knot vector, weight, and control points. The B-spline surface, entity type 128, is represented with common knot vector, weight, and control point in each direction as shown in Fig. 11.

```
This is the AutoRev Program that generates B-Spline Surface.            S      1
AutoRev is made by JaeWon in 1999                                       S      2
1H,,1H;,7HAutoRev,                                                      G      1
12Hchoi_126.igs,,31HTrout Lake IGES 009 Sep  1 1998,                    G      2
32,38,6,308,15,,1.0D0,0,,1,0.01D0,13H990721.045959,0.01D0,0.1D0,,,      G      3
10, 0, 13H990721.045959;                                                G      4
     128       1       0       1       1       0       0       000000001D      1
     128       2       2       1       0                                D      2
128,29,77,3,3,0,0,1,0,0,.,.,.,.,.06897,.103495,.138035,.172575,        1P      1
.207101,.241623,.276108,.31061,.34507,.379536,.413978,.448392,         1P      2
.482755,.517102,.551523,.585971,.620446,.654997,.689535,.724121,       1P      3
.758618,.793189,.827718,.862258,.896789,.931246,1.,1.,1.,1.,.,.,.,     1P      4
.,.,.034628,.04927,.062719,.075387,.087628,.10001,.112652,             1P      5
.125626,.139095,.152241,.164798,.176549,.188529,.200374,.21204,        1P      6
.223303,.234609,.245899,.259995,.275105,.290623,.303391,.315441,       1P      7
.327581,.339992,.352306,.36419,.375697,.387008,.398345,.409837,        1P      8

-77.443385,-276.959702,375.999911,-78.871976,-276.983987,              1P   1474
376.000031,-80.321652,-277.057464,375.99932,-81.743381,                1P   1475
-277.326849,375.99958,-83.168641,-277.550828,375.999478,               1P   1476
-84.592286,-277.806897,375.999517,-86.412125,-278.426024,              1P   1477
375.99949,-87.804266,-278.843181,375.9995,-88.690449,                  1P   1478
-279.220937,0,1,0,1;                                                   1P   1479
S      2G      4D      2P   1479                                        T      1
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Fig. 11 IGES file of B-spline surface

4. Experimental result

The algorithm of cross-sectional curve and surface generation is applied to the foot and face models, and their modeling error is verified in the Surfacer, a software for data modeling and error verification.

Fig. 12, 13 (a)-(f) represent the model, the scanned data, the compatible polylines, the compatible cross-sectional curve, the wireframe of generated surface, and the shaded image of generated surface, respectively. Fig. 14 shows the error between an original model and the generated surface using Surfacer. The comparison between the real face and the prototypes for NC machines and RP equipment is presented in Fig. 15 and numerical details are tabulated in Table 1.

The average error between the original surface and the generated surface is 0.04mm, 0.07 mm in each model respectively. The error is considered to be less than the tolerance, 0.05 ~ 0.1mm approximately, which is allowed by manual works in real workshop.

Maximum error is found in curvature deviation region. And the error around edge of surface is relatively bigger than the other regions, which comes from irregular distribution of starting and ending position.

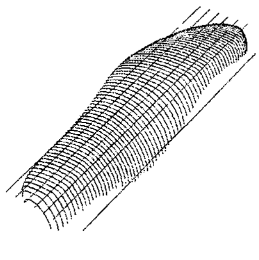
5. Conclusion

In this paper, reverse engineering technique is implemented by measuring complicated objects with a laser scanner and generating free-form surface. Manual intervention can be decreased with the use of an algorithm for the compatibility of point data. And a software is developed to generate automatically cross-sectional curve and loft surface from compatible point data.

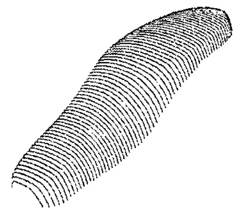
The data are produced in IGES file format when generating compatible point data, cross-sectional curve, and surface. Thus the manufacturing data are easily supplied to commercial CAM systems without any further data manipulation and the prototypes are built directly.

The generated surface through experiments has good quality with high precision from the comparison of the error between measured data and the generated surface. This error is considered to be less than the error in real workshops, so the reverse engineering technique proposed in this paper can be used for industrial applications and contributes to the automation process of part manufacturing.

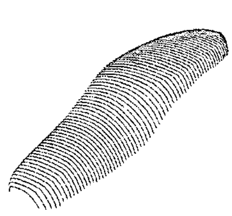
(a) Foot wear model



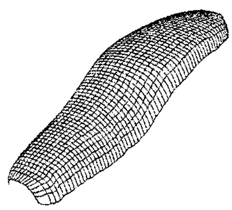
(b) Scanned data



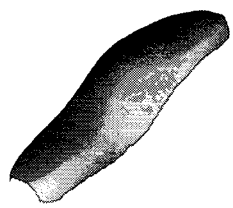
(c) Compatible polylines



(d) Compatible cross-sectional curve



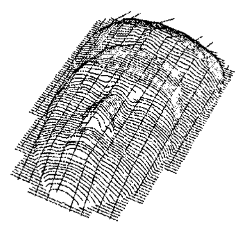
(e) Wireframe of generated surface



(f) Shaded image of generated surface

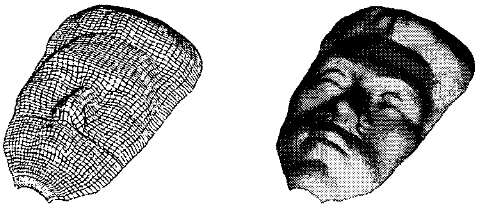
Fig. 12 Surface generation of foot wear model

(a) Face model



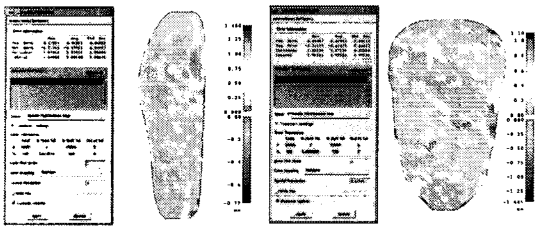
(b) Scanned data

(c) Compatible polylines (d) Compatible cross-sectional curve



(e) Wireframe of generated surface (f) Shaded image of generated surface

Fig. 13 Surface generation of face model



(a) Error on foot model (b) error on face model

Fig. 14 Comparison of error using surfacer

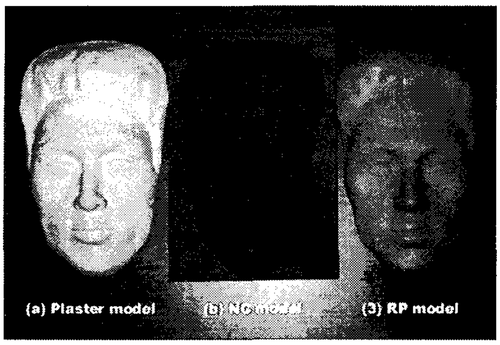


Fig. 15 Comparison of prototypes

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Table 1 Overall process and result

	Result	Foot	Face
Measuring process	Measuring device	Surveyor 1200	
	scale (mm)	100×280×40	150×240×45
	Scanning intervals (mm)	4	3
	Measured points	100254	185499
	polylines	757	1021
Compatibility of measured points	Preprocessed points	9483	15441
	Preprocessed Polylines	80	111
	Connected polylines	11	18
	Removed polylines	1	15
	Polygonal chain	2	3
	Sampled points	3144	5673
Cross-sectional curve and surface generation	Cross-sectional curves	68	78
	u-direction order	4	4
	v-direction order	4	4
	Control points (u×v)	16×68	30×78
Error	Average (+) error (mm)	0.0404	0.0706
	Average (-) error (mm)	-0.0347	-0.0748
	Maximum (+) error (mm)	0.5782	0.8036
	Maximum (-) error (mm)	-0.5327	-0.9712