163th Research Symposium, Touhoku Division of Society of Instrument and Control Engineerings
Document Number 163-9

The development of PC-based CAD system for reversing engineering

Bingyan Zhao*, Shigenori Okubo**

*Faculty of Engineering, Yamagata University

**Faculty of Engineering, Yamagata University

Key words: coordinate measurement machine, metrology, CAD/CAM, reverse engineering, curve and surface smoothing

Correspondence address: 4-3-16 Jonan, Yonezawa, 992, Japan
Okubo research laboratory, Faculty of Engineering, Yamagata University
Bingyan Zhao, Tel.: 0238-26-3245, Fax: 0238-24-6445 E-mail: zhaobing@mip3470.yz.yamagata-u.ac.jp

1. Introduction

Free shape objects are composed of a large number of free form surfaces, this characteristic distinguishes it from other mechanical products in the design and manufacturing process. In modern automobile design and manufacturing process, the coordinate measurement machine(CMM) is often used in those of the manufacturing and measurement of the 1:5 clay model, the master model, the push die and the fixtures. This is what we concerned for the system developing.

The CAD/CAM technology make the automobile body design and manufacturing a great profits, but most CAD/CAM systems such as ProEngineer, UGII, CADDS5, CATIA, Euclid-IS etc. run on the workstations rather than PC computer because of the complex calculations of free form curves and surfaces. Today the PC computer is developing fast and its performance have already been up to the requirement of CAD/CAM. Setting it apart from the existing commercial PC based CAD/CAM systems such as Autocad, Personal Designer, Microstation etc., the system proposed here is mainly for the reversing engineering, that is to say, the incorporation of CMM with the PC-based CAD/CAM system with which the following features hold:

1)To fully dig out the potential functions of CMM. Generally, the measurement software for CMM can merely deal with some simple deviation calculations and its measurement functions are very limited compared with the CAD/CAM system. The CMM incorporates with the CAD/CAM system can almost perform any measurement functions directly as opposed to transform it to the CAD/CAM system for further process.

2)To take the CMM as a input device of the CAD/CAM system can directly construct a three dimensional model in the system, here the CMM is referred as *three dimensional digitizer.*

3)To monitor the measurement process on-line in the computer screen and delete the rude points immediately as opposed to process it latter. Also can make notations or marks to classify the group of the measured entities for the easy of post process. Specifically, for the measurement of the automobile body, the points number is so great that it is difficult to classify points to this or that surface patches.

4)To combine the CMM and CAD/CAM system and NC machine into a integrated system can perform profile modeling of workpiece, but this profile modeling have more flexible than the only copy the workpiece, it could allow the user to modify the shape to the users requirements.

For example, it can allow user to measure the data points from the master model and construct the technical model by constructing the draw and step part of the die model as opposed to create a real technical model.

Based on the consideration of above reasons, an integrated CMM/CAD/CAM system is developed. There are following parts in this paper, section 2 is the general structure of the system, section 3 describing the compensation of the probe radius and the modeling construction, section 4 gives out a curve and surface smoothing algorithm. The last is the conclusion. To the limitation of the pages, the surface GC1 smoothing and the CAM part is not discussed here.

2. The system design

The main procedures of free shape objects, for example, automobile body, design and manufacturing is as following: 1) A concept design according to the technical requirements. 2) A 1:5 clay model is manufactured to evaluate the shape in real world and refine it. 3)With the CMM, the data points are digitized from the clay model and are transformed later into the CAD/CAM system to build the mathematical model. 4)The master model is manufactured from the mathematical model. 5)The mathematical model in the CAD/CAM system may be changed compatibly to the master model by digitizing some points of difference. 6)The design and manufacture of the push die and other relative fixtures and so on. The system proposed here is developed according to the procedures of the design and manufacturing of the free shape products.

As the system is originated from the incorporation of CMM with NC machine, the CMM and NC machine take the role of input and output devices respectively as in Fig. 1. The measurement functions is the submodule within the CAD/CAM system.

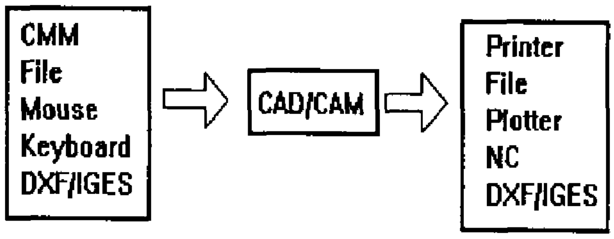

Fig. 1 The basic structure of the system

The general structure of the system is arranged according to the procedures of free shape products design and manufacture as in Fig. 2.

The system takes the wirframe and surface model, and the connection between CMM and computer is by RS-232c. The data points or the measured entities are directly displayed on the screen and stored into the CAD/CAM database.

The database are composed of one Entity list measured entities are directly displayed on the screen and stored into the CAD/CAM database.

The database are composed of one Entity list of 16-byte records, one for each entity and the records holds attributes which are common to all types of entities such as entity numbers, valid mark, layer, viewing mark, group, font, color and etc., the last one is the pointer for the geometry data list of the entity which include several standard subrecords of variable length.

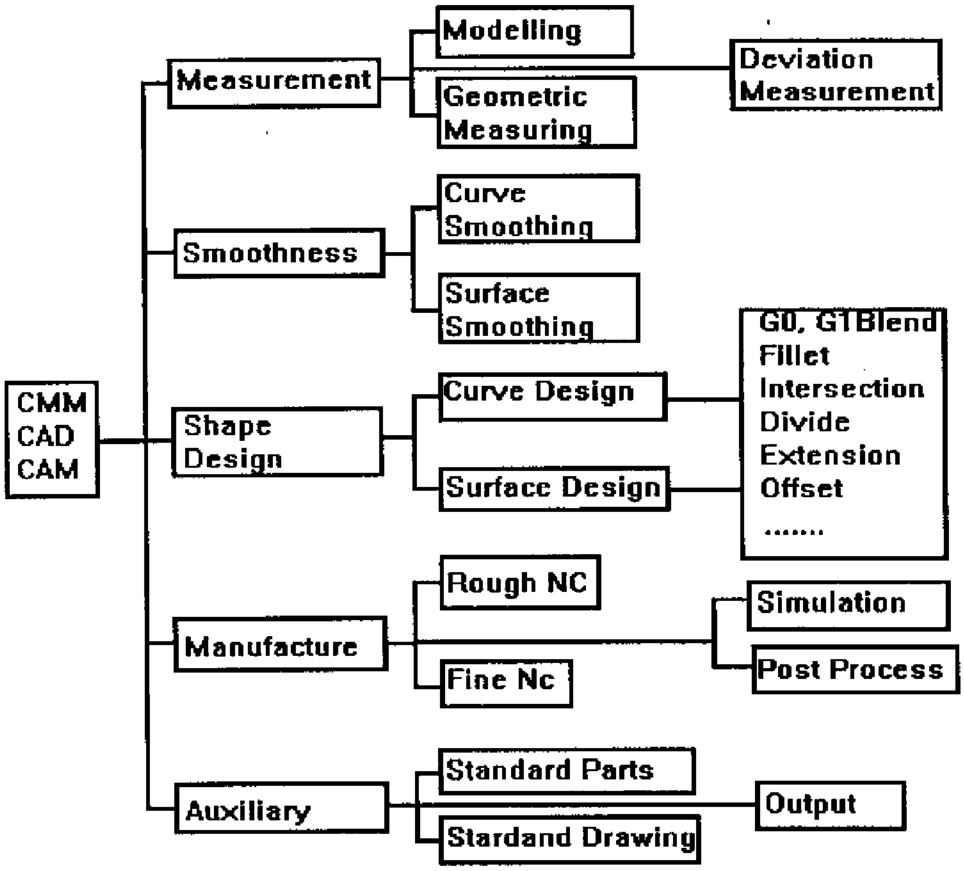

Fig. 2 The layout of the system

3. The radius compensation of CMM probe and three dimensional model constructing

The digitized data point is the center position of the CMM probe rather than the contact point on the surface of the being measured object. In order to obtain the points on the object, the probe radius must be compensated.

3.1 The measurement of one point

For merely one point, it is difficult to offset automatically if the measuring direction is uncertain. If the measured object is free form surface, the method to obtain the contact points is by measuring the surface which contain this points and project the point to the offset surface with the surface normal direction passing the point.

3.2 The measurement of spatial lines and circles

The traditional method is to adjust the measured line to parallel or perpendicular to one of the measurement axis, this is inconvenient both for the manipulation and for the reversing engineering purposes. Here the method of measurement is to measure the planes and by intersection of planes, the lines are obtained.

3.3 The measurement of curves and surfaces

The measurement of curve is commonly to

set one axis constant, i.e. a section curve, it is easy to offset a curve with the distance of probe radius in a plane. If the curve is not a section curve, as in Fig. 3, the surface that contains the curve must first be measured and project each measured points on the curve onto the offset surface, where each point has its own projection direction, the relative surface normal direction passing through the point. finally the projected points is smoothed to curve.

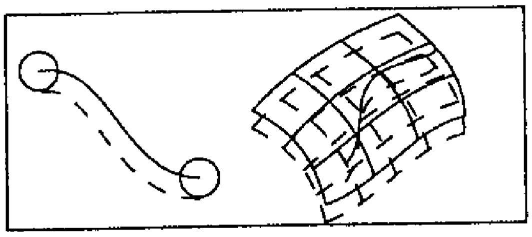

Fig. 3 Probe radius compensation of curve

For the measurement of the free form surface, several methods can be used to smooth the data points to surface and obtain the real one by the normal offset surface, this paper proposed a general scheme for the smoothing net grid points and the scatter distributed points to surface as in section 4.

If the above questions are solved, then the CMM can be refereed to the input device, a "three dimensional digitizer" with which the user can measure and construct the three dimensional model in the CAD/CAM system.

3.4 The automatically constructing the convex polyhegen object model with CMM

Based on CSG modeling method, any complex objects can be constructed by the Boolean operation of the standard primitives such as cube, sphere and cylinder etc.. It is easier to measure the sphere, the cylinder, but for the cube or convex polygon objects, the compensation of probe radius is more difficult.

For a polyhedral convex, it is more difficult to measure each edge of the object directly than to measure the planes and intersect them with each other to obtain the intersection lines. Also, it does not have to adjust the object to the easy of measurement and the probe radius can be compensated automatically.

Let $P_1(x_1,y_1,z_1), P_2(x_2,y_2,z_2), P_3(x_3,y_3,z_3)$ are the three points on a plane.

Vector $\vec{N} = \overrightarrow{P_1P_2} \times \overrightarrow{P_1P_3}$ directing to the inside of the object. Then the plane equation is $AX + BY + CZ + D = 0$.

Where

$$A = (y_2 - y_1)(z_3 - z_1) - (y_3 - y_1)(z_2 - z_1),$$

$$B = (x_3 - x_1)(z_2 - z_1) - (x_2 - x_1)(z_3 - z_1),$$

$$C = (x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_2 - y_1),$$

$$D = -(AX + BY + CZ).$$

The offset plane with distance d is

$$AX + BY + CZ + d - (Ax_1 + By_1 + Cz_1) = 0.$$

The polyhedral convex is closed, because all normals of the planes direct to the inside of the object. The following algorithm is to find all the edges of the polyhedral convex

1)Find all the planes π_i (i=1,2,...n)

2)Find the intersection line L of plane π_i, π_j $(i \neq j)$ as in Fig. 4.

3)Find the intersection point P_k between L and the plane π_k (k=1,2,...n, $k \neq i, j$)

4)By checking whether the P_k is inside the object or not to determine the two end of L, the check criteria is $A_m P_k x + B_m P_k y + C_m P_k z \geq 1.0e^{-5}$

5)Got to step 2) until all the edge line are obtained.

Here, the algorithm focuses on from measurement to model construction, the geometrical deviations and the position deviations are not included. For the precision measurement, the procedures are:

1)Measuring three points in clockwise while facing the plane, this is to determine the compensation direction of the probe radius.

2)Measuring the net points on the plane and using the least square method to obtain the geometrical deviation.

3)The least square plane is being used as the π_i (i=1,2,...n) for the constructing of the model.

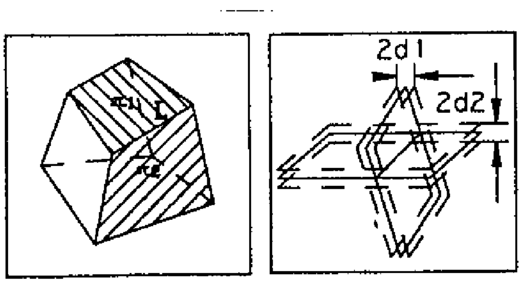

Fig. 4 Constructing convex object model

4. Curve and surface smoothing

The curve and surface smoothing have been studied intensely(M J Pratt '85, Nowacki and Reese, 83; Pottmann, 91; Hagen and Schultze,92; Hagen, H. and Bonneau G.-P. 93; MIG. Bloor, M.J. Wilson and H.Hagen, 95, Schumaker, L.L 76, Welch, W. and Witkin, A. 92), but little pay attention to the easy of measurement, here the smoothing scheme has little constraints on measurement as opposed to strictly to net grid points.

4.1 Curve smoothing

For a giving set of points $P_j\,(j = 1,2,,,m)$, find a parametric curve with control points $C_i\,(i = 1,2,,,M)$,then $P(u) = \sum_{i=1}^{M} B_i(u) \cdot C_i = P_j$ (j=1,2,..,m) (1)

With the variational principle, seek the curve f from the following functional

$$\rho(f) = \alpha \cdot E(f) + \beta \cdot \theta(f) \tag{2}$$

where $E(f)$ is the deviation item, $\theta(f)$ is smooth item, α, β are the approximation and smoothness weights.

$$\text{Then } \rho(f) = \sum_{j=1}^{m} \alpha_j \left\{ \sum_{i=1}^{M} B_{ji}(u) \cdot C_i - P_j \right\}^2$$

$$+ \sum_{j=1}^{m'} \beta_j \left\{ \sum_{i=1}^{M} B''_{ji}(u) \cdot C_i \right\}^2 . \tag{3}$$

Where m' is the number of points selected to evaluated the curvature of the curve.

From $\dfrac{\partial \rho}{\partial C_i} = 0$, the following matrix equation holds.

$$B^T \cdot \alpha \cdot (B \cdot C - P) + B^{*T} \cdot \beta \cdot B^* \cdot C = 0 \tag{4}$$

$$C = (B^T \cdot \alpha \cdot B + B^{*T} \cdot \beta \cdot B^*)^{-1} \cdot B^T \cdot \alpha \cdot P \tag{5}$$

Where $C \in R^{M\times 1}$, $B \in R^{m\times M}$, $B^* \in R^{m'\times M}$, $P \in R^{m\times 1}$, $\alpha \in R^{m\times m}$, $\beta \in R^{m'\times m'}$

In application, the parameter of points $P_j\,(j = 1,2,,,m)$ is calculated by sum of the accumulated chord lengths.

This curve smoothing scheme can also be used to smooth a set of points on "tracks" to surface. First , smooth each track to curve with a given control points KU, then smooth control points of each curves in another direction.

4.2 Surface smoothing

For a given grid points P_{IJ} (I=1,2,..,M, J=1,2,...,N), just as curve smoothing, for surface smoothing, the Variational function is

$\rho(f) = \gamma \cdot E(f) + \gamma_\theta \cdot \theta(f)$.

Where $E(f)$ deviation item , $\theta(f)$ smooth item, γ approximation weight, γ_θ smooth weight.

According to the shell inner energy presentation, take $\theta(f) = \iint_S (D^2_{uu} f + D^2_{vv} f + D^2_{uv} f) ds$ as the smooth item and represent it in discrete form, where $D^2_{uu} = B''_u \cdot C \cdot B^T_v$, $D^2_{uu} = B_u \cdot C \cdot B''^T_v$, $D^2_{uu} = B'_u \cdot C \cdot B'^T_v$.

$$\rho(f)=\sum_{I=1}^{N}\sum_{J=1}^{M}\left\{\gamma_U \sum_{i=1}^{n}\sum_{j=1}^{m} B_{uIi}(u)\cdot B_{vJj}(v)\cdot C_{ij} - P_{IJ}\right\}^2$$
$$+\sum_{I=1}^{N'}\sum_{J=1}^{M'}\left\{\gamma_{\theta IJ} \sum_{i=1}^{n}\sum_{j=1}^{m} B''_{uIi}(u)\cdot B_{vJj}(v)\cdot C_{ij}\right\}^2$$
$$+\sum_{I=1}^{N'}\sum_{J=1}^{M'}\left\{\gamma_{\theta IJ} \sum_{i=1}^{n}\sum_{j=1}^{m} B_{uIi}(u)\cdot B''_{vJj}(v)\cdot C_{ij}\right\}^2$$
$$+\sum_{I=1}^{N'}\sum_{J=1}^{M'}\left\{\gamma_{\theta IJ} \sum_{i=1}^{n}\sum_{j=1}^{m} B'_{uIi}(u)\cdot B'_{vJj}(v)\cdot C_{ij}\right\}^2 \qquad (6)$$

in which N', M' are the number of points on the surface that is sought.

There are $n \times m$ equation of form (6) which is equal to the control points of surface.

Then the following equation is holds.

$$2 \cdot B^T_u \cdot \alpha \cdot (B_u \cdot C \cdot B^T_v - P) \cdot \beta \cdot B_v$$
$$+2 \cdot B^T_{u\theta 1} \cdot \alpha \cdot (B_{u\theta 1} \cdot C \cdot B^T_{v\theta 1}) \cdot \beta \cdot B_{v\theta 1}$$
$$+ \cdot 2 \cdot B^T_{u\theta 2} \cdot \alpha \cdot (B_{u\theta 2} \cdot C \cdot B^T_{v\theta 2}) \cdot \beta \cdot B_{v\theta 2}$$
$$+2 \cdot B^T_{u\theta 3} \cdot \alpha \cdot (B_{u\theta 3} \cdot C \cdot B^T_{v\theta 3}) \cdot \beta \cdot B_{v\theta 3} = 0 \qquad (7)$$

In fact the above equation has the form of

$$A_1 \cdot C \cdot B_1 + A_{\theta 1} \cdot C \cdot B_{\theta 1} + A_{\theta 2} \cdot C \cdot B_{\theta 2} + A_{\theta 3} \cdot C \cdot B_{\theta 3} = B^T_u \cdot \alpha \cdot P \cdot \beta \cdot B_v \qquad (8)$$

Here we take the boundary condition into account. Let the control net points matrix $C = X + E$ where X is the inner control net points matrix, and E is the boundary control points matrix.

then we yields

$$A_1 \cdot X \cdot B_1 + A_{\theta 1} \cdot X \cdot B_{\theta 1} + A_{\theta 2} \cdot X \cdot B_{\theta 2} + A_{\theta 3} \cdot X \cdot B_{\theta 3} = D \qquad (9)$$

Where

$D = B^T_u \cdot \alpha \cdot P \cdot \beta \cdot B_v - A_1 \cdot E \cdot B_1 +$
$A_{\theta 1} \cdot E \cdot B_{\theta 1} + A_{\theta 2} \cdot E \cdot B_{\theta 2} + A_{\theta 3} \cdot E \cdot B_{\theta 3}$

$A_1 = B^T_u \cdot \alpha \cdot B_u$, $B_1 = B^T_v \cdot \beta \cdot B_v$,

$A_{\theta i} = B^T_{u\theta i} \cdot \alpha_\theta \cdot B_{u\theta i}$, $B_{\theta i} = B^T_{v\theta i} \cdot \beta_\theta \cdot B_{v\theta i}$

(i=1,2,3)

Solving the above linear equation, the control points C is obtained

$$x = \left\{[A_1 \otimes B^T_1] + \sum_{i=1}^{3}[A_{\theta i} \otimes B^T_{\theta i}]\right\}^{-1} \cdot \sigma(D) \qquad (10)$$

Where

$\sigma:\ C^{m\times n} \Rightarrow C^{mn\times 1}$, so that $\sigma(C) = x \in C^{mn\times 1}$

The (10) can be used to smooth both net points and only four or three boundaries points to surface. But for the convenient of measurement, it is often to measure the feature lines as the boundaries and some scatter data points inside, the scheme should have the ability to deal with the circumstance.

For one point P_k, find its parameter (u_k, v_k) by Newton-Raphson method from

$$\begin{cases}(P_k - S(u,v)) \cdot S_u(u,v) = 0 \\ (P_k - S(u,v)) \cdot S_v(u,v) = 0\end{cases} \qquad (11)$$

Where S(u,v) is the Coons surface constructed by the four boundaries. Then the scheme for scatter data points smoothing is

$$x=\left\{\sum_{k=1}^{L}[A_k \otimes B_k^T]+\sum_{i=1}^{3}[A_{\theta i} \otimes B_{\theta i}^T]\right\}^{-1} \cdot \sum_{k=1}^{L} \sigma(D_k) \quad (12)$$

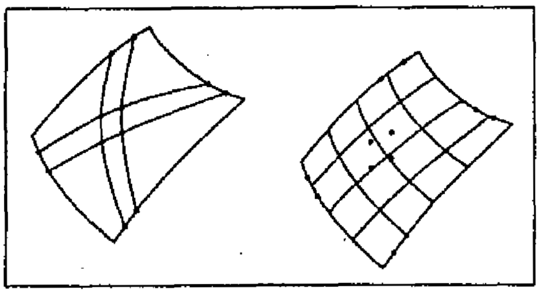

Fig. 5 Smoothing scatter data points to surface, the maximum deviation between point to the surface is 0.02, for the smoothness weight 0.01 in both u and v parameters directions.

6 Conclusion

The system proposed in this paper running on the PC computer having the advantage of easy for use. With the CMM as a three dimensional digitizer, the regular three dimensional model can be constructed directly from the measurement. The further investigation concentrates on the boundary detection of the measuring points from the free form surface object by the feature analysis to construct the surface automatically.

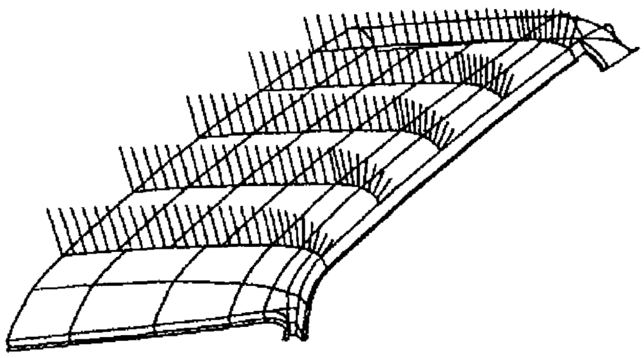

Fig. 6 A car roof finished with the system

References

1) Hagen, H. and G. Schulze, G. (1992) Variational design of smooth B-spline surfaces, in: Hagen, H.,ed., Topics in surface modeling, SIAM, Philadelphia, PA, pp 85-94
2) Hagen, H. and Bonneau G.-P. (1993), Variational design of smooth rational Bezier surfaces, Computing Suppl. 8, pp 133-138
3) M.J PRATT (1985) Smooth parametric surface approximations to discrete data, Computer Aided Geometric Design 2 pp 165-171.
4) M.I.G. Bloor, M.J. Wilson, H. Hangen (1995), The smoothing properties of varitional schemes for surface design, Computer Aided Geometric Design 12 pp 381-394.
5) Nowacki, H. and Reese,D. (1983), Design and fairing of ship surfaces, in: Barnhill, R.E. and Boehm, W., eds., *Surfaces in CAGD*, North-Holland, Amsterdam, pp 121-134
6) Schumaker, L.L (1976) Fitting surfaces to scattered data, in:Lorentz,G.G.,Chui C.K and Schumaker,L.L., eds., *Approximation Theory II*, Academic Press, New York, pp 203-268
7) Pottmann,H. (1991), Scatter data interpolation based upon generalized minimum network, Constrained Appro. 7, pp 247-256
8) Welch, W. and Witkin, A. (1992), Variational surface modeling, Comput. Graph. 26, pp 157-166.