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Integrated Precision Inspection System for Manufacturing of Moulds having CAD Defined Features

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An integrated precision inspection system has been developed for manufacturing moulds having CAD defined features. The techniques of precision measurement are implemented for CAD/CAI integration for moulds having sculptured surfaces with some basic features, such as, holes, slots and bosses. Features to be inspected are chosen in the CAD environment, and inspection planning is performed for each feature. The sampling-point strategies are: uniform distribution, curvature dependent distribution, or hybrid distribution of the two depending on the complexity of the sculptured surface. Line and plane features are divided into subintervals, and the measurement points are distributed at random positions in the subinterval. Prime number subintervals are considered for a circle feature, in order to avoid possible periodic distortion of the measurement features. The measurement path planning is performed considering collision avoidance and coordinate matching between the coordinates. The output of the planning is the machine code for a specific CMM having CNC capability. The machine code is downloaded to a specific CMM, and the measurement results are fed back to the computer. A new algorithm, called MINIMAXSURF, is developed to evaluate the form error precisely for sculptured surfaces. The algorithm considers the radius of the touch probe and evaluates the profile tolerance successfully by removing the unavoidable set-up errors. The developed measurement system has been applied to real moulds, demonstrating high performance and accuracy.

Keywords: CMM; Mould inspection; Precision measurement

1. Introduction

The design and manufacture of dies and moulds have been heavily dependent on human expertise, and the many-item–small-quantity characteristics would require flexible automation. Inspection and quality assurance of mould manufacture, however, has been one of the less automated processes. It requires inspection planning, CMM programming, error evaluation and quality assurance, and high dimensional accuracy becomes more important [1]. Thus, a computer-aided inspection system is desirable for automated inspection and precision measurement. Duffie et al. [2,3], proposed an inspection system for sculptured surfaces using the database, where the part accuracy was calculated by solving a set of nonlinear equations. Bojanic et al. [4] used feature-based modelling and a knowledge-based system for complex surfaces. Menq et al. [5] proposed an optimal match scheme with which the surface profile could be calculated. In this paper, an integrated precision measurement system is developed for the manufacture of moulds having CAD defined features. The techniques of precision measurement are implemented for CAD/CAI integration for moulds having sculptured surfaces with some basic features, such as, holes, slots and bosses.

A typical mould has sculptured surfaces for the cavity side, concavities of ribs and bosses for the core side, and holes for inserting pins. Features to be inspected can be chosen in the CAD environment, and the selected feature information can be grouped and transferred to the inspection system. Then inspection planning is performed for each feature selected to assure accurate measurements.

The measurement points are determined according to the selected feature. The sampling-point strategies are: uniform distribution, curvature-dependent distribution, or hybrid distribution of the two. Line and plane features are divided into several subintervals, and the measurement points are distributed at random positions in the subinterval. Prime number subintervals are considered for a circle feature in order to avoid possible measurement errors due to the distortion of the measurement features.

Measurement path planning is carried out considering collision avoidance and coordinate matching between the coordinates. The output of the planning is the machine code for a specific CMM having CNC capability, and is then downloaded to a specific CMM. The measurement results are fed back to the computer. A new algorithm, MINIMAXSURF,

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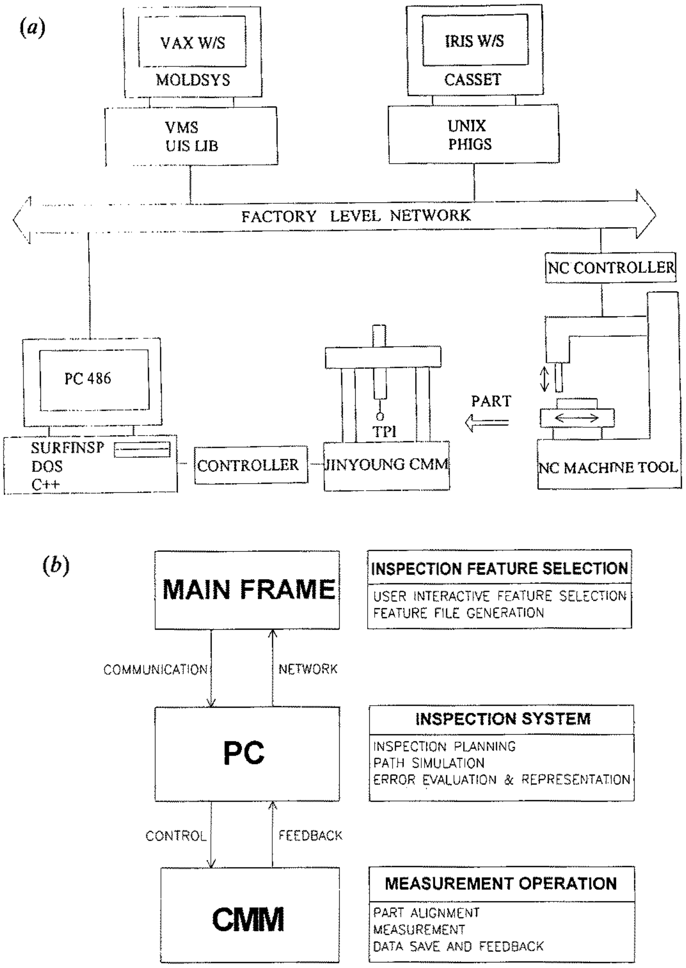


Fig. 1. (*a*) Configuration for computer-aided inspection system of mould manufacturing. (*b*) Conceptual framework of the developed system.

is developed to evaluate the form error precisely for sculptured surfaces, taking account of the radius of the touch probe. The profile tolerance and the set-up error can be evaluated from the measurement data. The developed measurement system has been applied to real moulds, and has demonstrated high performance and accuracy.

The inspection system has been developed around an IBM PC which links a mainframe computer with a CNC multi axis CMM. Fig. 1(*a*) shows the configuration for a computer-aided inspection system for mould manufacturing; Fig. 1(*b*) shows the conceptual framework of the inspection system developed in this research.

2. Features for Mould Inspection

In order to achieve a computer integrated inspection system, a feature-based inspection technique is applied, where the features to be inspected are chosen in the CAD environment, and several key features are considered for the mould inspection based on metrological concepts: i.e. sculptured surface, mould plate, pocket space for cavity/core block, and holes.

2.1 Sculptured Surfaces Mathematical Description

There are several ways of describing sculptured surfaces mathematically. It is usual to consider a sculptured surface as consisting of several patches of cubic polynomial surfaces: parametric polynomial surface, and *B*-spline surfaces are considered in this research. Let u,v be the principal parameter defining the principal direction in a surface patch.

Parametric Polynomial Surface

The points data, $P(u,v)$, on the surface are expressed as the sum of parametric polynomials of the 3rd order. That is,

$$P(u,v) = \sum_{i=0}^{3} \sum_{j=0}^{3} A_{ij}u^{i}v^{i} \tag{1}$$

where A_{ij} is the coefficient matrix of the column vector defining the polynomial.

B-spline Surface

The points data, $P(u,v)$, on the surface can be described in the *B*-spline form as follows:

$$P(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} Q^{*}_{ij}N_{i,3}(u)^{*}N_{j,3}(v) \tag{2}$$

where $Q_{ij}(i=1,2, \ldots, n;\ j=1,2, \ldots, m)$ are the control point data, $(m+1)$ and $(n+1)$ are the number of control points, and $N_{i,3}(u)$, $N_{j,3}(v)$ are the cubic blending functions for the u, v directions, respectively [6].

The feature data of a sculptured surface consist of the u,v parameter information, the control points data, and the profile tolerance of the sculptured surface.

2.2 Basic Features

A typical mould plate has holes for guide pins and inserted cavity/core blocks. The dimensional accuracy of the mould plate greatly affects the accuracy of the whole mould. The basic features of the mould consist of the mould plate, pocket space for cavity/core, and holes. The feature data of the mould plate comprise the mould plate dimension (length, width, height) and tolerance specification. The manufacturing tolerance data such as flatness, parallelism, and squareness must be specified for the three reference surfaces. The tolerance specification data are automatically included in the feature data file, as the plate is selected according to the KS(Korean Standards) system [7].

A rectangular pocket for a cavity/core is also inspected in order that the cavity block can be inserted precisely. The feature data file includes the classification type, identification name, and the depth of the pocket. The location of the corner points of the pocket are also assigned. The straightness error along each edge, parallelism error, and squareness error between the edges are specified in the tolerance data.

The hole feature is defined similarly. Classification type, number of holes, height data of the mould plate are assigned. The data for each hole are also specified, i.e. location of hole centre, nominal radius, depth, lower limit of radius tolerance,

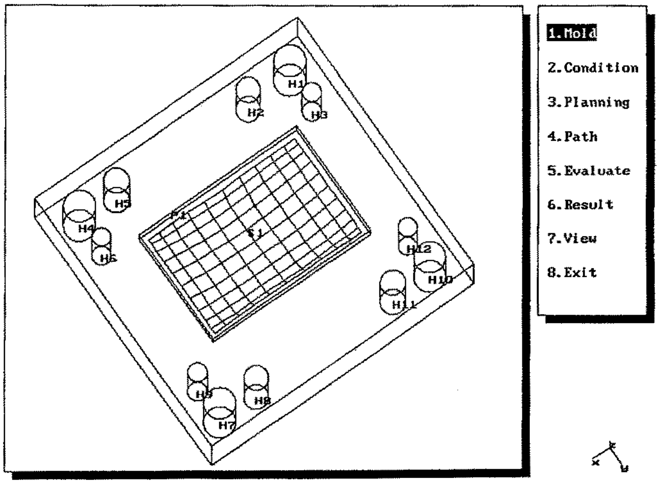


Fig. 2. A typical mould having a sculptured surface, block and holes.

upper limit of radius tolerance, roundness, and the hole location errors in the plate. Figure 2 shows a typical mould having a sculptured surface, block and holes.

3. Measurement Points Sampling and Path Planning

For the selected inspection features, the following inspection planning procedures are performed, i.e. measurement points sampling and corresponding CNC code generation for specific CMMs.

3.1 Measurement Points Sampling and Path Plan for Sculptured Surface

The measurement points distribution, i.e. measurement points sampling, is the key process for inspection planning. In this paper, three methods are proposed and implemented for sculptured surfaces, i.e. uniform distribution, curvature dependent distribution, and a hybrid distribution of the two.

Uniform Distribution Method

The basic idea of the uniform distribution method is that the grids formed by the measurement points have a nearly square distribution, and this gives uniform coverage for the sculptured surfaces. Suppose N points are to be distributed over a sculptured surface consisting of M surface patches. Let α be the dimensional ratio of the u direction to the v direction of the sculptured surface. Then the number of the measurement points, N_u, N_v, along the u, v directions in a patch can be determined as follows.

$$N_u = \text{round}\,(\sqrt{(N/M/\alpha)}) \qquad (3)$$

$$N_v = \text{round}\,(\alpha N_u) \qquad (4)$$

And the parameters, U_i, V_j along a specified surface patch are determined based on the uniform allocation. That is,

$$U_i = (i - 0.5)/N_u \quad (\text{i}=1,2, \ldots, Nu) \qquad (5)$$

$$V_j = (j - 0.5)/N_v \quad (\text{j}=1,2, \ldots, Nv) \qquad (6)$$

where 0.5 is used so that the sampled points are located at the middle of the surface grids.

Curvature Dependent Distribution Method

For high-curvature surface measurement, it is desirable to have more sampling points than for small-curvature surface measurement.

The measurement points can be distributed based on the normal curvature calculation along the sculptured surface. The normal curvature can be defined as;

$$\text{Normal curvature} = |\text{Curv}_u \times \mathbf{e}_n| + |\text{Curv}_v \times \mathbf{e}_n| \qquad (7)$$

where the Curv_u, Curv_v are the curvature vectors along the u, v direction, respectively, and $\mathbf{e}_n$ is the unit normal vector of the surface at the measurement points. The Curv_u, Curv_v are

$$\text{Curv}_u = |P_u|^3/|P_u \times P_{uu}| \qquad (8)$$

$$\text{Curv}_v = |P_v|^3/|P_v \times P_{vv}| \qquad (9)$$

where P_u, P_{uu}; P_v, P_{vv} indicate the first and second derivative of the sculptured surface along the u, v directions, respectively. The measurement points are distributed so that relatively more points are sampled on the section of higher curvature.

Hybrid Distribution Method

The hybrid method of measurement points distribution is a combination of the uniform distribution ($N1$ points) and the curvature dependent distribution ($N2$ points) such that $N1$ plus $N2$ makes the total number of measurement points, N. This is to avoid the situation where too many measurement points are concentrated on the sections of high curvature. The assignment of $N1$, and $N2$ of the N points distribution is done heuristically.

Path planning for measurement is based on the normal direction approach for improvement of accuracy on the sculptured surface. Let $XS_i(i=1,2, \ldots, n)$ be the target position for measurement on the surface, and NS_i be the normal vector at the position. Collision avoidance can be satisfied if the probe approaches and draws back at a sufficiently large distance, d, from the surface in the normal direction. Thus the approach point, XP_i, can be calculated as

$$XP_i = XS_i + d \times NS_i \qquad (10)$$

Figure 3 shows a typical example of the three methods of measurement points distribution for a sculptured surface: uniform distribution, curvature dependent distribution, and the hybrid of the two.

3.2 Measurement Points Sampling and Path Plan for Basic Features

The measurement points sampling for basic features aims at uniform coverage for the workpiece [8]. The measurement points are chosen to give a true representation of the geometric features. However, the distribution should not be so regular

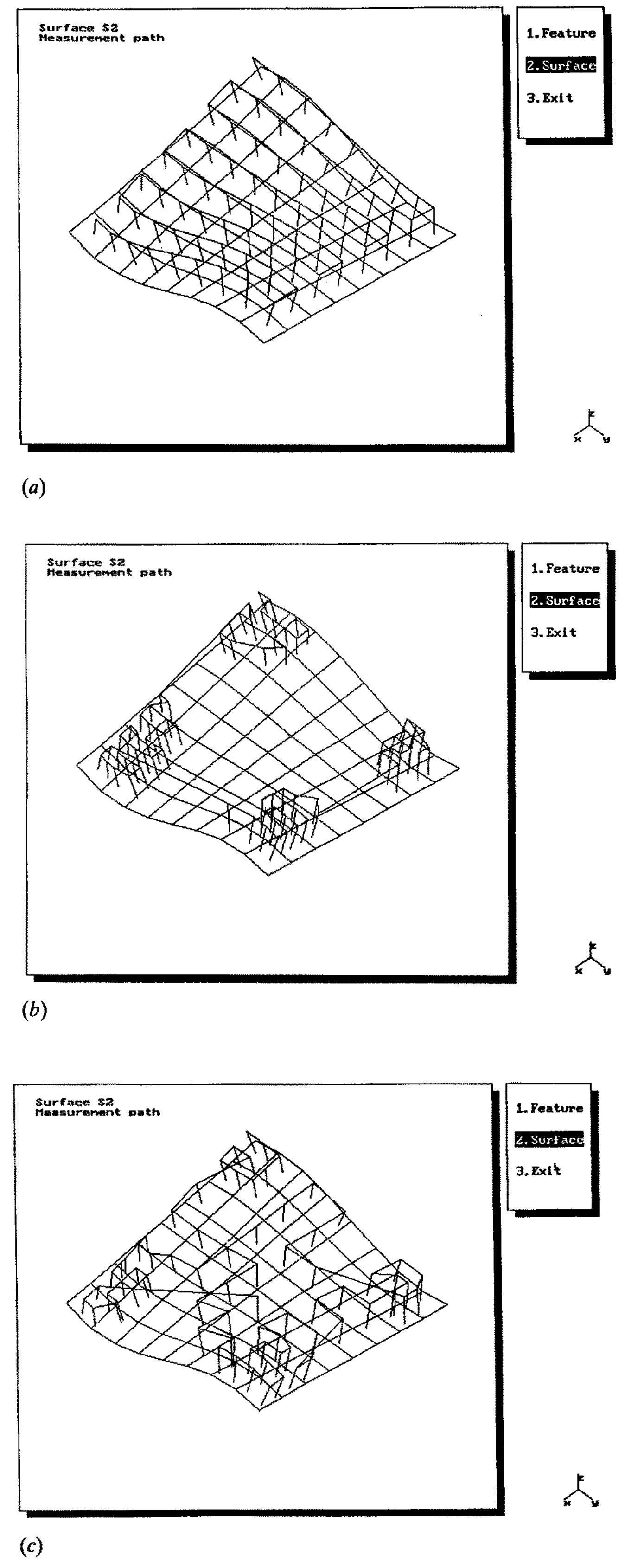


Fig. 3. (*a*) Uniform distribution method. (*b*) Curvature dependent distribution method. (*c*) Hybrid distribution method.

as to follow possible systematic or periodic deformations of the feature. The mould plate consists of 3 planes to be measured, one horizontal and two vertical surfaces. In order to achieve a nearly uniform distribution of N points on a rectangular segment of a plane, the rectangle is divided into $N1$ by $N2$ subrectangles, where $N1 \times N2$ is approximately equal to the total number of measurement points, i.e. N. The measurement points are chosen randomly in every subrectangle. This is to avoid possible measurement errors due to systematic or periodic deformation on the feature. A uniform pseudo random generator is used for this purpose.

A pocket for a cavity block consists of 4 straight lines to be measured. In order to achieve a nearly uniform distribution of N points on a line segment, the line segment is divided into N subintervals of equal length, and the measurement point is chosen randomly in each subinterval.

For holes, prime number distribution is performed for each circle, to detect the possible lobes on the circle, and a pseudo random number generator is used. Figure 4 shows a typical measurement points distribution on the plane, line and circle, respectively.

3.3 CNC Code Generation and Measurement Operation

Coordinate Alignment

Prior to generating CNC commands for a 3-axis CMM, a coordinate alignment procedure is performed. Coordinate alignment is the process of identifying the part coordinate (CAD coordinate) with respect to the CMM coordinate system. The traditional 6-point technique is adopted: the mould to be measured is positioned on the CMM, then the CMM probes a minimum of 6 points which are located on the clear cut surfaces or any reference surfaces of the mould plate. The relation between the part coordinates and the CMM coordinates can be uniquely determined. Let P_i, $Q_i (i=1,2, \ldots, n)$ be the CMM coordinate data and the CAD coordinate data, respectively. The transformation matrix, T, of $P_i = TQ_i$, between the two coordinate systems is required for CNC coding and error evaluation at a later stage. For the 3D case, the T matrix is of the order of 4×4 including rotation and translation factors, that is,

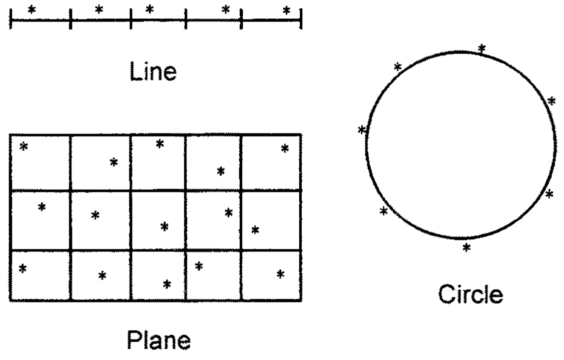


Fig. 4. Measurement points distribution for basic features.

$$T = \begin{bmatrix} T_{11} & T_{12} & T_{13} & Tx \\ T_{21} & T_{22} & T_{23} & Ty \\ T_{31} & T_{32} & T_{33} & Tz \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{and}$$

$$Pi = \begin{bmatrix} Px_i \\ Py_i \\ Pz_i \\ 1 \end{bmatrix} \quad Qi = \begin{bmatrix} Qx_i \\ Qy_i \\ Qz_i \\ 1 \end{bmatrix} \tag{11}$$

such that $P_i = TQ_i$, where $T_{jk}(j,k=1, \ldots, 3)$ are the scaling/rotation factors, and Tx, Ty, Tz are the translation in X,Y,Z axis, respectively. Px,Py,Pz are the XYZ coordinate of a point P in the CMM coordinates, and Qx,Qy,Qz are the XYZ coordinates of the corresponding point Q in the CAD stage.

The Euler angles(α,β,γ) of the X,Y,Z axis rotation can be evaluated as

$$\beta = \arctan 2(-T_{31}, \sqrt{(\mathrm{T11*T11+T21*T21})}) \tag{12}$$

$$\alpha = \arctan 2(T_{21}/\cos\beta,\ T_{11}/\cos\beta) \tag{13}$$

$$\gamma = \arctan 2(T_{32}/\cos\beta,\ T_{33}/\cos\beta) \tag{14}$$

where arctan 2 is the second arctangent function considering the sign convention. The transformation matrix, T, of $P_i = TQ_i$, for $i=1,2, \ldots, n$, can be determined using the least squares technique. Let e be the sum of the squares of the deviation, $P_i - TQ_i$, then

$$e = \Sigma|P_i - TQ_i|^2 \tag{15}$$

Equation (15) can be minimised if T is assigned as follows, using the pseudo inverse technique, that is,

$$T = (PQ^T)(QQ^T)^{-1} \tag{16}$$

The constructed relationship will be used for the practical CNC coding, and becomes the initial transformation matrix for the form error calculation in Section 4.

CNC Code Generation and Measurement Operation

After the inspection planning is displayed graphically on the computer screen, the result must be expressed in terms of the specific CNC code for a commercial CMM having CNC capability. Many modern CMMs have the TEACH mode where a specific measurement operation can be taught by an operator, then the CNC system stores the taught motions. In the PLAY BACK mode, the stored CNC codes are retrieved and sent to the CNC controller, and the measurement operations are performed. The CNC codes generated for a specific measurement operation are performed. The CNC codes generated for a specific measurement operation can be passed to the measurement mode as if they are from the TEACH mode. Thus the generated CNC codes are downloaded, and the measurement operations are performed.

4. Error Evaluation

The measurement results are fed back to the computer and the error analysis is performed for each feature inspected. The error evaluation algorithms are developed for:

1. Sculptured surface.
2. Basic features.

ISO Profile Tolerance

The error calculation is based on the comparison of the measured data with the CAD data. The profile tolerance of any surface is defined in ISO [9] as "the tolerance zone which is limited by two surfaces enveloping spheres of diameter, t, the centres of which are situated on a surface having the true geometrical form". Fig. 5(a) shows the ISO defined profile tolerance for a surface.

It is of metrological interest to note that the profile tolerance is the absolute maximum distance between the true geometrical form and the real surface measured, unlike the flatness in which the tolerance is defined as the deviation between the maximum and the minimum distances from a mathematically defined reference plane.

The profile tolerance definition can be applied to the case of CAD directed inspection, if the surface of true geometrical form can be replaced by the CAD surface.

Determination of Actual Measurement Points Considering Probe Radius

The measurement points on the surface have to be determined for the profile tolerance calculation. There are some reasons for the CMM measurement points not being identical to the planned points at the path planning stage, i.e. the discrepancy in the normal direction approach, and the unavoidable error in the positional control of the CMM. In practice, the control accuracy of CMMs of the CNC type is much worse than the measurement accuracy. Therefore the actual measurement points corresponding to the measured data have to be found on the sculptured surface, and a new method is proposed for determination of the actual measurement points.

When the measurement probe touches the surface, the measured data represents the centre point of the probe which is located on the offset surface to the sculptured surface, whose offset is the effective radius of the probe. The actual measurement points of the probe centre on the offset surface can be determined as the minimum distance point from the measured data.

In Fig. 5(b), let $Q_i(i=1,2, \ldots, N)$ be a point on the CAD defined surface, and R_i be the normal vector at the Q_i point, whose magnitude is the effective radius of probe, R. Then the point on the offset surface can be represented as

$$\text{Points on the offset surface} = Q_i + R_i \quad (i=1,2, \ldots, n) \tag{17}$$

Assume that P_i is the measured data which corresponds to the point, Q_i+R_i, on the offset surface, and there exists a transformation matrix, T, between the CMM coordinates and the CAD coordinates, satisfying $P_i = T(Q_i+R_i)$. The Euclidean distance between P_i and (Q_i+R_i) forms the deviation. Recalling that P_i is defined in the CMM coordinates, the squared Euclidean distance between the two points can be calculated as

$$\text{Euclidean distance} = |T^{-1}P_i - (Q_i + R_i)| \tag{18}$$

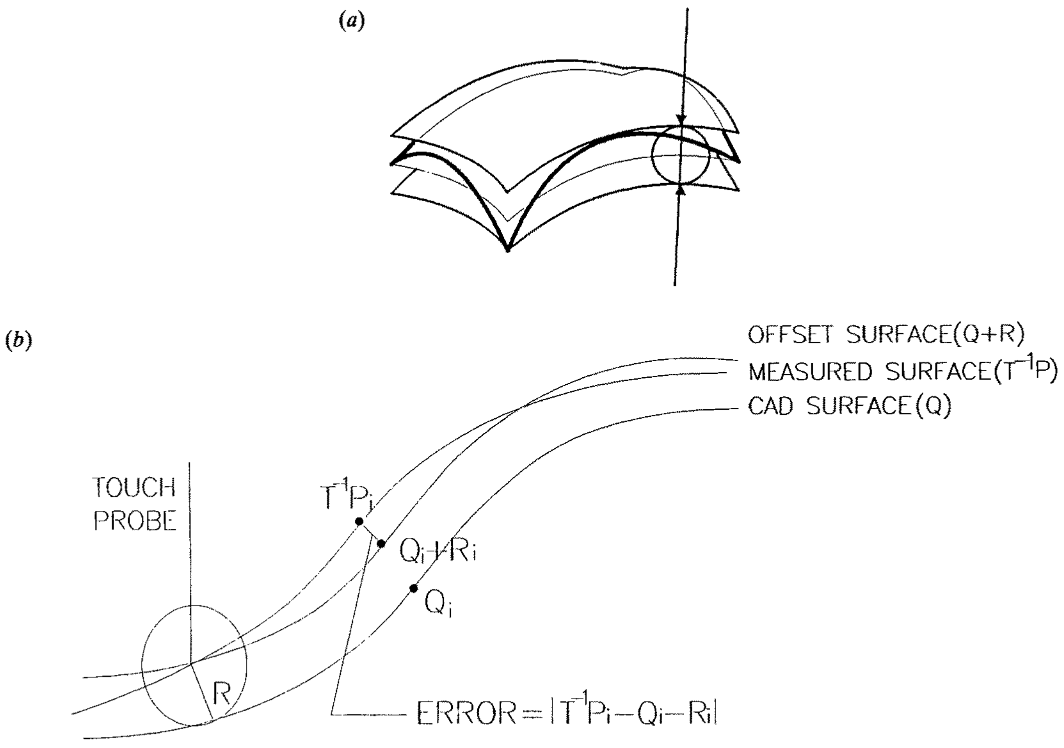


Fig. 5. (*a*) Profile tolerance of surface defined by ISO. (*b*) Deviation of sculptured surface.

providing that the transformation matrix, T, is known. The transformation matrix, T, can be initially assigned as the transformation matrix of the coordinate alignment, and assigned as the current transformation matrix, $T^{(k)}$ at a later stage, which will be evaluated at the stage of profile tolerance calculation.

In a practical measurement case, the CMM measured data, P_i, is obtained from the machine reading display, and the corresponding point, (Q_i+R_i), on the offset surface is found as the minimum distance point from the measured data. Equation (18) is the typical nonlinear formulation minimising the distance, and the subdivision technique is implemented in this research. The subdivision algorithm for the search for the nearest points is as follows:

1. Divide the surface into 4 subdivisions at $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ and 1 position in terms of the parameters defining the surface.
2. Calculate the squared Euclidean distance from the measured point to the points of $\frac{1}{4}$ and $\frac{3}{4}$ location.
3. Assign the shorter distance point as the nearest point, (Q_i+R_i), and select the half section of the shorter distance for subdivision.
4. Calculate $\delta = |(Q_i+R_i)^{(n)} - (Q_i+R_i)^{(n-1)}|$, where $(Q_i+R_i)^{(n)}$ is the currently determined nearest point and $(Q_i+R_i)^{(n-1)}$ is the previously determined nearest point.
5. Repeat step 1 to 4 until the calculated δ is not greater than the assigned tolerance.

Profile Tolerance (Form Error) Evaluation

When the actual measurement points are found, the Euclidean distance can be calculated using equation (18), and the Euclidean distance data can give the dimensional errors for the mould.

There are two types of error in the sculptured mould surface affecting dimensional accuracy of the mould products, i.e.

1. The form error (profile tolerance) which is the unique characteristics to the sculptured surface.
2. The set-up error involved in tilting or translation of the sculptured surface on the mould plate.

Generally, the form error and the set-up error are combined to give the dimensional errors for the sculptured surface. The relationship between the profile tolerance (form error) and the set-up error is illustrated in Fig. 6. In the case of mould manufacturing, the profile tolerance is unique to the machined cavity of the sculptured surface, and the set-up error is associated with the adjustment of the cavity in the pocket.

The metrological meaning of the set-up error is as follows. In the case of the flatness analysis of a plane, a mathematically defined reference plane is derived so that the maximum deviation is minimum for all possible transformations, and thus the maximum deviation is unique to the plane. Similarly, a mathematically defined sculptured plane having a set-up error from the CAD defined sculptured surface can be determined so that the maximum Euclidean distance is minimum for all possible transformations, so that the maximum Euclidean distance (profile tolerance) can be unique to the surface.

With the given total error, the form error and the set-up error are dependent on the transformation matrix, T, because the Euclidean distance between the measurement points and

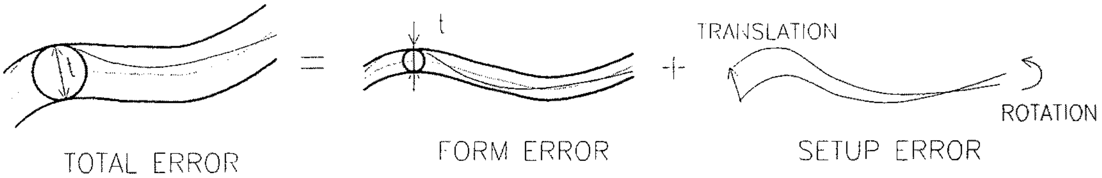


Fig. 6. Form error and set-up error for sculptured surface.

the CAD defined points is dependent on the T matrix as in equation (18). The transformation matrix, T, is also dependent on the actual measurement points, (Q_i+R_i). Thus, recursive iterations can be used for determining the transformation matrix and the Euclidean distance. For a trial transformation matrix, T, the trial form error, D, can be calculated as the maximum distance between the measurement points and the points on the offset curve, that is,

$$D = \max|T^{-1}P_i - (Q_i+R_i)| \quad \text{for } i=1,2, \dots, n \tag{19}$$

An optimal transformation matrix, T_{opt}, can be found such that the trial form error, D, be minimum, that is the profile tolerance. Thus the profile tolerance is

$$\text{Profile tolerance} = \min D$$
$$\text{for all possible transformations} \tag{20}$$

The calculated minimum form error is the profile tolerance which is unique to the sculptured surface, and the optimal transformation matrix, T_{opt}, then becomes the optimal set-up.

In this research, a new algorithm, called MINIMAXSURF, has been developed to evaluate the form error and the set-up error of a sculptured surface, using recursive iterations as follows. Assume $P_i(i=1,2, \dots, n)$ be the measured coordinate on the CMM coordinate, and $(Q_i+R_i)^{(k)}$ be the kth iteration value of the points on the offset curve. $(Q_i + R_i)^{(0)}$ is the initial value of $(Q_i+R_i)^{(k)}$, and the initial path planning points can be assigned for the initial value on the offset surface.

1. Find $T^{-1(k)}$ from P_i, $(Q_i+R_i)^{(k)}$ such that $P_i = T^{(k)} (Q_i+R_i)^{(k)}$, for $k=0,1,2, \dots, n$, using the pseudo inverse technique based on the least squares approach.
2. Find the nearest point $(Q_i+R_i)^{(k+1)}$ from $T^{-1(k)}P_i$ using the implemented subdivision technique.
3. Calculate the kth iterative form error, $E^{(k)}$, which is the maximum Euclidean distance over the sculptured surface, that is $E^{(k)} = \max|T^{-1(k)}P_i - (Q_i+R_i)^{(k+1)}|$, for $i=1,2, \dots, n$.
4. Calculate the convergence index, $\epsilon = (E^{(k)}-E^{(k-1)})/E^{(k-1)}$.
5. Repeat 1 to 4, with $k=k+1$ until $\epsilon <=$ TOL, where the TOL is a relative tolerance index, which is set as 0.0001.

The converged form error becomes the profile tolerance of the surface, and the transformation matrix, $T^{(k)}$, gives the optimal set-up. In Fig. 7(a), the algorithm of the SURFMINIMAX for form error calculation are shown.

The calculated kth form error was found to be decreasing as the iterations continue, and Fig. 7(b) shows a typical example of a sign plate illustrating that the form error decreases as the number of iterations increases.

Error Evaluation for Basic Features

Flatness, squareness and parallelism errors are involved in the mould plate inspection.

The flatness is the deviation of measured points with respect to the mathematically determined reference plane, and the flatness error is evaluated as the maximum deviation.

The squareness error is, in general, the out of squareness angle, and the squareness tolerance is the tolerance zone limited by two perpendicular planes to the given reference plane, where the two perpendicular planes contain the whole measured feature. The reference plane can be determined using the least squares technique.

The parallelism tolerance is defined as the tolerance zone limited by two parallel planes which is parallel to the reference plane, and the reference plane can be constructed as the best fit plane using the least squares technique.

Straightness, parallelism, squareness, and positional accuracy are calculated for the inspection of the space for cavity block. The straightness tolerance is defined by the minimum distance between two parallel lines containing the measured datum. The two parallel lines can be mathematically determined as the best fit line using the least squares technique. The positional accuracy of the space can be determined from the four corner points data using the 4 boundary straight lines measurement.

Roundness, radius, and the positional error (X,Y) are evaluated for hole inspection in moulds. The roundness tolerance is defined as the tolerance zone limited by two concentric circles a distance t apart. There are 4 conventional methods for roundness calculation, the least squares circle (LSC), the minimum zone circle (MZC), the minimum circumscribed circle (MCC), and the maximum inscribed circle (MIC). In this research, the least squares circle is used, as the centre coordinate as well as the roundness tolerance are to be evaluated.

The results of the error evaluation for the basic features are graphically displayed on the computer screen with user interactive selection.

5. Practical Application to Real Moulds and Discussion

The developed system has been applied to the real moulds, i.e.

1. A mould having a bicubic B-spline surface with basic features.
2. A pocket space for a cavity block having a bicubic polynomial surface.

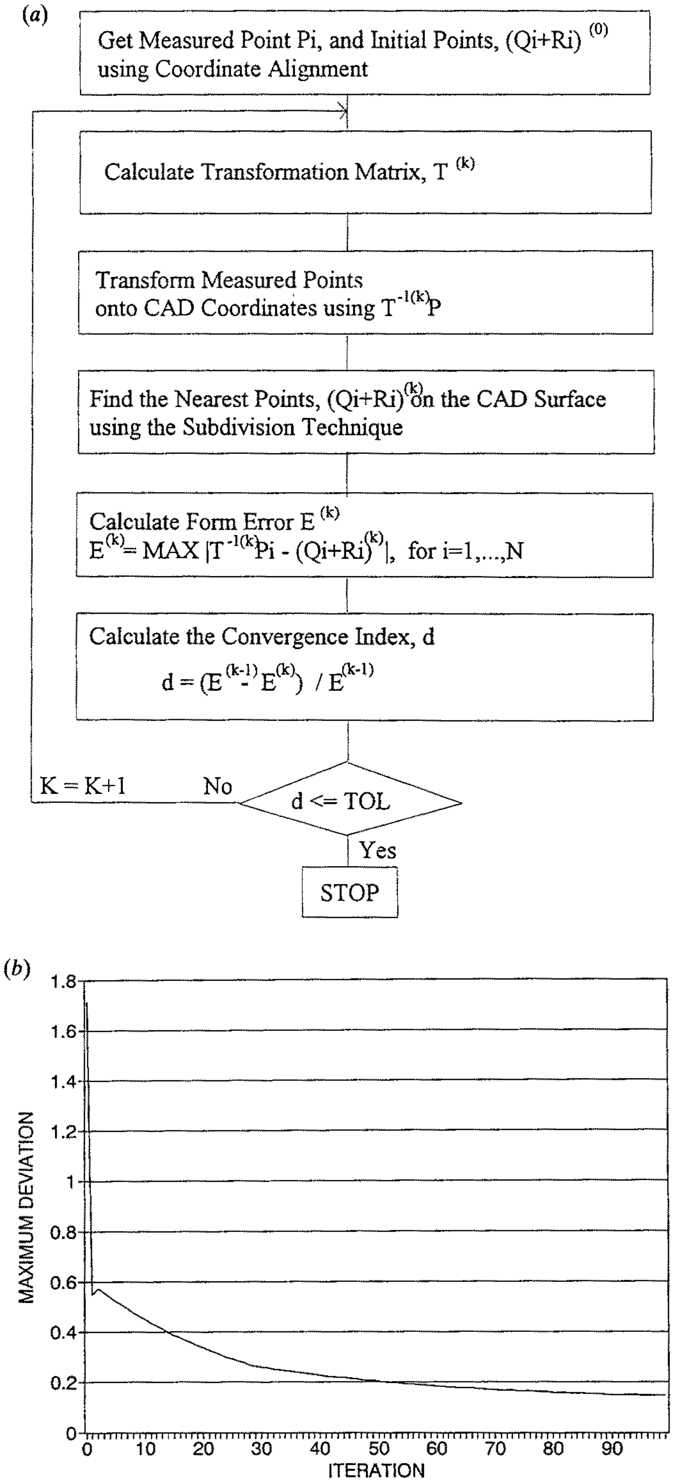


Fig. 7. (*a*) MINIMAXSURF algorithm for form error calculation. (*b*) Form error vs. number of iterations.

5.1 A Mould Having a Bicubic B-Spline Surface with Some Basic Features

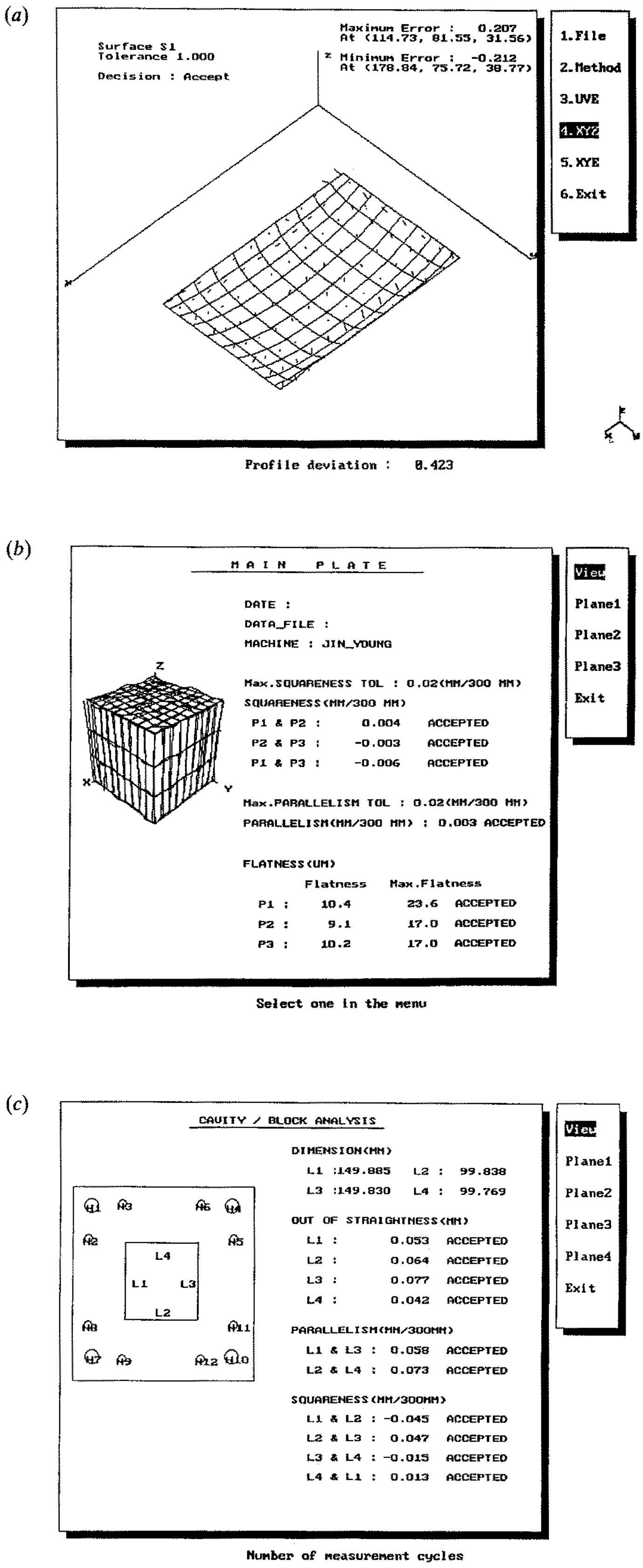
A mould base whose dimension is 250 mm × 250 mm × 50 mm was selected as a test mould as shown in Fig. 2(*a*), which was machined roughly. A cavity block of a bicubic *B*-spline surface is inserted and 12 holes are drilled for guide pins. Following the inspection planning procedures, the measurement operations are performed, and the errors are calculated. Figure 8(*a*) shows the error analysis of the sculptured surface: the form error is 0.423 mm, with the maximum error of 0.207 mm, and the mimimum error error of −0.212 mm. Thus, it can be observed that the maximum error point is 0.207 mm undercut, and the minimum point is −0.212 mm overcut. Figure 8(*b*) shows the inspection results for a mould plate feature, giving squareness, parallelism, and the flatness errors. Figure 8(*c*) shows the inspection results of a pocket for the cavity block, giving the straightness, parallelism, squareness error, and dimensional accuracy of the pocket.

5.2 A Cavity Block Having a Bicubic Polynomial Surface

A cavity block whose size is 150 mm × 150 mm × 30 mm is machined and is inserted into a mould. It has a bicubic polynomial surface on the block, and the inspection procedure is performed in order to check the machining accuracy of the sculptured surface. The form error is found to be 0.374 mm, with a maximum error of 0.187 mm (undercut) and a minimum error of −0.069 mm (overcut). Figure 9 shows the inspection results of the sculptured surface.

6. Conclusion

1. A feature based inspection system has been implemented and found to be useful for the computer integrated mould manufacturing process. Features such as sculptured surface, mould plate, pocket for cavity block, and holes for inserting pins are selected by the user, and the appropriate inspection specification can be interactively set in the CAD environment.
2. Flexible and efficient methods of measurement point distribution have been implemented for the inspection of sculptured surfaces to accommodate various combination of geometry.
3. A new method of recursive error calculation algorithm, MINIMAXSURF, has been implemented for sculptured surface measurement taking account of the radius of measurement probe. Thus the profile tolerance which is unique to the given surface can be calculated successfully.
4. Modular inspection planning procedures have been developed for the basic features of moulds such as the mould plate, pocket for cavity/block, and holes for inserting pins, aiming at uniform coverage for the features. Random samplings are performed within the uniform subintervals for the line and plane features. Prime number points are sampled for the circle feature, as they have been recommended from standards [9].
5. A high degree of computer integration has been demonstrated by having user friendly modules for feature selection, inspection planning, part alignment for the coordinate



(a)

```
Surface S1
Tolerance 1.000

Decision : Accept

Maximum Error :   0.207
At (114.73, 81.55, 31.56)

Minimum Error :  -0.212
At (178.84, 75.72, 38.77)

Profile deviation :   0.423
```

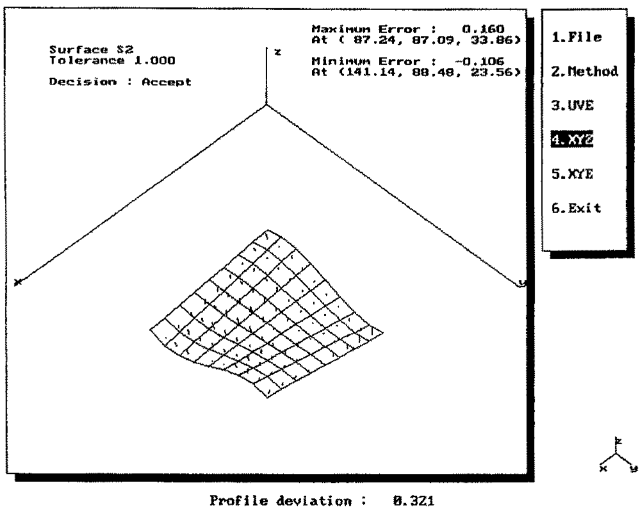
(b)

```
M A I N   P L A T E

DATE :
DATA_FILE :
MACHINE : JIN_YOUNG

Max.SQUARENESS TOL : 0.02(MM/300 MM)
SQUARENESS(MM/300 MM)
 P1 & P2 :     0.004    ACCEPTED
 P2 & P3 :    -0.003    ACCEPTED
 P1 & P3 :    -0.006    ACCEPTED

Max.PARALLELISM TOL : 0.02(MM/300 MM)
PARALLELISM(MM/300 MM) : 0.003 ACCEPTED

FLATNESS(UM)
         Flatness  Max.Flatness
  P1 :     10.4        23.6  ACCEPTED
  P2 :      9.1        17.0  ACCEPTED
  P3 :     10.2        17.0  ACCEPTED

Select one in the menu
```

(c)

```
CAVITY / BLOCK ANALYSIS

DIMENSION(MM)
  L1 :149.885   L2 :  99.838
  L3 :149.830   L4 :  99.769

OUT OF STRAIGHTNESS(MM)
  L1 :          0.053  ACCEPTED
  L2 :          0.064  ACCEPTED
  L3 :          0.077  ACCEPTED
  L4 :          0.042  ACCEPTED

PARALLELISM(MM/300MM)
  L1 & L3 :  0.058  ACCEPTED
  L2 & L4 :  0.073  ACCEPTED

SQUARENESS(MM/300MM)
  L1 & L2 : -0.045  ACCEPTED
  L2 & L3 :  0.047  ACCEPTED
  L3 & L4 : -0.015  ACCEPTED
  L4 & L1 :  0.013  ACCEPTED

Number of measurement cycles
```

Fig. 8. (*a*) Error analysis of a bicubic *B*-spline surface. (*b*) Inspection results for a mould plate. (*c*) Inspection results for a pocket.



```
Surface S2
Tolerance 1.000

Decision : Accept

Maximum Error :   0.160
At ( 87.24, 87.09, 33.86)

Minimum Error :  -0.106
At (141.14, 88.48, 23.56)

Profile deviation :   0.321
```

Fig. 9. Error analysis of a bicubic polynomial surface.

matching, error evaluation and representation. The developed system has been implemented around an IBM PC between a main frame computer (VAX) and a 3-axis CMM with CNC capability. The system can be easily applied to other commercial CAD/CAM systems with add-on interface modules.

6. A robust inspection system has been developed for mould manufacturing, by which practical and sophisticated inspection procedures can be performed easily with great flexibility.

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