A Computer-Aided Inspection Planning System for On-Machine Measurement - Part II : Local Inspection Planning -

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As a part II of theis research, new local inspection planning strategy is proposed in this paper based on the proposed inspection feature extraction method. In the local inspection planning stage, each feature is decomposed into its constituent geometric elements for more effective inspection planning. The local inspection planning for the decomposed features are performed to determine: (1) the suitable number of measuring points, (2) their locations, and (3) the optimum probing paths to minimize measuring errors and times. The fuzzy set theory, the Hammersley's algorithm and the TSP method are applied for the local inspection planning. Also, a new collision checking algorithm is proposed for the probe and/or probe holder based on the Z-map concept. Finally, the results are simulated and analyzed to verify the effectiveness of the proposed methods.

Key Words : Computer-Aided Inspection Planning (CAIP), Geometric Feature, Collision Avoidance, On-Machine Measurement (OMM)

1. Introduction

In the part I of these papers, a feature-based global inspection planning method for OMM system is proposed to develop more effective measuring methodology for complicated workpieces having many primitive features. In the part I, an optimum inspection sequence determination method is proposed by analyzing their nested relations and possible probe approaching directions. Thus, a series of heuristic rules are developed to achieve global inspection planning. In this paper, as a successive work, effective local inspection planning methodologies are proposed. An overall schematic diagram of the proposed feature-based local inspection planning strategy is illustrated in Fig. 1.

Local inspection planning is performed for each feature in this stage. First, each feature is decomposed, according to the proposed method, into its constituent geometric elements such as planes, circles, etc. Then, the tasks of this local inspection planning are : the determination of (1) the suitable number of measuring points, (2) their locations, and (3) the optimum probing paths to minimize measuring errors and times, (4) collision checking to avoid the probe and/or probe holder collision, and (5) the coordinate alignment method. In this research, the fuzzy set theory is applied to determine the suitable number of the measuring points, and the Hammersley's algorithm is used to locate the measuring points on the target surface. Here, the non-contacting measuring point problem is handled to relocate the measuring points. After determining the suitable measuring point locations for a given feature, the TSP (traveling sales person) algorithm is applied

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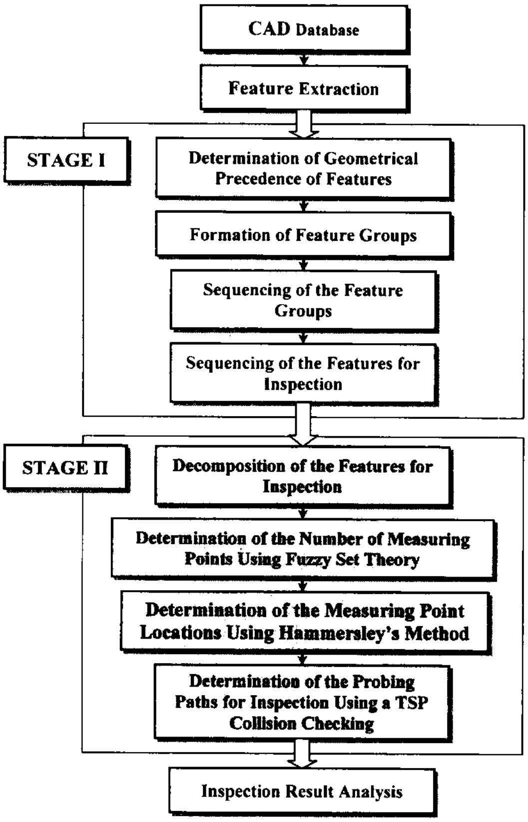


Fig. 1 Overall schematic diagram of the proposed local inspection planning strategy

to determine the optimum probing paths so that the feature can be inspected effectively with minimum measuring errors and times. Also, new probe and/or probe holder collision avoidance methods are proposed using Z-map concept. Finally, the proposed methods are simulated to verify their validity in real OMM process.

Detailed information and simulation results of the proposed method are explained in the following sections, and the results are analyzed to verify the effectiveness of the proposed feature-based local inspection planning strategy.

2. Decomposition of Feature for Inspection

For the measuring process using OMM, a touch-type probe is generally used, which performs point-to-point motions to get dimensional data of the target surface, usually one point at a time. Although the target workpiece is very complicated and has many machining features, it is composed of many geometric primitives such as planes, cylinders, and sculptured surfaces, etc. Also, when using a touch type probe, the probe repeats identical point-to-point motions to get point data of the primitives. The geometric tolerance evaluation, such as parallelism, squareness, etc., can be determined by manipulating the obtained point data set. Thus, it is necessary to decompose the features into easy-to-handle primitives for more effective local inspection planning.

The features, those are used for design and manufacturing convenience, can be decomposed into its constituent geometric elements. Generally, the geometric elements of each feature can be classified into two groups: analytic geometries and free-formed geometries as shown in Fig. 2. Again, the analytic geometries can be decomposed into the primitives such as ellipses, circles and planes, etc. The geometric tolerances of the elements can be determined as single geometries such as straightness, flatness, and roundness, etc., and/or integrated geometries such as parallelism, squareness, and angularity, etc.

As shown in Fig. 3, the feature decomposition procedure is composed of two steps: decomposition into (1) inspection features and (2) primitives for local inspection planning. In the first step of the decomposition into inspection features, the object is decomposed into the features for inspection such as pockets, planes and islands, etc. (Fig. 3(a)). In this step, the decomposed features are very similar to machining features. As shown in Fig. 3(b), the features obtained form the first step can be decomposed into the geometric primitives such as planes, cylinders, etc. Since the inspection process using OMM with a touch-type probe performs point-to-point motions to get the dimensional data of the target surface, such decomposition process makes it easier to build an inspection plan for complicated objects.

3. Local Inspection Planning for OMM

The local inspection planning includes the de-

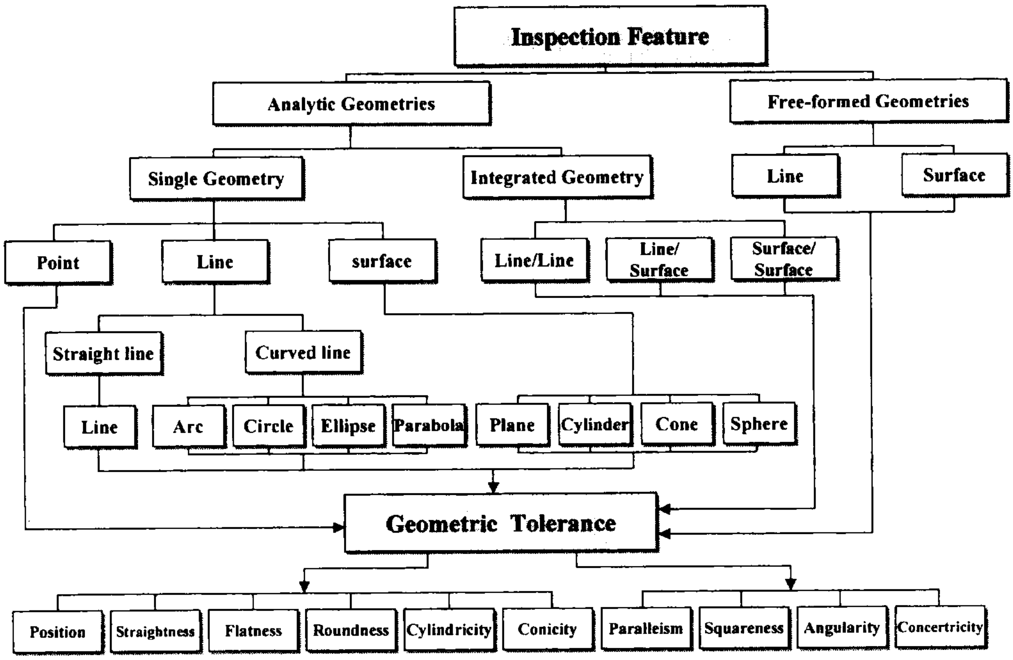
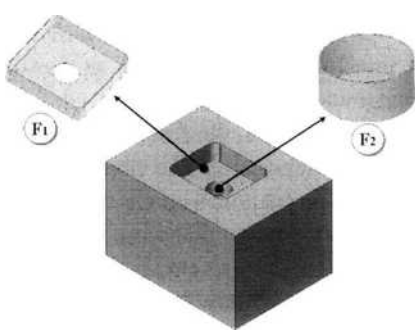
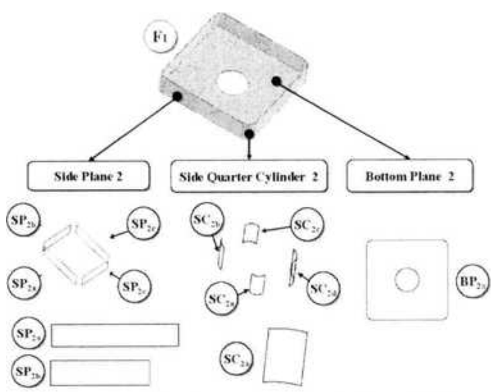


Fig. 2 Geometric feature classification for inspection



(a) Step 1 : The decomposition into inspection features



(b) Step 2 : The decomposition into primitive

Fig. 3 Decomposition of features for inspection

termination of the inspection parameters such as the suitable number of measuring points for each surface, the optimum locations of the points, and the probing path to minimize the total inspection. Also, the probe and probe holder collision problems and the relocation problems of the non-contacting measuring points are handled in this chapter. Detailed methodologies applied for the local inspection planning process are as follows :

3.1 Number of measuring points

Generally, the OMM using touch-type probes performs point-to-point motions to read 3-dimensional coordinates of the workpiece. Since the measurement reliability of the OMM strongly depends on the number of sampling points, more reliable results can be achieved as the number of measuring point increases. However, since the increase of the number of measuring points usually causes the increase of measuring time, the appropriate number of measuring points has to be determined for each feature by considering tolerance levels, geometric characteristics and desired confidence levels. To determine the optimum number of measuring points, some useful methods

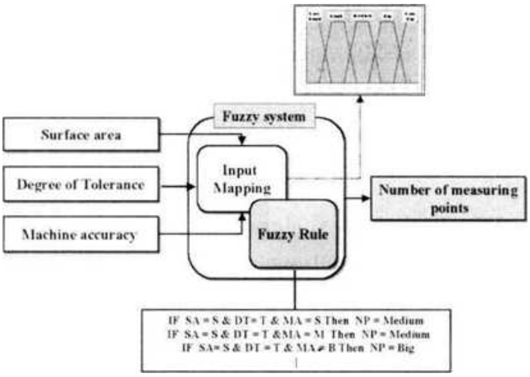


Fig. 4 Fuzzy system structure to determine the number of measuring points

were proposed based on the given design tolerance and machining accuracy (Menq et al. 1990), based on the least square approximation and the simulation (Dowling et al. 1997), and by applying the hybrid neuro-fuzzy method (Ha et al. 2000).

In this research, a fuzzy system, similar to the method proposed by Ha et al., is applied to determine the appropriate number of measuring points as shown in Fig. 4. In this system, the surface area of the target surface, the degree of design tolerance and the volumetric error of the machine tool used to produce the workpiece are used as input parameters.

3.2 Measuring point locations

To determine the measuring point locations on the target surfaces, the equi-interval sampling, random sampling, stratified sampling and hybrid sampling methods (Caskey et al. 1990, Cho et al. 1995) were proposed. In this research, Hammersley's algorithm is applied to determine the locations since it can achieve the nearly quadratic reduction of measuring points to satisfy the equal level of measuring accuracy compared to the equi-interval sampling method (Woo et al. 1993, Lee et al. 1997). The Hammersley's algorithm for various features is listed in table 1.

3.3 Relocation of Non-contacting points

Since the decomposed primitives may contain holes, slots and/or pockets, the measuring point locations obtained by applying the Hammersley's method onto the surface should be relocated. Ha et al. (2000) suggested an algorithm for the handling of non-contacting points. They generated triangular meshes for the surface that has non-contacting area, and moved the non-contacting points to the nearest mesh's center points. In this research, a new algorithm is suggested to avoid the unnecessary concentration of the measuring points. The suggested algorithm to relocate the non-contacting points is as follows:

Step 1: Apply the Hammersley's method for the entire surface.
Step 2: Decompose the surface into meaningful primitives (such as rectangles, triangles, ...).
Step 3: Determine the non-contacting points.
Step 4: Move the non-contacting points to the nearest primitives.
Step 5: Reapply the Hammersley's method to each point-added primitive.

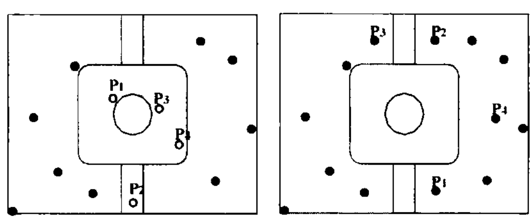
An example of the suggested non-contacting point relocation method is illustrated in Fig. 5.

3.4 Measuring sequence

After determining the suitable measuring points for the given surface, the appropriate probe paths

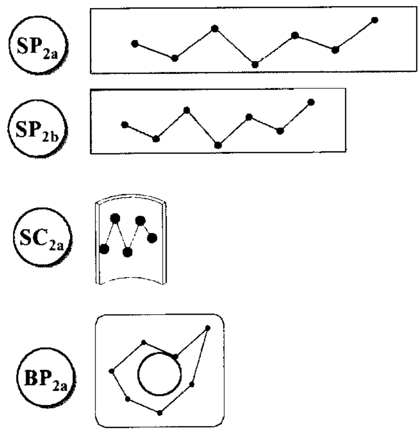
Table 1 Hammersley's algorithm for various features

Rectangular Surface	$s_i=\frac{i}{N},\ t_i=\sum_{j=0}^{k-1}\left(\left[\frac{i}{2^j}\right]Mod2\right)\times 2^{-j-1}$
Circular Surface	$s_i'=t_i^{\frac{1}{2}}\times R,\ t_i'=s_i\times 360°$
Cone	$s_i'=t_i^{\frac{1}{2}}\times R.\ t_i'=s_i\times 360°.\ w_i'=-s_i'\times h$
Hemisphere	$s_i'=\sqrt{R^2-(-R-w_i')^2}=\sqrt{1^2-(1-t_i)^2}\times R$ $t_i'=s_i\times 360°,\ w_i'=-t_i\times R$

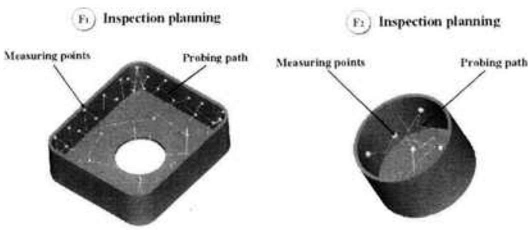


(a) Before (b) After

Fig. 5 Relocation of non-contacting points for base plane



(a) Probe path & measuring points for each primitive



(b) Inspection planning for feature **F1, F2**

Fig. 6 Generated probe path for inspection feature

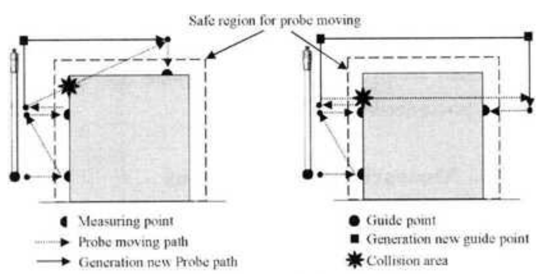
are generated so that the surface can be inspected effectively with minimum measuring errors and within the required time period. Since the measuring process uses a touch-type probe as a discrete type measurement, the measuring order of the points does not affect the inspection results. However, if the probe moves randomly between the measuring points, it may take an inefficient duration of time to inspect the entire surface. Thus, the measuring order of the points has to be determined to minimize the inspection time. In this research, the TSP (travelling salesperson problem) algorithm based on the simulated annealing method (Press et al. 1992) is implemented to generate the probe path between the measuring points (Lee et al. 1994). In this case, the objective function is given by :

$$E=\sum_{i=1}^{n}\sqrt{(x_i-x_{i+1})^2+(y_i-y_{i+1})^2+(z_i-z_{i+1})^2} \quad (1)$$

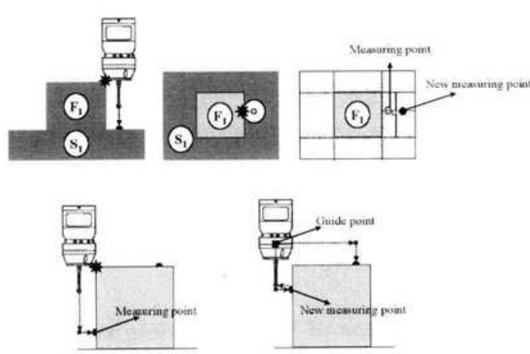
where, n is the number of the measuring points, (x_i, y_i, z_i) is the coordinate of each measuring point, E is the total distance of the probe path. If the measuring sequence is determined so that E should be minimized, it is possible to obtain the effective probe path minimizing the inspection time. The generated probe path based on TSP is shown in Fig. 6.

3.5 Collision avoidance

Although appropriate measuring sequences and probing paths are determined for the given workpiece using the above methods, there still remain probe collision possibilities when the probe moves between the features. The collision problem in the OMM operation can be divided into two categories such as the probe collision and the probe holder collision as shown in Fig. 7. Figure 7(a) shows the first case of the probe collision problem when the probe moves to the next guide point. Such problem can be resolved by inserting new guide points to avoid collisions as shown in the figure. Next case, the probe holder collision problem, is shown in Fig. 7(b). Such case is more severe than the first case since it can make the expensive transducer disable. The probe holder collision problem can be avoided by using longer

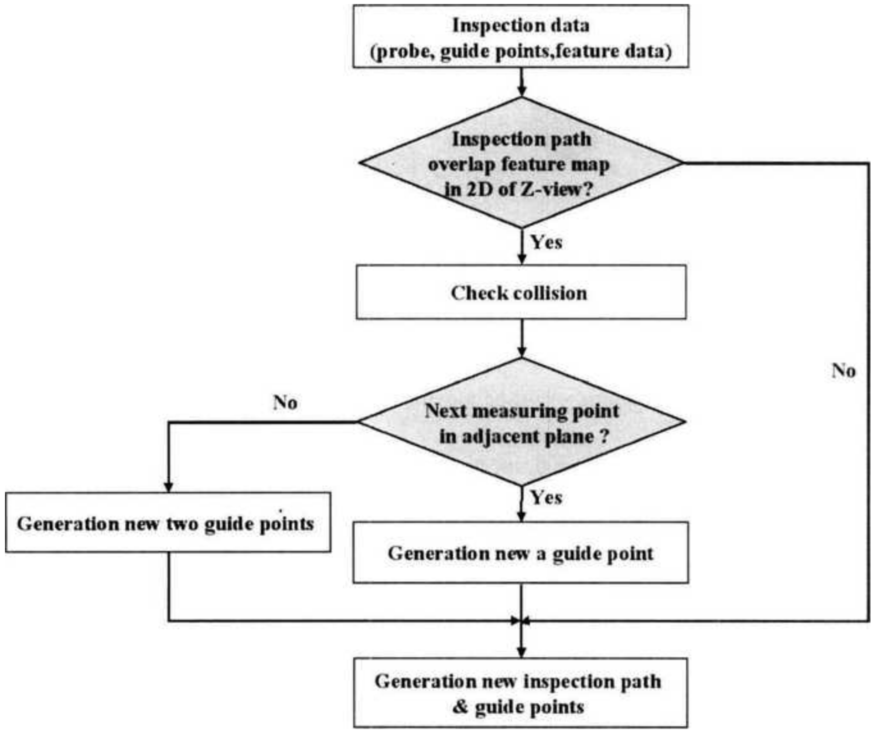


(a) The Probe collision example

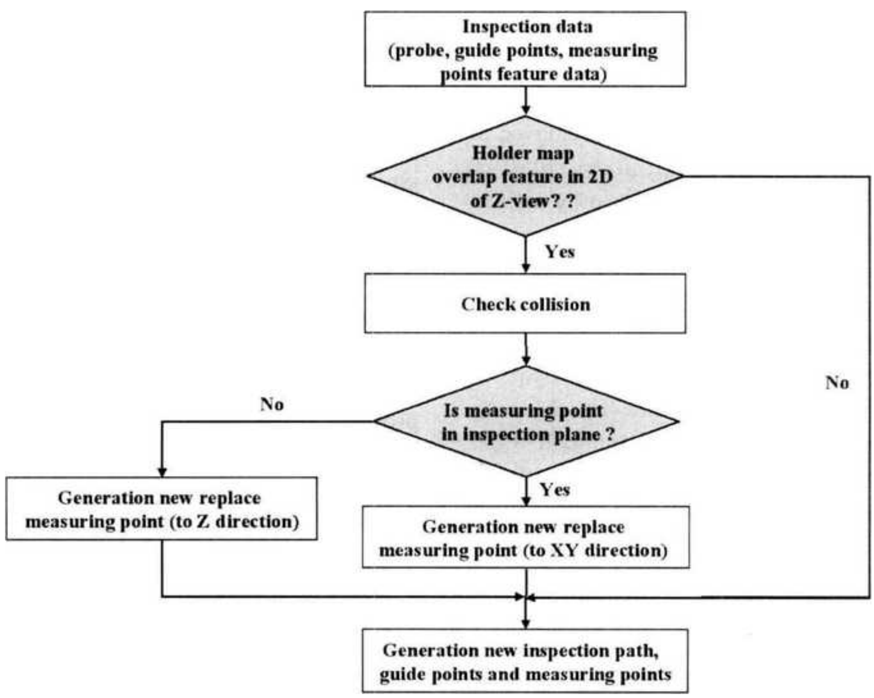


(b) The OMM probe holder collision example

Fig. 7 Examples of probe and probe holder collision



(a) The proposed schematic diagram for collision avoidance of probe



(b) The proposed schematic diagram for collision avoidance of probe holder

Fig. 8 Proposed collision avoidance algorithm

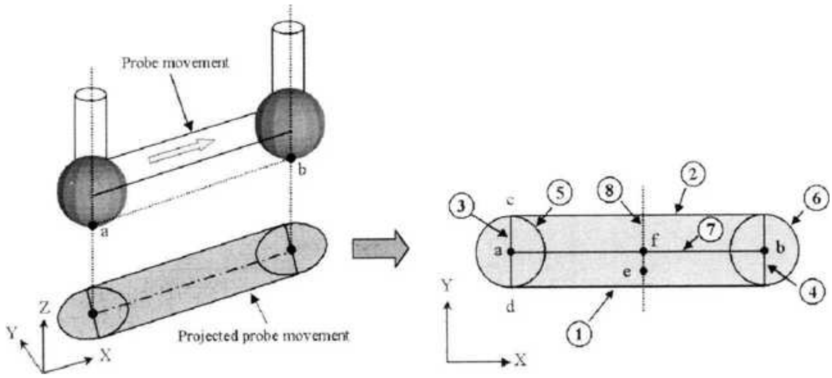


Fig. 9 Modeling of probe moving area for collision checking

probe stems or by moving the measuring point to safe regions as shown in the Fig. 7.

In this study, to detect the probe and/or probe holder collisions, a new methodology is proposed using Z-map as shown in Fig. 8. In this method, as a first step, a Z-map is generated for the given target workpiece, and then probe and/or probe holder moving trajectories are calculated according to the previously generated probing path. By calculating errors caused by the probe and/or probe holder trajectories, their collisions can be checked during the probing paths.

As shown in Fig. 9, while the probe linearly moves between two consecutive points **a** and **b**, the initially generated Z-map will be removed by the probe envelope if there are probe collisions between the paths. Thus, it is checked by calculating the errors between the initially generated Z-map and the finally created Z-map after the probe movement about a part. Such collision checking procedure can be achieved by the following method. As shown in Fig. 9, the volume of the probe moving envelope can be defined by the coordinates of probing **a**, **b** and probe radius **R**. First, it is necessary to verify whether the selected checkpoints exist inside this projected probe movement zone on the XY-plane. If they are, the coordinates of the probing surface can be defined by the intersection points between the probe moving envelope and the point vectors generated by the Z-map (Cho et al. 2002). Mathematical description of this concept is presented in the following paragraphs.

When an arbitrary checkpoint **e** exists inside the rectangle ①②③④, a supplementary point **f**, which is the intersection point between two lines ⑦ and ⑧, is taken into account in order to obtain Z-coordinate of the intersection point between the point vector of the check point **e** and the probing envelope. Since the checkpoint **e** is on the line ⑧, the Z-coordinate $\mathbf{z_f}$ of the point **f** is given by :

$$z_f = z_a + (z_b - z_a)\frac{(x_f - x_a)}{(x_b - x_a)} \tag{2}$$

where, $\mathbf{x_a}$, $\mathbf{x_b}$, $\mathbf{z_a}$ and $\mathbf{z_b}$ and X- and Z-coordinates of the probing points **a** and **b**. The Z-coordinate $\mathbf{z_e}$ of the check point **e** depends on the probe shape used, accordingly in the case of the generally used probe, $\mathbf{z_e}$ can be represented by (Cho et al. 2002):

$$z_e = z_f + R - \sqrt{R^2 - r_e^2},\ r_e = \sqrt{(x_f - x_e)^2 + (y_f - y_e)^2} \tag{3}$$

When the check point **e** is inside the circle ⑤ or ⑥, $\mathbf{z_e}$ can be calculated by substituting $\mathbf{x_a}$, $\mathbf{y_a}$ or $\mathbf{x_b}$, $\mathbf{y_b}$ for $\mathbf{x_f}$ and $\mathbf{y_f}$ in Eq. (2). In the case of a probe holder, $\mathbf{z_e}$ can be presented by :

$$z_e = z_f + r_2 - \sqrt{r_2^2 - (r_e - r_1)^2}\ (r_e > r_1),\ z_e = z_1\ (r_e \le r_1) \tag{4}$$

The probe collision can be checked by calculating the errors between the initially generated Z-map and the remained Z-map created by Eqs. (3) and (4). Figure 10 shows the Z-map and the calculated errors obtained using the proposed collision checking methods. As shown in Fig. 10 (b), there are errors along the probe movement. Thus, this means that the probe collision occurs

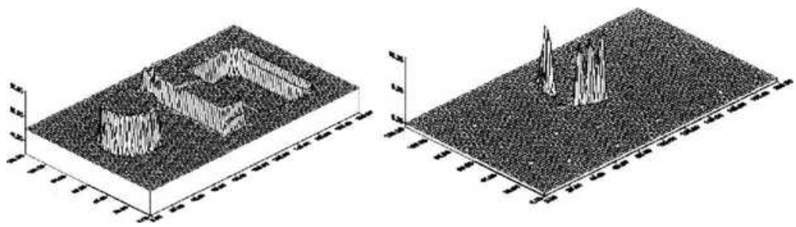
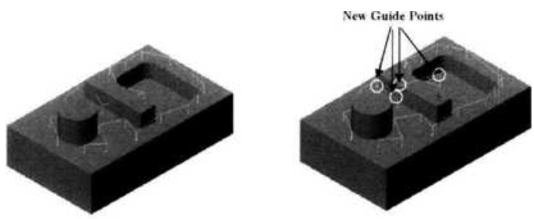


Fig. 10 Simulation results after collision checking using Z-map



(a) Before (b) After

Fig. 11 Modified probing path after collision checking

in such regions. The same procedure can be repeated for probe holder collision checking. Such collision problems can be resolved as follows :

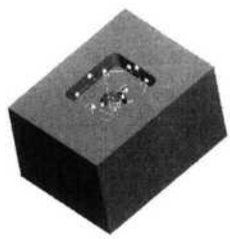
(1) Probe collision : insert additional guide points to correct the probing paths (Fig. 7 (a)).

(2) Probe holder collision : change the probe stem to longer one, or insert additional guide points to avoid collisions (Fig. 7 (b)).

Modified probing path after collision checking based on the proposed methods for the sample workpiece is shown in Fig. 11. From the figure, it can be seen that new guide points are added for probe and/or probe holder collision avoidance.

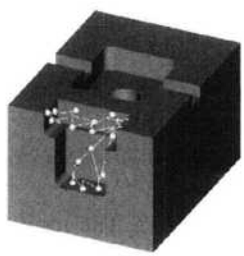
4. Simulation Results

Simulation works are performed to verify the effectiveness of the proposed feature-based inspection planning method. The feature-based inspection sequences described in chapter 3, global inspection planning for OMM of this research, the inspection plan of the example part consist of total 6 steps out of 32 processing. The inspection planning of 6 steps is determined by tolerance of

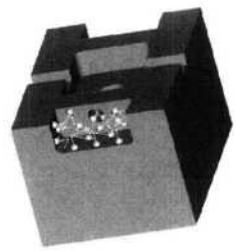


(a) Inspection of F_1, F_2 (process number 5)

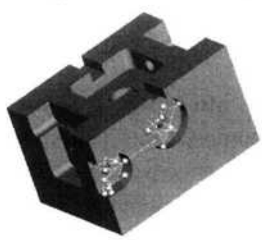
(b) Inspection of F_3, F_4 (process number 8)



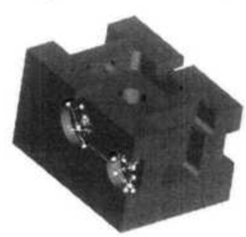
(c) Inspection of F_{15}, F_{16} (process number 13)



(d) Inspection of F_5, F_6 (process number 18)



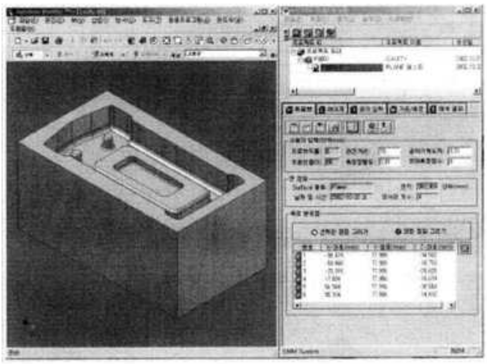
(e) Inspection of F_7, F_8, F_{11}, F_{12} (process number 25, left)



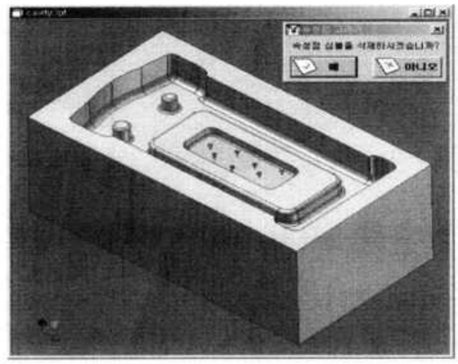
(f) Inspection of F_9, F_{10}, F_{13}, F_{14} (process number 8, right)

Fig. 12 Inspection planning results for the example part

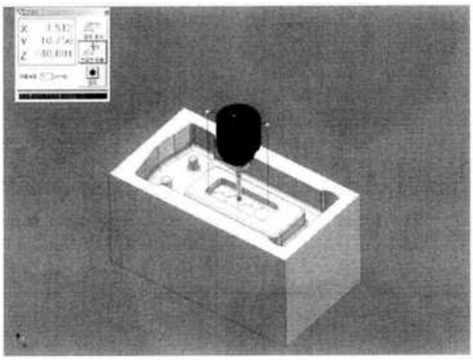
features and change of alignment. The simulated result for the example part considering each machining step, including measuring point locations and probing paths, is shown in Fig. 12. Also, the developed methodologies are implemented in



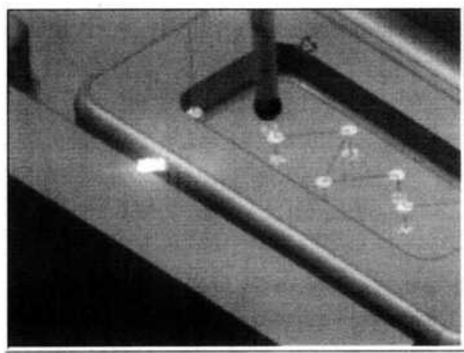
(a) OMM S/W main view



(b) Measuring point determination



(c) Touch probe operation & simulation



(d) Inspection simulation

Fig. 13 Illustration of developed program for OMM

OMM program as shown in Fig. 13. The results show that the proposed inspection planning system can be applied in real OMM system.

5. Conclusions

In feature-based local inspection planning, first, the features are decomposed into primitives for more convenient and effective inspection planning. Then, local inspection planning strategy is proposed to the decomposed inspection features. In the local inspection planning stage, the detailed inspection operations are carried out to determine the suitable number of the measuring points by applying the fuzzy set theory, the measuring point locations by applying the Hammersley's method, and the optimal probing paths to minimize the total inspection time by applying a TSP algorithm. Also, to resolve the probe and/or probe holder collision problem, a new collision avoidance method is proposed based on the Z-map concept. To validate the effectiveness, the developed inspection planning procedure is programmed and the simulation works are performed for an example part. As a result, it can be verified that the proposed featured-based local inspection planning method can be very effectively applied for complicated workpieces having many features, surfaces, and primitives in the real OMM operation.

References

Caskey, G., Hari, Y., Hocken, R., Palanivelu, D., Raja, J., Wilson, R., Chen, K. and Yang, J., 1990, "Sampling Techniques for Coordinate Measuring Machine," *Design and Manufacturing Systems Conference*, pp. 779~786.

Chang, T. C., and Wysk, R. A., 1985, An Introduction to Process Planning Systems, Prentice-Hall, Englewood cliffs, New Jersey, USA.

Cho, M. W. and Kim, K., 1995, "New Inspection Planning Strategy for Sculptured Surfaces Using Coordinate Measuring Machine," *International Journal of Production Research*, Vol. 33, No. 2, pp. 427~444.

Cho, M. W. and Seo, T. I., 2002, "Inspection Planning Strategy for the On-Machine Measurement Process Based on CAD/CAM/CAI Integration Concept," *The International Journal of Advanced Manufacturing Technology*, Vol. 19, pp. 607~617.

Cho, M. W., Seo, T. I, Kim, J. D. and Kwon, O. Y., 2000, "Reverse Engineering of Compound Surfaces Using Boundary Detection Method," *KSME International Journal*, Vol. 14, No. 10, pp. 1104~1113.

Descotte, Y. and Latombe, J. C., 1984, *GARI : An Expert System for Process Planning*, Solid Modeling by Computers, pp. 329~345, Plenum Press, NY.

Lee, G., Mou, J. and Shen, Y., 1997, "Sampling strategy design for Dimensional Measurement of Geometric Features Using Coordinate Measuring Machine," *International Journal of Machine Tools and Manufacturing*, Vol. 37, No. 7, pp. 917~934.

Lee, J. W., Kim, M. K. and Kim, K., 1994, "Optimal Probe Path Generation and New Guide Point Selection Methods," *Engineering Application of Artificial Intelligence*, Vol. 7, No. 4, pp. 439~445.

Lee, K. I., Lee, H., Noh, S. D., Shim, Y. B., and Cho, H. S., 1995, "A Process Planning System Using Group Technology and Rule-base," *IE Interfaces, Korean Institute of Industrial Engineers*, Vol. 8, No. 3, pp. 221~230.

Menq, C. H., Yau, H. T., Lai, G. Y. and Miller, R. A., 1990, "Statistical Evaluation of Form Tolerances Using Discrete Measurement Data," *ASME Winter Annual Meeting*, ASME, PED-Vol. 47, pp. 135~149.

Press, W. H., Teukolsky, S. A., Vetterling, W. T. and Flannery, B. P., 1992, *Numerical Recipes in C*, Cambridge University Press.

Rogers, M., 1994, "Case Study of Feature Representation in STEP," Part 48, Technical Report, Design Automation Laboratory, Department of Mechanical Engineering, Arizona State University, USA.

Shah, J. J., Mantyla, M., and Nau, D. D., 1994, *Advances in Feature-Based Manufacturing*, Elsevier Science B. V, Amsterdam, Netherlands.

Woo, T. C. and Liang, R., 1993, "Dimensional measurement of surfaces and their sampling," *Computer-Aided Design*, Vol. 25, No. 4, pp. 233~239.