A Computer-Aided Inspection Planning System for On-Machine Measurement - Part I : Global Inspection Planning -

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Computer-Aided Inspection Planning (CAIP) is the integration bridge between CAD/CAM and Computer Aided Inspection (CAI). A CAIP system for On-Machine Measurement (OMM) is proposed to inspect the complicated mechanical parts efficiently during machining or after machining. The inspection planning consists of Global Inspection Planning (GIP) and Local Inspection Planning (LIP). In the GIP, the system creates the optimal inspection sequence of the features in a part by analyzing the various feature information such as the relationship of the features, Probe Approach Directions (PAD), etc. Feature groups are formed for effective planning, and special feature groups are determined for sequencing. The integrated process and inspection plan is generated based on the sequences of the feature groups and the features in a feature group. A series of heuristic rules are developed to accomplish it. In the LIP of Part II, the system generates inspection parameters. The integrated inspection planning is able to determine optimum manufacturing sequence for inspection and machining processes. Finally, the results are simulated and analyzed to verify the effectiveness of the proposed CAIP.

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

1. Introduction

The functional requirements of a product which are specified in the design stage must be inspected after or during its manufacturing. Recently, the On-Machine Measurement (OMM) is widely-used as essential measuring equipment for the purpose of the direct inspection in manufacturing and the quality control. The OMM acts as a key role of the inspection of the precise and complicated mechanical workpieces. As the workpiece gets more complicated, the role of the OMM gets more significant as efficient dimensional measuring equipment. Because the CMM is controlled by the computer, it is very convenient for the storage, edit, and statistical analysis of its inspection data, and it can be easily integrated into a modern CIM (Computer-Integrated_Manufacturing) system (Cho et al. 2002).

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In the recent CIM (Computer-Integrated Manufacturing) researches, much effort has been made for the integration between the key technologies of the CIM. But in the inspection area, there has not existed such integration effort between CAD and CAI (Computer-Aided Inspection), while the integration between CAD and CAM through CAPP (Computer-Aided Process Planning) (Chang et al. 1985, Descotte et al. 1984, Lee et al., 1995) has been studied for over two decades. The inspection is carried out as a stand-alone process so far. The CAI also has to be integrated in the

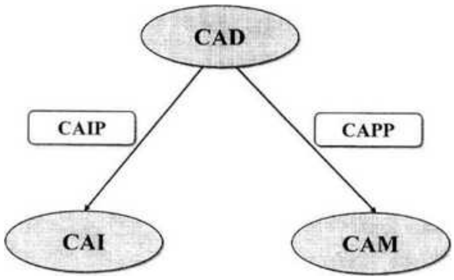

Fig. 1 The role of CAIP

CIM system. When the CAI is integrated into the CAM, a bridge is required to link the CAD and the CAI, and the CAIP (Computer-Aided Inspection Planning) is the solution. The role of the CAIP is represented in Fig. 1 conceptually.

When a complicate workpiece is inspected using OMM, the inspection sequence has to be considered. Since the inspection performance of the OMM, such as the measuring time, cost and errors, highly depends on the applied inspection planning strategy, the development of an optimal inspection planning strategy is strongly required to achieve more accurate and faster inspection results using OMM. In this research, a feature-based inspection planning strategy is proposed to develop more efficient measuring methodology for complicated workpieces comprising many primitive form features. An overall schematic diagram of the proposed feature-based inspection planning strategy is illustrated in Fig. 2, which is composed of the following two stages :

Stage I : Global inspection planning

In this stage, global inspection planning is performed to determine the optimum inspection sequence of the features. First, the geometrical precedence of the features is determined by analyzing their nested relations, and then the features are grouped according to the extracted characteristics. Next, the inspection sequence of the feature groups is determined, and then the sequence of the features in each group is determined to generate the global inspection plan. The planning procedure is represented as a series of the heuristic rules developed. The application of the rules results in the inspection sequence of the features of a workpiece. This global inspection

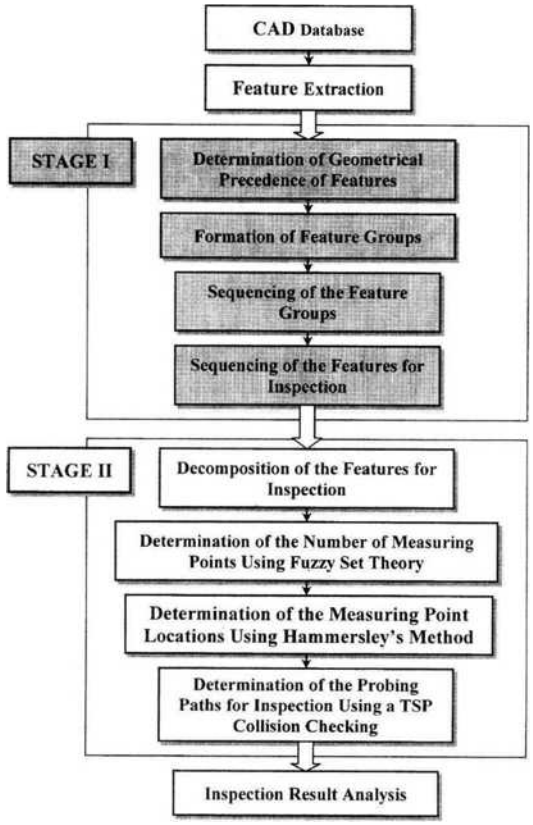

Fig. 2 Overall schematic diagram of the proposed inspection planning strategy

planning is explained in Part I of this paper.

Stage II : Local inspection planning

Local inspection planning is performed for each feature of a part in this stage. After the global inspection planning is finished and the inspection sequence of the features of a part is determined, each feature is decomposed into its constituent geometric elements such as plane, circle, etc. Then, the tasks of this local inspection planning are the determination of: the suitable number of measuring points, their locations, and the optimum probing paths to minimize measuring errors and times. This local inspection planning is explained in Part II of these papers.

The CAIP system developed in this study creates an inspection plan based on the feature information, rule-bases, and various algorithms. The functions of the CAIP system are the CAD interface and feature recognition, the determination of the inspection sequence of the features of a part, the determination of the number of measuring points and their locations, the determination of the probing paths, and the simulation and verification. The CAD interface and feature recognition is not included in this paper because it is a CAD-oriented technology and its function is performed using an independent software module.

2. Part Representation Based on Features for Planning

The feature is a meaningful geometrical entity of a solid model useful for engineering applications such as design, analysis, assembly, or various manufacturing functions. The features are defined and analyzed as the manufacturing planning purpose in this study. A manufacturing feature is commonly defined as a collection of related geometric elements which correspond to a particular manufacturing method or process, or which can be used to reason about the suitable manufacturing methods of processes for creating that geometry (Shah et al. 1994, Rogers 1994). The manufacturing features can be used for the inspection planning too because the measuring processes of the inspection using an OMM (On-Machine Measurement) or CMM (Coordinate Measuring Machine) system are very similar to the machining processes. The measuring process on an OMM is very similar to the machining process on a vertical milling machine or machining center, and the movement of a tool on the machine tool is not different with that of a probe in OMM. When the OMM is performed on a machining center, the probe can be considered as a tool. The machining process generates a feature, then, the measuring process inspects the generated feature with the same feature definition.

A part is represented as a combination of the predefined features. The features frequently used for the manufacturing purpose were investigated and classified. The identified features are defined as the example of Fig. 3. The figure shows the feature information that is needed for part representation, feature analysis, process planning and inspection planning. In the figure, the TAD (Tool

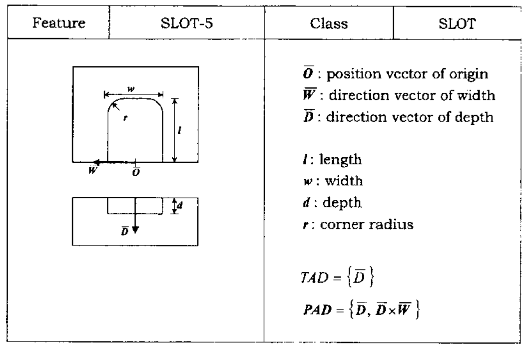

Fig. 3 A predefined feature

Approach Direction) represents the accessible direction of the tool to machine the feature, and the PAD (Probe Approach direction) represents the accessible direction of the probe to measure the feature. A pocket has only one TAD and PAD from its open top surface to the closed bottom surface. A closed slot of Fig. 3 has one TAD from the open top surface, while it has two PAD's from its two open surfaces. In OMM, the straight type probe is used generally, the machining is performed from the vertical direction of a part face, and the measurement is performed before the machining setup is changed. Therefore the TAD is used instead of the PAD, and the difference between the TAD and PAD does not cause the planning complexity in planning procedure.

The feature can be recognized from CAD files to utilize the feature information for the inspection planning. The feature recognition is not included in the scope of this research. An appropriate feature recognition method such as ASVP (Alternation Sum Volumes with Partitioning) (Shah et al. 1994) can be used for the purpose, and its result can be directly interfaced with this research. The inspection planning of this research starts from the feature information of a part recognized from 3D CAD files.

3. Feature Groups

When a part is represented as the combination of features, a feature is linked to other features usually. When the features of a part are handled for various planning purposes of manufacturing, the nested relationship of the features affects the planning. If each feature of a part is handled independently, the planning work is very complex. The treatment of a feature is influenced by the linked features in several ways such as the machining sequence, the approachability of the tool or probe, and the interference of the tool or probe. Therefore it is far more convenient that the features are grouped according to a proper standard of application and handled with the feature groups, rather than that each feature is dealt with independently. In the manufacturing planning systems, the planning has been performed based on the individual features of a part so far. If the features of a part is handled individually, the number of the combination of the planning paths are increased explosively as the number of the features of a part increases (Lee 1991). The grouping of the features decreases considerably the planning complexity. This feature grouping method is similar to the manual planning. Therefore the features are grouped for the convenience of planning in this study. The feature group is useful to handle many complicatedly nested features. The machining or inspection sequence of the features of a part heavily depends on the nested or parent-child relationship of the features. When the inspection of a feature is done, the next measurement is performed on the geometrically related features generally, if such machined features exist.

It is assumed that the inspection is planned after the process planning is done in this research, i. e., the convenience and effectiveness of the inspection planning of a part is not considered in its process plan. The process planning and the inspection planning are performed serially. In this case, the inspection plan for the OMM is directly influenced by the process plan already generated. The process plan is composed of the macro-process plan and the operation plan. The macro-process plan includes the processes, machines, the sequence of the processes, and the setups. The operation plan includes the detailed operations of a process, tools, jigs and fixtures, and so on. In the feature-based process planning, the determination of the sequence of the processes is based on the machining sequence of the features of a part. When a prismatic part is machined on a machining center, the inspection planning for the OMM has to be performed considering the sequence of the setups and the machining sequence of the features of the part. The inspection planning for OMM is the determination of the inspection sequence of the features under the guideline of the sequence of the setups and the features of the process plan.

The inspection planning work is explained through the example part of Fig. 4 in this paper. In Fig. 4, tight true position is required for F_2, and tight concentricity is defined to F_{10} and F_{14} with respect to F_8 and F_{12}, respectively. The nested relationship of the features is depicted in the precedence tree of the features of the example part in Fig. 5. In the figure, every feature of the part is numbered as F_N and the face surface of a part is numbered as S_M, where N is an integer and $M=1$ to 6. The feature precedence tree represents the geometrical parent and child relationship of the features of a part graphically. In the figure, the dotted or solid line between the features represents the nested relationship of the feature. But the whole precedence tree of the features of a part is very inconvenient to analyze the nested relationship of features for process and inspection planning. Therefore the whole tree is divided into the trees of the feature groups.

After the feature groups are formed, some feature groups that have special meaning can be

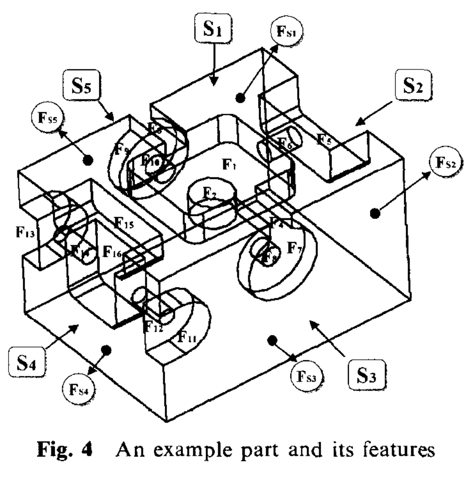

Fig. 4 An example part and its features

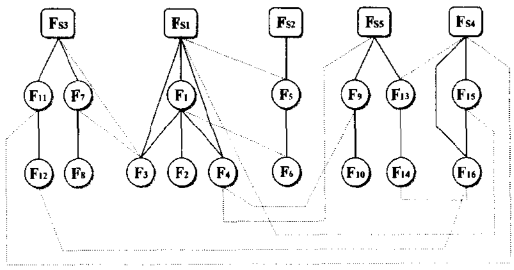

Fig. 5 The precedence tree of the features of the example part

found. There exist special types of features in a part that have meaningful characteristics for manufacturing planning. Their feature groups are classified into some types of groups and they are used for the determination of the priority in manufacturing planning. If the size of a feature is relatively large compared with the part size, the feature is the major feature and the feature group to which it belongs is called as the major feature group. The major feature takes an important role in the shape and function of the part. If many features are nested (geometrically related) to a feature, it is the hub feature and the feature group to which it belongs is called as the hub feature group. In the precedence tree of a part, if many branches are linked to a feature node, then it can be a hub feature. In many cases, the major feature is a hub feature simultaneously. If a feature requires precision machining or careful treatment, it is an important feature and the feature group to which it belongs is called as the important feature group. The important feature can be determined based on the dimensional and geometrical tolerances and the surface roughness. If a geometry element of a feature is referred to as a datum to that of another feature, it is a datum feature and the feature group to which it belongs is called as a datum feature group.

4. Global Inspection Planning for OMM

A series of rules of the global inspection planning system for OMM is developed by analyzing the precedence tree of the features of a part for the formation of the feature groups of a part and the determination of the feature precedence for process and inspection planning in this section.

It is generally known that the heuristic rules are developed and applied when : (1) problems in the domain cannot be well defined analytically, (2) the number of thc alternate solutions of a problem is very large, and (3) the domain knowledge is vast and the relevant knowledge needs to be used selectively. The global inspection planning corresponds to all of the three cases of the above statement. The planning of the global inspection means the determination of the measuring sequence of the features of a workpiece. When a human planner performs the task manually, he does not consider all the possible sequences. He tries to find his best measuring sequence of the features using his empirical planning knowledge, but it is scarcely systematic, general, and solidly reasonable. When a workpiece that has N features is measured, the number of the cases of the measuring sequences is N!. Even the search using a computer is usually practically impossible in the combinatory explosive problem. The heuristic rules explained in this section introduce an effective, systematic, and general method to plan the measuring sequences of the features of a workpiece.

4.1 Feature grouping rules

Feature Grouping Rule 1) Application of the identical TAD rule

If a feature does not have the same TAD with its geometrically related feature, the nested relationship between the two features is canceled.

The geometrical relation means the nested (parent-child or brother) relation between features. In the precedence tree of the example part in the Fig. 5, the connections between F_1 and F_6, and F_{12} and F_{16} are canceled because of different TAD's. The dotted connecting lines of Fig. 5 represent the relations of different TAD's, and they are cancelled. This rule guarantees the accessibility of the tool from one feature to another geometrically related feature.

Feature Grouping Rule 2) Formation of feature *groups*

After the cancellation of the relations of the different TAD, if any features are related with other features, the set of the related features makes altogether a feature group. A single feature that is not related with any other features makes an independent feature group. Each feature of a part belongs to a certain feature group. A feature group requires a parent surface. The parent surface is not considered as a feature in the application of this rule. If there exist multiple feature groups on one surface that have identical single features, the features make a single feature group altogether.

As an example, when this rule is applied to the precedence tree of Fig. 5 after the application of Feature grouping Rule 1, the feature groups are formed as Fig. 6. In the figure, a parent surface appears more than once in the trees of the feature groups.

Feature Grouping Rule 3) Determination of the main link of brother features

If more than one feature of a same depth in a feature group are connected to a same parent surface or feature, the main link to the parent feature is determined among the brother features as the following order :

(1) If there exists a feature whose depth is greater than those of other brother features, the link between the feature and the parent feature is the main link.

(2) If there exists a feature that has the more number of open faces than other brother features, the link between the feature and the parent feature is the main link.

(3) If there exists a major feature of the feature group, the link between the parent feature and the major feature of the feature group is the main link among the brother links.

(4) If there exists a feature that has more links than other brother features, the link between the feature and the parent feature is the main link.

(5) If there exist multiple main links of equal qualification, the choice of the main link is random.

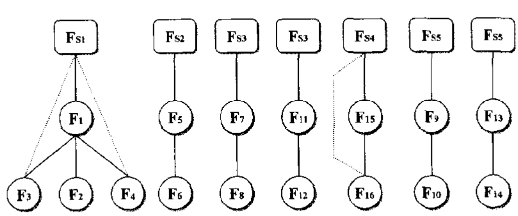

Fig. 6 Feature groups of the example part

The links between S_1 and F_1, and S_4 and F_{15} are determined as the main links in Fig. 6, which are represented using thick lines.

Feature Grouping Rule 4) Cancellation of shortcut paths

The links of the shortcut paths that do not pass through the main link are canceled in each feature group.

In Fig. 6, there exist two paths from S_1 to F_{16}. They are S_1-F_{15}-F_{16} and S_1-F_{16}. Then, the direct link between S_1 and F_{16} is the shortcut path. The shortcut paths are represented using dotted lines in the figure and they are cancelled.

4.2 Process planning rules

Process Planning Rule 1) Determination of the process planning order of feature groups

The machining sequence of the feature groups is determined using the following sub-rules :

(1) The major feature group is planned first.

(2) The hub feature group is planned next.

(3) The datum feature group is planned before the important feature group.

(4) The important feature group is planned last, if possible.

(5) The feature groups on one same setup are planned together on that setup during the application of the sub-rules (1), (2), (3) and (4) before the change to the next setup, if possible.

Process Planning Rule 2) Determination of the machining order of features in a feature group

The machining is performed according to the order of the feature groups. The machining sequence of the features in a feature group is determined using the following sub-rules :

(1) Depth-first sequencing is applied in the tree of a feature group.

Order	Feature Groups	Setups
1	S_1 — F_1 — F_3, F_2, F_4	S_1
2	S_4 — F_{15} — F_{16}	S_4
3	S_2 — F_5 — F_6	S_2
4	S_3 — F_7 — F_8	S_3
5	S_3 — F_{11} — F_{12}	S_3
6	S_5 — F_9 — F_{10}	S_5
7	S_5 — F_{13} — F_{14}	S_5

Fig. 7 The Order of feature groups of the example part

When a feature has multiple child features of an equal depth in the tree of a feature group, the next feature is determined among the child features as the order of the following sub-rules:

(2) If there exists a feature that has more links than other features, it is planned first.

(3) If there exists a feature whose origin is closer to that of the parent feature, it is planned first.

(4) The feature of the lager size is planned first.

(5) If a feature and its datum feature exist in a same feature group, the datum feature is planned first.

(6) If multiple identical features exist in a same feature group, they are planned together.

(7) An important feature is planned last, if possible.

(8) If there exist multiple child features of equal qualification, the sequencing is random

4.3 Inspection planning rules for OMM

Inspection Planning Rule 1) Setup confirmation

At every new setup, the correct orientation of the fixed workpiece is checked at first. The workpiece is positioned and fixed on a table of a machine tool for the machining of the features on its top surface. The setup orientation of the workpiece has to be coincided with the predetermined orientation of the operation planning. It can be checked by inspecting some surfaces and already

Sequence	Setup	Feature
1	S_1	F_1
2		F_2
3		F_3
4		F_4
5	S_4	F_{15}
6		F_{16}
7	S_2	F_5
8		F_6
9	S_3	F_7
10		F_8
11		F_{11}
12		F_{12}
13	S_5	F_9
14		F_{10}
15		F_{13}
16		F_{14}

Fig. 8 The feature sequence of the process plan

machined features, and it is called setup confirmation. The setup confirmation is performed just after a new setup.

Inspection Planning Rule 2) Inspection of alignment

Three orthogonal surfaces are inspected at each setup to determine the alignment error of the setup. The three orthogonal surfaces to be inspected are determined as follows:

(1) the present setup surface (the top surface of the present setup), and
(2) two orthogonal surfaces among four vertical surfaces. They are determined as:
  (a) the reference surface of the workpiece, if it is in the vertical surfaces,
  (b) the surface(s) on which the less number of already machined features reside, and
  (c) the surface(s) closer to the origin of the machine tool coordinates.

Inspection Planning Rule 3) Timing of inspection

The measurement for inspection is occurred just after:

(1) the machining of the last planned feature on every setup in the process plan, and
(2) the machining of an important feature.

For the example part, F_2 is an important feature and inspection is performed just after its machining.

Inspection Planning Rule 4) Sequencing of the features for OMM

The inspection of the features is performed on

Sequence	Setup	Feature
1	S_1	F_2 - F_1
2	S_1	F_4 - F_3
3	S_4	F_{16} - F_{15}
4	S_2	F_6 - F_5
5	S_3	F_{12} - F_{11} - F_8 - F_7
6	S_5	F_{14} - F_{13}
7	S_5	F_{10} – F_9

Fig. 9 The inspection plan of the example part

Sequence	Setup	Features	Processes
1	S_1		Inspection-Setup
2			Inspection-Alignment
3		F_1	Endmilling
4		F_2	Endmilling
5		F_2-F_1	Inspection-Features
6		F_3	Endmilling
7		F_4	Endmilling
8		F_4-F_3	Inspection-Features
9	S_4		Inspection-Setup
10			Inspection-Alignment
11		F_{15}	Endmilling
12		F_{16}	Endmilling
13		F_{16}-F_{15}	Inspection-Features
14	S_2		Inspection-Setup
15			Inspection-Alignment
16		F_5	Endmilling
17		F_6	Drilling and Reaming
18		F_6-F_5	Inspection-Features
19	S_3		Inspection-Setup
20			Inspection-Alignment
21		F_7	Endmilling
22		F_8	Endmilling
23		F_{11}	Endmilling
24		F_{12}	Drilling and Reaming
25		F_{12}-F_{11}-F_8-F_7	Inspection-Features
26	S_5		Inspection-Setup
27			Inspection-Alignment
28		F_9	Endmilling
29		F_{10}	Endmilling
30		F_{13}	Endmilling
31		F_{14}	Drilling and Reaming
32		F_{14}-F_{13}-F_{10}-F_9	Inspection-Features

Fig. 10 The integrated process plan of the example part

the unmeasured machined features according to the reverse feature order of the process plan.

4.4 Integrated process and inspection plan for OMM

The generated inspection plan in Fig. 9 is integrated with the process plan as Fig. 10. At every new setup, the setup is confirmed and the alignment of the workpiece is investigated. Then, the appropriate machining is determined on the features according to the machining sequence in Fig. 8 using process planning knowledge-base. (Lee et al., 1995). The inspection is planned just after the machining of the critical feature, or after the last machining of the setup.

5. Conclusions

The CAI is one of the key processes in the modern computerized manufacturing system. The CAI needs to be integrated into the CIM. The CAIP can take the role as a bridge between the CAD and the CAI. A CAIP system for OMM is developed in these papers in order to integrate the CAD and CAI systems. The proposed methods consist of two stages : global and local inspection planning. The inspection plan for the OMM determines the global(macroscopic) and local (microscopic) procedures of inspection. The global inspection planning in Part I of these papers includes the sequencing of the setups and form features of a part for efficient inspection. The local inspection planning in Part II includes the determination and sequencing of the measuring points on the surfaces of the form feature. The developed CAIP consists of the global and local inspection planning.

In the global inspection planning, a part is described using manufacturing features. The frequently used features are pre-defined, and their properties are analyzed for manufacturing planning. The nested relations of the features of a part are important for planning, and they are represented in the feature precedence tree. In OMM, the inspection sequence of the features heavily depends on the sequences of the setups and features of the process plan. The features are grouped based on the nested relationship of the features and the tool approach directions. The handling of the feature groups is much more efficient than that of the individual features for planning. The particular feature groups that have special meanings in planning are determined. The sequences of the setups and features of the process plan are determined by analyzing the characteristics of the feature groups and the features. The global inspection plan is generated based on the process plan. A series of heuristic rules are developed for the inspection planning in this study. The rules generate the effective global inspection plan successfully for the complicated part. 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

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. and Kwon, H. D., 2003, "Integrated error compensation method using OMM system for profile milling operation," *Journal of Materials Processing Technology*, Vol. 136, pp. 88～99.

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

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

Lee, H., 1991, "A Generic Learning System for Computer-Aided Process Planning, Ph. D. Dissertation," The Pennsylvania state University, University Park, PA.

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.

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

Stout, K. J., 2000, "Engineered Surfaces Part 1. - A Philosophy of Manufacture," *KSME International Journal*, Vol. 14, No. 1, pp. 72～83.