



**Computer-Aided Inspection Planning - the State of the Art**

Journal:	<i>International Journal of Production Research</i>
Manuscript ID:	draft
Manuscript Type:	State-of-the-Art Review
Date Submitted by the Author:	n/a
Complete List of Authors:	Zhao, Fiona; University of Auckland, Department of Mechanical Engineering Xu, X; University of Auckland, Department of Mechanical Engineering Xie, Sheng; University of Auckland, Department of Mechanical Engineering
Keywords:	INSPECTION PLANNING, STEP NC, INTEGRATION, MACHINE TOOLS
Keywords (user):	On-machine Inspection



# Computer-Aided Inspection Planning - the State of the Art

Fiona Zhao, Xun Xu, Shane Xie

University of Auckland, Department of Mechanical Engineering  
20 Symonds Street, Auckland, New Zealand

## Abstract

*Computer-Aided Inspection Planning (CAIP) has been a research topic for the past 25 years. Most of the CAIP systems were developed for Coordinate Measuring Machines (CMMs). The authors reviewed these CAIP systems and categorized them into two groups: tolerance-driven and geometry-based CAIP systems. Compared with CMMs, On-Machine Inspection (OMI) systems provide direct inspection in manufacturing and quality control, which is vital for automated production. Since the early 1990s, new CAIP systems have been developed for OMI systems. New technologies were developed in improving CAIP. New product data standards such as STEP and STEP-NC have been developed to provide standardized and comprehensive data models for machining and inspections. This paper systematically reviewed the recent development of these CAIP systems, new standard and technologies. A new notion of integrating the machining and inspection process planning based on the STEP-NC standard is discussed.*

**Key words:** Computer-Aided Inspection Planning (CAIP), STEP-NC, On-Machine Inspection (OMI), Integration

## 1. Introduction

Workpiece set-up, tool set-up and machined part inspections are of paramount importance to obtaining high-level product quality and minimum scrap production. The functional requirements of a product specified in the design stage must be frequently inspected after or even during its manufacture.

Inspection process planning is a part of the design and manufacturing activity that determines which characteristics of a product are to be inspected, where and when. Modern manufacturing is increasingly characterized by low volume, high variety production and tight tolerance, high quality products. Part and product inspection is evolving to be an important module of integrated manufacturing. Manufacturers are using in-process inspection to control production and achieve the desired quality rather than a means of acceptance or rejection at the end. This requires fast yet accurate inspection as well as effective integration with the product model and relevant database. The need for more automated inspection process planning and better decision support tools increases as the complexity and variety of products increase and the product development cycle decreases.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Decisions made in the course of process planning have a significant effect on the resulting product quality, in addition to the production time and cost. Some manufacturing methods and sequences selected during process planning may be more prone to errors and inconsistencies due to a large number of setups or improper choice of datums and references. Coupling manufacturing process planning with inspection process planning lead to the closure of the desired quality assurance loop and, when taken in the wider context of concurrent engineering, will ensure that quality is “designed-in” from the start, and reduce costly rejected and/or reworked parts (EIMaraghy *et al* 1994).

In a conventional quality control system, a workpiece machined on a machining centre requires being moved to a Coordinate Measuring Machine (CMM) to check its dimensional accuracy. The manual job set-up and inspection of machined parts are usually time consuming, subject to human errors, and often lead to longer lead times and the need to rework. The bottleneck problem is further compounded with the difficulty of capital investment and time delay of material flow between CMMs and machine tools in the factory. Touch-trigger probes allow manufacturers to inspect workpiece, assist job set-ups, deliver precise components, minimize scraps and maximize productivity.

Recently, the On-Machine Inspection (OMI) or On-Machine Measurement (OMM) is widely-used as the essential measuring equipment for the purpose of direct inspections in manufacturing and quality control, which is vital to an automated production system. OMI is a process that integrates the design, machining, and inspection aspects of manufacturing to allow a product to be inspected and accepted directly on a machine tool. This process is accomplished by using the machine tool as the inspection device while the part is secured on the machining center with its coordinate system intact. Using the machine tool as an inspection device eliminates the need for expensive inspection equipment, allowing the manufacturer to divert resources to other uses. There is no need for inspection fixture either, because the machine tool part fixture serves as the inspection fixture. As the workpiece gets more complicated, the role of OMI becomes more significant as efficient dimensional measuring equipment (Kim *et al.* 2001). Sensors present in a CNC system have the capability of providing accurate feedback from the different drive/motors. They are often limited in just performing these functionalities and not geared toward supporting any inspection tasks which are effectively what OMI is about.

A traditional objection to OMI is that it diverts machine time away from the actual machining. This notion can be overcome by measuring productivity in terms of total in-process time rather than machining cycle time. The view that OMI steals machining time overlooks the fact that checking a part off-line, a step that OMI seeks to replace, can impose the need for additional part handling and another setup, adding to in-process time, not to mention introducing the potential of the fixture error (Kamath R. 2000).

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Part inspection programs are either based on Dimensional Measuring Interface Standard (DMIS) (ANSI standard, 2001) or a vendor-specific bespoke routine. Process control for online inspection of components at the CNC machine tool is achieved through bespoke inspection programs based on ISO 6983 (G&M codes) (ISO standard, 1982). Even though significant progresses have been made, parts inspection on OMI and CMMs still represents islands of automation within the overall manufacturing process because of the low level information that G&M codes carry.

Another important aspect regarding inspection of discrete components is that of standardization. STEP (ISO 10303), AP219, and STEP-NC (ISO 14649) (ISO standards, 2004 and 2002) standards have been developed to provide the basis for standardization and integration of part inspections. The object-oriented STEP-NC data model provides a seamless and integrated programming interface for on-machine inspections as well as interoperable manufacturing. By providing high level information to machining systems, STEP-NC not only eliminates the costly and inefficient process of data post-processing, it also establishes a unified environment for the exchange of information between product design, machining process planning and inspection. It enables the realization of a closed, STEP-NC based machining process chain with data feedback and a consolidated data structure at each level.

With the aim of enabling quality control across the whole product development phase, this paper reviews the development of OMI, inspection process planning, and STEP-NC compliant inspection process.

## 2. Benefits and implementation requirement of On-Machine Inspection

Issues affecting OMI have been studied for some time, such as the computer architecture, open architecture CNC controllers, data acquisition, types of touch-trigger probes, etc (Kamath R. 2000). The benefits of OMI can be summarized as follows (Chung S. C. 1999, Kamath R. 2000, Renishaw technical specifications 2000, Lee *et al.* 2004, Cho *et al.* 2004):

- 1) cost and time saving through: (a) decreasing lead-time required for gages and fixtures, (b) minimizing need for design, fabrication, maintenance of hard gages, fixtures & equipment, (c) reducing inspection queue time and inspection time, and (d) eliminating rework of nonconforming product;
- 2) change from reactive inspection to proactive control by (a) integrating quality control into product realization process, (b) using characterized and qualified processes to increase product reliability, (c) focusing resources on prevention of defects instead of detection in the end (a post-mortem process), (d) utilizing real time process knowledge and control, and part acceptance/disposition, and (f) enhancing small lot acceptance capability;
- 3) elimination of non-value added operations such as lot inspection, sampling plans, receiving inspection, design, fabrication and maintenance of hard gages,

- 1  
2  
3  
4 and reworking nonconforming parts;
- 5 4) agile machining. OMI enables quick responses to product design changes. Since  
6 inspection operations are carried out on the same machining center, inspection  
7 gages and fixture changes are not required. New and existing technologies such  
8 as probing strategy, error compensation, data analysis software and fixture design  
9 technology can be integrated into the OMI system. As the errors occurring during  
10 machining processes can be detected by OMI, part distortion is eliminated.  
11  
12

13  
14 Successful implementation of OMI however requires some essential hardware and  
15 software requirements. A multi-tool capacity machine tool is needed to accommodate  
16 several tools including the probe. An open architecture controller is also essential for  
17 inclusion of any additional probing software that may be needed. The probing system  
18 which may be comprised of different probes, sensors and electronic elements, is  
19 needed for implementing the OMI process on the machine tool.  
20  
21

### 22 23 24 **3. Computer-Aided Inspection Planning (CAIP) systems for OMI and CMMs**

25  
26 CAIP may include automated or semi-automated modules capable of identifying and  
27 recognizing the dimensional inspection features along with the associated inspection  
28 constraints. It should be able to recommend an inspection method for each  
29 dimensional inspection feature. The resulting inspection operation also needs to be  
30 integrated into an overall inspection plan (Wong *et al.* 2005).  
31  
32

33  
34 Automatic inspection planning for dimensional and geometric inspections can be at a  
35 high or low level. The high level (macro planning) is concerned with producing a  
36 collection of setups. Each set-up is related to accessibility of the features to be  
37 inspected, the probes to inspect each type of feature and the relative orientation of the  
38 part. Attempts are made to group the features, the types of tolerances and the type and  
39 size of probes to be used. The low level planning primarily addresses the issue of  
40 point selection, path generation, and generation of an executable code. Although much  
41 of the inspection carried out in industry continues to be conducted using conventional  
42 metrological equipment, most previous work on CAIP system has been directed  
43 towards inspection operations performed on CMMs.  
44  
45  
46  
47  
48

49 Research on CAIP systems started from the early 1980s. Before the mid-1990s, most  
50 of the research works focused on the conceptual-level CAIP systems. These systems  
51 can be categorized into two groups: the tolerance-driven inspection process planning  
52 system and geometry-based inspection process planning. The former focused on  
53 planning inspections for those features that have specific tolerance requirements. The  
54 latter focused on planning the inspection process to obtain a complete geometric  
55 description of a machined workpiece using the inspection data. Hence, comparison  
56 can be made with the design model for a complete geometry inspection.  
57  
58  
59  
60

### 3.1 Tolerance-driven CAIP systems

One of the earliest efforts to develop a knowledge-based solution to generative inspection task planning was made by EIMaraghy and Gu (1987). The system was developed in PROLOG and used a feature oriented modeling approach. It took into consideration the characteristics of the CMMs, the function and geometry of the inspected part as well as the geometric and dimensioning standards and theories. It was the first system to group inspection features according to their datum, assign inspection priority based on the nature and magnitude of the assigned tolerance and check features accessibility in a given part orientation. Figure 1 shows the planning logic which resulted in a recommended features inspection sequence, probes selection and part orientation sequence.

[Insert figure 1 about here]

Helmy, H. A. (1991) at Lehigh University developed a feature recognition module that extracts the data of a component from its B-Rep geometric model, and then uses the data to generate a DMIS inspection program. Attributed Adjacency Graph (AAG) was used for inspection feature grouping. AAGs were introduced by Joshi and Chang (1988) to enable machined feature recognition for process planning. The recognition approach includes the procedures for each different manufacturing feature such as steps, slots and cylindrical holes. Using the recognition procedures, together with the AAG representation and a wireframe visualization interface, the features of a component to be inspected are selected interactively. The implementation of the system requires the user to enter the machine coordinated system, the number of measurement points required, and the tolerances to be measured.

Hopp and Lau K. C. (1983, 1984) developed an approach using an inspection control hierarchy to generate control codes for CMMs (Figure 2). After the user selects the required tolerance from a CAD database, the scope of the inspection is determined and the characteristics of the tolerance are identified. The surfaces involved in the characteristics are then selected for inspection and probing. The next steps including probing points and paths planning, machine motion and servo commands in the hierarchy are executed sequentially. A CMM control program is then generated. The approach of some commercial systems such as Valisys (IBM Corp. 1989) and Audimess (VW-GEDAS 1990) are similar to this method.

[Insert figure 2 about here]

Medland and Mullineux (1990, 1992, and 1993) tried to make CMMs an integral part of the integrated manufacturing system. The inspection plan is created automatically from a CAD feature-based model. The CAD model contains information about the features, their significance (i.e. importance of their dimensional accuracy for the

1  
2  
3  
4 acceptance of the part), the need for different probe types and attitude to reach the  
5 feature, special requirements to achieve the necessary accuracy (e.g. number of points)  
6 and the importance given to the manufactured processes involved. The developed  
7 system is modular and based on a manufacturing network where communication is  
8 achieved through files exchange within a integrated manufacturing environment. The  
9 measuring activities are controlled by a combination of dedicated programs and a  
10 constraint modeling system.  
11  
12

13  
14 The system developed by Merat *et al.* (1991) is part of a large effort to develop a  
15 Rapid Design System (RDS). The objective is to reduce the time from design to  
16 manufacture and inspection. This combined generative/retrieval planning system aims  
17 at automating inspection planning of machine parts whose geometry and tolerances  
18 are represented as features. An overall inspection plan consists of fragments each of  
19 which relates to how toleranced geometry of a given feature is to be inspected. These  
20 Inspection Plan Fragments (IPF) are generated based upon rules and methods used in  
21 industrial practices. A single tolerance can be inspected in many ways resulting in the  
22 generation of many IPFs. Inspection planning is, therefore, the selection of  
23 appropriate IPFs which result in an overall time efficient plan. The IPF is generated  
24 by a macro called the IPF Generator. For each tolerance it generates a corresponding  
25 IPF with a suitable CMM probes, probing orientations and any required inspection  
26 tools other than CMMs such as depth micrometers. Feature accessibility analysis is  
27 not included and the inspection steps for various features are not prioritized or  
28 clustered to generate an optimal sequence.  
29  
30  
31  
32  
33  
34

35 The system developed by Yao and Menq (1991, 1992) consists of five modules: (1)  
36 inspection specification, (2) automatic inspection planning, (3) CMM verification, (4)  
37 CMM execution, and (5) comparative analysis. The core of the system is a  
38 knowledge-based inspection planner that monitors the process flow and assists in  
39 decision-making. The main function of the inspection specification module is to  
40 translate functional requirements, tolerances, manufacturing parameters and CMM  
41 constraints, into inspection specifications. The results of the specification module are  
42 used by the planning module to generate the probe path. The manufacturing accuracy  
43 and tolerance specification are taken into consideration. The generated path is then  
44 verified to ensure a collision-free path. The execution module carries out the  
45 inspection and generates the data. The measurement data together with the design  
46 model and inspection attributes are processed by the comparative analysis module to  
47 generate an inspection report.  
48  
49  
50  
51  
52  
53

54 Tannock *et al.* (1993) developed a measurement planning system. They classified  
55 their measurement workpiece by the feature-based method, and established  
56 measurement planning data through inquiry. Brown and Gyorog (1990) discussed a  
57 prototype system named IPPEX (Inspection Process Planning EXpert system) for the  
58 development of a generative process planning expert system for dimensional  
59 inspection. IPPEX uses a product geometric modeler coupled with a dimensional and  
60 tolerance modeler to generate inspection instructions in the form of an operation plan

and as a part program in compliance with the DMIS standard.

### 3.2 Geometry-based CAIP systems

Duffie N. *et al.* (1984) developed a technique to obtain a measured database for a machined part and then compared with a CAD database. Inspection features were defined by operators. The inspection of part surfaces is carried out automatically using a tactile sensor. This inspection process results in the collection of a database of measured coordinates on the part surface. This measured database is compared with a CAD database defining the desired part geometry, then results in a determination of the error between the actual measured part and the desired part geometry at each measured point. Menq C-H *et al.* (1992) developed an optimal match scheme that aligns the measurement data with the design data in CAD-directed dimensional inspection. Cho and Kim (1995) developed a flexible three-dimensional inspection system for sculptured surfaces by employing CMM, CAD database and vision system technology. The proposed system (shown in Figure 3) performed optimum inspection planning, recognition of the workpieces, and compensation for alignment errors. The recognition/localization database is generated from the CAD database based on the new concept called Z-layer. Then, a 3D shape of the object on the table of the CMM is constructed by using a vision guided CMM.

[Insert figure 3 about here]

Corrigall and Bell (1989, 1990) at Loughborough University of Technology, UK have developed a system for code generation for CMMs using geometric data and relationship information of the component defined in a product model. Datum setting operations, measuring and probe orientations, probing points and safe rapid paths are automatically determined, and part programs for a CMM are also generated. This system inspects 100% of the geometry of a component with the exception of those geometric elements which lie beyond the capacity of CMM.

The Design to Inspection project led by Sira (1992) aimed to develop methods that would support the design process, ensuring that designs could be manufactured and inspected consistently and sufficiently. Prototype software, known as CAVES (Computer Aided Validation Expert System), was developed to validate designs. The project identified the limitation of current geometric modelers and concluded that a powerful product modeling system is required if product validation is to be achieved in an automated environment.

### 3.3 Recent CAIP research for OMI and CMMs

Research works on OMI systems started from the early 90s. The CAIP systems must have the modules for the following tasks:

- 1) Identification/recognition of the inspection features for non-CMM-inspection (feature recognition and decomposition) or inspection feature analysis for CMMs
- 2) measuring points/sampling selection and optimization.
- 3) collision-free probing path planning and generation
- 4) inspection execution

In this section, relevant research work will be reviewed in the above order.

### 3.3.1 Inspection feature recognition

Inspection features are rooted from the dimensions and tolerances that have a significant influence upon the functionality of the component. Determination of these inspection features used to rely upon the skill and experience of inspection engineers. Most of the research works reviewed in previous section either required the user to specify each and every face needed to be probed during inspection, or feature may be automatically selected but it only works for the machined part features that have been previously recorded and controlled. Therefore, the degree of automation was severely limited. Recently, the research works focused on recognizing inspection features directly from a CAD model.

Wong *et al.* (2005) proposed a feature recognition approach for non-CMM-inspection, based on the environment of the Generic Computer-Aided Process Planning Support System (GCAPPSS) proposed by Yuen *et al.* (2003). Figure 4 shows the GCAPPSS system. A key feature of GCAPPSS is the Generic Object Information System (GOIS) hierarchically organized into five layers. The GOIS provides the CAD model data including detailed geometric data, topological information, primitive template features (PTF) and variations of PTFs (VPTF).

[Insert figure 4 about here]

This research classified the most frequently occurring dimensional inspection measurands into following seven cases:

- Case 1: The distance between two parallel faces: length, width, gap, slot, fin,

height, protrusion, depth, recess and thickness. The actual measurement process depends on the shape, size and orientation of the pair of faces of interest.

- Case 2: The diameter of a complete cylinder/hole.
- Case 3: The diameter or radius of a partial cylinder/hole or a cylindrical face.
- Case 4: The distance between a cylinder/hole and a parallel face.
- Case 5: The distance between a pair of cylinders/holes.
- Case 6: Co-ordinate measurement (or profile) measurement of a curved surface (free-form or otherwise) with respect to a bounded reference plane.
- Case 7: A combination of the above. A wide range of measuring equipment and length standards may be used during this stage.

Dimensional inspection features was classified into four basic types: external, internal, offset or features requiring coordinate (or profile) measurement of a curved surface. The GOIS is capable of capturing and representing all the information necessary for extracting the above types of features.

The research proposed the Multi-Attributed Spatial Graph (MASG) technique to facilitate extraction and recognition of inspection features. One problem of the proposed algorithm is that it will generate enormous numbers of different inspection ways. The authors proposed a knowledge-based technique—by using a series of “filters” to subject individual inspection process. The research defined ten filters to be of particular importance in the inspection domain.

- 1) Product specifications filter: to process the specifications of a part which provide the information necessary for making inspection decisions.
- 2) Domain filter: to determine the features that need special attention.
- 3) Application filter: to decide the features that need close inspection.
- 4) General practice filter: to decide what parts must be inspected while others don't.
- 5) Trade practice filter: to determine the tolerance and accuracy that are required in certain trade domain.
- 6) Process capability filter: to check if the machining process capability fully

satisfies the tolerance requirement.

- 7) Role/task filter: to select inspection features by analyzing the critical role and task performed by the part that requires special attention and inspection.
- 8) Special attention filter: to select the dimensional features with previous failure records.
- 9) Customer filter: to specify the special customer requirements on the workpiece that needs inspection.
- 10) User (manual) filter: for some products, the sizes and quality constraints could be varied to suit different market sectors.

### 3.3.2 Inspection feature grouping and decomposition

Lee *et al.* at Inha University (2004), Korean proposed an optimal inspection planning strategy (Figure 5) for workpieces comprising many primitive form features. This is a two-stage process.

[Insert figure 5 about here]

- Stage I: Global inspection planning:

In this stage, optimum inspection sequence is determined. 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 an inspection sequence of the features

- Stage II: Local inspection planning:

In this stage, 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 measurement points, their locations, and the optimum probing paths to minimize measuring errors and times.

The inspection planning process starts with feature extraction and decomposition. In this research, a part is represented as a combination of the predefined features (Figure 6).

[Insert figure 6 about here]

Tool Approach Direction (TAD) represents the accessible direction of the tool to machine the feature, and Probe Approach Direction (PAD) represents the accessible direction of the probe to measure the feature. The inspection planning for OMM is the determination of the inspection sequence of the features under the guidelines of the sequence of the setups and the features of the process plan.

Feature grouping is the first step used for the determination of the priority in manufacturing planning. A series of rules of the global inspection planning system for OMM have been developed. They are (1) application of the identical TAD rule; (2) formation of feature group; (3) determination of the main link of brother features; and (4) cancellation of shortcut paths.

At the local inspection planning stage, each feature is firstly decomposed into its constituent geometric elements such as planes, circles, etc. Then, the following inspection process planning is performed:

- the determination of the suitable number of measuring points and their locations,
- the determination of the optimum probing paths to minimize measuring errors and times, and
- collision checking to avoid the probe and/or probe holder collision.

Chung, S. C. (1999) proposed an OMM system for free-form surfaces. An IGES translator was developed to translate CAD/CAM output files into IGES files. Trimmed NURBS surfaces are extracted through the IGES translator. Measurement codes are generated by means of coordinate transformation and the uniform sampling software (which is proposed in this research) linked with the IGES translator. Cho and Seo (2002) later used the techniques to develop an inspection planning strategy for the on-machine measurement process based on CAD/CAM/CAI integration. Figure 7 shows the inspection process planning comparison between OMM and CMMs.

[Insert figure 7 about here]

This research tried to integrate CAM with CAI by taking into account the geometric information of the machined surface. For this purpose, the analysis of the machined surface shape was performed in order to carry out the CAI process effectively. This analysis corresponds to the machining error prediction process, which predicts the machined surface shape. The key is to simulate the geometrical form of the machined surface. The machining errors can then be predicted by comparing this simulated machined surface with the designed surface in the CAD system.

### 3.3.3 Inspection feature cluster analysis for CMM inspection

Zhang et al. (2000) proposed a feature-based inspection process planning system for CMMs. The proposed system is a prototype designed to produce an inspection process planning directly from a CAD model. The prototype inspection process planning system includes five functional modules: the tolerance feature analysis, accessibility analysis, clustering algorithm, path generation and inspection process simulation. The tolerance feature analysis module is used to input the tolerance information and establish the relationship between the tolerance information and surface feature. The accessibility analysis module evaluates all the accessible probe relationship between the tolerance information and surface feature. The clustering algorithm module groups the inspection probe and surface features into inspection group so that time for inspection probe exchange and calibration can be reduced to minimum. The path generation module determines the number of measurement points, their distribution and their inspection sequences. The inspection process simulation module animated display the inspection probe path and check whether a collision occurs between the part and the inspection probe.

### 3.3.4 Measuring points/sampling selection and optimization

Generally, the inspection processes carried out on CMMs or OMM use touch-type probes to perform point-to-point motions when recording 3-dimensional coordinates of the workpiece. The measurement reliability 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 leads to the increase of measuring time, the appropriate number of measuring points has to be determined for each feature and the tolerance to be measured. Elkott et al. (2002) reviewed research works on sampling strategies for CMM inspection. Based on this review and the following review, the authors summarized the literature review of sampling for inspection planning (Table 1).

[Insert table 1 about here]

#### 1) Measuring points optimization and allocation methods for OMM inspections

Some useful methods have been proposed to decide proper measuring points for each feature by considering tolerance levels, geometric characteristics, and desired confidence levels. Menq *et al.* (1990) developed a method based on the given design tolerance and machining accuracy to determine the optimum number of measuring points. Dowling, *et al.* (1997) discussed the statistical issues that arise when CMMs are used. They carried out research and simulation on commonly used methods for estimating a feature's deviation range—the orthogonal least squares and minimum-zone methods. Huang *et al.* (2002) proposed a knowledge-based inspection

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

planning system for CMMs. This system integrates part geometry information, tolerance information and heuristic knowledge of experienced inspection planners to determine the numbers and positions of measuring points.

Based on previous research, Lee *et al.* (2004) and Cho *et al.* (2004) proposed a similar fuzzy system for determining the optimum number of measuring points. The surface area of the target surface, the grade of design tolerance and the volumetric error of the machine tool used to produce the workpiece are used as input parameters. The Hammersley's algorithm is used to locate the measuring points on the target surfaces. At the same time, the non-contact measuring point problem is handled to relocate the measuring points. Since the decomposed primitives may contain holes, slots and/or pockets where some measuring points may lie on, these measuring points should be relocated. The algorithm developed by Huang *et al.* (2002) was applied to relocate these non-contact measuring points.

## 2) Sampling selection and allocation methods developed for CMMs

CMM acquires data on a point-by-point basis, which are used to create a geometric model, usually called the substitute geometry, for the feature being measured. The computed results are affected by different factors. The sampling strategy consists of the number and locations of sampling points chosen to be probed by the CMM. The effect of selecting a particular measurement sampling strategy has been recognized as a major component of measurement uncertainty (Woo and Liang, 1993). This effect is due to the systematic and pseudo-random errors contained in the measurement system Caskey *et al.* (1990).

Elkott *et al.* (2002) stated that the previous research emphasized the sampling of primitive shapes, i.e. conical shapes, spheres, cylinders and planar surfaces. Researchers who worked on the sampling of free-form surfaces often adopted a uniform sampling pattern. Others who applied surface features-based methodologies developed algorithms that require large sample sizes to inspect free-form surface features. Moreover, while a few developed methodologies attempt to optimize sample size, they do not seek the optimal locations of the sample points. Most methods depend to a great extent on the skills of the users of those systems. To overcome these shortcomings, several solutions to the sampling problem have been combined in one system. This is done by automatically selecting a sampling algorithm that best suits the surface being inspected.

Jiang and Chiu (2002) developed a statistical method for the determination of the number of measurement points for 2D rotational part features. The authors proposed a feature-based technique to determine a sufficient number of measurement points for CMMs. To use a feature-based approach in determining the number of measurement points, an acceptable error amount must be provided as the decision criterion. However, the errors caused by the measurement and the part dimension deviation from the norm are normally not separated. For form features, it is logical to use form

1  
2  
3 tolerances as the acceptable error amount since it best represents the limit of the sum  
4 of all possible error sources. Regression and least square methods were used for  
5 checking if the number of selected measuring points satisfies the requirement.  
6  
7

### 8 9 **3.3.5 Probing path planning and generation**

#### 10 11 **1) Probing path planning and generation for OMM inspections**

12  
13 In the OMM system proposed by Lee *et al.* (2004) and Cho *et al.* (2004), the  
14 appropriate probe paths are generated, after determining the suitable measuring points  
15 for the given surface by using Traveling Sales Person (TSP) algorithm. TSP  
16 algorithms have been used by some researchers to generate the probing path to  
17 minimize the inspection time (Lee *et al.* 1994, Lee *et al.* 2004 and Cho *et al.* 2004).  
18  
19

20  
21 Before inspection starts, collision avoidance analysis is also required. The collision  
22 problem in an OMM operation can be divided into two categories, i.e. the probe  
23 collision and the probe holder collision. A new methodology to detect the probe  
24 and/or probe holder collisions called Z-map has been proposed (Lee *et al.* 2004 and  
25 Cho *et al.* 2004). A Z-map is generated for the given target workpiece, and then probe  
26 and/or probe holder moving trajectories are calculated according to the previously  
27 generated probing path. By calculating the errors caused by the probe and/or probe  
28 holder trajectories, collisions can be checked and avoid.  
29  
30

#### 31 32 **2) Probing path planning and generation for CMMs**

33  
34 Albuquerque *et al.* (2000) used an iterative method of point placement and collision  
35 avoidance for multiple, interacting features to automatically generate probe tool path  
36 (Figure 8). Many requirements have been considered. Firstly, point placement  
37 schemes should be flexible enough to work on different surface types such as planar,  
38 cylindrical and conical surfaces. An important consideration is that surfaces formed  
39 from intersecting features can have multiple connected arbitrary domains. Points  
40 should be placed only in non-cutout regions and away from the edges of the surface.  
41 Another requirement is that points should be distributed over surfaces such that they  
42 obtain the required information for the specified tolerance. In order to determine point  
43 accessibility, accurate and fast collision detection should be facilitated by modelling  
44 the probe and probe arm by simple bounding entities. Finally, path planning should be  
45 optimal within the constraints of point measurement order and collision-avoidance.  
46  
47  
48  
49  
50  
51  
52  
53

54  
55 [Insert figure 8 about here]

56  
57 Due to the complexity of direct 3D point placement on arbitrary multiple connected  
58 regions of known surface types, a simpler approach is to use surface mapping to 2D  
59 and subsequent point placement in the plane. This works well for arbitrary regions  
60 containing holes. However, accessibility check cannot be carried out in 2D owing to

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

volume interactions with the measured surface. To overcome this, a useful feature of the solid-modeller enables planar faceting of all curved surfaces, allowing efficient collision detection to be made on planar surfaces. A list of surfaces to be measured is obtained from the overall inspection planner. For each of these surfaces an initial set of points is generated, constrained only by the desired minimum configuration and number of inspection points on each surface. The section on point placement addresses the mapping and subdivision techniques for this point placement. Each set of measurements is checked for measurability after transforming inspection points and the model into the CMM workspace. This process is followed by iterative re-placement of points in accessible regions. After a sufficient number of measurable points have been placed during the iteration process, a collision-free path is generated.

Ainsworth *et al.* (2000) developed a probe path generation system that utilises interactions between CAD systems and the users. The system has three stages, path generation, modification, and verification. The order in which the measurement points are negotiated must be adapted to the geometry in question. With each inspection feature being essentially sampled over a grid of points, the measurement may be performed in unidirectional or bi-directional scans. The former is generally better suited to closed and/or highly folded surfaces, and the latter is more suited to relatively flat, open surfaces. By using the CAD model and the generated sampling points as the input, the implemented path planning software initially generates a measurement path for each selected entity, based on the default parameters set by the user. The path is displayed as a set of line segments, together with the 3D model of the part. Following this, the system allows the user to modify interactively any of the path parameters. Finally, the defined measurement path is post-processed into machine executable programming code.

Lin and Murugappan (2000) proposed a framework for automatic CMM inspection probing planning. A three-phase approach is taken, i.e. (a) developing a general algorithm for path generation; (b) selection of a CAD system with an API (application programming interface); and (c) implementation of the algorithm. The main objective of this work is to develop a general algorithm for CMM inspection path generation, which can be implemented with any CAD system API. The algorithm assumed that the CMM probe is a point object. This helps in converting collision detection of the moving probe with the part, into the simpler detection of collision of a single point with the part. Fixtures are not considered in this research.

#### 4 STEP and STEP-NC enabled inspections

Lin and Chow (2001) integrated a STEP data module with an IDEF0 model for CMM inspection process planning. The EXPRESS data module of STEP was used in this research to provide object-oriented measuring information flow design framework in order to increase the efficiency of system designers in developing measuring system.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Most common data models for OMI are G-code based. This being the case, inspection and machining operations are characterized by a complex sequence of manual and automated activities based on various software applications and exchange formats. Lack of geometry information in the code leads to a uni-directional information flow (Zhao *et al.* 2006). Changes made in an NC part and inspection programme cannot be fed back to the CAD/CAM system, as the context of single movement or switching instructions normally gets lost (Xu and He 2004, Xu and Mao 2004). The STEP-NC (ISO 14649) data model (ISO standard, 2002), in contrast, provides a higher level of information for manufacturing processes including the part geometry and tolerances, hence enables a bi-directional information flow. STEP-NC not only eliminates the costly and inefficient process of post processing, it also establishes a unified environment for the exchange of information between product design applications, manufacturing process planning and inspection. With geometrical information about a part available at the controller, the controller can carry out “positive” inspection operations. The advantage of CNC controller can be fully utilized. Shop floor experiences can be used to develop new way of machining the part (Legge, D. I. 1996).

Some STEP-NC compliant inspection systems have been proposed; most of them utilize CMMs for inspection. Brecher, et al in the Laboratory for Machine Tools and Production Engineering (WZL) at Aachen University, Germany developed a system for a closed-loop process chain which intergraded inspections into the STEP-NC machining information flow (Wolf *et al.* 2006). The research presents a system that supports milling a workpiece, inspection of several workpiece features and feeding back the measured results to the product model. Their research focused on the closure of a broad process chain by integrating inspection activities into the STEP-NC based process chain and feeding the results of the manufacturing operation in terms of the obtained measurement data, back to process planning. The inspection operations are carried out on a CMM.

In the United States, NIST, Boeing, General Electrics, Unigraphics and other some industry partners worked on a STEP-enabled Closed-Loop Machining (CLM) scenario using ISO 10303 AP 238 for probing activities (Hardwick M. 2005). ISO 10303 AP 238 (ISO standard, 2004) is the AIM (Application Interpreted Model) of STEP-NC ARM (Application Reference Model), which is effectively ISO 14649. The demonstration in May 2005 highlighted the use of probing results collected on a CNC machine to generate the modified AP238 data. At the demonstration, offsets were coupled due to the possible  $\theta$  misalignment, and resident single-axis offsets could not be used to accomplish the full transformation. Thus, one AP238 program was used for probing, a second AP-238 program specified the machining operations in nominal coordinates, and the STEP-NC converter generated the NC codes using the nominal AP238 program and the acquired transformation immediately prior to machining.

Ali, *et al.* from the Loughborough University, UK (Ali *et al.* 2006) developed an inspection framework for closing the inspection loop through integration of

1  
2  
3 information across the CAx process chain. The major feature of the proposed  
4 STEP-compliant inspection framework is the inclusion of high-level and detailed  
5 information in terms of an inspection Workplan, Workingstep, and a mechanism to  
6 feedback inspection results across the total CAx process chain. STEP-NC (ISO  
7 14649-16), DMIS and AP219 are used as the basis for representing the product and  
8 manufacturing models. This research mainly focused on the utilization of CMMs.  
9  
10  
11

12  
13 Suh *et al.* (2002) present a method of indirect measurement based on the virtual gears  
14 model (VGM), obtained by NURBS fitting of the surface points measured by CMM.  
15 Geometric error measurement is required to evaluate the grade of the manufactured  
16 gears. Due to the complexity of the spiral bevel gear, direct measurement with the  
17 physical part has been conducted in a very limited way. By comparing the VGM with  
18 CAD model (soft-master model), various errors such as tooth profile error and tooth  
19 trace error can be automatically measured. The developed method is simple and  
20 robust without requiring a special measuring device, and hence it can be applied for  
21 the industrial practice as a means for measuring the tooth profile and tooth trace errors  
22 which cannot be measured by the conventional method. Further, the model-based  
23 method can be incorporated on the advanced CNC controller based on the new  
24 CAM–CNC interface scheme of STEP-NC as an on-line inspection module.  
25  
26  
27  
28  
29

30 In 2006, the Automotive Industry Action Group's (AIAG) MEtrology Project Team  
31 (MEPT) started to explore STEP-NC enabled solutions. This is in conjunction with  
32 the work on Dimensional Markup Language (DML) and the new Quality  
33 Measurement Data (QMD) standard that have been underway for some time. Airbus  
34 presented its requirements for tolerances in next generation CNC machining. A  
35 demonstration of the results of a closed loop machining test using AP-203 Edition 2  
36 tolerance data prepared by Boeing and an Okuma machine tool with a probing system  
37 owned by Boeing was presented at the meeting.  
38  
39  
40  
41

42 Northrop Grumman presented GD&T in the context of the various STEP Application  
43 Profile (AP) standards, such as AP224, AP219 and AP238. Most of these STEP  
44 standards are for non-inspection operations minus AP219. AP219 addresses inspection,  
45 but is limited to inspection results reporting. It became clear that the several  
46 standards/specifications under the oversight of the MEPT, namely, I++ DME, DMIS,  
47 DML, QMD, and Scan Data, should generally fit well within the context of the  
48 appropriate STEP APs.  
49  
50  
51  
52

## 53 **5 Discussions**

54

55 With the development of more sophisticated machine controls, touch trigger probes,  
56 and the increasing demand for automated production systems, OMI has become  
57 widely-used and developed for the purpose of direct inspection during machining  
58 processes for quality control since the early 1990s. OMI can overcome the bottlenecks  
59 of inspection processes with use of a CMM system, such as measuring time, difficulty  
60

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

with capital investment, and time delay of material flow between CMMs and machine tools in the factory. OMI can provide real-time, on-line quality control during machining processes. However, research works on developing CAIP systems for OMI are mostly based on the prior research for CMMs. Some focused on developing different modules of CAIP for CMMs or OMI, such as inspection feature recognition/extraction, measuring points/sampling selection and optimization, and probing path generation. New technologies such as neuron-network and fuzzy logic algorithms have been used in developing these modules.

In spite of the extensive research in the field, there are two main issues unaddressed. First, inspection process planning has been largely carried out in isolation from machining process planning. For the inspections that are carried out on a CMM, since the workpiece has to be moved from the machine tool to a CMM, inspection is physically separated from machining. In the case of OMI, most of the inspections were assumed to be after the machining process planning. Therefore, it is perhaps acceptable to consider machining process planning and inspection process planning in tandem. However, when inspections need to be carried out in-between manufacturing processes, the status-quo method is proved inadequate. Inspection process planning need to be considered together with machining process planning. An optimal machining sequence without OMI operations may no longer be optimal when OMI operations are placed and intertwined with the machining operations.

Second, research around OMI has focused on offering one-off solutions rather than integrated solutions in that inspections are treated as part of an integral product development chain. The main reason can be attributed to the diversity of various operation platform/environments across the entire process chain and lack of data model and standard that can facilitate a consolidated environment. Such problems have already been recognized in a smaller scope, i.e. among the metrological systems (Horst 2005).

## 6. Conclusions and future trends

In the past two decades, most of the research in the area of computer-aided inspection planning has been focusing on developing CAIP systems for CMMs. In the early days of CAIP development, the research work was also limited at the conceptual level. These research works can be divided into two categories: the tolerance-driven CAIP systems and the geometry-based CAIP systems. The tolerance-driven CAIP systems focus on identifying inspection features based on workpiece tolerance requirements. Features with tight tolerance requirements are inspected. Inspection planning is based on these selected features. The feature selection process was mainly done manually, e.g. by a quality control engineer. Therefore, this is an error-prone process. The geometry-based CAIP systems intend to build up a geometrical model based on the inspection results and compare it with the design model. Hence, the entire workpiece has to be measured. This leads to longer process time.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

With an international effort in developing a standard for the exchange of produce model data - STEP and STEP-NC as well as related application protocols - it is now possible to build a standardized data model for the entire product process including inspections. STEP and STEP-NC provide high-level information including the crucial tolerance information for inspection processes. A consolidated data model can be built for both machining and inspection process planning. It is then possible to have an integrated process planning system for both machining and inspection processes. Critical features and tolerances of a workpiece can be closely inspected during machining processes. This system takes into account the variables that affect inspection as well as machining, such as the capability of a machining center, the tolerances, tool wear and etc. The output of the system will be an optimal machining sequence embedded with inspection operations. The machining process can be kept in a closely monitored and controlled environment. As STEP and STEP-NC support bi-directional informational flow in the process, on-line feedback of the machining process is feasible. Changes can be easily made and the machining process be modified in time.

Future research in the area may be envisaged along different strands. Development of a comprehensive STEP and STEP-NC data model for integrated machining and inspection process planning is one of them. The development of inspection feedback analysis system based on the abovementioned new standards and technology is also an essential element in achieving a closed-loop machining environment. To develop such a system, a number of issues need to be addressed as discussed in the paper. One of the important issues is for example, how to analyze and utilize the inspection results in order to inform the subsequent machining operations. As the technologies used in the inspection devices mature and product quality requirements become more stringent, on-machine inspection will take the centre stage for quality assurance in manufacturing.

**Reference:**

- Ainsworth, I., Ristic, M., and Brujic, D, CAD-Based Measurement Path Planning for Free-Form Shapes Using Contact Probes, *International Journal of Advanced Manufacturing Technology*, Vol. 16, pp. 23-31, 2000.
- Albuquerque, V. A., Liou, F. W., and Mitchell, O. R., Inspection Point Placement and Path Planning Algorithms for Automatic CMM Inspection, *International Journal of Computer Integrated Manufacturing*, Vol. 13, n 2, pp. 107-120, 2000.
- Ali, L., Newman, S. T., and Petzing, J., Development of a STEP-compliant Inspection Framework for Discrete Components, *Proceedings of the Institutions of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 219, n 7, pp. 557-563, 2006.
- American National Standard Institute, ANSI/CAM-I 104.0-2001, Part 1, DMIS 4.0 Standard, Part 1, 2001. Available online at:  
<http://www.cami.org/storelistitem.cfm?itemnumber=8>, (14/03/2005)
- Brown, C. W., and Gyrog, D. A., Generative Inspection Process Planner for Integrated Production, *The Winder Annual Meeting of the American Society of Mechanical Engineers*, pp. 151-162, 1990.
- Caskey, G., Hari, Y., Hocken, R., Palanivelu, D., Raja, J., Wilson, R., Chen, K., and Yang, J., Sampling Techniques for Coordinate Measuring Machine, *Design and Manufacturing Systems conference*, pp.779-786, 1990.
- Caskey, G., Hocken, R., Palanvelu, D., Raja, J., Wilson, R., Chem K., and Yang, J., Sampling Techniques for Coordinate Measuring Machines, *Proceedings of the NSF Design and Manufacturing Systems Conference*, 1992.
- Cho, M. W., and Kim, K., New Inspection Planning Strategy for Sculptured Surfaces Using Coordinate Measuring Machine, *International Journal of Production Research*, Vol. 33, n 22, pp. 427-444, 1995.
- Cho, M.-W., and Seo, T.-L., Inspection Planning Strategy for the On-Machine Measurement Process Based on CAD/CAM/CAI Integration, *International Journal of Manufacturing Technology*, Vol. 19, pp 607-617, 2002.
- Cho, Myeong-Woo, Lee, Honghee, Yoon, Gil-Sang, Choi, Jin-Hwa, A Computer-Aided Inspection Planning System for On-Machine Measurement-Part II: Local Inspection Planning, *KSME International Journal*, Vol. 18, pp. 1358-1367, 2004.
- Cho, M.-W., Lee, H., Yoon, G.-S., and Choi, J., A Feature-Based Inspection Planning

1  
2  
3 System for Coordinate Measuring Machines, International Journal of Advanced  
4 Manufacturing Technology, Vol. 26, pp. 1078-1087, 2005.  
5  
6

7 Chung, S. C., CAD/CAM Integration of On-the-machine Measuring and Inspection  
8 System for Free-formed Surfaces, Proceedings of American Society for Precision  
9 Engineering, Vol. 20, pp. 267-270, 1999.  
10  
11

12 Corrigall, M. J., and Bell, R., An Inspection Plan and Code Generation for Coordinate  
13 Measuring Machines, Proceedings of 9<sup>th</sup> International Conference of Automated  
14 Inspection and Product Control, pp. 145-154, 1989.  
15  
16

17 Corrigall, M. J. Inspection Plan and Code Generation for Coordinate Measuring  
18 Machines in a Product Modeling Environment, PHD thesis, Loughborough  
19 University of Technology, 1990.  
20  
21

22 Dowling, M. M., Griffin, P. M., Tsui, K-L., Zhou, C., Statistical Issues in Geometric  
23 Feature Inspection Using Coordinate Measuring Machines, Technometrics,  
24 Vol.39, n 1, pp. 3-17, 1997.  
25  
26

27 Duffie, N., Bollinger, J., Piper, R., and Kroneberg, M., CAD Directed Inspection and  
28 Error Analysis Using Patch Databases, Annals CIRP, Vol. 33, n 1, pp. 347-350,  
29 1984.  
30  
31

32 Edgeworth, R., and Wilhelm, R., Adaptive Sampling for Coordinate Metrology,  
33 Precision Engineering, Vol. 23, pp. 144-154, 1999.  
34  
35

36 EIMaraghy, H. A., and Gu, P. H., Expert System for Inspection Planning, Annals of the  
37 CIRP, Vol. 37, n 1, pp. 85-89, 1987.  
38  
39

40 EIMaraghy, H. A., and EIMaraghy, W. H., Computer-Aided Inspection Planning  
41 (CAIP), *Advances in Feature Based Manufacturing*, edited by J. J. Shah, et al.,  
42 pp. 363-396, 1994 (Elsevier).  
43  
44

45 Elkott, D. F., ElMaraghy, H. A., and Elmaraghy, W. H., Automatic Sampling for  
46 CMM Inspection Planning of Free-Form Surfaces, International Journal of  
47 Production Research, Vol. 40, n 11, pp. 2653-2676, 2002.  
48  
49

50 Fan, K., Leu, M., Intelligent Planning of CAD-directed Inspection for Coordinate  
51 Inspection Using Coordinate Measuring Machines, Computer Integrated  
52 Manufacturing Systems, Vol. 11, pp. 43-51, 1993.  
53  
54

55 Fang, K., Wang, S., and Wei, G., A Stratified Sampling Model in Spherical Feature  
56 Inspection Using Coordinate Measuring Machines, Statistics and Probability  
57 Letters, Vol.51, pp: 25-34, 2001.  
58  
59

60 Hardwick, M., STEP-NC Probing Demonstration EASTEC 2005 Exposition &

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Conference, 24-26 May 2005, West Springfield, MA USA. Available online at:  
<http://www.isd.mel.nist.gov/projects/stepnc/>

Helmy, H. A., Feature Recognition and CAD-Directed Inspection Using Solid Geometric Representation, PHD thesis, Lehigh University, 1991.

Hocken, R., Raja, J., and Babu, U., Sampling Issues in Coordinate Metrology, Manufacturing Review, Vol. 6, pp. 284-294, 1993.

Hopp, T. H., and Lau, K. C., A Hierarchical Model-Based Control System for Inspection, Proceedings of the 5<sup>th</sup> International Symposium on Automated Integrated Manufacturing, pp. 169-187, 1983.

Hopp, T. H., CAD-Directed Inspection, Annals of the CIRP, Vol. 33, n. 1, 1984.

Horst, J., Make Interoperability Happen, Quality, Vol. 44, Issue 11, pp. 42-45, November, 2005.

Huang, I., Lee, H., and Ha, S., Hybrid Neuro-fuzzy Approach to the Generation of Measuring Points for Knowledge-based Inspection Planning, International Journal of Production Research, V 40, n 11, 2002.

IBM Corp., Valisys-for quality in the making, An advertising booklet. 1989.

International Organization for Standardization, ISO 6983/1, Numerical control of machines – Program format and definition of address words – Part 1: Data format for positioning, line and contouring control systems, First edition, 1982.

International Organization for Standardization, ISO 14649-1, Data model for Computerized Numerical Controllers: Part 1 Overview and fundamental principles, ISO TC 184/SC 1, July 04, 2002.

International Organization for Standardization, ISO/WD10303-219, Industrial automation systems and integration-Product data representation and exchange-Part 219: Application protocol: Dimensional inspection information exchange, 2004.

International Organization for Standardization, ISO/FDIS 10303: Industrial automation systems and integration – Product data representation and exchange - Part 238: Application Protocols: Application interpreted model for computerized numerical controllers, 2004.

Jiang, B. C., and Chiu, S. D., Form Tolerance-Based Measurement Points Determination with CMM, Journal of Intelligent Manufacturing, Vol. 13, pp. 101-108, 2002.

- 1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60
- Joshi, S., and Chang, T. C., Graph-based Heuristics for Recognition of Machined Features from a 3D Solid model, *Computer-Aided Design*, Vol. 20, n 2, pp. 58-66, 1988.
- Joshi, S., and Chang, T. C., Expert Process Planning System with Solid Model Interface, *International Journal of Production Research*, Vol. 26, n. 5, pp. 864-885, 1988.
- Juster, N. P., Hsu, L. H., and Pennington, A. D., The Selection of Surfaces for Inspection Planning, *Advances in Feature Based Manufacturing*, edited by J. J. Shah et al., pp. 333-362, 1994.
- Kamath, R., On-Machine Inspection and Acceptance (OMIA), Master of Science Dissertation, University of Missouri-Rolla, USA, 2000.
- Kim, D., and Ozsoy, T., New Sampling Strategies for Form Evaluation of Free Form Surfaces, *Proceedings of the 1999 ASME Design Engineering Technical Conference*, 1999.
- Kim, Kyung-Don, and Chung, Sung-Chong, Synthesis of the Measurement System on the Machine Tool, *International Journal of Production Research*, Vol. 39, pp 2475-2497, 2001.
- Kim, W., and Raman, S., On the Selection of Flatness Measurement Points in Coordinate Measuring Machine Inspection, *International Journal of Machine Tools and Manufacture*, Vol. 40, pp. 427-443, 2000.
- Lee, J. W., Kim, M. K., and Kim, K., Optimal Probe Path Generation and New Guide Point Selection Methods, *Engineering Application of Artificial Intelligence*, Vol. 7, n 4, pp. 439-445, 1994.
- Lee, G., and Mou, J., Design of the Sampling Strategy for Dimensional Measurement of Geometric Features Using Coordinate Measuring Machine, *Japan/USA Symposium on Flexible Automation, ASME Vol.2*, pp. 1193-1200, 1996.
- Lee, G., Mou, J., and Shen, Y., Sampling Strategy Design for Dimensional Measurement of Geometric Features Using Coordinate Measuring Machine, *International Journal of Machining Tools and Manufacturing*, Vol. 37, n 7, pp. 917-934, 1997.
- Lee, Honghee, Cho, Myeong-Woo, Yoon, Gil-Sang, Choi, Jin-Hwa, A Computer-Aided Inspection Planning System for On-Machine Measurement-Part I: Global Inspection Planning, *KSME International Journal*, Vol. 18, n 8, pp. 1349-1357, 2004.

- 1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60
- Legge, D. I., Off-line Programming of Coordinate Measuring Machines, Luleå University of Technology, ISSN 0280-8242 / HLU-TH-L-1996/19-L--SE / NR 1996:19.
- Lin, Y. J., and Murugappan, P., A New Algorithm for CAD-Directed CMM Dimensional Inspection, International Journal of Advanced Manufacturing Technology, Vol.16, pp. 107-112, 2000.
- Lin, Z.-C., and Chow, J.-J., Integration Planning Model of IDEF0 and STEP Product Data Representation Methods in a CMM Measuring System, International Journal of Advanced Manufacturing Technology, Vol. 17, pp. 39-53, 2001.
- McKay, A., The Structure Editor Approach to Product Description, Technical report, The University of Leeds and Loughborough University of Technology, 1988, ISS Project.
- Medland, A. J., Singh, R., Sittas, E., and Mullineux, G., Intelligent Communication between CAD and Manufacturing Activities, Proceedings of the 28<sup>th</sup> MATADOR Conference, pp. 305-312, 1990.
- Medland, A. J., The Computer-Based Design Process, Chapman &Hall, second edition, 1992.
- Medland, A. J., and Mullineux, G., Strategies for Automatic Path Planning of Coordinate Measuring Machines, 24<sup>th</sup> CIRP International Seminar on Manufacturing Systems, 1992.
- Medland, A. J., Mullineux, G., Butler, C., and Jones, B. E., The Integration of Coordinate Measuring Machines within a Design and Manufacturing Environment, Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture, Vol. 207, n. B2, 1993.
- Menq, C. H., Yau, H. T., Lai, G. Y. and Miller, R. A., Statistical Evaluation of Form Tolerances Using Discrete Measurement Data, ASME Winter Annual Meeting, Vol.47, pp135-149, 1990.
- Menq, C. H., Yau, H. T., and Lai, G. Y., Automated Precision Measurement of Surface Profile in CAD Directed Inspection, IEEE Transactions on Robotics and Automation, Vol. 8, n 2, pp. 268–278, 1992.
- Merat, F. L., Radack, G. M., Roumina, K., and Ruegsegger, S., Automated Inspection Planning within the Rapid Design System, Proceedings of IEEE International Conference on Systems Engineering, pp. 42-48, 1991.
- Orady, E., Chen, Y., Li, S., and El-Baghdady, A., A Fuzzy Decision-Making System

1  
2  
3  
4 for CMM Measurements in Quality Control, The 2000 Pacific Conference on  
5 Manufacturing, 2000.  
6

7 Pahk, H., Jung, M., Hwang, S., Kim, Y., Hong, Y., and Kim, S., Integrated Precision  
8 Inspection System for the Manufacturing of Moulds Having CAD-Defined  
9 Features, International Journal of Advanced Manufacturing Technology, Vol. 10,  
10 pp. 198-207, 1995.  
11  
12

13  
14 Philips, S. Coordinate Measuring Machines and Systems, Performance evaluation, J.  
15 Bosch(ed.), pp. 39-74, 1995.  
16

17  
18 RENISHAW Technical Specifications, Probing Systems for CNC Machine Tools,  
19 H2000-3020-07-C, 2000.  
20

21  
22 Sira Ltd., Design to Inspection Project, Technical report, Sira DtoI project, Sira Ltd,  
23 1992.  
24

25  
26 Suh, S. H., Lee, E. S., Kim, H. C., and Cho, J. H., Geometric Error Measurement of  
27 Spiral Bevel Gears Using a Virtual Gear Model for STEP-NC, International  
28 Journal of Machine Tools & Manufacture, Vol. 42, pp. 335-342, 2002.  
29

30  
31 Tannock, J. D. T., Cox, D. R., Lee, H., and SimsWilliams, J. H., Intelligent Inspection  
32 Planning and Computer Aided Inspection, Proceedings of the Institute of  
33 Mechanical Engineering, part B: Journal of Engineering Manufacture, Vol. 207,  
34 pp 99- 104, 1993.  
35

36  
37 VW-GEDAS, Audimes, graphic-interactive programming system of cnc-coordinate  
38 measuring machines, version 1.1, 1990.  
39

40  
41 Wolf, J., Vittr, M., and Brecher, C., Closed-loop CAPP/CAM/CNC Process Chain  
42 Based on STEP and STEP-NC Inspection Tasks, International Journal of  
43 Computer Integrated Manufacturing, Vol. 19, n 6, pp 570-580, 2006.  
44

45  
46 Wong, F. S. Y., Chuah, K. B., and Venuvinod, P. K., Automated extraction of  
47 dimensional inspection features from part computer-aided design models,  
48 International Journal of Production Research, Vol. 43, No. 12, pp. 2377-2396,  
49 2005.  
50

51  
52  
53 Wong, F. S. Y., Chuah, K. B., and Venuvinod, P. K., Automated Inspection Process  
54 Planning: Algorithmic Inspection Feature Recognition, and Case Representation  
55 for CBR, Robotics and Computer-Integrated Manufacturing, Vol. 2, pp. 56-68,  
56 2006.  
57

58  
59 Woo, T., and Liang, R., Optimal Sampling for Coordinate Measurement: Its  
60 Definition and Algorithm, Quality Through Engineering Design, pp. 333-346,

1  
2  
3 1993.  
4

5  
6 Xu, X.W., and He, Q., Striving for a Total Integration of CAD, CAPP, CAM and CNC,  
7 Robotics and Computer-Integrated Manufacturing Vol. 20, pp: 101-109, 2004.  
8

9  
10 Xu, X., and Mao, J., A New Data Model for Process Planning and Its Role in  
11 Collaborative Manufacturing. Transactions of the ASME. Journal of Computing  
12 and Information Science in Engineering, 2004.  
13

14  
15 Yau, H. T., and Menq, C. H., Path Planning for Automated Dimensional Inspection  
16 Using Coordinate Measuring Machines, Proceedings of the 1991 IEEE  
17 International Conference on Robotics and Automation, pp. 1934-1939, 1991.  
18

19  
20 Yau, H. T., and Menq, C. H., An Intelligent Planning Environment for Automated  
21 Dimensional Inspection using Coordinate Measuring Machines, ASME Journal  
22 of Engineering for Industry, Vol. 114, pp. 222-230, 1992.  
23

24  
25 Yau, H. T., and Menq, C. H., An Automated Dimensional Inspection Environment for  
26 Manufactured Parts using Coordinate Measuring Machines, International Journal  
27 of Production Research, Vol. 30, n 7, pp. 1517-1536, 1992.  
28

29  
30 Yuen, C. F., Wong, S. Y., and Venuvinod, P. K., Development of a Generic  
31 Computer-Aided Process Planning Support System, Journal of Materials  
32 Processing Technology, Vol. 139, Issues 1-3, pp.394-401, 2003.  
33

34  
35 Zhang, Y., Nee, A., Fuh, J., Neo, K., and Loy, H., A Neural Network Approach to  
36 Determining Optimal Inspection Sampling Size for CMM, Computer Integrated  
37 Manufacturing System, Vol. 9, pp. 161-169. 1996.  
38

39  
40 Zhang, S. G., Ajmal, A., Wootton, J., and Chisholm, A., A Feature-Based Inspection  
41 Process Planning System for Coordinate Measuring Machine, Journal of  
42 Materials Processing Technology, Vol. 107, pp. 111-118, 2000.  
43

44  
45 Zhao, F., Xu, X., and Xie, S., STEP-NC Enabled On-line Inspection in Support of  
46 Closed-loop Machining, Robotics and Computer-Integrated Manufacturing,  
47 Available online at 8<sup>th</sup> December, 2006.  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

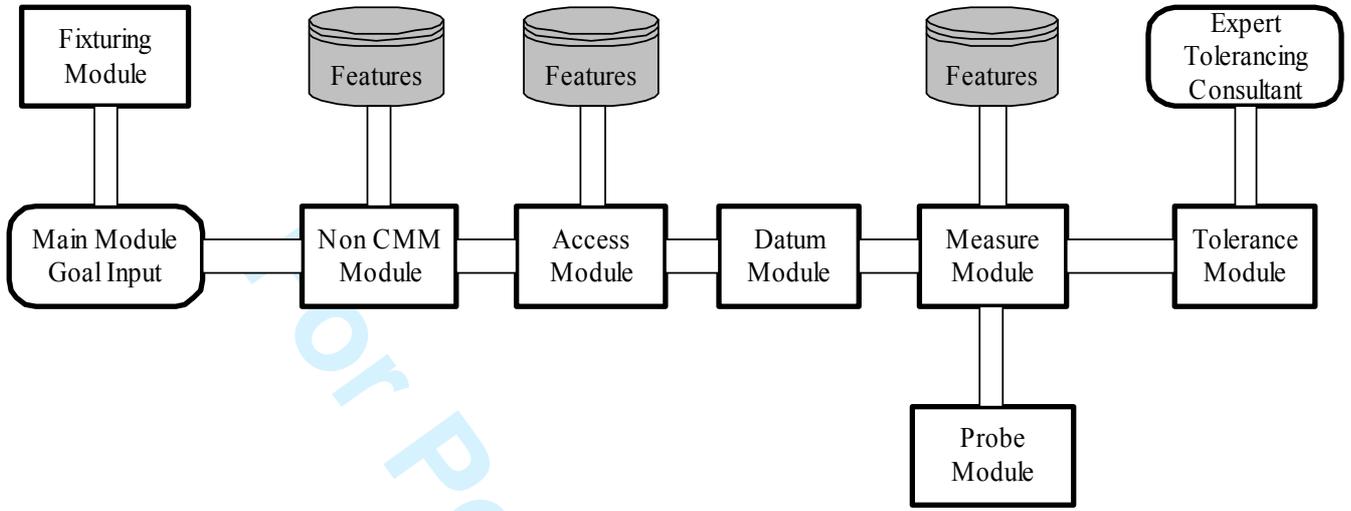


Figure 1: Inspection planning system model (EIMarghy and Gu 1987)

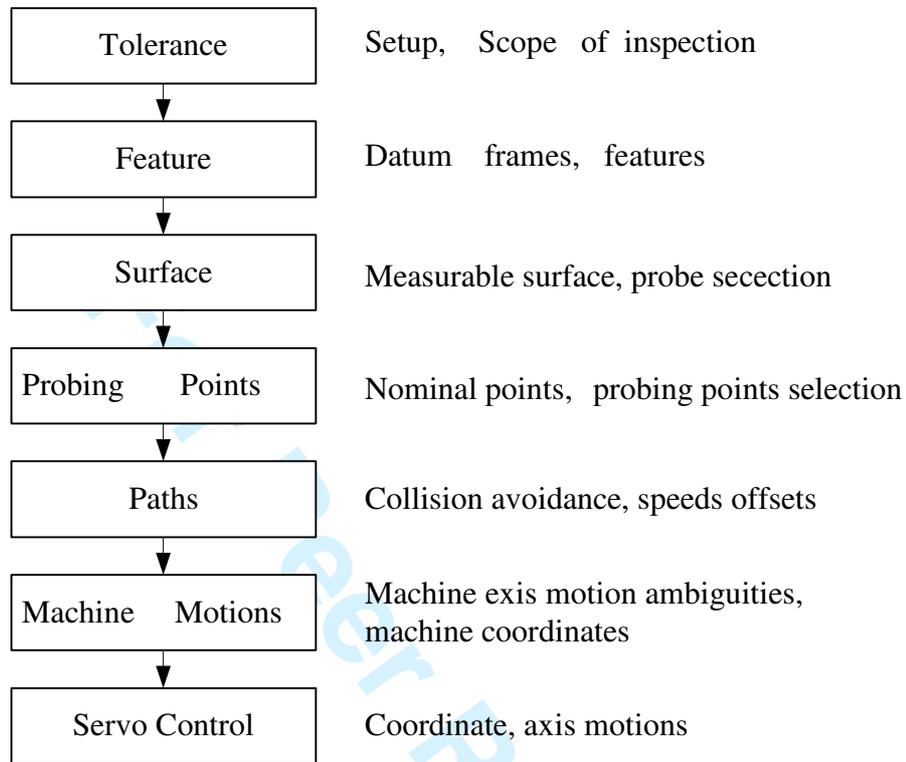


Figure 2: An inspection control hierarchy (Juster *et al.* 1994)

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

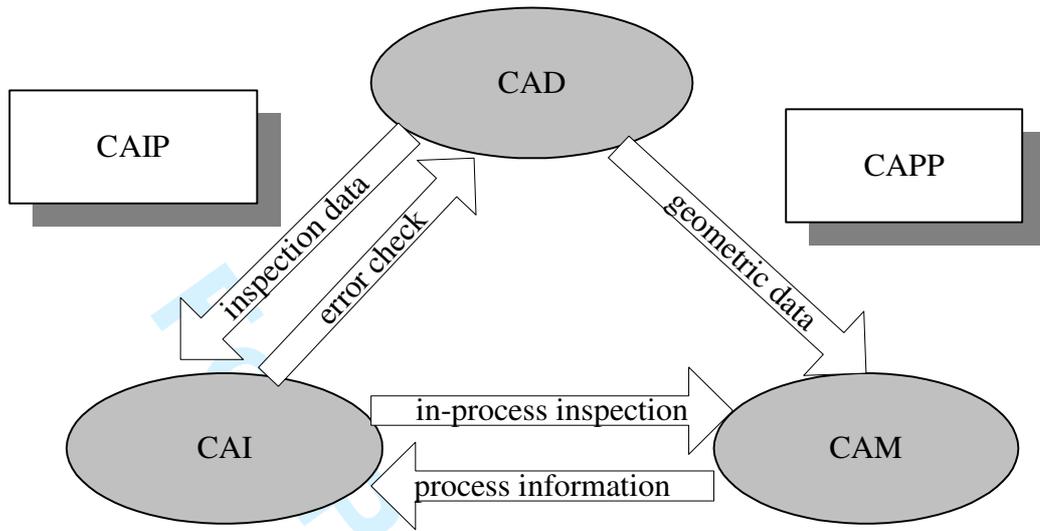


Figure 3: The role of CAIP and the interrelations between CAD/CAI/CAM (Menq *et al.* 1992)

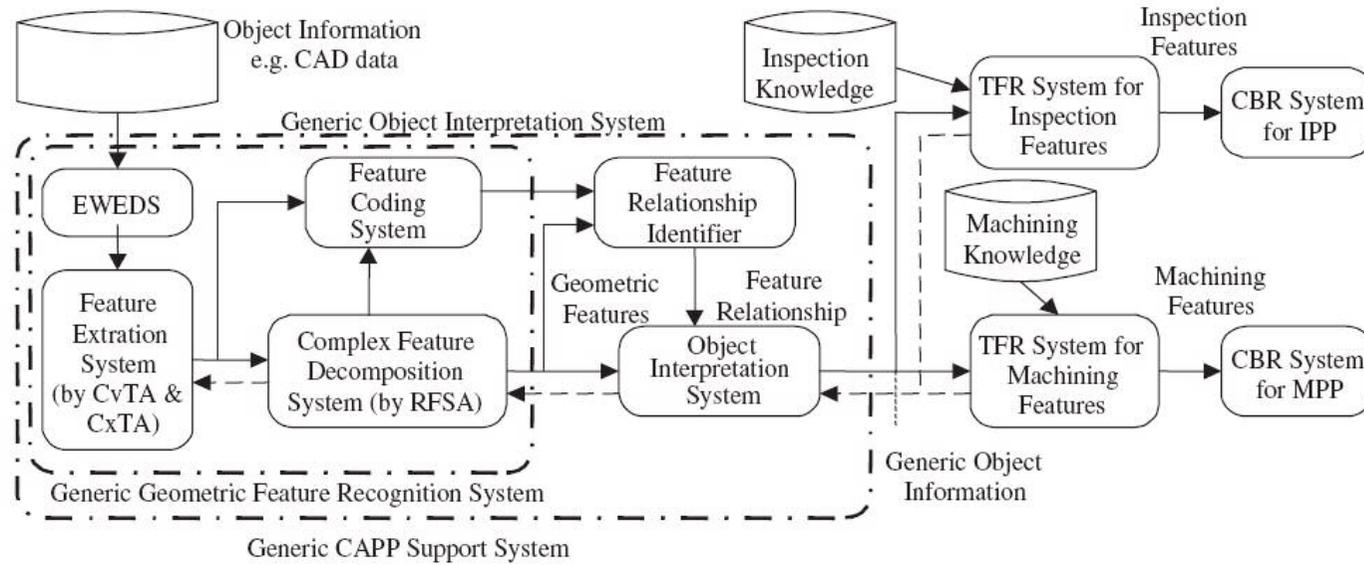


Figure 4: The framework of GCAPPSS (Wong *et al.* 2005)

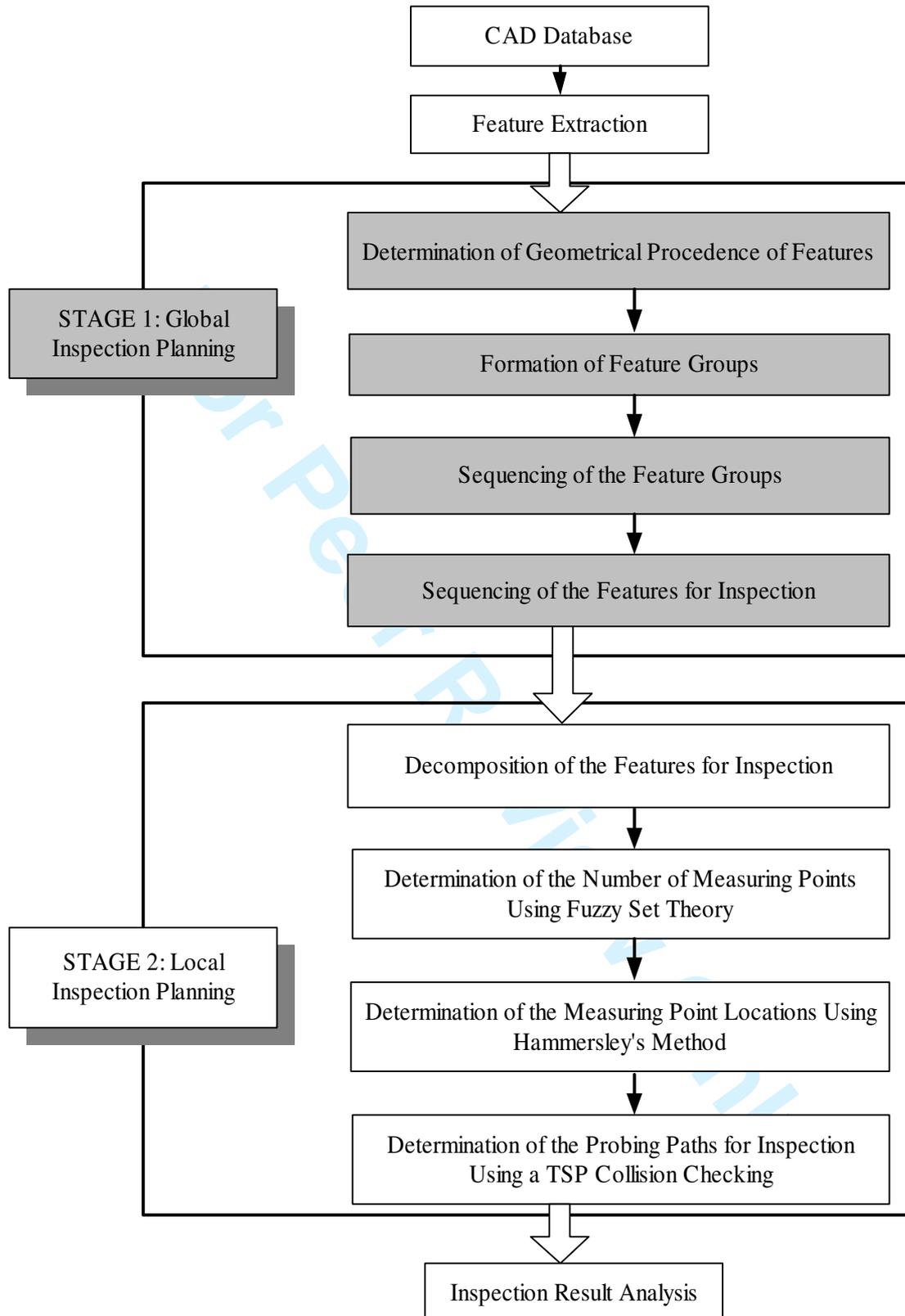


Figure 5: The overall schematic diagram of the proposed OMM systems (Lee *et al.* 2004, Cho *et al.* 2004)

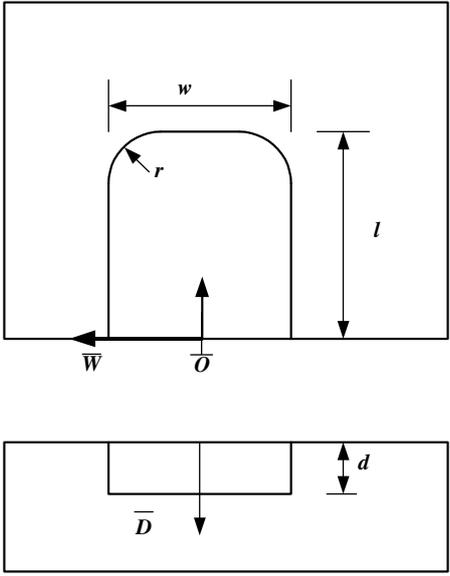
Feature	SLOT-5	Class	SLOT
		<p> <math>\bar{O}</math> : position vector of origin  <math>\bar{w}</math> : direction vector of width  <math>\bar{D}</math> : direction vector of depth  <math>l</math> : length  <math>w</math> : width  <math>d</math> : depth  <math>r</math> : corner radius </p> <p> <b>TAD = { <math>\bar{D}</math> }</b> </p> <p> <b>PAD = { <math>\bar{D}, \bar{D} \bar{w}</math> }</b> </p>	

Figure 6: A predefined feature (Lee *et al.* 2004)

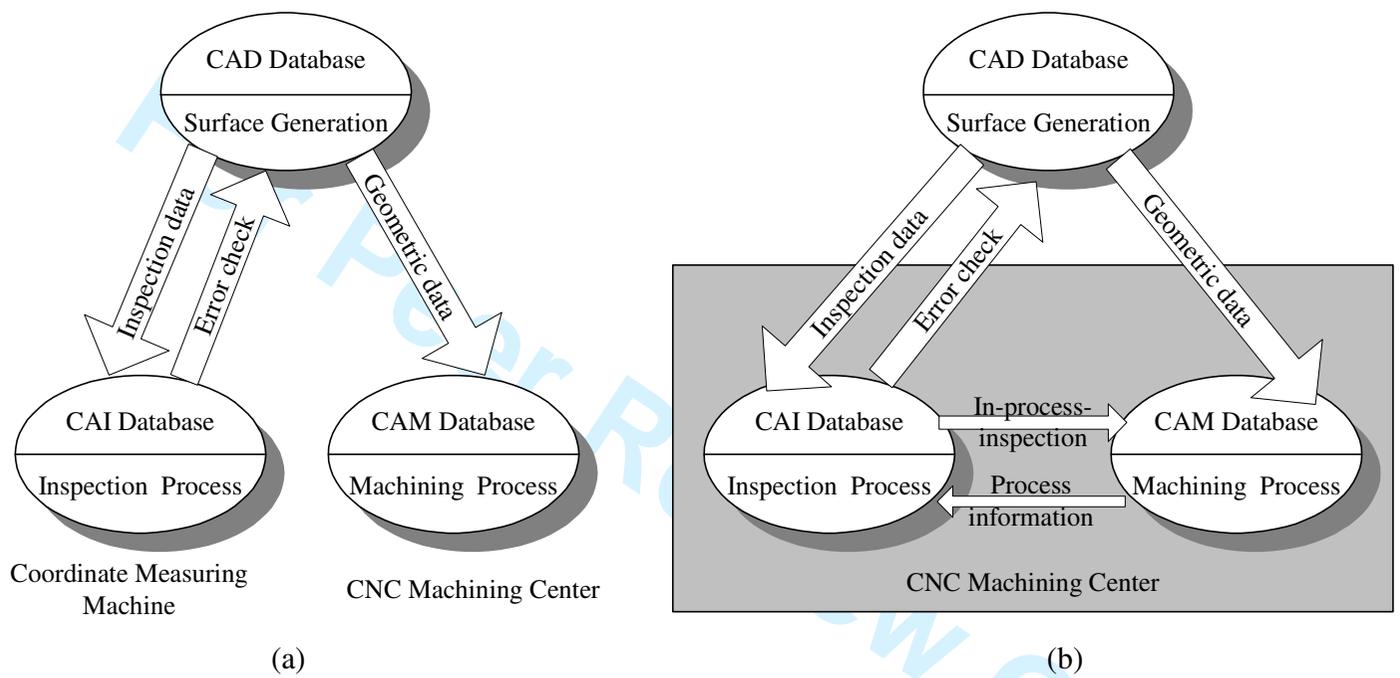


Figure 7: Inspection processes using (a) CMM, and (b) OMM (Cho and Seo 2002)

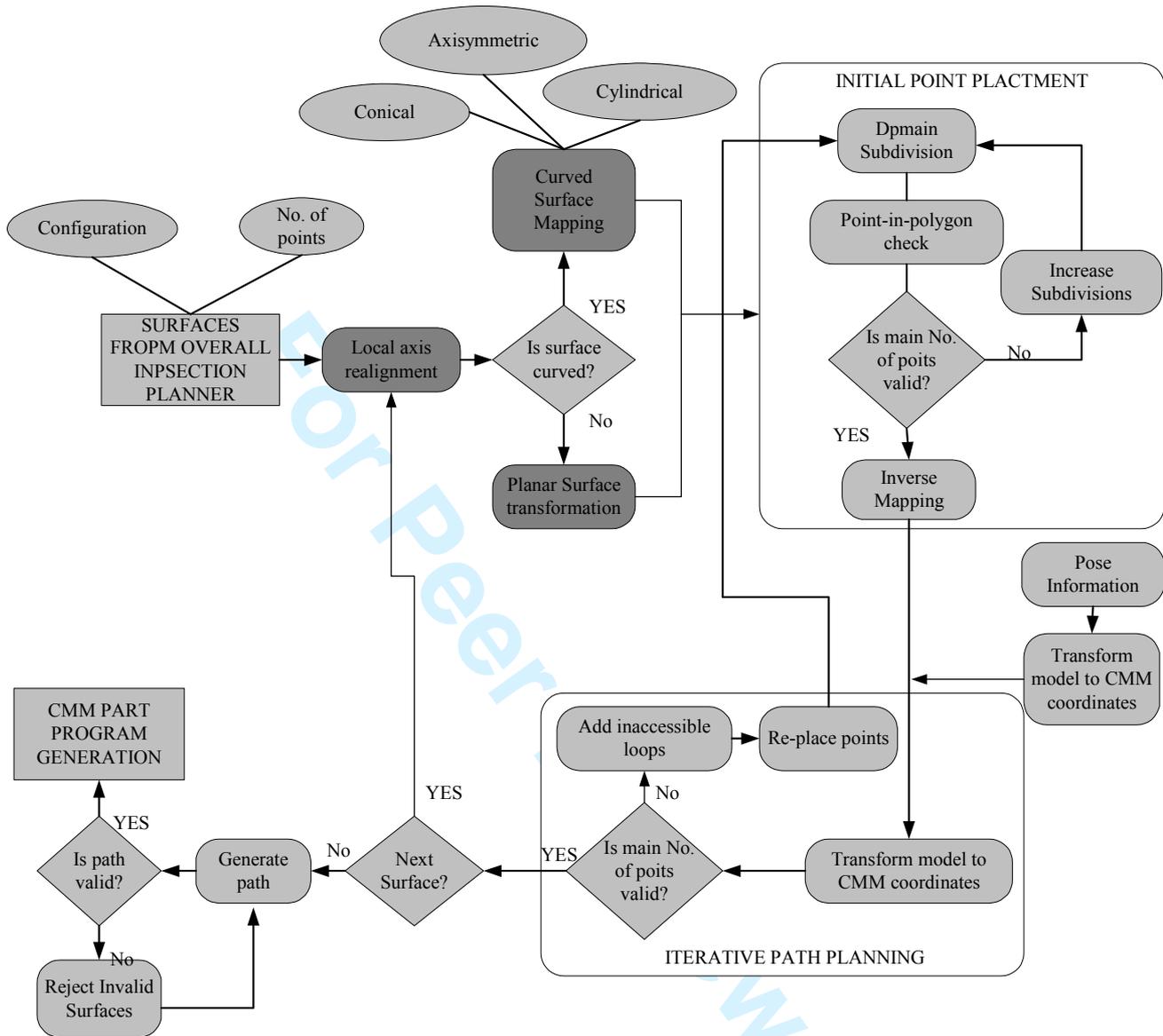


Figure 8: Flowchart of CMM inspection planner (Albuquerque *et al.* 2000)

	Prismatic and conical surfaces	Free form surfaces
Sampling optimization	Woo and Liang 1993, Zhang et al. 1996, Cho, Lee et al 2004-2005, Jiang and Chiu 2002	Menq et al., 1990-1992, Jiang and Chiu 2002, Elkott et al. 2002 Cho, Lee et al 2004-2005,
Sample size	Woo and Liang 1993	Menq et al., 1990-1992
Alternate sampling plans	Hocken and Group 1992-1997, Fan and Leu 1993, Lee and Mou 1996	Menq et al. 1990-1992, Pahk et al. 1995, Elkott et al. 2002
Sample location	Woo and Liang 1993, Hocken and Group 1992-1997, Fan and Leu 1993, Zhang et al. 1996, Lee and Mou 1996, Oray et al. 2000, Kim and Raman 2000, Fang et.al 2001, Cho, Lee et al. 2004-2005	Menq et al.1990-1992 , Pahk et al 1995, Kim and Ozsoy 1999, Edgeworth and Wilhelm 1999, Elkott et al. 2002 Cho, Lee et al 2004-2005,

Table 1: Literature reported on sampling for inspection planning