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Survey paper

Computer-Aided Inspection Planning—The state of the art

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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.

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1. Introduction

Inspection process planning is an integral part of the design and manufacturing activities. It determines what characteristics of a product are to be inspected, where and when. Modern manufacturing is increasingly characterized by the low volume, high variety production, tight tolerance, and 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.

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

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sequences selected during process planning may be more prone to errors and inconsistencies due to a large number of set-ups 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 [20].

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, On-Machine Inspection (OMI) or On-Machine Measurement (OMM) has been widely used as the preferred measuring equipment for the purpose of direct inspections in manufacturing and quality control, which is a vital feature for 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 [43]. Sensors present in a CNC system have the capability of providing accurate feedback for 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 set-up, adding to in-process time, not to mention introducing the potential of the fixture error [41].

Part inspection programs are either based on Dimensional Measuring Interface Standard (DMIS) [4] 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) [33]. 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.

Increasingly, standardization of discrete component inspection becomes a necessity. To meet the need, STEP (ISO 10303), AP219, and STEP-NC (ISO 14649) standards have been developed to provide the basis for standardization and integration of part inspections [34–36]. 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 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. [41]. The benefits of OMI can be summarized as follows [11,13,41,49,64]:

(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) changing 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, and reworking nonconforming parts;
(4) agile machining. OMI enables quick responses to product design changes. Since inspection operations are carried out on the same machining center, inspection gages and fixture changes are not required. New and existing technologies such as probing strategy, error compensation, data analysis software and fixture design technology can be integrated into the OMI system. As the errors occurring during machining processes are detected and recorded as they appear, part distortion can be "corrected" promptly through adjusting the subsequent machining operations.

Successful implementation of OMI however requires robust and reliable hardware and software. A multi-tool capacity machine tool is often a must. An open architecture controller is also essential for inclusion of any additional probing software that may be needed. The probing system which may be comprised of different probes, sensors and electronic elements, is needed for implementing the OMI process on the machine tool. The feedback mechanism needs to be in place and in real time.

3. Computer-Aided Inspection Planning (CAIP) systems for OMI and CMMs

CAIP may include automated or semi-automated modules capable of identifying and recognizing the dimensional inspection features along with the associated inspection constraints. It should be able to recommend an inspection method for each dimensional inspection feature. The resulting inspection operation also needs to be integrated into an overall inspection plan [72].

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

Research on CAIP systems started from the early 1980s. Before the mid-1990s, most of the research works remained at the conceptual-level CAIP systems. These systems can be categorized into two groups: (a) the tolerance-driven inspection process planning system and (b) geometry-based inspection process planning. The former focused on planning inspections for those features that have specific tolerance requirements. The latter focused on planning the inspection process to obtain a complete geometric description of a machined workpiece using the inspection data. Thus, comparison can be made with the design model for a complete geometry inspection.

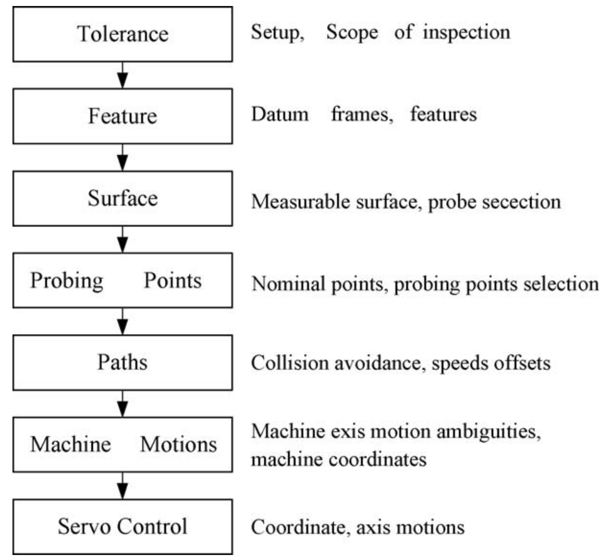

Fig. 2. An inspection control hierarchy [40].

3.1. Early research (prior to 1995) on CAIP systems

Early research (prior to 1995) on CAIP systems is reviewed briefly. The focus is on CAIP systems for $2^1/_2$ D features. Free-form surface inspection is quite a different research area. The interested readers are referred to the review article by Li and Gu [51].

3.1.1. Tolerance-driven CAIP systems

One of the earliest CAIP systems was developed by EIMaraghy and Gu [19]. It used the knowledge-based approach to generate inspection tasks. The system was developed in PROLOG and used a feature-oriented modelling approach. It took into account 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. Fig. 1 shows the planning logic which resulted in a recommended features inspection sequence, probes selection and part orientation sequence. The system has a modular structure and features serve a key role.

Helmy [25] 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 to group the inspection features. AAGs were introduced by Joshi and Chang [38,39] to enable machined feature recognition for machining 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 [27,28] developed an approach using an inspection control hierarchy to generate control codes for CMMs (Fig. 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. Next, probing points, paths planning, machine motion, and servo commands are carried out sequentially. A CMM inspection program is then generated. Some of the commercial systems such as Valisys [32] and Audimess [70] use a similar approach.

Medland and Mullineux [55–58] tried to integrate CMMs with a manufacturing system. The inspection plan is created automatically from a feature-based model, which contains information

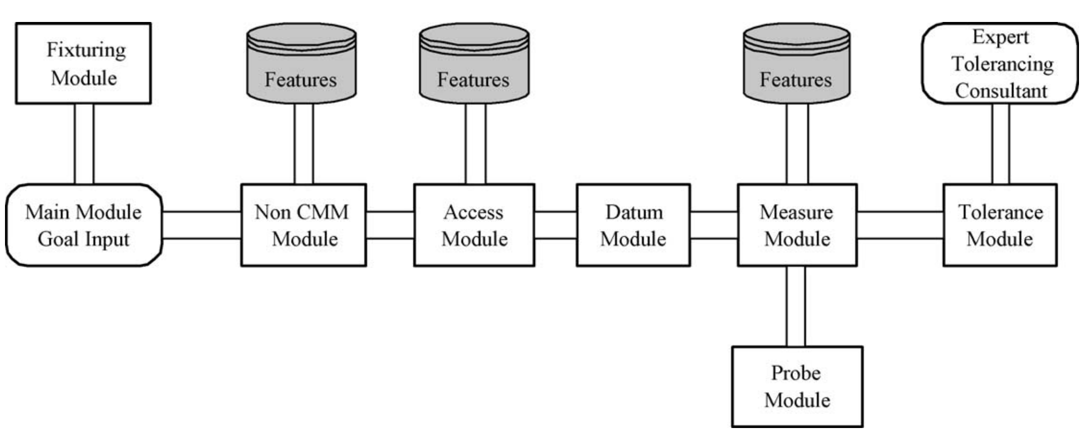

Fig. 1. Inspection planning system model [19].

about the features, their significance (i.e. importance of their dimensional accuracy for the acceptance of the part), the need for different probe types and attitude to reach the feature, special requirements to achieve the necessary accuracy (e.g. number of points) and the importance given to the manufacturing processes involved. The developed system is modular and based on a manufacturing network where communication is achieved through files exchanged within an integrated manufacturing environment. The measuring activities are controlled by a combination of dedicated programs and a constraint modelling system.

The system developed by Merat et al. [61] is part of a large effort to develop a Rapid Design System (RDS). The objective is to reduce the time from design to manufacture and inspection. In this system, tolerances are represented as features. An overall inspection plan consists of fragments, each of which relates to how toleranced geometry of a given feature is to be inspected. These Inspection Plan Fragments (IPF) are generated based upon rules and methods used in industrial practices. Inspection planning is the selection of appropriate IPFs which result in an overall time efficient plan. The IPF is generated by a macro called the IPF Generator. For each tolerance it generates a corresponding IPF with a suitable CMM probe, probing orientations and any required inspection tools other than CMMs such as depth micrometers. Feature accessibility analysis is not included and the inspection steps for various features are not prioritized or clustered to generate an optimal sequence.

The system developed by Yau and Menq [77–79] consists of five modules: (1) inspection specification, (2) automatic inspection planning, (3) CMM verification, (4) CMM execution, and (5) comparative analysis. The core of the system is a knowledge-based inspection planner that monitors the process flow and assists decision-making. The main function of the inspection specification module is to translate functional requirements, tolerances, manufacturing parameters and CMM constraints, into inspection specifications. The results of the specification module are used by the planning module to generate the probe path. The manufacturing accuracy and tolerance specification are taken into consideration. The generated path is then verified to ensure a collision-free path. The execution module carries out the inspection and generates the data. The measurement data together with the design model and inspection attributes are processed by the comparative analysis module to generate an inspection report.

Tannock et al. [68] developed a measurement planning system. They classified their measurement workpiece via a feature-based approach, and established measurement planning data through inquiries. Brown and Gyorog [6] discussed a prototype system named IPPEX (Inspection Process Planning EXpert system) for the development of a generative process planning expert system for dimensional inspections. IPPEX uses a product geometric modeller coupled with a dimensional and tolerance modeller to generate inspection instructions in the form of an operation plan and as a part program in compliance with the DMIS standard.

All the above reviewed research works focused on developing conceptual level CAIP systems for CMMs. Most of these CAIP systems need inspection operator's input for either selecting inspection features, or tolerances that need to be inspected. This type of research has laid a good foundation for the later-stage CAIP research.

3.1.2. Geometry-based CAIP systems

Unlike a tolerance-driven CAIP system, geometry-based CAIP systems largely ignore the tolerance information, but focus on the geometry-matching between the machined part and the designed shape. Duffie et al. [17] 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.

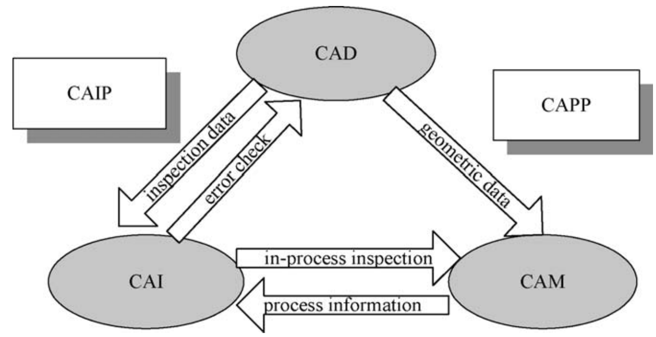

Fig. 3. The role of CAIP and the interrelations between CAD/CAI/CAM [9].

Menq et al. [60] developed an optimal match scheme that aligns the measurement data with the design data during the CAD-directed dimensional inspection. Cho and Kim [9] developed a flexible three-dimensional inspection system for sculptured surfaces by employing CMM, CAD database and vision system technology. The proposed system (shown in Fig. 3) performed optimum inspection planning, recognition of the workpiece, and compensation for alignment errors. The recognition/localization database was generated from the CAD database based on a new concept called Z-layer. Then, a 3D shape of the object on the table of the CMM was constructed by using a vision guided CMM.

Corrigall and Bell [14,15] 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 [65] 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 modellers and concluded that a powerful product modelling system is required if product validation is to be achieved in an automated fashion.

Geometry-based CAIP systems have not received as much attention as for the tolerance-driven CAIP systems. In comparison with a tolerance-driven CAIP system, a geometry-based system tries to measure the entire part leading to a time-consuming process.

3.2. Recent CAIP research for OMI and CMMs

The CAIP systems must have modules for the following tasks:

(1) inspection feature selecting and sequencing;
(2) measuring points/sampling selection and optimization;
(3) collision-free probing path planning and generation (including probe probing accessibility and orientation);
(4) inspection execution.

From the middle of 1990s, research in CAIP started to focus on one or some of the above tasks for a CAIP system. At the same time, non-CMM measurement and non-contact devices such as 3D optical scanners gradually mature. Therefore, CAIP system research for non-CMM measurement methods has become another major research trend. Compared with traditional touch probes, non-contact probes are able to provide a large amount of data in a relatively short time with higher accuracy. Bogue discussed the limitations of contact, probe-based CMMs and described a new, laser-based 3D geometrical scanning system which has been developed jointly by Metris and Volvo for assembling purposes [83]. Vezzetti presented a selective sampling acquisition approach for boundary definition in reverse engineering applications [84]. The proposed approach is developed for optical scanning devices. Minoni and Cavalli [85] proposed an optical measuring probing system, which can be used to perform on-line measurement. However, these optical equipments also have stringent requirements on the measuring environment. For example, mist, unclean workpiece surfaces, reflective surfaces, and temperature may lead to measurement errors. Auilar et al. [86] analyzed the accuracy and error mechanisms of laser scanning probes using simulations and experiments. Several tests have been carried out on a laser scanning probe fixed in a CMM to determine the main error sources of the sensor. The research on CAIP for optical measurement devices is still limited.

In this section, these relevant research works will be reviewed in the above order for OMI and CMM respectively.

3.2.1. Inspection feature selecting and sequencing

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 the previous sections 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, research has been done to recognize/extract inspection features directly from a CAD model and sequence them automatically. Inspection features are selected/extracted according to tolerance requirements. However, research on OMI and CMMs followed different approaches on sequencing inspection features. Researchers tend to group inspection features according to machining feature sequence for OMI, while the sequencing of inspection features for CMM is mostly based on probe accessibility and minimizing probe orientation.

3.2.1.1. Inspection feature recognition/grouping and sequencing for OMI. Wong et al. [72,73] 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. [80]. Fig. 4 shows the GCAPPSS system. A key feature of GCAPSS is the Generic Object Information System (GOIS), which consists of a generic geometric feature recognition system, a feature relation identifier, and an object interpretation system. The GOIS accepts the object information from the CAD model data in the Extended Winged Edge Data Structure (EWEDS), and processes them through a feature extraction system to identify simple and complex feature. The output of the generic geometric feature recognition system contains features that are different from the machining features. The feature relationship identifier receives this geometric feature information and establishes feature relationship information for the object interpretation system, which provides machining and inspection process planning systems generic object feature information respectively.

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

(1) The distance between two parallel faces which can be a length, width, gap, slot, fin, height, protrusion, depth, recess or thickness. The actual measurement process depends on the shape, size and orientation of the pair of faces of interest.
(2) The diameter of a complete cylinder/hole.
(3) The diameter or radius of a partial cylinder/hole or a cylindrical face.
(4) The distance between a cylinder/hole and a parallel face.
(5) The distance between a pair of cylinders/holes.
(6) Coordinate measurement (or profile) measurement of a curved surface (free-form or otherwise) with respect to a bounded reference plane.
(7) A combination of the above. A wide range of measuring equipment and length standards may be used during this stage.

One problem of the proposed algorithm is that it often generates enormous numbers of different inspection ways. The authors have proposed a knowledge-based technique—by using a series of "filters" to subject individual inspection process.

Lee et al. [49] at Inha University, Korea proposed an optimal inspection planning strategy (Fig. 5) for workpieces comprising many primitive form features. This is a two-stage process.

- Stage I: Global inspection planning

  At 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

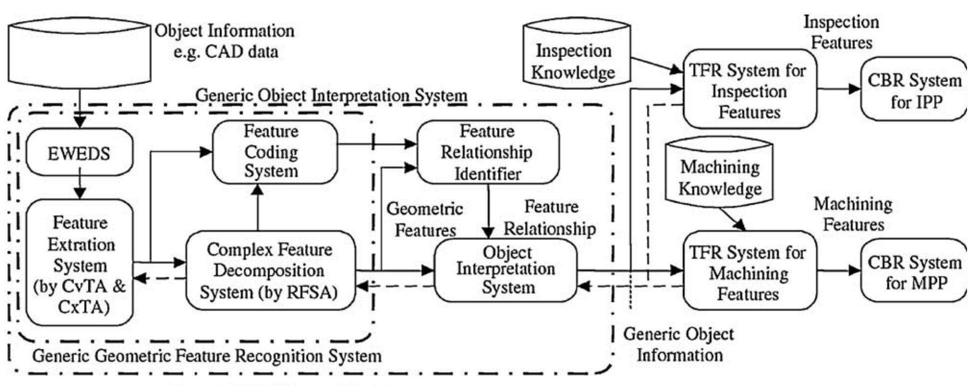

Fig. 4. The framework of GCAPPSS [72,73].

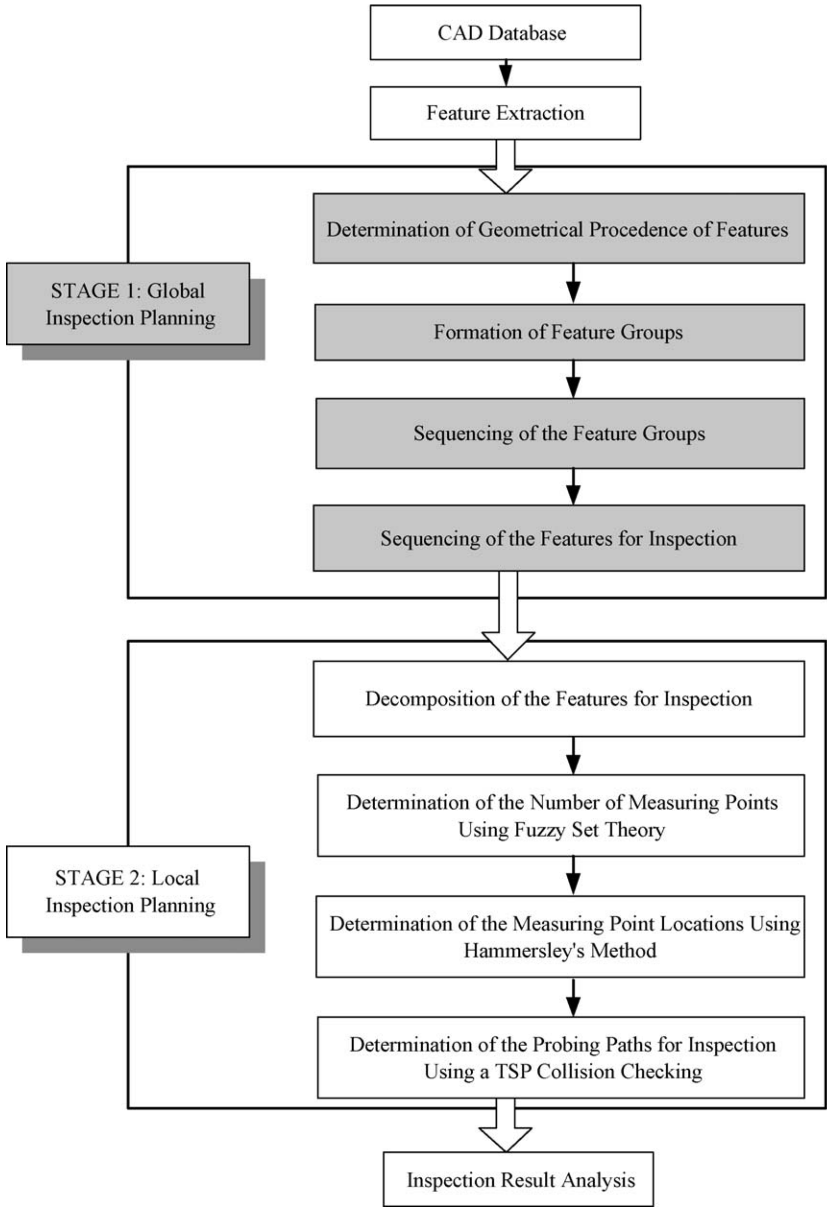

Fig. 5. The overall schematic diagram of the proposed OMI systems [11,49].

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

  Each feature is then decomposed into its constituent geometric elements such as plane, circle, etc. The tasks of this local inspection planning are to determine 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 (Fig. 6).

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 (Fig. 6). 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 OMI have been developed. They are (1) application of the identical PAD 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.

Chung [13] proposed an OMI 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 [10] later used the techniques to develop an inspection planning strategy for the OMI process based on CAD/CAM/CAI integration. Fig. 7 shows the inspection process planning comparison between OMI and CMMs.

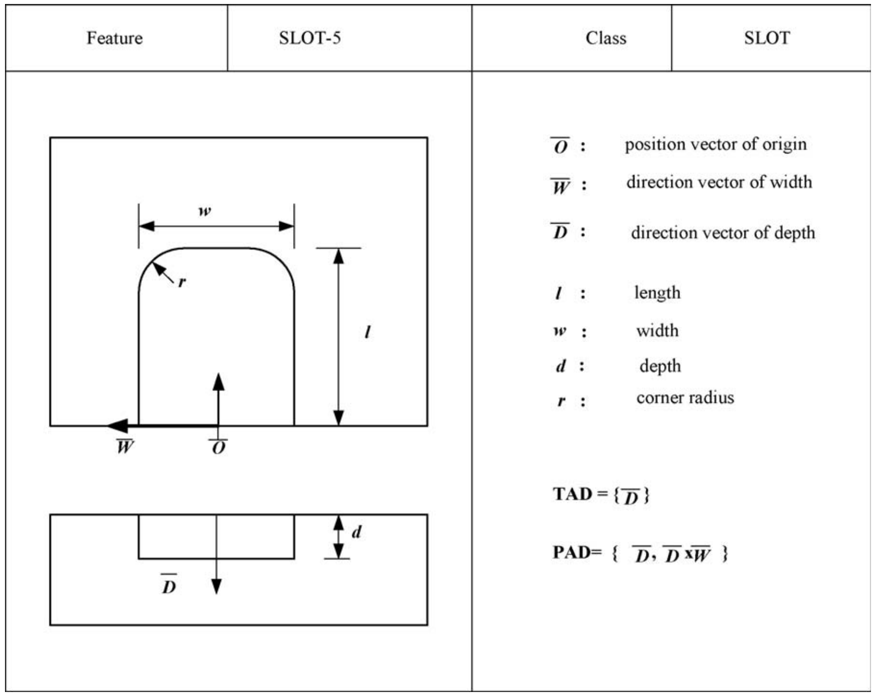

Fig. 6. A predefined feature [49].

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.

3.2.1.2. Inspection feature cluster analysis for CMM inspection. As the inspection operations carried out on a CMM are mostly for inspecting machined part, the sequencing of inspection feature is based on the probe accessibility and probing orientation analysis.

Zhang et al. [82] 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 (Fig. 8): 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 relationships 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 provides an animated display of the inspection probe path and checks whether a collision occurs between the part and the inspection probe.

Vafaeesefat and ElMaraghy [69] proposed a methodology to automatically define the accessibility domain of measurement features and group them into a set of clusters. The methodology

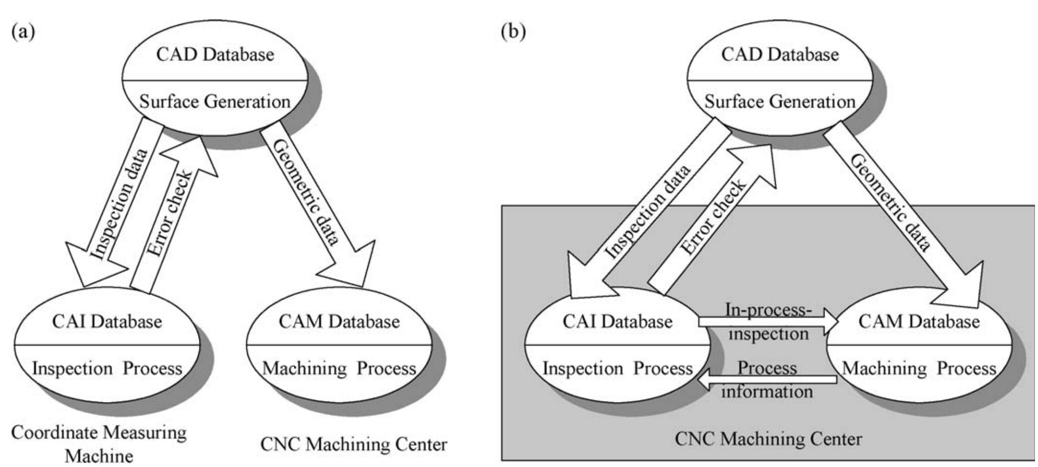

Fig. 7. Inspection processes using (a) CMM, and (b) OMI [10].

Fig. 8. Flowchart of the proposed feature-based inspection process planning system [82].

uses the CAD model of the workpiece and tolerance information as input to an algorithm for defining feature accessibility. The CAD model is first converted to the STereo Lithography (STL) or Virtual Reality Model Language (VRML) format for Probe Orientation Module (POM). The user chooses the type of probes and measure features, defines the coordinate systems, specifies tolerances and datums for measurement points, and generates probe paths.

Limaiem and ElMaraghy [52] proposed a Computer-Aided Tactile Inspection Planning (CATIP) system. Inspection features are selected based on a CAD model and the tolerance requirements. These inspection features are the input of the system, which contains four modules (Fig. 9). As it is shown in Fig. 9, the sequence of inspection features is based on their accessibility and minimization of probe orientation.

Hwang et al. [31] proposed a CMM inspection planning system for the purpose of minimizing the number of part set-ups and probe orientations. Inspection features are selected based on the tolerance specifications by the users. After receiving the inspection feature information, the proposed system firstly analyses the accessibility of each feature. Then the feature accessible information is used to derive the required part set-up and probe orientation. Based on a proposed decision rule to minimize the number of changes of part set-up and probe orientation in this research, the sequence of inspection features were decided.

From the above review, it can be concluded that probe accessibility and probing orientations are the major considerations for CMM-based inspection feature grouping and sequencing. The CAIP systems for CMMs, apart from the different focuses of each research, mostly analyze the accessibility of each inspection feature and the necessary probe orientation changes in order to decide the sequence of inspections. The effort is to minimize the change of probe orientations which contribute to the bulk of CMM inspection time. However, inspection feature grouping and sequencing for OMI are entirely different from CMMs. As a part is machined and inspected on the same machining center, machining feature sequence is the main consideration of inspection feature sequence. Therefore, the aforementioned CAIP systems for OMI used different technique to group and sequence inspection features. Probe accessibility and probing orientation are of minor significance for these systems.

3.2.2. Measuring/sampling points selection and optimization for both CMM and OMI

The inspection processes carried out on CMMs or OMI often use touch-type probes to perform point-to-point motions when recording 3D coordinates of a workpiece. The larger number of measuring points (or sampling points) is chosen, the 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. The research for CAIP systems for both CMMs and OMI does not seem to have major differences in this aspect. This section reviews the related research on touch-type probes. Since a scanning probe collects measuring points by dragging along the measurement surface, a large amount of data can be collected in a relatively short period of time. The measuring point allocation and probing path planning for scanning probes is very different from that of touch-type probes. Research in this area is scratchy.

Elkott et al. [21] 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). The brief review of the research works in the table is represented in the following paragraphs.

Some useful methods have been proposed to decide proper measuring points for each inspection feature by considering tolerance levels, geometric characteristics, and desired confidence levels. Menq et al. [59] developed a method based on the given design tolerance and machining accuracy to determine the optimum number of measuring points. Dowling et al. [16] discussed the statistical issues that arise when CMMs are used. They carried out research and simulation on commonly used

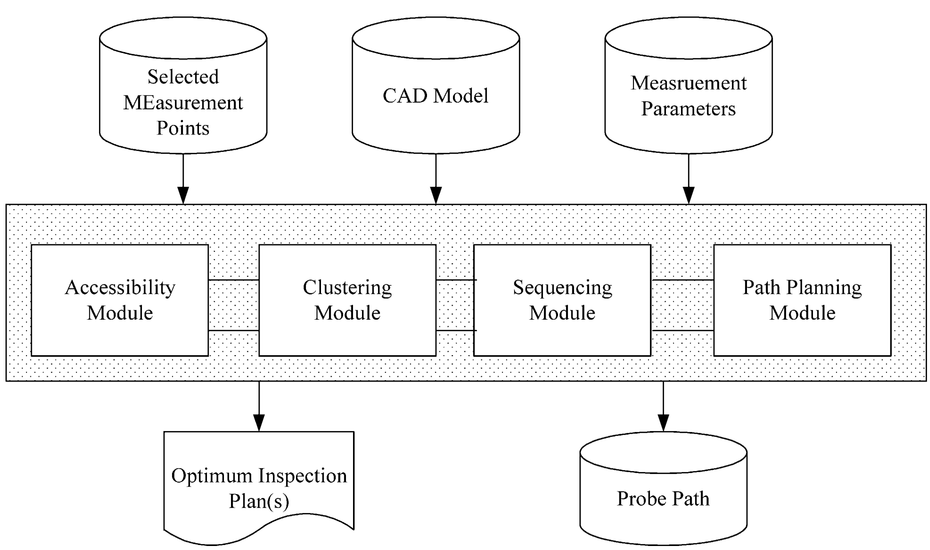

Fig. 9. The proposed CATIP system structure [52].

Table 1
Literature reported on sampling for inspection planning.

	Prismatic and conical surfaces	Free-form surfaces
Sampling optimization	Woo and Liang, 1993 [74] Zhang et al., 1996 [81] Cho et al., 2004–2005 [11,12] Jiang and Chiu, 2002 [37]	Menq et al., 1990–1992 [59,60] Jiang and Chiu, 2002 [37] Elkott et al. 2002 [21] Cho et al., 2004–2005 [11,12]
Sample size	Woo and Liang, 1993 [74]	Menq et al., 1990–1992 [59,60]
Alternate sampling plans	Hocken et al., 1993 [26] Fan and Leu, 1993 [22] Lee and Mou, 1996–1997 [47,48]	Menq et al., 1990–1992 [59,60] Pahk et al., 1995 [62] Elkott et al., 2002 [21]
Sample location	Woo and Liang, 1993 [74] Hocken et al., 1993 [26] Fan and Leu, 1993 [22] Zhang et al., 1996 [81] Lee and Mou, 1996–1997 [47,48] Oray et al., 2000 [66] Kim and Raman, 2000 [44] Fang et al., 2001 [23] Cho et al., 2004–2005 [11,12]	Menq et al., 1990–1992 [50,60] Pahk et al., 1995 [62] Kim and Ozsoy, 1999 [42] Edgeworth and Wilhelm, 1999 [18] Elkott et al., 2002 [21] Cho et al., 2004–2005 [11,12]

methods for estimating a feature's deviation range—the orthogonal least squares and minimum-zone methods. Huang et al. [30] proposed a knowledge-based inspection 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 this previous research, Lee et al. [49] and Cho et al. [11] proposed a similar fuzzy system for determining the optimum number of measuring points for their proposed OMI system. 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. [30] was applied to relocate these non-contact measuring points. As it is reviewed in this paragraph, the techniques for selecting proper measuring points for OMI systems are mostly "borrowed" from the research for CMMs.

The effect of selecting a particular measurement sampling strategy has been recognized as a major component of measurement uncertainty [74]. This effect is due to the systematic and pseudo-random errors contained in the measurement system [7,8]. Elkott et al. [21] 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 feature-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 [37] 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 is normally not separated. For form features, it is logical to use form tolerances as the acceptable error amount since it best represents the limit of the sum of all possible error sources. Regression and least square methods were used for checking if the number of selected measuring points satisfies the requirement.

3.2.3. Probing path planning and generation

Apart from the probing path generation research included in the CAIP research reviewed in Section 3.2.1, there are substantial research focus on generating optimal probing path for touch-type probes. This section reviews these researches.

3.2.3.1. Probing path planning and generation for OMI inspections. In the OMI system proposed by Lee et al. [49] and Cho et al. [11], probe paths are generated after the suitable measuring points for the given surface are determined using the Traveling Sales Person (TSP) algorithm. TSP algorithms have been used by some researchers to generate the probing path to minimize the inspection time [11,46,49].

Before inspection starts, collision avoidance analysis is also required. The collision problem in an OMI operation can be divided into two categories, i.e. the probe collision and the probe holder collision. A new methodology to detect the probe and/or probe holder collisions called Z-map has been proposed [49,11]. A Z-map is generated for the given target workpiece, and then probe and/or probe holder moving trajectories are calculated according to the previously generated probing path. By calculating the errors caused by the probe and/or probe holder trajectories, collisions can be checked and avoided. These probing path generation systems are mostly based on the similar previous research for CMMs.

3.2.3.2. Probing path planning and generation for CMMs. This section reviews recent research works on probing path planning for CMMs. The research focused on generating collision-free probing path for inspection operations carried out on CMMs. It is assumed that the inspection features be sequenced previously for these research works.

Albuquerque et al. [2] used an iterative method of point placement and collision avoidance for multiple, interacting features to automatically generate probe tool path (Fig. 10). A

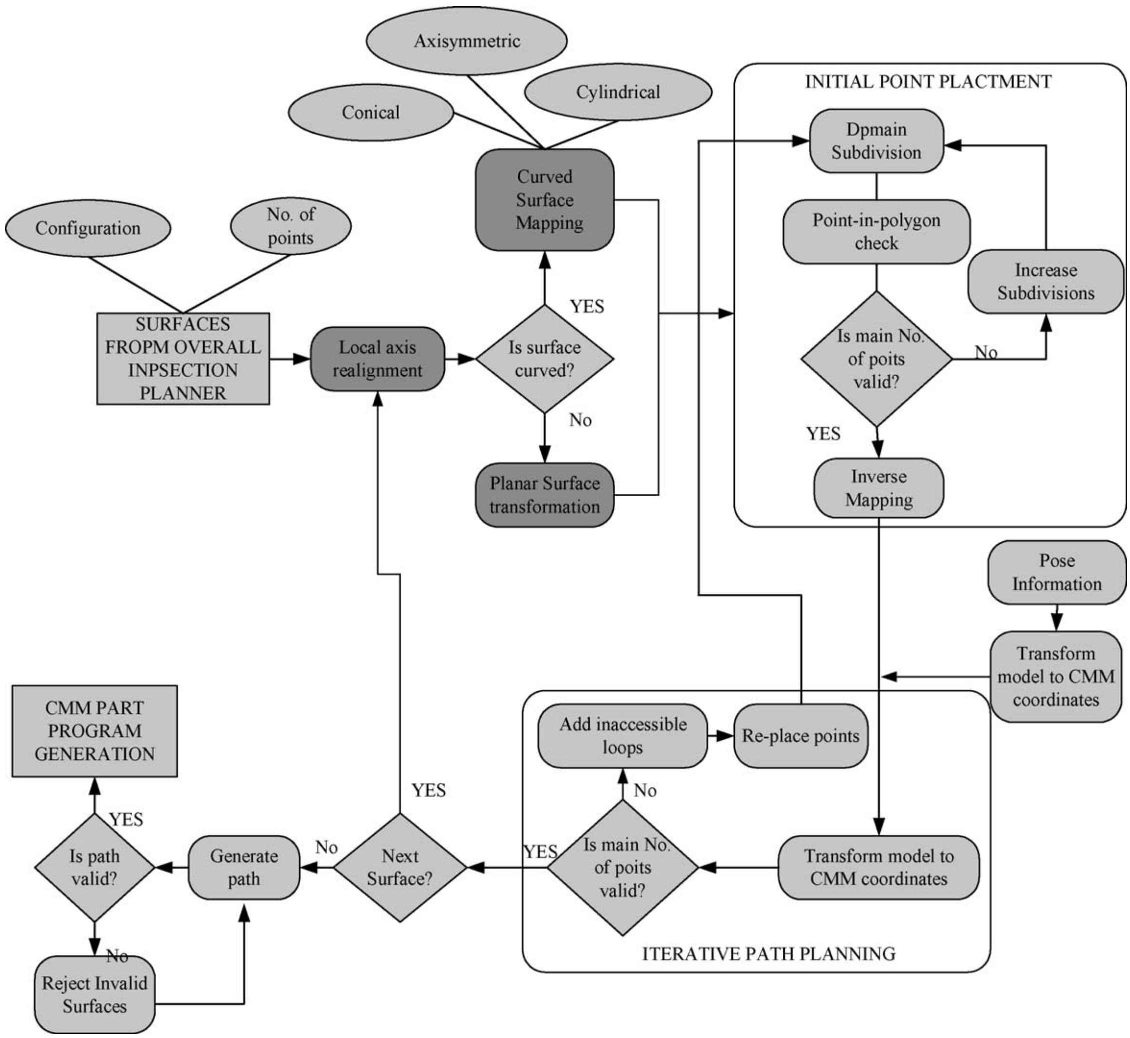

Fig. 10. Flowchart of CMM inspection planner [2].

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 the transforming inspection points and the model into the CMM workspace. This process is followed by iterative re-placement of points in accessible regions. After sufficient number of measurable points has been placed during the iteration process, a collision-free path is generated. This research considered many requirements such flexible and accessible point placement, feature intersecting, and probing path optimization.

Ainsworth et al. [1] developed a probe path generation system that utilizes 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 uni-directional 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 [53] proposed a framework for automatic CMM inspection probing planning. A three-phase approach was 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

All the CAIP systems discussed as above are based on G&M codes. Because of the low level information that G&M codes carry, parts inspection on OMI and CMMs still represents islands of automation within the overall manufacturing process. Since the development of STEP and STEP-NC, some related research focused on developing STEP and STEP-NC enabled inspection-planning systems.

Lin and Chow [54] integrated a STEP data module with an IDEF0 model for CMM-based 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.

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 geometric information in the code leads to a uni-directional information flow [5]. 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 [75,76]. The STEP-NC (ISO 14649) data model, 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 inspections. 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 ways of machining a part [50].

Some STEP-NC compliant inspection systems have been proposed; most of them utilize CMMs. Brecher and co-workers [71] in the Laboratory for Machine Tools and Production Engineering (WZL) at Aachen University, Germany developed a system for a closed-loop process chain which integrated inspections into the STEP-NC machining information flow. The work focused on closing 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 were carried out on a CMM.

In the United States, NIST, Boeing, General Electric, Unigraphics and some other industry partners worked on a STEP-enabled Closed-Loop Machining (CLM) scenario using ISO 10303 AP 238 for probing activities [24]. ISO 10303 AP 238 [36] 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. Different AP238 programs were used for probing, and machining operations. 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 [3] developed an inspection framework for closing the inspection loop through integration of information across the CAx process chain. The major feature of the proposed STEP-compliant inspection framework is the inclusion of high-level and detailed information in terms of an inspection Workplan, Workingstep, and a mechanism to feedback inspection results across the total CAx process chain. STEP-NC (ISO 14649-16), DMIS and AP219 are used as the basis for representing the product and manufacturing models. This research mainly focused on the use of CMMs.

Suh et al. [67] presented a method of indirect measurement based on the virtual gears model (VGM), obtained by NURBS fitting of the surface points measured by CMM. Geometric error measurement is required to evaluate the grade of the manufactured gears. Due to the complexity of the spiral bevel gear, direct measurement with the physical part has been conducted in a very limited way. By comparing the VGM with CAD model (soft-master model), various errors such as tooth profile error and tooth trace error can be automatically measured. The developed method is simple and robust without requiring a special measuring device, and hence it can be applied for the industrial practice as a means for measuring the tooth profile and tooth trace errors which cannot be measured by the conventional method. Further, the model-based method can be incorporated on the advanced CNC controller based on the new CAM–CNC interface scheme of STEP-NC as an on-line inspection module.

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

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

5. Discussions

With the development of more sophisticated machine tool, advanced touch-trigger probes, and increasing demand for automated production systems, inspections in particular on-machine inspections have become more and more widely accepted. The purpose is to enable direct inspections during machining processes for quality control. OMI can overcome the bottlenecks of inspection processes that are typical of a CMM system (e.g. measuring time, difficulty with capital investment and time delay of material flow between CMMs and machine tools in the factory). OMI enables real time, on-line quality control during machining processes.

However, research work on developing CAIP systems for OMI is 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. Some researchers have also suggested to use non-contact probing equipment such as ultrasonic [63] and laser scanning probe/sensor [45].

Based on the above review, the authors believe that there are still a number of issues unaddressed. The remaining part of this section discusses these issues.

Firstly, inspection process planning has been mainly carried out in isolation from machining process planning. This does not present a major problem for inspections carried out on a CMM. This is because inspections are carried out in isolation from machining. As a matter of fact, it has been deemed acceptable to consider machining process planning and inspection process planning in tandem. However, when inspections need to be carried out in-between manufacturing processes as in OMI, the status-quo method becomes inadequate. Inspection process planning needs 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.

Secondly, 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 [29].

Thirdly, employing OMI for inspection during machining may be advantageous in the context of process control. The use of non-standard bespoke G/M canned cycles with very limited mechanisms for feedback of inspection results prohibits a desired integration of inspection with machining operations. Coupled with this is the demand for integration and standardization with the evolution of new standards such as STEP and STEP-NC.

6. Conclusion and future trends

This paper reviewed the development of CAIP research for primitive formed features. In the past two decades, most of the research in the area has been focusing on developing CAIP systems for CMMs. In the early days of CAIP development, the research works also stayed 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 quality control engineers. Therefore this is an error-prone process. The geometry-based CAIP systems on the other hand 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.

From the mid-1990s, OMI started to attract attention of CAIP researchers. OMI has many benefits comparing with traditional CMMs, such as cost and time saving, change from reactive inspection to proactive control, elimination of non-value added operations, and agile machining. However, the lack of standardized data model for the consolidate environment of the entire machining chain limited the integration of OMI with machining process.

With an international effort in developing a standard for the exchange of produce model data—STEP and STEP-NC as well as the related application protocols—it is now possible to build a standardized data model for the entire product process encompassing machining and 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 machining and inspection, such as the capability of a machining center, the tolerances, tool wear, 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.

Apart from the aforementioned standard development, new types of measurement equipment such as scanning probes, 3D optical probes are being developed and more and more widely used. This type of equipment presents a new prospective for inspection process planning. Some of the advantages of this equipment include higher accuracy, fast speed, and provision for quantitative measurement information. However, different inspection process planning schemes must be developed accordingly as they are not point sampling. New techniques are to be developed to achieve faster inspection processes and better inspection results.

Based on the above discussion, future research work can be expected in the following areas.

- Development of comprehensive STEP and STEP-NC data models in support of integrated machining and inspection process planning.
- Development of inspection feedback analysis system based on the abovementioned new standards and technology for achieving a closed-loop machining environment.
- Development of a machine error prediction database that can be included in the inspection planning for monitoring the machining accuracy and actively controlling the machine errors.
- Mechanism of analyzing and utilizing the inspection results to inform and “guide” the subsequent machining operations.

As technologies for the inspection devices mature and product quality requirements become more stringent, on-machine inspection will take the centre stage of quality assurance.

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