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Corresponding Author: Dr. haibin zhao, Ph.D

Corresponding Author's Institution: K.U.Leuven

First Author: haibin zhao, Ph.D

Order of Authors: haibin zhao, Ph.D; Jean-Pierre Kruth, Professor; Nick Van Gestel, Ph.D; Bart Boeckmans, Master; Philip Bleys, Ph.D

Abstract: Combining multiple sensors on CMMs (Coordinate Measuring Machines) is useful to fulfill the increasing requirements on both complexity and accuracy in dimensional metrology. Yet, the methodology to plan measurement strategies for systems combining different types of sensors is still a major challenge. Such planning is commonly done in an interactive way. This paper presents a methodology which can create inspection plans automatically for CMM inspection combining a touch trigger probe and a laser scanner. The inspection features are specified based on the extracted geometry features and the associated PMI (Product and Manufacturing Information) items from a CAD model. A knowledge based sensor selection method is applied to choose the suited sensor for each inspection feature. For touch trigger measurements, the sampling strategy considers the measurement uncertainty calculated by simulation. A geometry-guide method is developed for collision-free probing path generation. For laser scan measurements, the required view angles and positions of the laser scanner are determined iteratively, based on which the scan path is generated automatically. The proposed methodology is tested for several cases and validated by measurement experiments. The methodology provides suited planning results and can be used for automated dimensional inspection, i.e. Computer Aided Quality Control (CAQC).

***Cover Letter**

Editor-in-chef
K.T.V. Grattan
Journal of Measurement

Dear Editor:

Enclosed for your consideration is an original research article, entitled "Automated dimensional inspection planning using the combination of laser scanner and tactile probe".

1. All authors of this research paper have directly participated in the planning, development and analysis of this study.
2. All authors of this paper have read and approved the final version submitted.
3. The contents of this manuscript have not been copyrighted or published previously.
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6. There are no directly related manuscripts or abstracts, published or unpublished, by any authors of this paper.

In this manuscript, we propose a novel automated inspection planning system for CMM geometrical measurements combining laser scanner and tactile probe. The measurement strategies are planned automatically based on the full accessibility of the design specifications. The experiments show that the system provides reasonable inspection planning results. The system is useful for dimensional metrology.

Thank you very much for your consideration. If you have any questions, please don't hesitate to contact me at my email address: zhaohb08@yahoo.com or at my mobile phone :+32 (0)485 166 410.

Best regards!

Haibin ZHAO

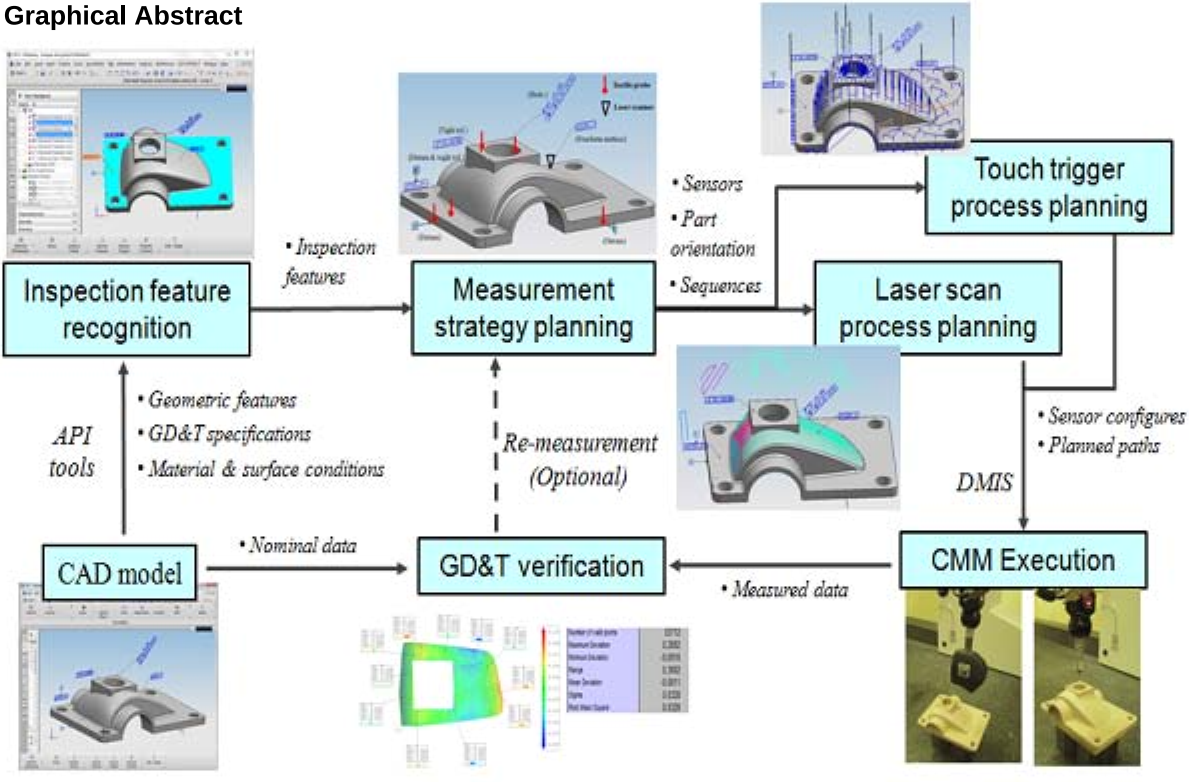
03/11/2011

***Highlights**

Highlights

- We develop an inspection planning system for CMM measurements
- Laser scanner and tactile probe are combined in that system
- CAD model is used to guide the inspection planning for each inspection feature
- Inspection path is generated automatically for both sensors

Graphical Abstract



Potential reviewers

Prof. T. Pfeifer

Institute: Rheinisch-Westfälische Technische Hochschule Aachen (RWTH), Aachen, Germany

Email: T.Pfeifer@wzl.rwth-aachen.de

Tel: +49 241 80-27412

Fax: +49 241 80-22193

Address: Werkzeugmaschinenlabor, RWTH Aachen, D-52056 Aachen, Germany

Prof. L. Monostori

Institute: Hungarian Academy of Sciences, Budapest, Hungary

Email: laszlo.monostori@sztaki.hu

Tel: +36 1 2096 990

Fax: +36 1 4667 503

Address: H-1111 Kende utca 13-17, Budapest, Hungary

Prof. A. Weckenmann

Institute: Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

Email: albert.weckenmann@qfm.uni-erlangen.de

Tel: +49-9131-85-26520

Fax: +49-9131-85-26524

Address: R. 1.07, Nägelsbachstraße 25, 91052, Erlangen, Deutschland

Automated dimensional inspection planning using the combination of laser scanner and tactile probe

Haibin Zhao [a,*], Jean-Pierre Kruth [a], Nick Van Gestel [a], Bart Boeckmans [a], Philip Bleys [a]

[a] *Katholieke Universiteit Leuven, Department of Mechanical Engineering, Celestijnenlaan 300b, 3001, Leuven, Belgium*

Abstract

Combining multiple sensors on CMMs (Coordinate Measuring Machines) is useful to fulfil the increasing requirements on both complexity and accuracy in dimensional metrology. Yet, the methodology to plan measurement strategies for systems combining different types of sensors is still a major challenge. Such planning is commonly done in an interactive way. This paper presents a methodology which can create inspection plans automatically for CMM inspection combining a touch trigger probe and a laser scanner. The inspection features are specified based on the extracted geometry features and the associated PMI (Product and Manufacturing Information) items from a CAD model. A knowledge based sensor selection method is applied to choose the suited sensor for each inspection feature. For touch trigger measurements, the sampling strategy considers the measurement uncertainty calculated by simulation. A geometry-guide method is developed for collision-free probing path generation. For laser scan measurements, the required view angles and positions of the laser scanner are determined iteratively, based on which the scan path is generated automatically. The proposed methodology is tested for several cases and validated by measurement experiments. The methodology provides suited planning results and can be used for automated dimensional inspection, i.e. Computer Aided Quality Control (CAQC).

Key words: Automated inspection planning, Computer Aided Quality Control (CAQC), Coordinate Measuring Machine (CMM), Multiple sensor integration, CAD model, Dimensional metrology

* Corresponding author:
Email address: zhaohb08@yahoo.com (H. ZHAO)
Tel: +32 (0)16 32 29 87

1 Introduction

Dimensional inspection of workpieces, to ensure their conformity to design specifications, is a critical part in manufacturing [7,14]. CMMs (Coordinate Measuring Machines), have become a standard tool for dimensional inspection in industry. As requirements on complexity and accuracy of dimensional metrology increases, multi-sensor measurements combining different sensors are implemented to achieve both holistic geometrical measurement and improved reliability of measured data [22]. Because laser scanners and tactile probes have complementary characteristics in capability [17], Systems combining the two are quite common [3,4,8,18]. However, researches in literature only focus on fusing/analyzing data from multiple sensors. Few investigation has been made in measurement strategy planning for such systems. Typically, the measurements were performed in interactive ways (e.g. using a joystick and/or interactive programming), which are usually time consuming, prone to mistakes and far from optimal.

Since the inspection performance of CMM systems (e.g. measuring time, cost, measurement uncertainty, etc.) highly depends on the inspection planning strategy [5], it is strongly recommended to apply automated inspection planning. In the last decades, work has been reported on issues of inspection planning, especially for tactile probing or laser scanning. A hierarchical planning system was developed by Yau and Menq to make tactile inspection plans [24]. Some methods attempted to automate the tactile inspection planning at two different levels [5,20]. The high (global) level specifies the setups and the corresponding feature sequences, while the low level makes the inspection path for each feature. Methods to optimize the numbers of part setups, probe orientations and feature sequences for tactile inspection planning have been discussed [9]. Automated inspection planning frameworks for CMM-based laser scanning are reported in [13,14]. Surveys of the inspection planning techniques can be found in [11,25]. Those papers only concentrate on inspection planning for single-sensor measurements (tactile probing or laser scanning). Few research is reported on automated inspection planning for CMM systems combining the two. [16] introduced a hybrid inspection planning method, but only sensor selection and inspection feature sequencing are discussed. There is no proof that their system can create inspection plans automatically. The inspection planning for CMM inspection combining tactile probing and laser scanning is still not well addressed.

The present paper proposes a methodology to create hybrid inspection plans automatically for CMM inspection combining a laser scanner and a touch trigger probe. The flowchart of the proposed methodology is illustrated in fig. 1, where the bold arrows represent the process flow and the thinner arrows represent the information flow. At the beginning, the inspection features being

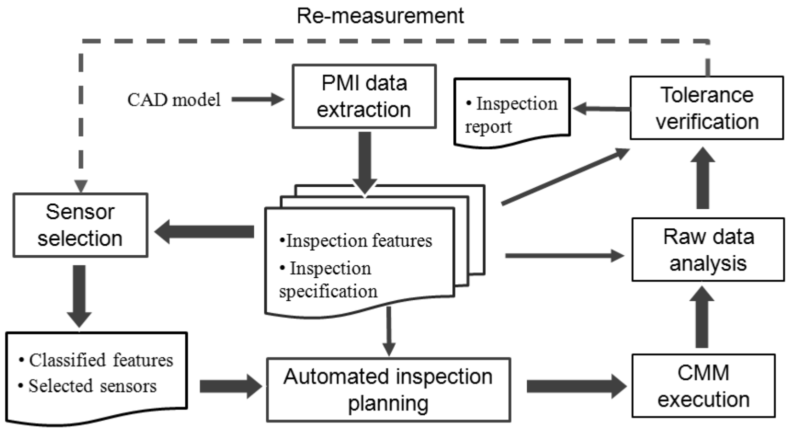


Fig. 1. Overview of the proposed inspection process

measured are identified and constructed based on the part's CAD model. Next, a knowledge-based sensor selection approach is applied to choose the most suitable sensor for each specified inspection feature. The inspection features are clustered according to their selected sensors. Then, two inspection planning modules - laser scanning module and tactile probing module - are developed to plan the inspection process automatically for all the specified inspection features. The generated inspection plans are written as DMIS (Dimensional Measuring Interface Standard) document for real CMM measurement. Finally, the measured data is collected and evaluated for tolerance verification. The re-measurement process is performed to re-capture the point data from where the initial data don't have good enough quality. The automated inspection planner ensures that the advantages of laser scanner and touch-trigger probe can be fully achieved. Saving measuring time and cost is another benefit of the automated inspection planner.

The main contributions of our work can be summarized as follows:

(1) A CAD-based methodology is proposed to plan hybrid inspection process automatically for CMMs utilizing a combination of a tactile probe and a laser scanner.
(2) A knowledge-based method is developed to deduce and select the most suited sensor for feature inspection.
(3) Automated inspection planning modules are developed for both laser scanning and touch trigger probing.

The remainder of the paper is organized as follows. Section 2 proposes the method for inspection feature construction. Section 3 discusses the knowledge-based sensor selection method. Section 4 describes the automated inspection planning module for touch trigger probing, while the module for laser scanning is given in section 5. Section 6 presents a case study for verification. Section 7 is the conclusion.

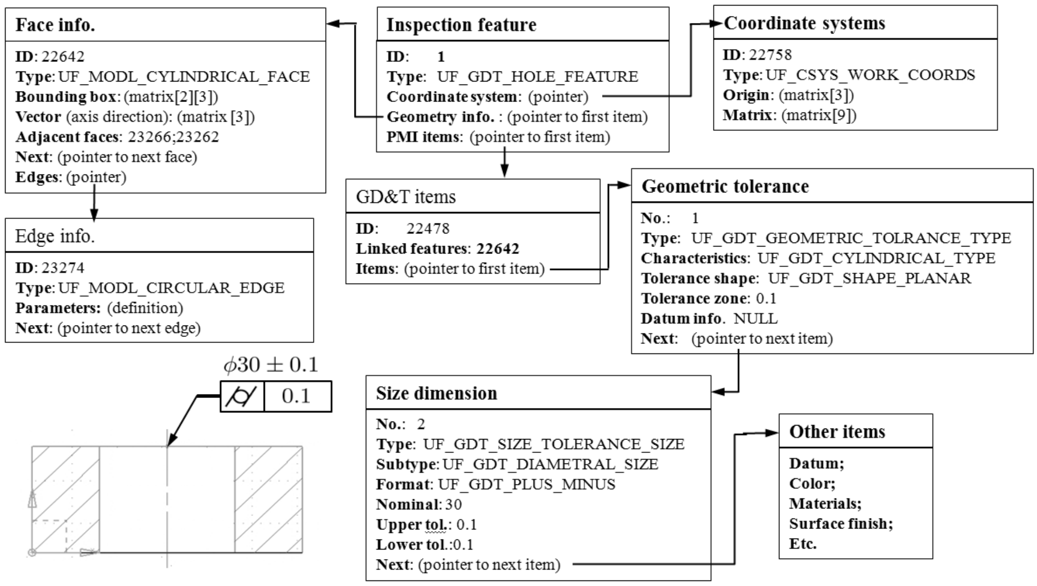


Fig. 2. The inspection feature and its associated specifications

2 Inspection feature construction

The first step of inspection planning is inspection feature construction. Inspection feature is a representation to interpret the design specifications for inspection purpose. An inspection feature is expressed as a geometric feature associated with the corresponding PMI (Product and Manufacturing Information) data [19]. PMI conveys non-geometric attributes necessary in product development, including the information such as GD&T (Geometrical Dimensioning and Tolerancing), surface finish, material, etc.

A complete CAD model usually contains not only geometric information but also PMI data. It provides a natural way for inspection feature construction. Most existing inspection systems interpret the CAD information in terms of the standard file formats, such as STEP, IGES, etc. One shortage is that only the geometric information is recorded and PMI data is not included. This makes that most existing systems can only use geometric information [1], or need extra tedious work to establish the link between tolerance information and the relevant geometric data [16,26].

This paper solves the problem by constructing inspection features directly from native CAD files (Unigraphics NX). It allows that both geometric and PMI data can be extracted and associated automatically. The geometric features which are specified by GD&T items are firstly identified. The relevant PMI items are then extracted in order to construct the complete inspection feature. An inspection feature for a hole is given in fig. 2.

3 Sensor selection

A laser line scanner (fig. 9 (b)) and a touch trigger probe (fig. 9 (c)) have complementary capabilities and limitations [16,17]. In order to achieve the advantages of both sensors, the sensor selection should be considered carefully. Many factors could influence sensor selection: the characteristics of the available sensors, the part to be measured itself, the measuring environment, etc. The proposed approach addresses the factors which may be specified in CAD mode, including:

(1) GD&T specifications.
The selected sensor should ensure the reliability of the measured point data, that means the sensor uncertainty should satisfy the requirement of the tolerance being measured. A commonly used ratio of sensor uncertainty and feature tolerance are 1:5 or 1:10. For example, in order to maintain a 1:5 ratio, the selected sensor must be five times more accurate than the tolerance being inspected. Considering that laser scanning is much faster than touch trigger probing, if the laser scanner fulfils the uncertainty requirement, it will be preferred for saving inspection time.

(2) Geometric attributes.
The geometric attributes, involving geometric dimensionality (2D shape like circle, line, etc. or 3D shape such as surface, etc.), geometric type (e.g.: hole, shaft, etc.), shape type (e.g. cylinder, plane, etc.), geometric size, etc., are important factors for sensor selection. For example, it is more convenient to measure a deep hole using tactile measurement than using laser scanning, it is logical to choose the tough trigger probe for such internal features even though the tolerance might not be tight.

(3) Other specified PMI items.
Besides the GD&T specification, other PMI items, such as material, surface finish, color, etc. have influences on sensor selection. It is known that tactile probe is not suitable to measure soft/flexible materials while laser scanner is competent for such tasks. Laser scanner is sensitive to the optical conditions (reflectivity, color, etc.) of the surface being measured. It is still difficult to scan a polished surface without any preparation (spraying it with white powder for example), but tactile probe provides robust solutions for such conditions. These PMI items should be considered carefully for sensor selection.

Fig. 3 gives an example of sensor selection, which proves that the proposed method can provide reasonable results. After sensor selection, the inspection features are clustered into two groups: tactile group and scan group. Corresponding inspection planning modules have been developed for each group respectively.

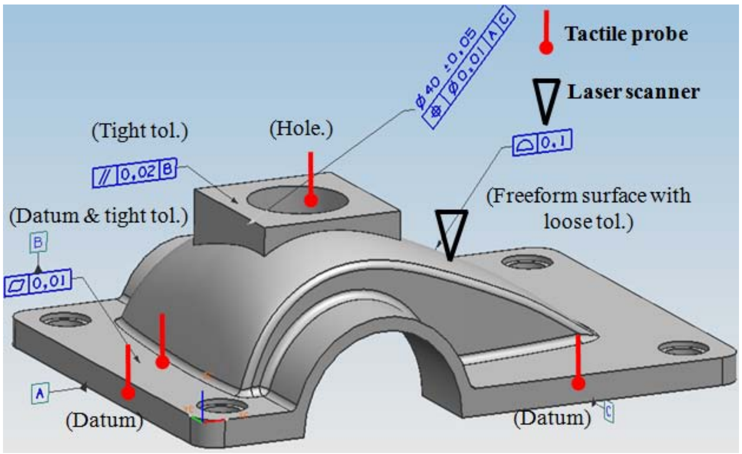


Fig. 3. The sensor selection result for the given workpiece

4 Automated inspection planning for touch trigger measurement

4.1 Sampling strategy

The sampling strategy is to determine the representative points which are to be measured to approximate the real feature. The required number and distribution of the sampling points should be determined based on the geometric characteristics, tolerance specifications and desired confidence level [2,12,23]. Some methods have already been proposed to determine the number of sampling points [6] or their distribution [2,12].

In our approach, the sampling strategy is based on measurement uncertainty simulation. The initial number of sampling points is determined based on the method proposed in [15]. Two different methods are developed to determine the distribution of the sampling points: Hammersley algorithm [12] and uniform distribution. After deleting/modifying the unaccessible points by accessibility analysis [21], the valid points are used for measurement uncertainty simulation [10]. If the estimated measurement uncertainty is too high to meet the required confidence level, a new set of sampling points with larger number is generated and the measurement uncertainty is simulated till the confidence level is met.

4.2 Automated collision-free path generation

Potential collisions should be detected and avoided when moving the probe from one position to the next. Most reported methods for collision avoidance follow interactive ways [5], which are usually inefficient. This paper proposes a method to generate collision-free paths automatically.

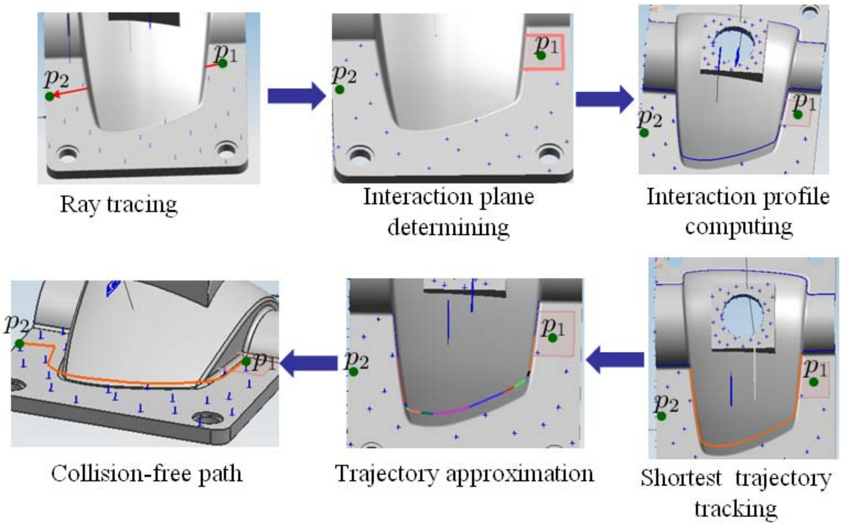


Fig. 4. Automated collision-free path generation

Assuming two points $\mathbf{p_i}$ and $\mathbf{p_j}$ need to be connected, the path between them is planned based on the following procedures (see fig. 4):

(1) **Half-ray tracing.** A half-tray (denoted as $\mathbf{l_{ij}}$) is traced from $\mathbf{p_i}$ to $\mathbf{p_j}$ to check whether obstacles (denoted as $\mathbf{O_c}$) exist between $\mathbf{p_i}$ and $\mathbf{p_j}$. If there is no collision, the line path is generated by connecting $\mathbf{p_i}$ and $\mathbf{p_j}$ directly. Otherwise, the routine goes to step (2).

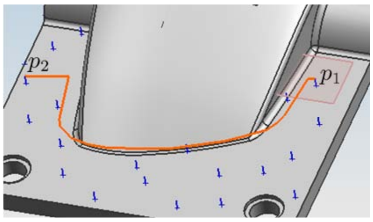
(2) **Path plane setting.** A path plane is a plane on which a collision-free path between $\mathbf{p_i}$ and $\mathbf{p_j}$ is laid. Any plane passing through $\mathbf{l_{ij}}$ can be set as path plane. Fig. 4(2) gives an example. Once the path plane is determined, denoted as $\mathbf{P_p}$, the intersection profile between $\mathbf{P_p}$ and $\mathbf{O_c}$ is computed to guide the collision-free path generation.

(3) **Valid trace basis determining.** The convex hull of the intersection profile is computed The feasible shorter path from $\mathbf{p_i}$ to $\mathbf{p_j}$ along the convex hull is searched and selected. The line segments on the selected convex hull ($\mathcal{S}_{ij}$) provide the trace basis for path generation.

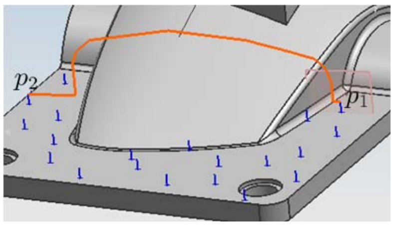
(4) **Collision-free path generation.** Based on $\mathcal{S}_{ij}$, the collision-free path can be easily generated by offsetting $\mathcal{S}_{ij}$ with a safe distance. Obviously, the generated paths should be different on different path planes. Fig. 5 shows an example of the path generation on two perpendicular path planes. It is reasonable to select the path with the shortest length.

5 Laser scan planning

Three issues should be fixed for laser scan planning: view angle calculation; scanner elevation determination and scan path generation. As a preliminary step, the feature surface is sampled by a set of dense points based on which



(a)



(b)

Fig. 5. The collision-free path on different intersection planes: (a) on the retract plane; (b) on the plane perpendicular to the retract plane

the laser scan path is generated.

5.1 View angle calculation

Because of occlusion and limitation of a specific view angle, it usually requires several view angles to capture full information of a feature. For a given scan feature, the occlusion region is first detected and separated from the rest of the feature. The occlusion region will be measured in a tactile way. For the region which can be possibly scanned (denoted as $\mathcal{R}$). the view angle planning method is based on an iterative process over the following 6 basic steps:

(1) **Initialization:** The point set that is not allocated to a view angle is denoted as $\mathcal{R}_\mathbf{u}$, it is initialized as $\mathcal{R}$:

$$\mathcal{R}_\mathbf{u} = \mathcal{R} \tag{1}$$

(2) **View angle seed creation:** A view angle seed is created by selecting the normal vector of a random point in $\mathcal{R}_\mathbf{u}$. The selected point is denoted as $\mathbf{p}_j$ and its normal is denoted as $\vec{n}(\mathbf{p}_j)$:

$$\vec{v}_{seed} = \vec{n}(\mathbf{p}_j) \quad (\mathbf{p}_j \in \mathcal{R}_\mathbf{u}) \tag{2}$$

The direction of the CCD camera optical axis is determined based on triangulation principle, denoted as $\vec{v}_r$ (see fig. 7).

(3) **Covering region calculation:** The covering region corresponding to $\vec{v}_{seed}$ is evaluated. A point can be covered by $\vec{v}_{seed}$ only when it can be accessed by both the laser projecting line (line along $\vec{v}_{seed}$) and the CCD optical axis line ($\vec{v}_r$), and meanwhile the following constraint is satisfied:

$$\mathcal{R}_\mathbf{c}(\vec{v}_{seed}) = \{\mathbf{p}|\ \beta(\vec{n}(\mathbf{p}), \vec{v}_{seed},) < \theta_s, \mathbf{p} \in \mathcal{R}_\mathbf{u}\} \tag{3}$$

Where, $\beta(\vec{n}(\mathbf{p}), \vec{v}_{seed})$ is the included angle between $\vec{n}(\mathbf{p})$ and $\vec{v}_{seed}$. θ_s is the specified maximum reflective angle. θ_s of our implemented laser scanner (Metris LC60Dx) is specified as 75^o.

(4) **Covering region checking:** Once the covering region $\mathcal{R}_c(\vec{v}_{seed})$ is calculated, a new view angle is computed as the mean normal of $\mathcal{R}_{\mathbf{c}}(\vec{v}_{seed})$:

$$\vec{v}_N = \frac{\sum\limits_{\mathbf{p_j} \in \mathcal{R}_{\mathbf{c}}(\vec{v}_{seed})} \vec{n}(\mathbf{p_j})}{||\sum\limits_{\mathbf{p_j} \in \mathcal{R}_{\mathbf{c}}(\vec{v}_{seed})} \vec{n}(\mathbf{p_j})||} \tag{4}$$

The covering region corresponding to $\vec{v}_N$ is then calculated using the method proposed in step (3), denoted as $\mathcal{R}_{\mathbf{c}}(\vec{v}_N)$. The sizes of $\mathcal{R}_{\mathbf{c}}(\vec{v}_{seed})$ and $\mathcal{R}_{\mathbf{c}}(\vec{v}_N)$ are then compared. If $\mathcal{R}_{\mathbf{c}}(\vec{v}_N) > \mathcal{R}_{\mathbf{c}}(\vec{v}_{seed})$, $\vec{v}_{seed}$ is updated as $\vec{v}_N$ ($\vec{v}_{seed} = \vec{v}_N$) and the process goes back to step (3); otherwise the process goes to step (5).

(5) **Updating:** $\vec{v}_{seed}$ and its corresponding covering region $\mathcal{R}_{\mathbf{c}}(\vec{v}_{seed})$ are outputted and the uncovered region $\mathcal{R}_{\mathbf{u}}$ is updated as:

$$\mathcal{R}_{\mathbf{u}} = \mathcal{R}_{\mathbf{u}} - \mathcal{R}_c(\vec{v}_{seed}) \tag{5}$$

(6) **Termination:** The process goes back to step (2) for new view angle calculation. It stops when the condition $\mathcal{R}_{\mathbf{u}} = \varnothing$ is satisfied.

5.2 Scanner elevation determination

Given a view angle $\vec{v}_p$, the limited field of view (FOV) on depth (see fig. 7) usually requires to position the laser scanner at several elevations in order to capture points on its corresponding covering region $\mathcal{R}_{\mathbf{c}}(\vec{v}_p)$. This section aims at determining the positions of these elevations of the laser scanner for a given $\mathcal{R}_{\mathbf{c}}(\vec{v}_p)$.

The basic idea of the proposed method is described as: a region growing mechanism is used to cluster $\mathcal{R}_{\mathbf{c}}(\vec{v}_p)$ into several groups; the points in the same group can be scanned by the laser scanner within the same elevation. The elevation of the laser scanner for each group is computed finally. The algorithm are presented below, where, $\mathcal{G}_{\mathbf{u}}$ denotes the set of points which hasn't been clustered in $\mathcal{R}_{\mathbf{c}}(\vec{v}_p)$ yet.

(1) **Initialization:** Initially, $\mathcal{G}_{\mathbf{u}}$ is assigned as $\mathcal{R}_{\mathbf{c}}(\vec{v}_p)$:

$$\mathcal{G}_{\mathbf{u}} = \mathcal{R}_{\mathbf{c}}(\vec{v}_p) \tag{6}$$

(2) **New group seed creation:** $\mathcal{G}_{\mathbf{u}}$ is projected along the direction $\vec{v}_p$ and the top extreme point is calculated as the seed of a new group $\mathcal{G}_{\mathbf{i}}$:

$$\mathbf{p_{seed}} = \{\mathbf{p_r} | \mathbf{p_r} \cdot \vec{v}_p = max\{\mathbf{p_i} \cdot \vec{v}_p\}, \mathbf{p_i} \in \mathcal{G}_{\mathbf{u}}\} \tag{7}$$

(3) **Group growing:**

The group $\mathcal{G}_\mathbf{i}$ grows by merging the points which can be scanned within the same elevation as $\mathbf{p_{seed}}$. When a point in $\mathcal{G}_\mathbf{u}$ (denoted as $\mathbf{p_k}$) is encountered, the projection distance between $\mathbf{p_k}$ and $\mathbf{p_{seed}}$ along $\vec{v}_p$ is computed:

$$\ell = |(\mathbf{p_k} - \mathbf{p_{seed}}) \cdot \vec{v}_p| \tag{8}$$

If F_h is the height parameter of FOV (see fig. 6(b)), the point p_k is merged into $\mathcal{G}_\mathbf{i}$ when $\ell \leq F_h$:

$$\mathcal{G}_\mathbf{i} = \mathcal{G}_\mathbf{i} + \mathbf{p_k} \tag{9}$$

The $\mathcal{G}_\mathbf{u}$ is then updated by removing $\mathbf{p_k}$:

$$\mathcal{G}_\mathbf{u} = \mathcal{G}_\mathbf{u} - p_k \tag{10}$$

If $\ell > F_h$, the group growing process moves to the next point and terminates when all the points in $\mathcal{G}_\mathbf{u}$ are checked. The corresponding elevation to $\mathcal{G}_\mathbf{u}$ is denoted as E_i.

(4) **Determining the position of** E_i: In order to determine the spatial position of E_i (P in fig. 6 (b)), the bounding box of $\mathcal{G}_\mathbf{i}$ is first computed. Let $\mathbf{B}_{max}$ and $\mathbf{B}_{min}$ represent the two extreme points of the bounding box along $\vec{v}_p$. The spatial position of E_i (see fig. 6(b)) is determined as:

$$\mathbf{C}_{\mathbf{G_i}} = \frac{1}{2}(\mathbf{B}_{max} - \mathbf{B}_{min}) \tag{11}$$

$$\mathbf{H} = D + d \tag{12}$$

The position of the laser scanner for each point in $\mathcal{G}_\mathbf{i}$ can then be determined as:

$$\mathbf{P}_{\mathbf{E_i}} = [(\mathbf{C}_{\mathbf{G_i}} - p_k) \cdot \vec{v}_p + H] \cdot \vec{v}_p \tag{13}$$

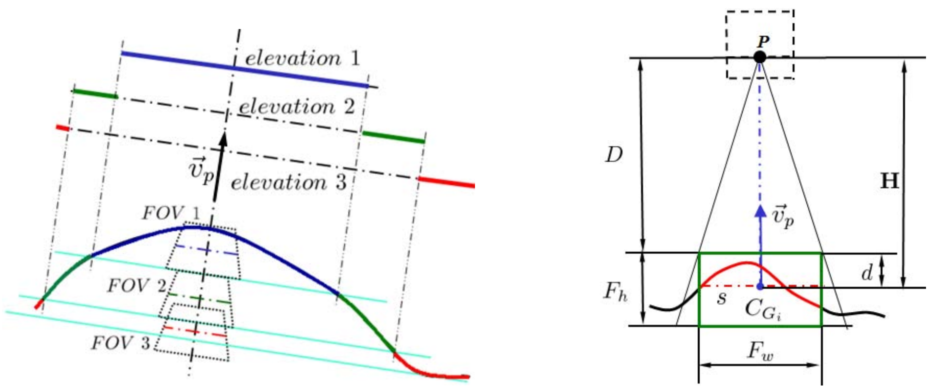
Where, $\mathbf{C}_{\mathbf{G_i}}$ is the middle point of $\mathcal{G}_\mathbf{i}$. D is the stand-off distance of the selected laser scanner. $d = \frac{1}{2}F_h$ is the distance from $\mathbf{C}_{\mathbf{G_i}}$ to the upper limit line of the FOV. $\mathbf{P}_{\mathbf{E_i}}$ is the relative position of E_i to the point p_k in $\mathcal{G}_\mathbf{i}$.

(5) **Termination:** The iterative process terminates when $\mathcal{G}_\mathbf{u} = \varnothing$.

An example is given in fig. 6 (a). For the given feature, three elevations of the laser scanner are generated to cover the whole surface.

5.3 Scan path generation

This section addresses the method to generate the scan path for each view angle and its corresponding covering region. The scan paths include two parts:



(a) (b)

Fig. 6. The position determination of the moving plane of the laser scanner

one is the scan lines followed by the laser scanner for point exploration; the other one is the connection lines, which are used to guide the laser scanner moving form one scan line to another. Three issues are considered in the scan path planning: (1) determination of moving directions; (2) generation of scan lines; (3) generation of connection lines.

(1) Determination of moving directions ($\vec{v}_M$)
$\vec{v}_M$ (see fig. 7) is the direction along which the scanner moves to capture points. Once the view angle is determined, the direction of the laser stripe ($\vec{v}_s$) is fixed. The covered region width ($\tilde{s}$) of each scan followed $\vec{v}_M$ is determined by:

$$\tilde{s} = s \cdot sin\theta \tag{14}$$

Where, $s = F_w$ is the laser stripe length, F_w is the width of the laser scanner's FOV (Field of View). θ is the included angle between $\vec{v}_s$ and $\vec{v}_M$.

The optimal moving direction is determined to minimize the total length of the scan lines for a given covering region. Accordingly, given a series of θ within $(0, 180^o)$, the total length of scan lines is computed for each of them. θ with the minimal total scan length is chosen to generate the moving direction.

(2) Generation of scan lines
For the covering region associated to a given view angle, the scan lines are generated along the moving direction $\vec{v}_M$. There are three parameters need to be determined in order to generate the scan lines for each covering region: the number of scan lines, the starting and ending points of each scan line.

Given the covering region $\mathcal{R}_{\mathbf{c}}(\vec{v}_p)$ associated to $\vec{v}_p$, the bounding box of $\mathcal{R}_{\mathbf{c}}(\vec{v}_p)$ is firstly projected to a plane with normal direction as $\vec{v}_p$ (e.g. the plane P_{prjt} in fig. 8). "The global scan lines" are then computed in that plane. The direction of each global scan line is along $\vec{v}_M$. The number of

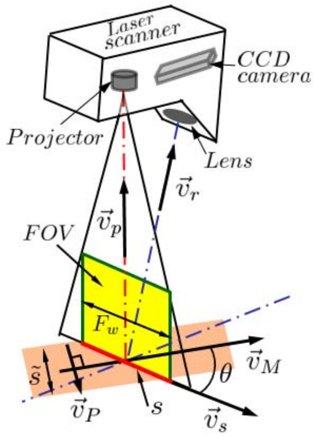


Fig. 7. The moving direction of the laser scanner

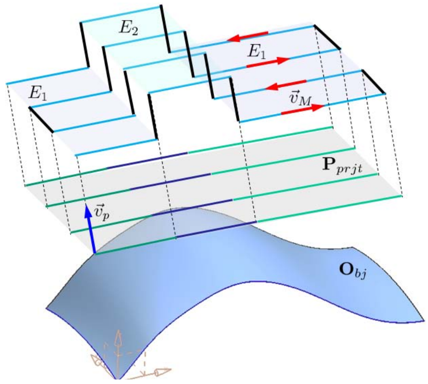


Fig. 8. The connection lines' generation

the global scan lines can be calculated as:

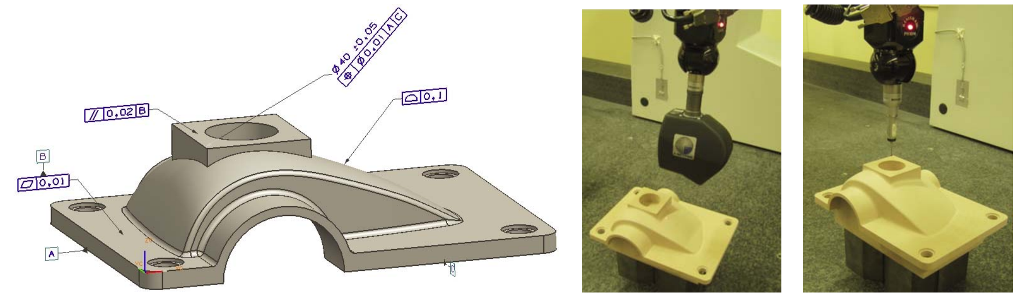
$$N = \lceil \frac{L_P}{(1-\delta) \cdot \tilde{s}} \rceil \tag{15}$$

Where, L_P is the length of bounding box projected along $\vec{v}_P$, $\vec{v}_P = \vec{v}_M \times \vec{v}_p$, shown in fig. 8, δ is the overlap percentage between two neighboring scans. $\lceil \star \rceil$ denotes the nearest integer that is larger than $\star$.

These N global scan lines are constructed regardless the elevation information. However, the final scan lines should be generated on each elevation. For this purpose, the global scan lines are projected on each elevation (e.g. E_1 and E_2 in fig. 8). The starting and ending points of the scan lines on corresponding elevation are computed based on its convex hull.

(3) Generation of connection lines

The connection lines (the black lines in fig. 8) are generated to connect the separated scan lines so as to move the laser scanner from one scan line to the next one during the scanning. The connection lines are generated based on the following rules:



(a) (b) (c)

Fig. 9. Experiment setup of the studied case: (a) CAD model of the workpiece; (b) setup for laser scanning; (c) setup for tactile probing

- The scan lines should be connected if their projections on P_{prjt} follow the same line. They should be connected in order along the related moving direction. The connected scan lines are viewed as scan profile.
- The two scan lines should be connected if one scan lines is the end of its own scan profile and the other is the starting of the neighbor scan profile next to the first one.

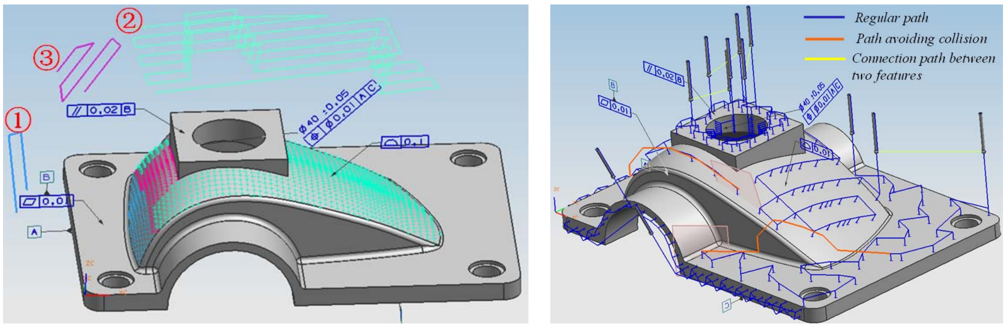
6 Applications

6.1 Application setup

The modules for automated CMM inspection combining laser scanning and tactile probing have beeen developed in Visual C++ 2005 and embedded in Unigraphics NX 5.0 with UG/Open API tools.

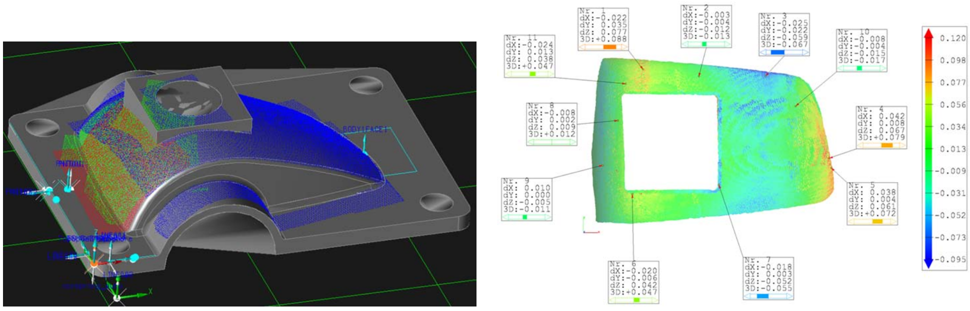
An application is implemented in order to verify the proposed methods. The CAD model of the tested workpiece (fig. 9 (a)) is designed in Unigraphics. The actual workpiece is made of Ureol material(fig. 9). The applied CMM measurement system combined a Metris LS50 laser line scanner (fig. 9 (b)) and a Renishaw TP20 touch trigger probe (fig. 9 (c)).

The proposed methods are tested for two cases. In the first case, the freeform feature is destimated for laser scanning by associating a loose surface profile tolerance. In the other case, tactile probing is selected due to a tighter surface profile tolerance. In both cases, other features associated with geometrical tolerances are selected as "tactile probing features".



(a) (b)

Fig. 10. Inspection paths for the studied case (a) laser scan paths; (b) tactile paths



(a) (b)

Fig. 11. The scanning result based on the planned scan strategy (a) the initial scan point cloud; (b) the comparison with the CAD model

6.2 Results of Laser scan planning

In the first case, the freeform feature is determined as a "laser scan feature" by the sensor selection method. Fig. 10 (a) demonstrates the planning result, in which, three view angles are generated automatically, specified as (1):($A:67.5^o$,B:0.0^o); (2):(A:7.5^o,B:-82.5^o); (3):(A:30.0^o,B:-22.5^o). The points and lines in different colors represent the corresponding covering regions and scan paths. The acquired initial point data when executing the planned path is given in fig. 11 (a). Fig. 11 (b) shows the comparison with the CAD model; the detailed comparison is given in tab. 1 (collum "SURF-2").

6.3 Results of tactile probing planning

In the second case, the freeform feature and other features associated with tolerances are planned for tactile probing. Two probe orientations are planned for all the six tactile probing features, specified as (1) (A:0.0^o,B:0.0^o); (2) (A:30.0^o,B:90.0^o). The planning result is illustrated in fig. 10 (b), where the highlighted polylines is generated for collision-avoidance. The actual probing

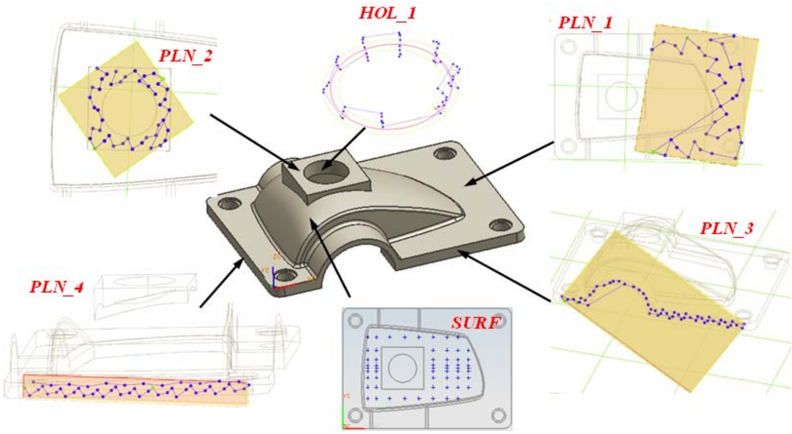


Fig. 12. The actual measured points on each feature

path and the acquired point data for each feature are given in fig. 12. The detailed CAD comparison is given in tab.1.

Tab. 1: The measurement results based on the generated inspection planning.

Feature	PLN_1	PLN_2	PLN_3	PLN_4	HOL_1	SURF-1	SURF-2
Points	37	44	53	49	61	58	33712
Results	Flat.	Flat.	Flat.	Flat.	Cylin.	Dev.	Dev.
(mm)	0.1905	0.0191	0.1132	0.0521	0.0643	max.:0.0569	max.:0.2892
						min.:-0.0351	min.:-0.091
						(σ=0.0228)	(σ=0.0328)

7 Conclusion

This paper proposes a methodology for automated hybrid inspection planning for CMM-based measurements combining a laser line scanner and a touch trigger probe. The geometric features and their relevant PMI items are extracted from CAD model for inspection feature specification. A knowledge-based method is developed to select the suited sensor for each inspection feature. The measurement strategies are automatically planned by the developed inspection planning modules.

The measurement uncertainty is considered by the sampling strategy for tactile inspection planning. A profile-based collision-avoidance method is proposed for probing path generation. For laser scanning, an iterative method is proposed in order to compute the necessary view angles for a given feature. The required positions of the laser scanner are specified as elevations, based on which, the scan path is generated automatically. The experiments demonstrate the proposed methods can provide reasonable solutions for CMM inspection combing laser scanning and tactile probing.

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