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REVIEW ARTICLE

Touch Probe Measurement in Dimensional Metrology: A Review

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ABSTRACT – Coordinate measuring machines (CMMs) are the standard displacement systems used for measurements in dimensional metrology. Since measurement with a touch probe mounted on a CMM provides high accuracy, repeatability, and reliability, it has been widely used for mechanical part inspection in manufacturing. The inspection process requires the use of several sensor orientations and optimal positioning of the part in order to measure all features. Recently, the field of probing path planning has become a huge and active research field. In this paper, various techniques aimed at generating the probe paths for part inspection are reviewed. Multiple issues related to the positioning of the part to maximise accessibility, analysis of probe accessibility to measure all inspection features, optimisation of the measurement sequence, distribution of measurement points, and collision avoidance are mentioned. The common research approaches and potential algorithms in this field are also discussed in this paper.

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INTRODUCTION

Coordinate Measuring Machines (CMMs) are high-performance measuring devices in the industry for the verification of part conformity [1, 2, 3]. Generally, dimensional and geometric tolerances are verified using a touch probe mounted on CMM. In the context of industry 4.0 or the Fourth Industrial Revolution (4IR), inspection planning plays an important role in the inspection procedures. A well-planned inspection will provide the required information in a short period with a high degree of accuracy [4]. Recently, computer-aided inspection planning (CAIP) has appeared as one of the main research topics in computer-aided inspection (CAI) [5]. The aim of CAIP is to find out what features of the inspection part are to be inspected, with which sensors, and in what sequence. The CMMs equipped with a touch probe are the most common CAIP systems. In general, the CAIP process uses the geometrical and dimensional specifications from a computer-aided design (CAD) model as its inputs.

Probe path planning is usually based on the characteristics of the sensor and the surfaces to be measured (specifications, dimensions, and complexity of the surface) to determine the number of measurement points and their distributions [3, 6]. The following aspects have been addressed to deal with the probe paths planning: probe accessibility analysis, the definition of measurement points, the study of collision problems, and path optimisation. The inspection plan can be generated as a high-level inspection plan (HLIP) and a low-level inspection plan (LLIP) [7]. In the HLIP, the optimal part setups and the minimum number of accessible probe orientations are determined to measure the whole inspection features. Whereas in the LLIP, optimum locations of the measuring points are determined, and then the probe path is generated to minimise the total inspection time. Cho et al. [5, 8] propose the sequencing of inspection features in the HLIP and the collision evidence in the LLIP.

This paper is organised as follows; in section 2, works concerning the extraction of inspection data that are required for inspection planning are reviewed. Section 3 concentrates on the issues of high-level inspection planning, where the part setup and probe orientation analyses are discussed. The low-level inspection planning is detailed in section 4 to describe sampling strategies, probe path planning, and collision avoidance problems. The paper ends with some conclusions and suggestions for future research in Section 5.

INSPECTION DATA RECOGNITION

A CAI system requires information about the part to be inspected, which is contained in the CAD model. This information is represented using several methods for feature representation, such as boundary representation (BREP), wireframe representation, or constructive solid geometry (CGS). The feature recognition step is performed to transfer the information obtained from the CAD system to the CAI [9]. The CAIP then generates the inspection process plan based on the feature concept and the knowledge of the expert system [5]. In the literature, most authors have used the concept of the feature as a support for generating inspection plans. A feature is a generic form with a set of attributes and knowledge associated with it, used in the reasoning to describe the product [10]. Moreover, it can be defined as a characteristic of the part, which has a semantic meaning in relation to the application [11]. Thus, the feature term has several meanings depending on the context and the field of application. It can be an inspection feature, design feature,

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manufacturing feature, assembly feature, material feature, form feature, or robotic feature [10, 12]. Generally, an inspection process can be based on one of the following three concepts: measuring features [13, 14, 15], manufacturing features (form, machining) [5, 9, 16, 17, 18, 19, 20], and inspection features [12, 21, 22, 23].

The measurement feature is the elementary geometrical shape that can be measured as a plane, a cylinder, or a sphere. The manufacturing feature is defined as the geometrical shape resulting from manufacturing operations such as a pocket, island, and slot. Unlike the measurement feature and manufacturing feature are independent of the inspection information (e.g. tolerance interval and specification type), the inspection feature combines both the geometrical shape and the tolerance information of the feature. In the example shown in Figure 1(a) [24], the inspection feature IF1 is composed of two measurement features (plans) and information related to the symmetry specification. If the measurement feature concept was used, the feature considered as a pocket.

Cho et al. [5] develop an inspection approach using the notion of manufacturing feature, which is defined as the result of a manufacturing operation such as pocket and slot, shown in Figure 1(b). The measuring feature defined by the elementary surfaces (plane, sphere, and cylinder) is shown in Figure 1(c) and is used by Yuen et al. [14] to define an inspection plan. In metrology, the notion of a feature must be combined with information on the associated specifications. Zhao [25] has developed an on-machine inspection approach (inspection during a machining process). In their work, the inspection feature is extracted from manufacturing features contained in the *STEP NC* file of the part by considering the surfaces associated with specifications that need to be measured. Zhao et al. [26] use the concept of surfaces with specifications to define the inspection path.

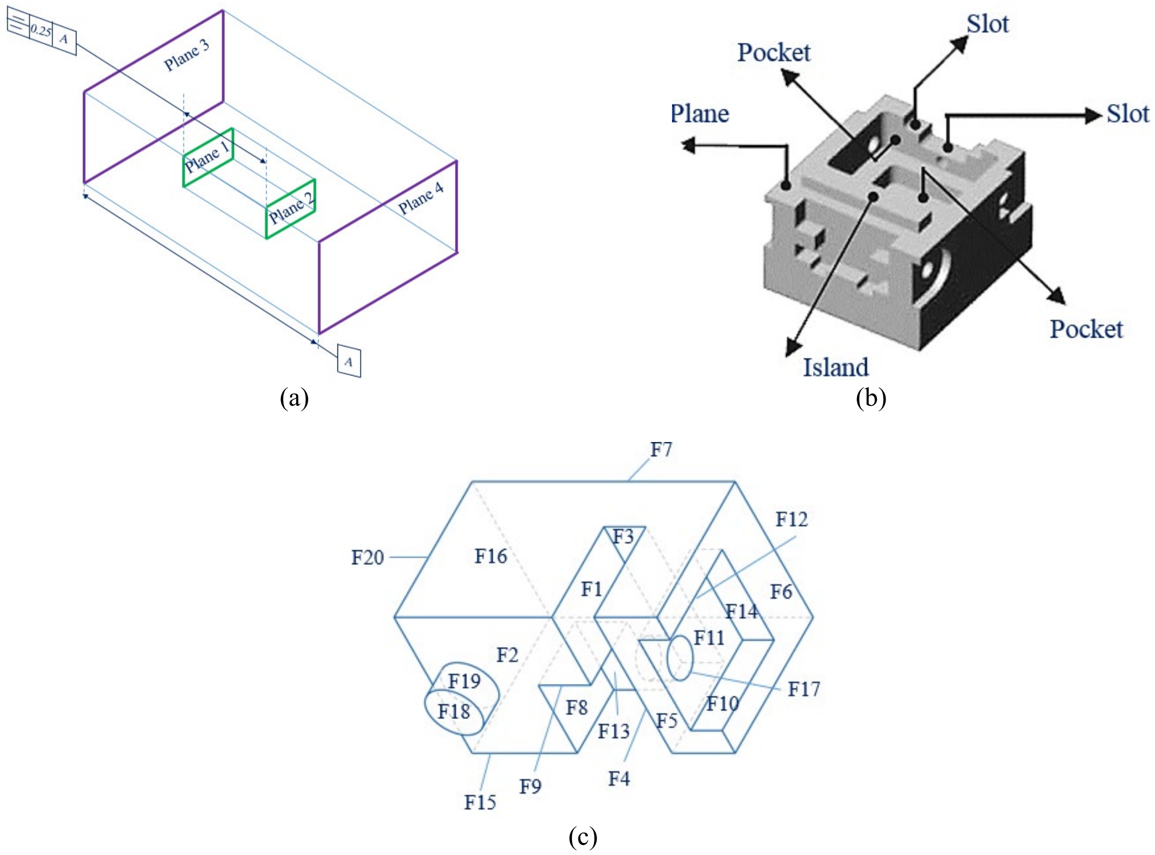

Figure 1. (a) Inspection feature, measuring feature and manufacturing feature adapted from [24], (b) Manufacturing features adapted from [5] and (c) Measuring feature adapted from [14].

In [27], Wong et al. propose to identify and recognise inspection features composed of faces as well as the constraints associated with the inspection features. The inspection plan of the part is a measurement sequence of the inspection features. Since a face can belong to more than one inspection feature, this leads to certain faces of the part being measured several times during each inspection feature measurement. In this context, a set of knowledge-based filters has been developed to address the problem of increasing the number of faces to be measured. In another study**,** Wong et al. [28] divide inspection features into four classes comprising external dimensional inspection features, internal dimensional inspection features, offset dimensional inspection features, and curved surface features. Duan et al. [29] decompose inspection features as follows; tolerance features (dimensional, form, orientation, location, and runout tolerance), geometric features formed by surface characteristics, attribute information, and inspection process information.

In the literature, several techniques of feature recognition were proposed depending on the feature definition. Prabhakar et al. [30] propose the following automatic feature-recognition algorithms categorised as the machining region-based, rule-based, graph-based, constructive solid geometry-based, and application-based algorithms. Another classification of feature recognition methods proposed by Al-Ahmari et al. [12] is the syntactic pattern recognition approach, logic-based approach, graph-based approach, expert system approach, volume decomposition and composition approach, 3D feature recognition from a 2D feature approach. A summary of feature recognition methods is presented in Table 1.

Due to the significant development of new file exchange formats, BREP files are now used to extract inspection information. The most convenient format for automatic inspection planning is the STEP file supporting the AP242 application protocol that contains, in addition to geometrical information, the PMI (Product and manufacturing information) such as dimensional and geometrical tolerance, surface properties, and associated verification principles and requirements, etc. The syntax pattern recognition approach is the most widely used method for performing more automatic recognition using a standard exchange file (e.g. STEP file). This approach has been exploited by NIST (National Institute of Standard and Technology) to develop the STEP File Analyser and Viewer. This software allows automatic recognition of all the features defining the part and its attributes [22].

Table 1. Summary of feature recognition methods.

Feature recognition method	Principle	Advantages	Disadvantages
Syntactic pattern recognition approach	A Parser is used to analyse the syntax written in the description language of the part	Automatic recognition	Require knowledge of the syntax used in the description file Complexity increases when applying to non-prismatic parts
Logic-based approach	Features are recognised one by one, according to a set of heuristic rules describing the features	More suitable to recognise manufacturing features using B-REP and CSG modelling	Require writing rules for every specific feature The ambiguous and non-unique representation of the rules makes the method inflexible and cumbersome
Graph-based approach	Base on matching the feature graph to the appropriate subgraph	Applied to several domains (not only manufacturing features) Ability to recognise isolated features	Require significant processing and computations to build the subgraphs of the feature of the main graph
Expert system approach	Based on the transformation of knowledge and experience of the expert in rule set	A more realistic approach to feature recognition than one based on graphs and logic	Require production knowledge and an inference engine
Volume decomposition and composition approach	Based on the decomposition of the part volume into convex cells and the combination of these cells into machining features	Introduced mainly for machining features.	Computationally complex Unable to generate non-convex machining features
3D feature recognition from a 2D feature	2D features are first extracted, rule-based, and graph-based approaches are then used to get the 3D feature	Adapted to prismatic pieces	Recognition of a limited number of features Limited to prismatic features

HIGH-LEVEL INSPECTION PLANNING

After decomposing the part into inspection features, to perform the inspection process of the part, the geometry of these features is analysed to determine the part positioning and accessible touch probe orientations. This issue is generally dealt with using the probe approach directions (PADs). A PAD is the accessible direction of the probe to measure a given inspection feature [5, 31]. By analysing all PADs of the inspection features, part setups and probe orientation can be determined [24, 32].

Part Setups

The part setup is defined as a suitable positioning of the part in the measurement volume. Some works integrate the analysis of part setup into accessibility analysis. Part setup based on part-oriented analyses is first conducted, and then the probe configuration based on feature-oriented analyses is performed as in Figure 2. In Figure 2(a), the probe orientations and part orientation in the CMM are demonstrated. With one position of the inspection part, some features can be directly measured. For example, in Figure 2(b), cylinders can be measured by two probe orientations in a one-part position. However, the accessibility of two cylinders in Figure 2(c) is not allowed, and two-part positions are then required.

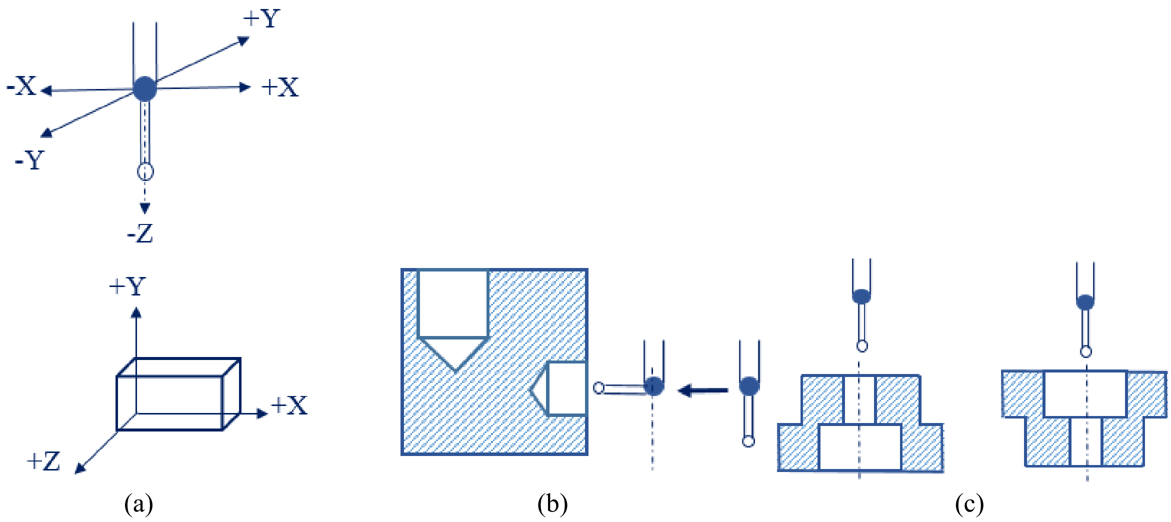

Figure 2. Probe orientation change and setup change; (a): probe orientation on the CMM volume, (b): probe reorientation, (c) part setup change adapted from [3].

One of the important issues in probe path planning for CMM is to minimise the number of part setups and the number of probe configurations, which leads to reducing measurement time and human intervention in the measurement process. In work proposed by Stojadinovic et al. [31], depending on the number of inspection features and their characteristics, a general matrix is created and optimised by a genetic algorithm (GA) to determine the optimal setup. Hwang et al. [3] introduced a greedy heuristic procedure to minimise the time of part setup changes set by considering six orientations for a prismatic part. Ziemian et al. [33, 34] addressed accessibility issues and used the geometric projection technique to specify the accessible zones for each inspection feature. The heuristic technique is also employed to define a set of part orientations on the CMM volume. Kweon et al. [35] propose a methodology in which the concept of visibility maps (VMap) and clustering procedures are utilised to provide the minimum number of part setups. A method proposed by Corrigall et al. [36] to determine part orientations and probe configurations is mainly based on the analysis of the probe approach directions (PAD) generated for each surface to be inspected. Kamrani et al. [21] provide a graphical method for part setup based mainly on identifying the part side with a minimum number of inspection features. This face serves as the basic face for the orientation of the part in the machine.

The methods mentioned above are mainly applied for prismatic measurement parts. For a free form surface, the setting of parts with irregular shapes is considered by Lai et al. [37]. A summary of part setup methods proposed in the literature is presented in Table 2.

Probe Orientation Analyses

The probe orientation analysis is known in certain works as a probe accessibility issue. Accessibility analysis is a three-dimensional reasoning task that attempts to determine the directions along which a probe may come into contact with a given portion of the surface [31]. The optical sensor visibility problem is a generalisation of the problem of global probe accessibility since the directions of probe accessibility correspond to the visibility points of a laser sensor [38, 39, 40]. In the literature, several works have used different methods to study accessibility, such as ray-tracing [41], the intersection of spherical crowns [42], local and global projection techniques [33, 34] and [43], visibility maps [35], accessibility cone [44], the mathematical method [45] or transformation of part surfaces into facets (STL) and consideration of inspection points as a set [46].

Alvarez et al. [46] analyse the accessibility of a part represented by its STL file (triangulation) in two phases: a local analysis and a global analysis. The former considers only possible collisions of the probe with the surface itself (analysis of the directions normal to the surface), and the latter considers possible collisions with the whole part (calculation of multiple intersections between the probe and all the normal vectors). Vafaeesefat et al. [47] use the notion of accessibility domains in all points of the surfaces (vertices of facets in an STL file). Once the accessibility of a point is defined, the feasibility of measuring in any probe directions can be checked by Boolean operations. A grouping algorithm is proposed to classify directions according to accessibility domains. Hwang et al. [3] use Hopfield neural networks to minimise the number of probe directions and workpiece positioning. In [5], the problem of accessibility is addressed by defining the probe approach direction for each surface. A series of heuristic rules is developed by analysing the surfaces' information to be inspected, such as the relationship between the possible approach directions of the probe. The sequence of the surfaces to be inspected and the measurement path are determined. Martinez et al. [48] describe a procedure for modelling the knowledge required for selecting the adequate probe orientations during the inspection planning. Kamrani et al. [21] used Probe Approach Direction (PAD) and Approach Direction Depth (ADD) analysis to study accessibility and develop a clustering algorithm. The features having the same PAD can be inspected in a single operation. Probe orientation analysis is considered as the least expensive and inaccurate operation in terms of a time-consuming, manual procedure compared with part setup operation.

Table 2. Summary of part setup methods.

Part setup method	Principle	Advantages	Disadvantages
Hwang et al. [3]	Based on the Chvatal's greedy heuristic	Limit number of part setups Easy to implement	Applied for prismatic measurement parts
Kamrani et al. [21]	Two different approaches: artificial neural network and graphical method	Limit number of part setups Feasibility in real manufacturing applications	Applied for prismatic parts and some of the axisymmetric parts
Stojadinovic et al. [31]	Based on genetic algorithm (GA)	Limit number of part setups GA can be easily adjusted and adapted to various problems	Applied for prismatic measurement parts.
Ziemian et al. [33, 34]	Based on heuristic technique	Limit number of part setups, Generate a list of equally acceptable setups	Applied for prismatic measurement parts
Kweon et al. [35]	Based on visibility maps (VMap) and clustering procedure	Reduce the number of part setups subject to greater uncertainty of measurement	Only applied for prismatic measurement parts
Corrigall et al. [36]	Based on probe approach directions (PADs)	Each surface is ensured to be probed from the approach direction	Consider parts features perfectly aligned with the X, Y, and Z axes of the CMM
Lai et al. [37]	Based on rough positioning and a fine positioning	Applied for free form part	Difficult to obtain the optimal the part coordinate

LOW- LEVEL INSPECTION PLANNING

In the local inspection planning process, each feature is decomposed into its measuring elements, and then the number of measuring points, their location, and the optimal sampling sequence for collision-free measurement are determined.

Sampling Strategies

The definition of measuring points consists of establishing the number of measuring points required and their distributions. In work [49], the number of points is set to 3×2 points for flat surfaces and 6×2 points for cylindrical surfaces. The minimum number of probing points for each type of basic geometry is different from the number used to create the geometry. The measuring time is directly related to the number of measuring points. The more points there are, the longer the measure execution time will be. On the contrary, the measurement uncertainty is quite low when the number of measurement points increases. Therefore, the number of measurement points must be chosen according to the metrological requirement to ensure a better compromise between a minimum time and acceptable measurement uncertainty. The number of measuring points is usually determined from a practice sheet [50]. For example, Zhao [51] uses the British standard [52] to choose a minimum number of measurement points necessary for each entity. Measuring points should be distributed equally over the entity to be measured. The measurement points are placed on the surface to be controlled by means of distribution strategies. Barari et al. [53] show that changing the distribution of the same number of measuring points changes the inspection results in terms of measurement accuracy. Uncertainty of inspection results due to the change in the location of measuring points can be up to 36% of the range of result deviations. The effectiveness of choosing a particular distribution strategy has been recognised as a major component of the measurement uncertainty [54]. Distribution strategies can be divided into two broad categories: standard distribution strategies and adaptive sampling strategies [55, 56, 57]. This classification is based on the complexity of the surface of the part. Each strategy is more adopted with regard to its respective surfaces.

In the standard distribution, a fixed number of measuring points are distributed over the surface. In addition, the complexity of the surface is not taken into account when distributing the measuring points over the entire surface. These methods include distribution techniques such as uniform, random, Hammersley Sequence (SM), Halton-Zaremba Sequence (SHZ), and stratified distribution. They are characterised by their simple implementation. In a random distribution, the points are distributed irregularly (randomly) over the entire measurement surface and generally provide an unrealistic representation of the geometric element. Conversely, in a uniform distribution, the points are distributed homogeneously (arranged at identical intervals) over the entire surface. Stratified distribution is a technique in which the entire surface is divided into subsets (also called Strata). A grid distribution is a kind of stratified distribution method, where the surface is divided into grids. The number of grids is equivalent to the number of measurement points, and each grid provides a randomly selected measurement point. The Hammersley sequence theory was proposed by [58]. This method was used by [59] to distribute measurement points in the case of inspection of prismatic parts. The advantage of these standard methods is their simplicity and short calculation times. In adaptive distribution strategies, additional measurement points are added to an initial distribution to increase the accuracy of the reconstructed substitute geometry. This process is continued until a maximum number of measurement points is reached or until the substitution geometry becomes indifferent to the addition of more measurement points.

In this paper, we distinguish between two types of surfaces, canonical forms and complex shapes. The most suitable strategy for distributing the measuring points for each type of surface is different depending on the associated measurement uncertainty. Woo et al. [60] have studied three distribution methods: uniform, Hammersley sequences, and Halton-Zaremba sequences. They concluded that uniform distribution is not as efficient and effective as other methods. Thus, the uniform distribution method may not allow accurate measurement. The Halton-Zaremba sequence can only be defined in 2D, whereas the Hammersley sequence is more general in its applications. In the work of [61], through the evaluation of the root mean square error (RMSE) between points measured with three distribution strategies and a global deviation model (MDG), researchers have shown that the Hammersley sequence is more efficient in terms of uncertainty than random and uniform distributions. The Hammersley sequence should be preferred over the SHZ sequence and uniform distribution when inspecting canonical components [8]. Hammersley's sampling strategy for a plane surface is based on the calculation of coordinates (s, t) as shown in Eq. (1):

$$s_i = i/N \ , \ t_i = \sum_{j=0}^{k-1} \left(\left[\frac{i}{2^j} \right] Mod2 \right) . 2^{-(j+1)} \tag{1}$$

where $k = \log N$, $Mod2$ is a mathematical operator giving the result of the remainder of the division of the term by two, and N is the number of measured points i = 0, 1, 2, ..., (N-1).

By modifying the 2D Hemmersly sequences, the distribution of the measuring points for the different types of elements can be defined.

With the adaptive distribution strategy, the number of measuring points and their distributions vary according to the complexity and curvature of the measuring surface [57]. This means that complex parts of the surface contain a greater number of points, while simpler regions contain the least number of points[62]. The adaptive distribution strategy is the most appropriate for evaluating the specifications associated with complex shapes. It is a dynamic approach that adapts to the actual geometry and surface profile of the surface [63]. Several adaptive distribution techniques have been proposed in the literature. They start by defining an initial distribution of measurement points and then introducing more points in areas with the maximum errors between the surrogate and nominal models. The difference between these works is in the way the initial distribution is defined, the definition of the substitution geometry from the initial measurement points, the method of adding points in each iteration, and the stopping criteria. Recently, intelligent adaptive sampling methods using kriging models [64] and Gaussian process (GP) regressions [55, 62] have been developed based on the reasonable inference of unknown surfaces. In the probe sampling approach proposed by Zhao et al. [26], the sampling strategy is based on the measurement uncertainty simulation.

Path Optimisation

To improve the efficiency of the inspection process, Bo Li et al. [65] use the concept of adjacency graphs to determine the best sequencing of measurement entities. Measurement points and transition points are shown in red and blue, respectively. The probe moves slowly between the transition point and the measuring point while the movement between the transition points is fast. The sequence of measurement points is optimised in each entity. After completing the measurement of a given entity, the probe moves to the nearest entity. Stojadinovic et al. [66] use the ant colony algorithm to optimise the probe trajectory by defining the best sequence of measurement points that minimises measurement time. The issue of probe path optimisation can be achieved by minimising the length travelled by the probe between the measurement points in the inspection feature.

Mohib et al. [49] have developed a travel salesperson problem (TSP) formulation for the sequencing of inspection tasks. This is accomplished by taking into account the minimisation of measurement time taken by the following tasks: part repositioning, sensor changes, probe orientation changes and probe travel time.

Collision Problem Analysis

Another important aspect during measurement with the contact sensor is the avoidance of collisions between the sensor and the workpiece to be measured on the one hand and between the sensor holder and the workpiece on the other hand [6, 67]. Han et al. [68] provide a spherical model for collision detection as a part of the probe path planning. A sphere is created whose centre is the point on the surface. The radius of the sphere is greater than or equal to the distance between the centre of rotation and the probe ball. The collision avoidance problem is then related to searching for a certain free space in the sphere space to place the probe. A cone containing the collision-free measurement directions is established in Figure 3. Yuewei et al. [69] rely on the concept of local accessibility cones for collision detection calculations. The algorithm is based on the verification of possible collisions between the probe and the surface to be measured in a given displacement. If a path has a collision problem, control points are added, as shown in Figure 4.

Al-Ahmari et al. [12] divide collision problems into two categories: probe collision and probe holder collision. The first category can be solved by inserting new crossing points to avoid collisions, as shown in Figure 5. The probe-holder collision problem can be avoided by using longer styli or by moving the measurement point [8]. In [65], an algorithm based on convex envelopes is used to generate collision avoidance paths (Figure 6).

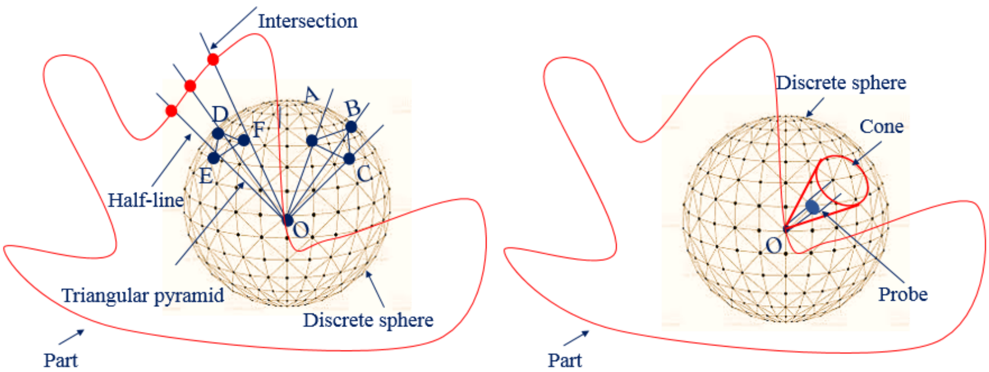

Figure 3. Spherical collision analysis model adapted from [67].

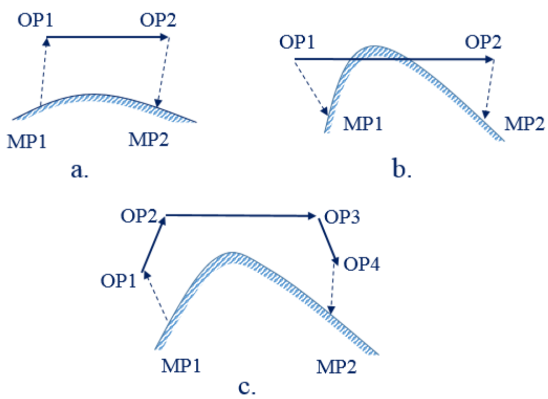

Figure 4. Definition of control points in the case of collisions adapted from [69].

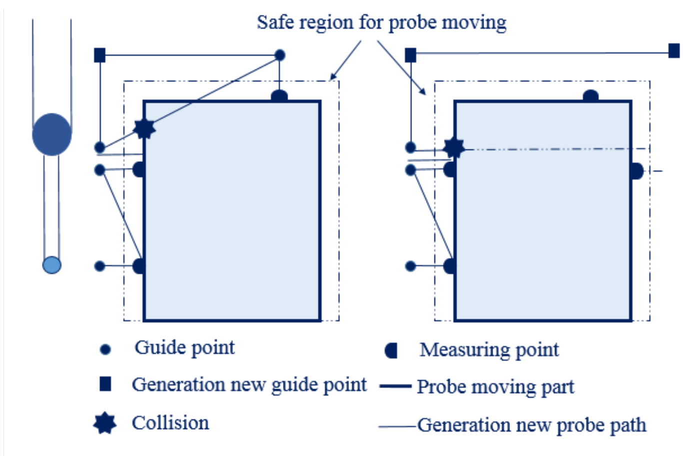

Figure 5. Collision between probe and workpiece adapted from [8].

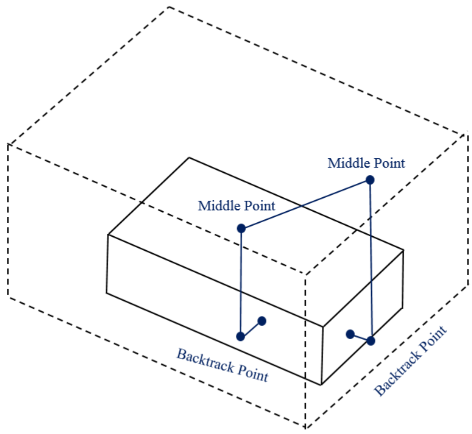

Figure 6. Convex hull to generate paths without collisions adapted from [65].

The collision avoidance problem is essentially a constrained optimisation problem involving geometric constraints and uncertainty constraints. Geometric constraints are related to the practical limits of the stylus length on a given CMM. Whereas uncertainty constraints are related to the measurement uncertainty associated with the length of each stylus. The length of the stylus introduces additional uncertainty in the probe measurements. A longer stylus has a higher measurement uncertainty than a shorter stylus. The analysis of probe and probe holder collisions is further complicated by geometry and uncertainty constraints of optimisation problems. This is an integral aspect of the perspectives considered in this work.

CONCLUSION

This paper reviewed the developed works on computer-aided inspection planning research using a touch probe on CMM. Most of the studies are focused on the automation of the data transfer between the CAD and CAI using different formats of exchange files. The notion of feature is used to perform the inspection planning process. The feature includes both geometrical information and tolerance information. Other work has been investigated on the high-level planning to optimise the accessibility of the probe to measure all features in a short measuring time. This leads to associate each inspection feature with the suitable probe orientation and then establish the optimal sequencing of features to reduce the orientation changes and part repositioning.

For the low-level inspection planning, several works have investigated developing sampling strategies for both prismatic and free form surfaces. The point distribution depends on the geometry of the inspection feature and the tolerance to be inspected. The optimisation of the probe path can reduce the measurement time taking to travel between sample points in inspection features and between the inspection features in the part. The collision checking should be performed between the part and the probe on one hand and between the part and probe holder on the other hand. On the basis of the above analysis, future works can be expected in the following topics:

i. Developing a complete CAIP system including all operations: feature extraction, part setup, probe orientation analysis, accessibility analysis, definition and distribution of measuring points, collisions checking.
ii. Developing a neutral format STEP supporting automated data transfer from the CAD models to the CAI process.
iii. Developing a feedback process of inspection results to the manufacturing process and correcting the manufacturing parameter based on the evaluation of tolerance features.

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