Inspection Path Generation in Haptic Virtual CMM

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ABSTRACT

An inspection path generation methodology for virtual coordinate measuring machines (VCMM) based on haptic technologies is presented in this paper. Introducing a haptic device into CMM inspection path planning leads to the development of the proposed novel CMM off-line inspection path planning environment called haptic virtual CMM (HVCMM). HVCMM is an accurate model of a real CMM, which simulates a CMM's operation and its measurement process in a virtual environment with haptic perception. Due to the force feed back in the operation, the inspection path planning process is more intuitive, efficient, and user-friendly. The inspection path generation procedure is carried out in several steps: first, the measuring points are selected by operators using "point-and-click" method; second, the measuring points are offset according to the surface geometry and the offset points are linked with line segments; third, the linked path is traced by the virtual CMM probe to perform collision detection; fourth, when a collision occurred, an auxiliary point method and a teach pendant method are developed to generate a collision-free path with the aid of haptic constraint plane. The aim of these algorithms is to minimize the computation of collision detection. Examples are given on a HVCMM prototype system to demonstrate the proposed methodology.

Keywords: Haptic modeling; Coordinate measuring machine; Collision-free path planning.

1. INTRODUCTION

In today's advanced manufacturing industry, the amount of products that have complex and aesthetic shape is increasing. In order to ensure high quality products, inspection for shape and function of products is indispensable. For the inspection of dimensions and tolerances, parts are measured by using appropriate equipment.

Coordinate measuring machines (CMMs), as one of the most powerful metrological instruments, are widely used to examine the conformity of the produced parts with the designer's intent in 3D dimensional sizes, positions and forms. In contrast to non-contact type measuring machine, such as laser scanners, contact type measuring devices provide for more accurate data, but its measuring speed is very slow. Due to these characteristics, contact type measuring devices are used for measuring parts consisting of primitive features where massive data are not needed.

As modern manufacturing is characterized by low-volume high-variety production and close tolerance high-quality products, CMMs' measurement methods and programs vary frequently according to the type of parts and features as well as their requirements. Due to the high cost in procuring a CMM machine, it is highly desired to generate the measurement programs of parts off-line based on their CAD data without operating a real CMM. The output of off-line programming is usually in DMIS (Dimensional Measuring Interface Standard) file format.

Generally, planning for CMM inspection can be divided into two levels. Low-level inspection planning involves selecting a set of specific points to be measured in each surface [1], assessing measurement points' accessibility [2-4], clustering and sequencing of measurement points [5], generation of collision-free probe path [6], and the integration of these tasks into a computer-aided inspection planning system [7, 8]. High-level inspection planning seeks to determine how to setup the part on the CMM table, which faces to inspect in each setup, which probes to use, how to orient these probes [9, 10]. A great deal of research has been done in CAD-based automatic inspection planning with different planning methods and algorithms, such as expert system [11], neural network [12, 13], genetic algorithms [14, 15], fuzzy logic [16], intelligent planning environment [17], hierarchical planning system [18], intelligent inspection planning in OOP environment [19], feature-based method [20], knowledge-based method [21] and so on. Medeiros *et al*. proposed a method of off-line programming of CMM using a hand-held stylus [22]. In their method, no CAD model is required. Instead, programming is made by an operator using an actual part and a hand-held stylus equipped with a position-sensing device.

Li and Gu provided a comprehensive literature review of methodologies, techniques and various processes of inspections of parts with free-form surfaces including measurement data acquiring methods, inspection planning, geometric description methods, the free-form surface localization and comparison techniques, etc [23].

Virtual reality developed in a special way in the last 20 years according to the development of computers. As the inevitable outcome of combining virtual reality with coordinate measuring technique, the virtual coordinate measuring machine (VCMM) is developed for the automation of CMM measurement operations and improvement of measurement productivity [24]. VCMM is an accurate model of real CMM, which simulating CMMs' operation and their measurement process within a virtual environment. It enables CMM off-line programming to take place exactly as if an operator were sitting in front of a real CMM. Teach pendant programming is made by pointing a cursor at the 3D CAD model to generate the inspection path of a part. Collision is checked while playing 3D inspection process simulation. Therefore, it no longer needs to wait for real parts or the actual CMM to start programming on-line. It should be noticed that current VCMM uses a keyboard or a mouse to point the cursors at the 3D CAD model. It is inconvenient, slow, and inaccurate for complex parts.

Haptic interfaces are typically positioning devices like joysticks that can provide force feedback. In recent years, haptic modeling has been used in the fields of medicine, education, entertainment, computer arts, engineering design and manufacture, tele-operation, and motor skill training. With advances in computing, haptic systems began to become available for virtual reality applications, in which user can touch or feel virtual object. A critical issue in virtual haptic design is the development of a mechanics model for different materials and shaping methods. Since haptic devices are designed to simulate physical processes, haptic modeling technologies have become an integral part of virtual prototyping systems where realistic process modeling is required (http://www.senable.com). Using haptic modeling, a user can not only view the objects designed in the CAD environment, but also touch, feel, grasp, and move them in the virtual environment to detect possible collisions with other objects.

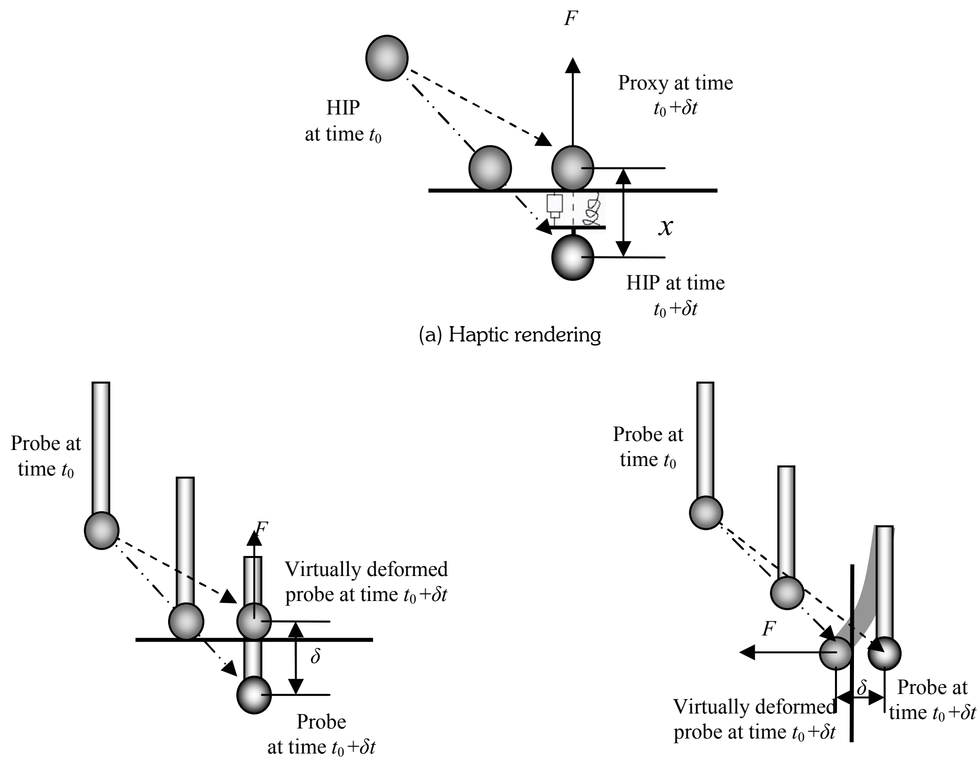
2. HAPTIC VIRTUAL CMM (HVCMM)

Introducing a haptic device into CMM inspection planning leads to the proposal of a novel CMM off-line inspection path planning environment, haptic virtual coordinate measuring machine (HVCMM) that makes use of haptic modeling technique for CMM off-line programming [25]. HVCMM is an accurate model of a real CMM, which simulating a CMM's operation and its measurement process in a virtual environment with haptic perception. HVCMM is motivated by the limitations of existing VCMM systems on their inconvenience, slow, and inaccuracy for complex parts' inspection path programming. It enables CMM off-line programming to take place exactly as if an operator were in front of a real CMM and moving a real CMM probe while feeling the sense of collision among probe, part, fixture, etc. In this paper, the collision detection and collision response with a bent probe is presented in detail. To generate the inspection path of a part, teach pendant programming is made by pointing a probe at the three dimensional computer-aided design (CAD) models using a haptic device. Furthermore, there is a force feedback when the probe reaches the surface of part besides showing the contact in the HVCMM environment. In this way, it is much easier to generate collision-free probe path than using other off-line inspection planning methods. To achieve quick collision detection, surface model is used to represent the part. The HVCMM not only facilitates the inspection path planning, but also speeds it up. The proposed HVCMM can also be used for the training of CMM operation without worrying about any damage of the machine. The haptic response is implemented with a PHANToM® haptic arm delivered from SensAble© Technologies.

Fig. 1. The HVCMM system configuration

2.1 System Configuration

The proposed HVCMM system, as shown in Fig. 1, mainly consists of three parts: a PHANToM® Desktop haptic device with 6 degrees of freedom (DOF) of position feedback and 3 DOF of force feedback, a virtual CMM model, and a CMM off-line programming module. In our implementation, the haptic and visual rendering machine is a desktop PC with dual 2.2 GHz CPU and 1.0 GB RAM. The software framework is implemented in Visual C++. OpenGL is used for run-time visual rendering. The user interface of the HVCMM system consists of a PHANToM®, standard mouse and keyboard, and on-screen GUI controls.



(a) Haptic rendering

(b) Approaching a horizontal plane

(c) Approaching a vertical plane

Fig. 2. Model the probe stylus as a deformable tool

With force feedback, a user can experience the feeling of moving a CMM probe to touch a part on the CMM table. The operator holds the stylus of the haptic device to move the CMM probe to the 3D CAD model of a part to define the inspection points. The haptic virtual CMM simulates CMM operation and its measurement process with haptic perception. Inspection path planning tasks, including high and low levels inspection planning mentioned above are done in the CMM off-line programming module.

2.2 Haptic Modeling of Collision

Collision response is a major subtask of haptic rendering. When a collision is detected, a proper force must be calculated and feedback to the user. There are two kinds of collision response in the proposed HVCMM interface, collision with the probe tip and collision with other parts of the CMM.

The collision between an object model and any part of the CMM except the probe tip is invalid and damaging in actual CMM measurement. This kind of collision must be detected and alerted. Whenever such a collision is detected, the following force model is used to calculate the responding force F:

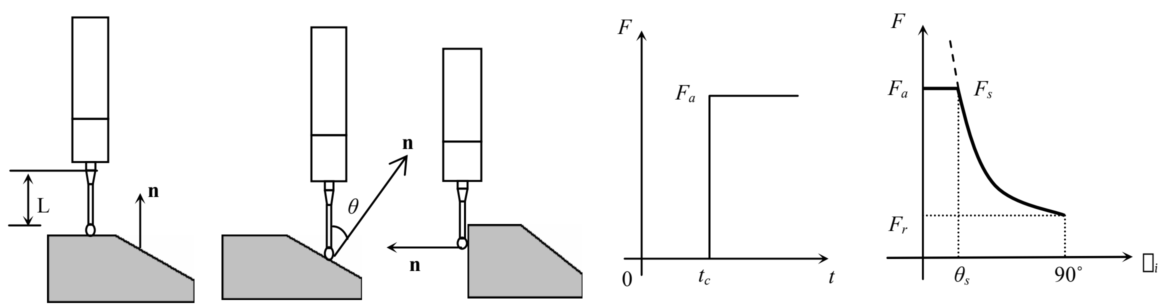
$$F = -c\frac{v}{|v|}, \qquad (1)$$

In which $\boldsymbol{v}$ is the velocity of the probe assembly, c is a constant coefficient, which can be explained as the stiffness of the object surface. The coefficient c is usually set as the maximum force the haptic device could exerted, *i.e.*, around 10 Newton for the PHANToM® haptic device. The above force model implies that when this kind of collision occurs, the feedback force is the maximum of the haptic device and its direction is opposite to the movement of the probe assembly. Such a feedback force provides the user a feeling of colliding with an impenetrable rigid object. This force indicates that the contact is invalid, and the stylus must be repositioned to select a surface point so that only the stylus tip is in contact with an object. Eqn (1) may not accurately reflect the direction of feedback force, nevertheless a large enough feedback force serves the purpose of alerting the user of a invalid collision between the CMM and a part.

Before presenting the force model for probe tip collision response, the basic concept of point based force model is described here briefly. Haptic rendering simulates the contact forces between virtual models and reflects those forces to a user through a haptic device. This interaction is dependent on the geometric representation of the models and the haptic contact model. The major task of the haptic rendering algorithms is to calculate feedback forces from the information about the interaction of the haptic interface point (HIP) and the model. As illustrated in Fig. 2 (a), HIP is allowed to move freely until it collides with the model. A local point on the surface closest to the haptic interface point is found as the proxy point, and the relationship between the penetration direction and the surface normal at the closest point determines the direction of the force to be applied. The magnitude of the force is calculated according to Hooke's law and based on a damper-spring model as in Fig. 2(a). However, such a point based force model is not suitable to the HVCMM because the probe tip is connected to a stylus with different elasticity in different directions. As shown in Fig. 2, when a vertical probe is approaching a horizontal surface (b) or a vertical surface (c), the probe stylus will exhibit different elasticity and give a different force response. Intuitively, given the same deformation δ in the two cases, the force in case (b) is much larger than that in case (c). In order to have a more realistic force feedback, a new mechanics model is proposed. In this mechanics model, the probe stylus and tip is modeled as a deformable tool.

When a probe tip comes into contact with a part, the direction and the magnitude of collision force depend on the probe contact angle θ between the probe and the normal of touched surface of the part and the probe velocity. The affection of contact angle on the force is considered first. As shown in Fig. 3, different contact angle θ gives a different felt force as the elasticity of the stylus is different in different directions. The following equations provide an estimate about the difference in spring constant in two extreme conditions as shown in Fig. 3(a) and (c):

In the case of Fig. 3(a), the axial displacement δ_a can be calculated as



(a) Axial collision (b) General case (c) Radial collision (d) Instant force for axial collision (e) The general force feedback model

Fig. 3. Force model for collision response

$$\delta_a = \frac{FL}{EA} \tag{2}$$

$$F_a = k_a \delta_a \tag{3}$$

$$k_a = \frac{EA}{L} \tag{4}$$

where E is modulus of elasticity, L is the length of the stylus and k_a is the spring constant. δ_a is the axial displacement of the probe tip, *i.e.* the penetration depth.

And in Fig.3 (c), the radial displacement δ_r is calculated by

$$\delta_r = \frac{5FL^3}{48EAr^2} \tag{5}$$

$$F_r = k_r \delta_r \tag{6}$$

$$k_r = \frac{48EA}{5L}C^2 \tag{7}$$

where $C = \frac{r}{L}$, r is the radius of the stylus, and k_r is the spring constant.

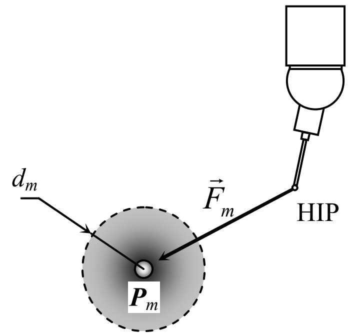


Fig. 4. Magnetic force filed for a measuring point

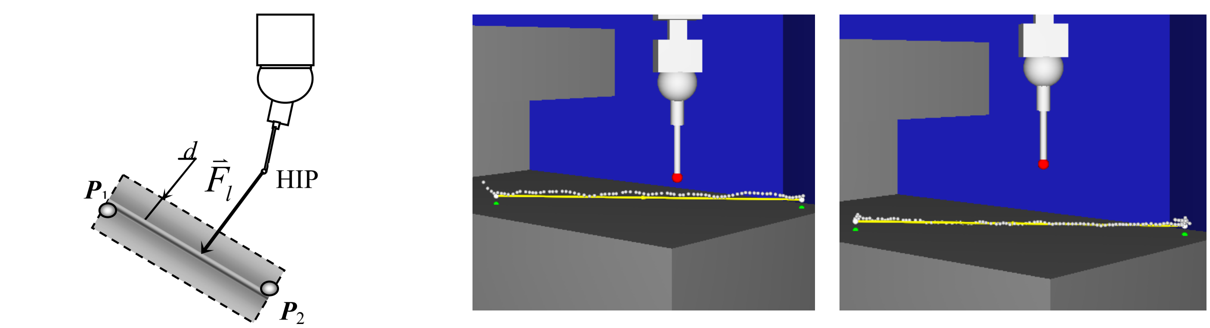
Based on the above equations, for a typical stylus of r = 2 *mm* and L= 100 *mm*, C=2/100=0.02, the ratio between the two spring constant k_a and k_r is about 260. That is, the spring constant of k_a is normally much bigger than k_r. So, different forces could be felt by the user when the contact angle θ_i is different. At a give time t_c, if the approaching angle θ_i is equal to 0°, k_a is used. The felt force is instant at F_a as shown in Fig.3 (d). When k_r is used, the smallest contact force F_r is fed back to the user. There is a transition in-between k_a and k_r when θ_i varies. The equivalent spring constant k_i in the intermediate cases is calculated by,

$$k_i = \frac{k_r}{\sin\theta_i} \tag{8}$$

In summary, the relationship between contact angle θ_i and feedback force F_i is represented as

$$F_i = \begin{cases} k_a \cdot \delta_a & \theta_i \le \theta_s \\ \dfrac{k_r}{\sin\theta_i} \cdot \delta_r & \theta_s < \theta_i < 90° \\ k_r \cdot \delta_r & \theta_i = 90° \end{cases} \tag{9}$$

where θ_s is a small angle at which the maximum servo force F_s of the haptic device has been reached. That is, the feedback force will no longer change even if the contact angle θ_i changes. As illustrated in Fig. 3(e), when the contact angle θ_i is smaller than θ_s, the feedback force is set to F_a.



(a) Magnetic force field around a line segment (b) Line tracing without force guidance (c) Line tracing with force guidance

Fig. 5. Constraint force model for line segment tracing

In the proposed HVCMM system, the probe tip is not moved very fast. Assume the maximum speed υ_{max} is 100 *mm/s*. In order to reflect the effect of velocity of probe movement on force feedback, a velocity coefficient k_υ is multiplied to the forces calculated from equation 3 and 6.

$$k_\upsilon = \upsilon / \upsilon_{max}, \tag{10}$$

where υ is the probe tip velocity. This equation indicates the response force is proportional to the velocity of the probe tip.

The above mechanics model provides a kind of fidelity as if the user is holding and moving the stylus of a real coordinate measuring machine. Two additional force models are employed for data collection and collision detection, which are briefed in the following subsections.

2.3 Haptic Modeling of Measuring Points

In our implementation, the selected measuring points and the corresponding offset points are modelled as "magnetic points". That is, when the HIP is located within a predefined neighbouring space, an attractive force to that point is sent to PHANToM as a guiding force to help the operator to reach these points and record them. As illustrated in Fig. 4, the force model of the magnetic point is as follow,

$$\boldsymbol{F}_m = \begin{cases} k_m D_m, & D_m < d_m \\ 0, & otherwise \end{cases}, \qquad (11)$$

where $\boldsymbol{F}_m$ is the force magnitude; D_m is the distance between HIP and the measuring point $\boldsymbol{P}_m$; k_m is a predefined constant indicating the strength of the magnetic force; d_m is a constant indicating the effective field of the magnetic force.

2.4 Haptic Modeling of Line Segment Tracing

Given a line segment defined by two points, a force model is employed to attach an attracting force to it. The force magnitude is proportional to the distance between the HIP and the line segment and the force direction is along the perpendicular line from the HIP to the line segment. Such a line segment is called "magnetic line". As illustrated in Fig. 5(a), the force model is represented as follow,

$$F_l = \begin{cases} k_l D_l, & (D_l < d_l) \bigcap (HIP \;\; is \;\; between \, S_1 \;\; and \;\; S_2) \\ 0, & otherwise \end{cases}, \qquad (12)$$

where F_l is the magnitude of the constraint force; D_l is the distance between HIP and the line segment defined by points $\boldsymbol{P_1}$and $\boldsymbol{P_2}$; S_1 and S_2 are the planes defined by $\boldsymbol{P_1}$, $\boldsymbol{P_2}$ and the vector $\overrightarrow{P_1P_2}$, respectively; k_l is a predefined constant indicating the strength of the constraint force; d_l is the constant specifying the effective space of the constraint force. Such a force model provides a haptic guidance to improve the line segment tracing accuracy.

Fig. 5(b) and (c) shows the traced points with visual guidance only and haptic guidance, respectively, it can be observed that haptic guided line segment tracing can produce much better data to ensure the traced path is coincident with the line segment, while visually guided tracing brings a lot of noise data caused the unstable hand movement - vibration.

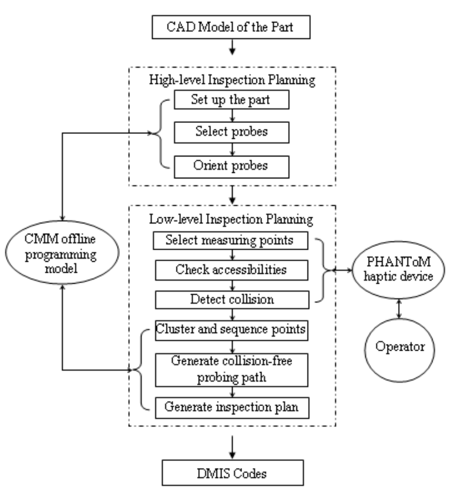
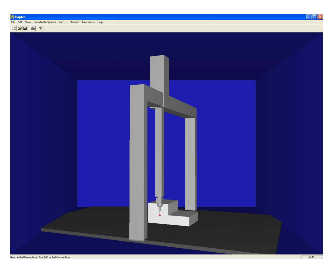
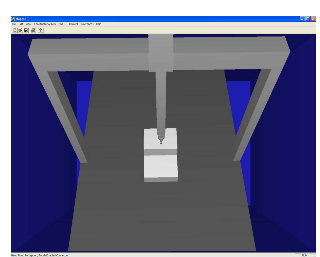


Fig. 6. Flow chart of HVCMM



(a) Perspective view



(b) Top view

Fig. 7. Viewing the part

3. INSPECTION PATH GENERATION

There are two main advantages in the proposed HVCMM system over conventional VCMM systems: firstly, a haptic device is more intuitive in defining measurement points in a 3D environment as the user can feel the contact; secondly, the built-in collision detection mechanism provided by the haptic device can reduce the computational burden of collision-free inspection path.

Figure 6 is the flow chart of the proposed inspection path generation method. The whole inspection plan task is mainly composed of two subtasks: high level planning, which deals with part orientation, probe selection, etc.; and low level planning, which deals with measuring point selection and linking. In the HVCMM system, CAD model is loaded into the workspace. As shown in Fig. 7, the part can be viewed and repositioned/reorientated within the workspace. After probe is selected and orientated, measuring points are defined by the operator using the haptic stylus in a "point-and-click" way. Since both the part under inspection and the VCMM are modelled as impenetrable objects, each defined measuring point is accessible. In order to achieve better measurement accuracy, measuring points are offset outward in the normal direction of the surfaces. The offset points are then linked to generate the first version of the inspection path. Collision detection is then carried out by the operator holding the haptic stylus to trace the linked path. When a collision occurs between two measuring points, it can be avoided by redefining measuring point, changing the sequence of measuring points, or generating additional path to bypass the obstacle.

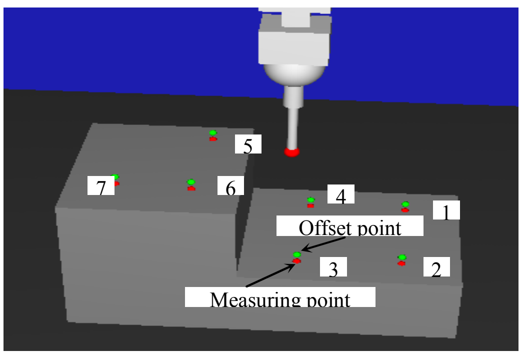


Fig. 8. Offset of measuring points

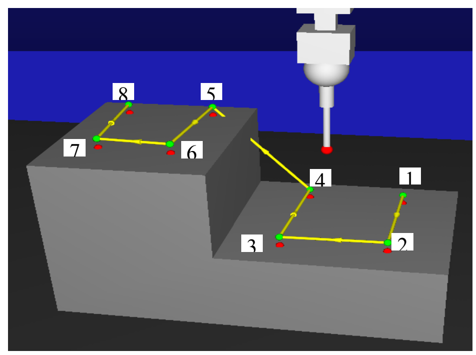


Fig. 9. Guiding path generated by direct linking OPs

3.1 Measuring Point Selection

In a HVCMM system, measuring point (MP, for short) is selected interactively. The operator can use the haptic stylus to touch the part surfaces and explore it. MP is defined simply by click the button on a stylus as a trigger. Because the part and VCMM are haptically modelled as impenetrable objects, the selected MP is a collision-free point, which is also called accessible measuring point (AMP).

Usually, better accuracy can be achieved when the probe approaches the MP in the normal direction of the surface. Therefore, each MP is offset in the normal direction to generate the corresponding offset point (OP, for short), as shown in Fig. 8. The line segment defined by each pair of MP and OP is the approaching and retracting path for that MP and haptically modelled as magnetic line. MP and OP are modelled as magnetic points. The operator can make

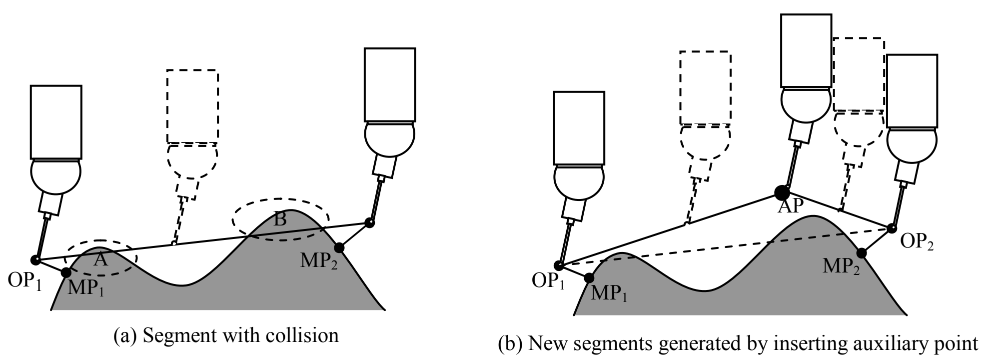


Fig. 10. Collision avoidance by inserting auxiliary points

sure that the defined MP and OP are accessible and the line segment between them is collision free by holding the virtual probe to touch the OP and trace the approaching/retracting path. Otherwise, the defined MP should be discarded.
Each MP/OP pair is labelled with a sequence number. The sequence of MPs can be adjusted by changing the associated sequence numbers. Insertion and deletion of MPs are also permitted.

3.2 Path Linking and Collision Detection

Once the measuring points on the surface have been created, the shortest path is by linking the OP points by straight line segments as illustrated in Fig. 9. The path so generated is called "guiding path". The whole or part of guiding path could be in the final inspection path.
Each segment of the guiding path is haptically modelled as magnetic line. Collision detection is carried out in the same way of investigating the line segment linking a MP/OP pair. The operator holds the virtual probe and traces the guiding path. With the aid of force guidance, the tracing operation could be done easily and effectively. It should be noted that a segment of the guiding path not intersecting the part model does not guarantee that the segment is collision-free, since collision may occur between the part model and other parts of the probe assembly. Therefore, tracing the whole guiding path is necessary. When a collision occurred, the corresponding segment of guiding path is marked. Those collision-free segments are remained as part of the final inspection path, while segment with collision (e.g. segment 4-5 shown in Fig. 9) will be further processed.

3.3 Collision Avoidance

The goal of collision avoidance is to find a collision-free bypass to replace the segment with collision. Two kinds of bypass generation methods are proposed for different complexity level of the collisions: auxiliary point method and teach pendant method. The former is used for simple collision avoidance; the latter is used when a complicated bypass is needed.

3.3.1 Auxiliary Point Method

In some simple circumstances, as illustrated in Fig. 10, collision can be avoided by inserting one or more auxiliary points in between the two measuring points. Collision with the tip happens when any surface of the part is in the traversing trajectory of the probe, such as when traversing from OP_1 to OP_2, collision occurs at region A and B as shown in Fig. 10(a). The traversing path of the probe tip is $\overline{OP_1OP_2}$. The operator can intuitively insert an auxiliary point at somewhere around point AP to create the new traversing path $\overline{OP_1APOP_2}$. The new segments are then haptically modeled as magnetic lines to perform collision detection. If they are collision-free, the new path segment will substitute the old one. Otherwise, AP needs to be relocated or more auxiliary points need to be inserted.

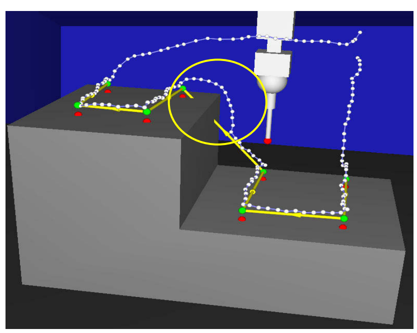


Fig. 11. Path generation using teach pendant method

The auxiliary point method is feasible when the collision avoidance path is evident and a bypass consists of several line segments can be found. The time of collision detection will increase when more and more auxiliary points are inserted to the guiding path. And then the collision detection is no more efficient and turns into a tedious interaction. If such a complex situation exists, a "teach pendant method" could be more suitable.

3.3.2 Teach pendant method

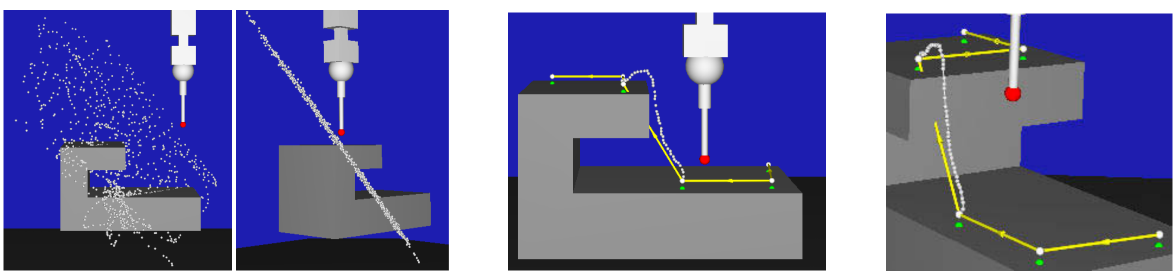
The teach pendant method is based on an assumption: the line segment can be considered collision-free if its length is small enough. That means if a path consists of a set of collision-free points with a large enough density, the path can be considered collision-free. The haptic device updates the HIP position at 1K *Hz*, even if the HIP moving speed is 1 *m/s*, the distance moved in one cycle is only 1 *mm*. Therefore, we can use the haptic device as a teach pendant to find a collision-free path and sampling the path at a high enough frequency. Then a collision-free path is generated by linking the sampling points using line segments. Based on the assumption, the generated path is collision-free and needs not to perform collision detection any longer.

When the HVCMM is in teach pendant mode, its movement is recorded at a high frequency. The recording procedure is started from an end point of a segment of guiding path with collision. Whenever a collision occurs, the position of HIP is not recorded and the previous accessible point is used at the starting point to continue the path recording procedure, until the HIP reach the other end point of the segment.

The collected point data needs to be simplified. If the distance between two successive points is smaller than a predefined threshold value, they are merged as one point. If the distance between two non-successive points is smaller than a predefined threshold value, they are merged as one point and those points between them are removed from the list because they form a closed loop. The simplified path is used to replace the old segment with collision. Figure 11 shows an example of sampling points collected and the new path generated. It is noticed that the collision occurred in the circle region is avoided.

The path recorded could be very irregular due to the unconstrained movement of HIP in three-dimensional space. A force constraint plane could be used, if feasible, to confine the HIP movement within a plane, as shown in Fig. 12(a). The force constraint plain is defined by the segment under consideration and operator selected point. Fig. 12(b, c) is an example path segment recorded with the help of a force constraint plane.

From the above, it can be seen that the user can move the probe at ease as there is no need to worry about collision because the collision causes no damage to CMM. Even if an un-wanted collision occurs, the user needs only to redefine a point, and a collision free path is always recorded. Therefore, the generation of collision-free probe path using HVCMM is much easier than that using other off-line inspection planning methods.



(a) Point cloud constrained on a plane

(b) Recorded point on a constraint plane

(c) Collision-free path generated

Fig. 12. Force constrained plane used in path tracing

4. CONCLUSIONS

The proposed collision free inspection path generation methodology has these advantages: simplified collision detection process and alleviated computing burden; the experiences operators are considered in the path planning procedure; STL files and freeform surfaces can be used. It is not an automatic inspection path planning method, but an interactive method featuring intuitive operation. Usually, an interactive programming system could be hard-to-use and tedious in operation. However, with the aid of force feedback and three dimensional positioning functions provided by haptic device, the interaction is intuitive, convenient, and efficient. In the proposed system, collision detection is performed by the built-in mechanism of the haptic device.

5. ACKNOWLEGEMENTS

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