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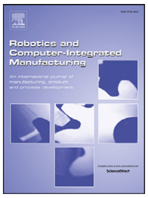

Sweep scan path planning for five-axis inspection of free-form surfaces

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ABSTRACT

Five-axis inspection machine is an emerging powerful means to inspect the product quality of free-form surfaces in mechanical manufacturing. However, the inspection efficiency is always a bottleneck to its better usage. Sweep scan, which is an emerging five-axis surface inspection technology, takes full account of the unique characteristics and working capacities of the five-axis inspection machine and hence has a greater efficiency advantage over the traditional five-axis surface inspection technologies. This paper presents a practical strategy for automatically generating an efficient sweep scan path for an arbitrary free-form surface. The strategy is based on the idea of first decomposing the given free-form surface into patches of elementary shapes and then devising algorithms to plan optimal sweep scan paths for each type of the elementary shapes. Four case studies on scanning different free-form surface shapes are reported to test the developed methodology. Experimental comparison between the proposed method and the popular isoplanar zigzag method demonstrates the significant improvement in terms of inspection efficiency, and a further analysis explicitly verifies the advantages of the proposed sweep scan methodology.

1. Introduction

Products with free-form surface shapes are increasingly required to be manufactured with extremely high fidelity to their original designs, such as marine propellers, aircraft structure parts, molds and dies, etc. Due to various sources of machining error [1–3], it is important to examine the conformity of the manufactured surface to the designer's intent for verifying the quality of the final product. For this purpose, surface inspection is a crucial step in the cycle of product realization. Five-axis Coordinate Measuring Machine (CMM) is often the first-choice solution for free-form surface inspection in the mechanical manufacturing domain, due to its tremendous advantages over the traditional three-axis CMM (on flexibility) and various non-contact measuring systems (on accuracy, efficiency, and operation restrictions) [4].

The complexity of free-form surfaces poses considerable difficulties for free-form surface measurement with CMM [5–7]. To deal with them, a good number of research works on automatic CMM inspection for free-form surfaces have been reported during the past decades. Generally, starting with a Computer-Aided Design (CAD) model, the path planning for free-form surface inspection needs to solve two major problems: which points on the surface should be measured and how to measure them.

The crux of measurement point determination is to seek a balance between measurement accuracy and time efficiency due to the obvious observation: higher measurement accuracy usually needs more measurement points but also longer inspection time. The methods of inspection point sampling are generally divided into two categories: geometric feature-based methods and adaptive methods. A uniform sampling strategy may probably suffice for relatively flat surfaces. However, for a complex surface, e.g., with highly varying surface curvature, it is more reasonable to sample the surface based on its complexity, such as the mean curvature based method [8]. Some hybrid approaches [9,10] were developed to heuristically determine the sampling points on surfaces with different complexity levels, by combining multiple sampling criteria, such as surface curvature, patch size, etc. Unlike feature-based point sampling methods, the adaptive point sampling methods [11–13] are proposed from the point of view of reverse engineering. It first evaluates the deviation between the CAD model and a substitute surface, where the substitute surface is reconstructed from the predetermined sampling points. If the deviation is beyond a preset threshold, more sampling points are added accordingly. This process iterates until some stopping criteria are met.

After the sampling points are determined, the next task is to design an effective collision-free probing path, mainly involving the accessibility analysis and measurement sequence optimization. The accessibility analysis is to check whether a collision would happen during a measurement motion [14,15]. Through accessibility analysis, all feasible orientations for the probe stylus approaching a measurement point could be found and often represented as a set, e.g., the concept of local accessibility cone and global accessibility cone [16–18]. With the specified sam-

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pling points and their associated feasible approach orientations, another research topic is on how to reduce the non-measurement motion, which is actually a problem of finding an optimal sequence to pass through all the measurement points and is generally solved by a heuristic-based optimization strategy [19].

In addition to the above, some specific constraints should be integrated into the five-axis inspection path planning in different practical situations. Heo et al. [20] presented a pioneering five-axis measurement plan for an impeller by using a CMM with two rotated indexing probe. The indexing probe can rotate along two rotation axis at 7.5° movement intervals for each pulse command. As the frequent change of the probe orientation is very time-consuming, it is desirable for the probe head to keep the same orientation as much as possible. The method of Heo et al. [20] partitions the impeller surface into several regions and uses only one feasible probe orientation to approach all the points in each region, so that the total probe orientations are simplified. Li et al. [21,22] proposed methods of generating five-axis interference-free inspection path for impeller blades using an probe mounted on a five-axis machine tool. Due to the stringent physical limit on the speed and acceleration of the rotary motions of the machine tool, drastic probe orientation change should be avoided. The unique advantage of the methods of Li et al. is that the generated inspection path is smooth so as to guarantee a stable speed and acceleration of the rotary motions of the five-axis machine tool.

Yet, all the above mentioned works focused on point-by-point measurement mode. This is because most CMM's use a point-by-point probe which must slowly approach each measurement point before the contact. This type of surface inspection is extremely time-consuming, especially if the number of inspection points is large.

With a leap of technology, a continuous five-axis measurement technology has been developed recently, which can keep the probing stylus tip moving along a continuous path on the surface and output dense data points at a very high speed (hundreds of points per second). The continuous inspection is implemented on a new type of five-axis measurement machine, which has a motorized articulating probe head, with two extremely light rotary axes, mounted on a traditional three-axis CMM. Owing to its quite different working mode, the path planning methods with respect to the point-by-point inspection mode can hardly be applied to the continuous five-axis inspection.

Currently, the research on continuous five-axis inspection path planning is scarce. Elkott and Veldhuis [11] investigated three types of continuous inspection paths, referred to as automatic isoparametric line scan, curvature-based isoparametric line scan and isoplanar line scan. In essence, their work concentrated only on the geometric issues of the surface-to-be-inspected, but independent of the five-axis inspection machine. However, when viewed from the perspective of the inspection machine, the inspection motion must be finally decomposed into every single-axis movement of the five-axis machine, through the inverse kinematic transformation and post-processing [23]. For any five-axis inspection machine, the kinematic characteristics and working capacity for each axis may differ significantly from each other, e.g., its three translational linear XYZ axes have a greater inertia and move much slower than its two rotary axes. Although the servos have the power to drive the heavy XYZ axes at high speed, it is not recommended to do so due to the possibility of introducing excessive measurement errors [24]. The investigation on the dynamic errors of continuous five-axis inspection [25] suggested that, to achieve high inspection speed while maintaining the measurement accuracy, the faster moving components of the machine should be as light as possible. Catering to this consideration, recently a novel continuous inspection path planning method [26,27], called "sweep scan", was proposed, where the probe head moves along a smooth simple path around the surface profile whilst the motorized stylus performs a specific spiral sweep movement on the surface, as illustrated in Fig. 1(a). Compared to other types continuous inspection path, such as the isoplanar line scan path shown in Fig. 1(b), where the probe head needs to move back and forth by the heavy XYZ axes, the sweep scan achieves a significant improvement on inspection efficiency by arranging the majority of the inspection movement to its agile rotary axes and thus dramatically reducing the working load of the XYZ axes.

However, the method in [26,27] depends on humans to specify the paths of the probe head and the tip separately for certain types of surfaces, such as a cylindrical patch, and thus can hardly be applied to an arbitrary free-form surface. In our previous works [28], we proposed a semi-automatic sweep scan path planning method for free-form surfaces based on some predefined conditions, e.g., the input surface must be able to be scanned by a single sweep scan, which usually needs a huge amount of manual preprocessing. Obviously, it is desirable to have an automatic sweep scan path planning method for an arbitrary free-form surface, and this is the objective of the work in this paper.

In this paper, we conduct a systematic study of five-axis sweep scan and propose a practical method of automatically generating a sweep scan path for an arbitrary free-form surface. The rest of the paper is organized as follows. Section 2 gives an insight on sweep scan involving its unique characteristics, the sampling point determination, and some observations, to help plan the probe head locus. Section 3 presents an overview of the proposed sweep scan path planning method, followed by the key implementation details in Section 4 (surface partition) and Section 5 (sweep scan path planning for elementary shape). The effectiveness and advantages of the proposed method are demonstrated by a set of comparison experiments in Section 6. The conclusions are given in Section 7, together with a discussion of future work.

2. Preliminaries

2.1. Requirements of five-axis sweep scan

The five-axis inspection machine used in our work is composed of a COORD3 UNIVERSAL 15.9.8 CMM with three linear axes X, Y and Z and a Renishaw Revo probe head system with two high-speed rotary axes A and C, as shown in Fig. 2. The stylus is allowed to slightly deflect and keep the tip moving continuously on the surface to be inspected. The exact location of the tip is calculated based on the positions of the five axes and the deflection of the stylus which is measured by transmitting and receiving a laser beam through the hollow shaft of the stylus. The measurement accuracy of this five-axis inspection machine is up to 1.5 μm.

A sweep scan inspection is a joint movement of the three linear axes and the two rotary axes. However, the kinematical working capacities, i.e., the allowable maximal speed and acceleration, between the three linear axes and the two rotary axes are quite different, because of the difference in their mechanical configurations. For the three linear axes, the large arms associated with them are generally composed of steel and marble, and hence are extremely heavy. Thus, large speed or acceleration of the three linear axes may induce severe inertia effect which in turn introduces inaccuracies to the measurement result [24,25]. In the contrast, the working load on the two rotary axes is very small because they only need to drive the extremely light stylus which is usually made of carbon fiber. Therefore, to maintain a high inspection accuracy, the allowed maximal speed and acceleration for the three linear axes should be far lower than that for the two rotary axes – typically, as for our inspection machine, the limit on the linear speed of the stylus tip with respect to the head is more than 50 times over that of the head itself.

Per the foregoing reasons, an efficient sweep scan path should let the rotary axes, which have super kinematical capabilities, take over the majority of the inspection work while the three linear axes play an auxiliary role during the inspection. In other words, the probe head should move along a smooth and relatively short path while the stylus sweeps quickly on the surface.

Specifically, to realize a sweep scan, the positions and orientations of the stylus should be determined with respect to the sampling points. Explicitly, we need to determine the sampling point sequence $\mathbf{p}_i|_{i=1..n}$ over the given surface S and their corresponding probe head center position