Robotics and Computer Integrated Manufacturing 54 (2018) 17–34

Contents lists available at ScienceDirect

Robotics and Computer Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Path planning method for on-machine inspection of aerospace structures based on adjacent feature graph

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ARTICLE INFO

Keywords:
On-machine inspection
Path planning
Voronoi diagram
Greedy search algorithm
Aerospace structures

ABSTRACT

On-Machine Inspection (OMI) system has been playing an important role in modern aeronautical manufacturing, owing to its high efficiency, great convenience, and low application cost. The inspection path planning of OMI, which aims to find an optimal path that traverses all inspection points without collisions and by costing as little time as possible, is a main bottleneck that limits the achievements of higher efficiency and less inspection time. Besides, the path planning for OMI in aerospace manufacturing faces new challenges, which are barely explored, because aerospace structures have unique characteristics of complex geometrical features, large-scale dimensions and high-precision processing requirements. Thus, this paper proposes a novel, easily-implemented and robust inspection path planning method to plan paths for OMI of aerospace structures based on the properties of aerospace structures. In order to lift the inspection efficiency, this method makes three improvements on the path planning. First, reorganize the inspection features based on the cluster technology. Second, construct the adjacent feature graph based on Voronoi Diagram to plan the path. Third, a search algorithm is designed to search the adjacent feature graph to decide the sequence of inspection features and a convex hull based algorithm is used to avoid collisions. The proposed method has been tested for several cases and solid experimental results have shown that these improvements take effects in path planning for OMI of aerospace structures and suited paths can be provided for the inspection.

1. Introduction

Dimensional inspection is getting more and more important with the increasing requirements of accuracy and efficiency of manufacturing workpieces. On-Machine Inspection system as a new intelligent inspection system has been widely applied in various fields owing to its great convenience without disassembly, low application cost by reusing the CNC machine and high inspection quality by avoiding second-fixture positioning errors [1]. It is especially useful in aerospace manufacturing field, where the workpieces are usually geometrically complex and tend to deform during second-fixture processes. The OMI system, working like a 3D Coordinate Measuring Machine (CMM), usually consists of four modules: inspection feature recognition, inspection points generation, path planning and inspection execution [1]. The first module analyzes the CAD model and recognizes the target features for inspecting [2–6]. The second module generates inspection points according to recognized inspection features [7,8], including the determination of the number of inspection points [9,10] and how to sample these points [11,12]. The third module plans the inspection path which traverses all inspection points only once and has no interferences with workpieces and the environment. The forth module is the process that the CNC machine takes a sensor to inspect all points along the path generated by path planning. This paper proposes a robust and easily-implemented path planning method to plan the path based on the chief characteristics of aerospace parts with a given set of inspection points. Additionally, this paper focuses on the touch system, which uses a probe as the sensor, since it is widely adopted in aerospace manufacturing field due to its higher precision compared to the non-touch system, which uses a laser scanner as the sensor. Because the inspection execution of OMI could occupy much time, it is crucial to find an optimal inspection path and two common principles of the inspection path are short in length and collision-free with the workpiece and the environment.

Many researchers have made lots of efforts to improve the path planning method to gain a shorter path. Because of the similar objective between the Travel Salesman Problem (TSP) [13], which is a famous NP problem, and the path planning problem, many path planning approaches got inspired by the TSP are proposed. These methods based on

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https://doi.org/10.1016/j.rcim.2018.05.006
Received 13 February 2018; Received in revised form 17 April 2018; Accepted 22 May 2018
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TSP can mainly be divided into two groups. The first group formulates all inspection points as a TSP and applies a certain TSP algorithm to it. Spitz et al. [14] used the method Probability Roadmap Planner (RRP) to construct a roadmap, which connects all inspection points and some extra points generated for avoiding collisions. Then a TSP algorithm was used to compute a path through all inspection points in the roadmap. Albuquerque et al. [15] used the strategy that iteratively replaces the original inspection points till the probe could access the inspection points without collisions and then calculating the path of all points was formulated as a TSP and the nearest neighborhood search algorithm [16–18] is used to compute the path. Lin et al. [19] used the LKH solver, which is an efficient TSP solver implemented by Helsgaun [20–22] for the Lin–Kernighan TSP Heuristic [23], to optimize the surface-filling curve type tool path in order to improve the efficiency of finishing the free-form surface. Han et al. [24] established a 3D ant colony map for the measurement space and proposed an improved Ant Colony Optimization (ACO) algorithm to rapidly obtain the security inspection path for CMMs. The second group divides the inspection points into groups according to geometrical tolerances at first and then processes the following steps: (i) plan the path in every feature; (ii) plan the sequence of features; (iii) plan the transfer path between two features. Slavenko et al. [4] researched on prismatic parts and analyzed the inspection (points sampling and path planning) of features including the point, plane, circle, hemisphere, cylinder, cone, truncated cone, truncated hemisphere. They then proposed an intelligent approach to plan the inspection path based on the CAD model and tolerances. Their another paper [25] modelled each feature of prismatic parts as a TSP and used the ACO algorithm [26] to solve this problem.

In order to avoid collisions, many approaches have been proposed. For example, Spitz et al. [14] used RRP to construct collision-free segments. This kind of methods were barely used in later because constructing paths without collisions needs a mass of computing-costing geometry computations. Yau et al. [6] proposed heuristically planning method to avoid collisions, the main idea of which is to modify a raw path that is generated without consideration of avoiding collisions. Zhao et al. [27] proposed generating collision-free path on different path planes. Slavenko et al. [4] proposed an iterative procedure that generates some transition points to avoid collisions.

Besides, some researchers have worked on the inspection of special features or parts. Yadong et al. reviewed methodologies, techniques and various processes of inspections of parts with free-form surfaces in [28]. Zhou et al. [29] proposed a sweeping scan path planning for free surface in the five axis machine. Pengcheng et al. [30] focused on the automatic generation of inspection path for five axis machine and for that they developed a practical algorithm which fully considered and utilized the unique kinematic characteristics of the five-axis inspection machine. Zhang et al. [31] decomposed the free-form surface into patches of elementary shapes and then planned sweep scan paths for each pathes. Ye et al. [32] extrapolated cubic spline curves to estimate boundary points of surface-open features and then the probe stylus can search and compensate the boundary to generate paths. The navigating stylus is a new inspection tool which slides along a whole curve to inspect the surface and gets (theoretically) infinitely many points. The navigating stylus avoids problem of point sampling that is complicated by itself. PengCheng et al. [33] used the digraph on the aggregated accessibility domains of the guiding-path and trajectory-curve paradigm to generate the shortest scanning curves for a navigating stylus to inspect arbitrary free-form surface. As a base theory, Barton et al. [34] used the discrete sequence of circular arcs to approximate the original curve and apply this theory to the free-form surface. And advanced PSO algorithms were used to optimize the tool path of the 5-axis machine in [35]. The feedrate of the cutter was optimized according to the tool curve in [36,37].

However the inspection of aerospace structures is barely explored and the methods above get hardly satisfied results when applied to aerospace structures. So this paper presents an easily-implemented and robust inspection path planning method for aerospace structures. This method makes some important improvements based on the properties of aerospace structures and these improvements make the proposed method plan suited path for OMI of aerospace structures. The main novel points of this paper are:

1. First, analyze the properties of aerospace structures. Then, cluster the inspection points based on faces and reorganize all inspection features;
2. Construct the adjacent feature graph based on Voronoi Diagram. Design a greedy search algorithm to search the graph to plan the sequence of features;
3. Use the technology of convex hull to generate middle points for avoiding collisions.

The technology of clustering to reorganize the inspection features gets rids of the drawbacks of inspections by following the geometrical features. The combination of Voronoi Diagram and graph searching returns more reasonable sequences of points and features. The convex hull decreases the complex geometrical computations. Because of those, many redundant segments in the inspection path can be avoided and the inspection efficiency can be lifted.

The remainder of this article is organized as follows. Firstly the characteristics of aerospace structures will be discussed in Section 2. Secondly the path planning method will be introduced and discussed in Section 3. Then Section 4 will show the experiments and compare the results. Finally Section 5 gives the conclusion and last section gives the acknowledge.

2. OMI for aerospace structures

2.1. Properties of aerospace structures

Considering the precision and efficiency of manufacturing, the OMI system has been widely used in aeronautical manufacturing. However the inspection path generated by current approaches is low-efficient, so much time is cost in the inspection of workpieces, which becomes a bottleneck of OMI for aerospace structures. The deeper reason is that the currently applied methods don't take the properties of aerospace structures into account.

Aerospace structures are various parts used in aircrafts. Considering the mass and strength of parts, most of them are made of special materials which are hard to manufacture. In order to cut weight, the aerospace structures remove the inner materials to form cavities and thus aerospace structures use plates or stiffeners to load forces. For high stability, reliability and security, each structure is large-sized to reduce many redundant assemblies. According to the aerodynamics theory, aircrafts are designed to be streamlined, for which aerospace structures have many surfaces, complex profiles and irregular shapes. All these properties make the inspection of aerospace structures distinct from that of other parts and turn out to be hard to deal with. The influence of these properties can be summarised as follows (examples of aerospace structures are shown in Section 4):

- Most aerospace structures are large-size. There are long distances between two features or two points. Thus, the sequences of inspection points and inspection features could have a great impact on the length of the whole path.
- Aerospace structures have many stiffeners. The locations and dimensions of stiffeners usually need to be inspected, because aerospace structures rely on stiffeners to get basic mechanical behaviour. The problem is that the points for inspecting stiffeners are scattered and far away from each other and meanwhile stiffeners could be obstacles which impede the inspection process.
- For the special appearance design, the profiles and surfaces of aerospace structures need to be inspected. Inspecting profiles and

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