Robotics and Computer-Integrated Manufacturing 30 (2014) 305–314

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

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

Coverage path planning for eddy current inspection on complex aeronautical parts ☆

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ARTICLE INFO

Article history:
Received 18 January 2013
Received in revised form
15 October 2013
Accepted 22 October 2013
Available online 22 November 2013

Keywords:
Coverage path planning
Triangular mesh
Segmentation
Eddy current testing
Automation
Aerospace industry

ABSTRACT

Non-destructive testing (NDT) plays a critical role in controlling the structural integrity (therefore the quality) of aeronautical parts, during fabrication as well as during maintenance. Eddy current (EC) testing is one of the most used NDT techniques in the aerospace industry. However, EC testing is still mainly performed by human operators and reliability as well as repeatability is not always guaranteed. To solve these issues, automating this NDT technique with a robotic system is investigated. In this paper, an EC probe equipped with a passive compliant system is assumed to be attached to the end-effector of a 6-DOF manipulator arm to carry on the inspection. Then, assuming that a 3D model of the inspected part is known a priori, a coverage path planning method using a zigzag (or rastering) pattern adapted to EC testing on aeronautical structures with a complex geometry is proposed. To reach this objective, the approach adopted in this work is to adapt existing coverage path planning techniques based on a "divide-and-conquer" strategy used for spraying applications to EC inspection. More precisely, three successive segmentations are applied to the surface to be inspected so that consistent rastering paths can be generated. Simulation results are shown for a complex part of an aeronautical structure to demonstrate the efficiency of the proposed method.

1. Introduction

In the aerospace industry, non-destructive inspections are critical tasks used to ensure the quality of manufactured parts. However, most of the non-destructive testing techniques commonly used in this industry are currently performed by human operators. In addition to being repetitive and time-consuming, results heavily depend on each inspector's skill which significantly impacts the reliability and repeatability of these inspections. To address these issues, automating NDT as much as possible is the most plausible solution.

Many NDT techniques exist but one of the most frequently used to inspect aeronautical parts is eddy current testing. This technique requires conductive materials and consists in moving a probe constituted of electrical coils over the inspected surfaces in order to generate eddy currents in the latter by a magnetic field. Thus, perturbations of this field result in an electric signal which can be used to detect surface and near-surface cracks. However, to avoid noised signals caused by lift-off variations, the EC probe must be moved while keeping a normal orientation with respect to the inspected surfaces and (usually) a mild contact with them. In an effort to automate this technique, it is proposed in this paper to handle the EC probe with a 6-DOF manipulator arm using an offline programming motion. Moreover, the EC probe is assumed to be spring-loaded along its main axis to deal with slight uncertainties in geometry and positioning. Then, to deploy such a system in practice, it is first necessary to solve the *coverage path planning* problem in order to inspect all surfaces of interest without missing any spot.

This problem has been studied for many years, particularly for numerical control (NC) machining [1] and material deposition applications such as spray painting [2,3], thermal spraying [4] and spray forming [5]. Coverage path planning is also a well-known issue in other applications like cleaning [6], arable farming [7], demining [8], etc.

Until now, few works have been led to automate EC inspection. Most of the existing automatic systems for this application are dedicated to a specific range of parts, especially those with a symmetrical axis (shafts, tubes, bearings). When a part has a more complex shape, a dedicated automatic system is often designed to

☆ EC: eddy current.

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http://dx.doi.org/10.1016/j.rcim.2013.10.002

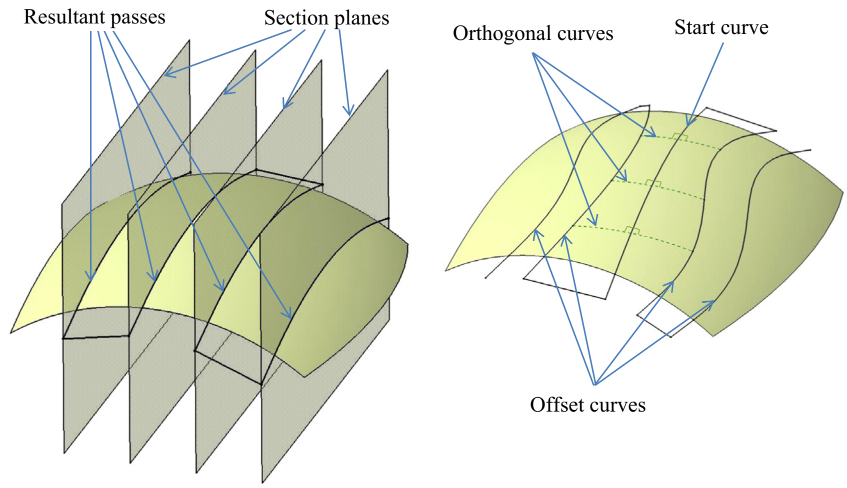

Fig. 1. Construction of paths with section planes (left) and with offset curves (right), adapted from [14].

inspect this particular shape [9]. In one of the most recent works on this topic, a 7-DOF robotic arm using position-force control strategies has been proposed to perform an EC inspection on surfaces with unknown geometry [10]. However, though detection of defects is satisfying at low scanning speeds, they observed that the EC probe has difficulties to keep a contact with the surface at speeds greater than 0.5 mm s^{-1}, resulting in losses of data and, as a result, defects might go undetected.

In order to generate paths for EC inspection, it is proposed in this paper to adapt existing coverage path planning techniques for spraying applications. Indeed, paths for the latter applications present additional constraints compared with EC inspection (e.g. uniformity of material deposition, minimization of waste) but they are based on similarly usable zigzag patterns. Moreover, many studies have been published about path planning for spraying applications. Among these, several have proposed a framework to generate paths that, in addition to meeting coating constraints (uniformity, minimization of material waste), can also deal with complex 3D surfaces while reducing a cycle-time process [5,11,12]. Therefore, it is believed that paths for EC inspection can benefit the experience acquired throughout these works. In the next section, it is explained how some of the aforementioned frameworks have been adapted to EC inspection.

2. Outline of the proposed method

To automatically generate an inspection path, it is first assumed that the geometry of the surface to inspect is known, e.g. from a CAD model. Different approaches to compute coverage paths using such a model have been proposed in the literature. For instance, [13] has worked on coverage path planning using known parametric surfaces. Other authors have generated paths based on a triangular approximation of the surface geometry using the STL file format obtained from the CAD model. In [14] two methods have been identified to generate zigzag paths on a known surface: one using section planes, and another using offset curves, cf. Fig. 1 (adapted from [14]). In [15], section planes have also been chosen to construct the coverage paths. Although these methods work well for flat or relatively flat surfaces, problems arise for more complicated 3D shapes (e.g. surfaces with high curvatures or with holes). To address such limitations, some authors used a “divide-and-conquer” strategy: the global surface is partitioned into simpler patches so that the simpler methods to generate paths can be applied [12,5].

Inspired by these works, the general framework to generate zigzag paths for EC inspection as proposed in this paper is to first, partitioning the global STL surface into patches with three successive segmentation techniques based on surface geometry and topology, and then, generating paths on each patch by using the “section planes” method. This framework is illustrated in Fig. 2. Nevertheless, the main difference between coverage for material deposition applications and inspection is that the latter does not need to meet uniformity constraints. Hence, some steps developed in [5] and [12] are adapted in order to build a complete coverage of the EC probe on complex 3D surfaces, without adding complexity to algorithms due to uniformity constraint. Furthermore, some improvements are proposed in this paper to extend the boustrophedon algorithm [16], used to segment a 2D surface with convex holes inside based on topology, to more general types of surfaces (cf. Section 5.3).

The first segmentation, referred to as “watershed segmentation”, aims at partitioning the surface into regions separated by borders presenting local maxima of curvature. Thus, the new regions are expected to contain less variations of curvature, leading to more regular shapes and subsequently, more regular paths. However, based on variations of curvature, this segmentation does not guarantee a low absolute curvature inside these regions (for example, the watershed segmentation has no effects on a cylinder, whose curvature is constant everywhere), and some regions may not be flat enough to generate paths using section planes (cf. Section 6). Then, to ensure proper flatness, an additional segmentation based on normal directions of each triangular facet is applied to the previous regions to obtain a new segmentation with a maximum deviation angle (angle between two facets) lower than a fixed threshold value in each new region. These two successive segmentations ensure the partition of the surfaces into geometrically simple patches. However, patches with a complex topology (for example patches with holes) can still remain and result in paths leading to a long cycle-time or collisions between the EC probe and the part (cf. Section 5.1). Therefore, a final segmentation, called “Morse decomposition”, is applied to the patches to get topologically (and geometrically) simple subsurfaces.

The following sections detail these three segmentations, the path generation method, and the results obtained when applied to a structural part of an aircraft with a relatively complex shape. It