An integrated approach of reverse engineering aided remanufacturing process for worn components

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ABSTRACT

The worn mechanical components/parts arrived in the remanufacturing system exhibit highly uncontrolled variabilities in failure conditions as well as structures and shape complexities. With the aid of reverse engineering (RE) technologies, a quick and accurate acquisition of the damaged areas of the worn part is attainable and thereby facilitates remanufacturing operations necessary to bring the parts back to like-new conditions. In this paper, a reverse engineering based approach is proposed to aid the remanufacturing processes of worn parts. The proposed approach integrates 3D surface data collection, nominal model reconstruction, fine registration, extraction of additive/subtractive repair, tool path generation and actual machining process, seeking to improve the reliability and efficiency of manual repair process. For nominal model reconstruction, a Prominent Cross-Section algorithm embedded with curvature constraint is proposed to automatically identify the boundary of the part's damaged area and thereby eliminate the defective point clouds from the reconstruction process. With the nominal reconstruction model and the 3D model of the worn part, a modified ICP algorithm integrating curvature and distance constraints is proposed to achieve a best-fit position of the two models by automatically identifying and eliminating the unreliable corresponding pairs through iterations. The proposed approach is demonstrated through remanufacturing of two different mechanical components and is approved to be efficient and effective.

1. Introduction

Remanufacturing of waste or deposited mechanical products/components has emerged as a promising practice to reduce environmental impacts and financial expenditure by extending their lifespan [1]. However, the worn products/components arrived in the remanufacturing facility exhibit highly uncontrolled variabilities in parts' quality conditions as well as the complexities in parts' shapes, dimensions and structures [2]. The current manual repair to restore its original shape is time and labor intensive, and also produces inconsistent quality [3]. Automation of such recovery processes for worn part is of significant importance to overcome the intrinsic problems arising from part-to-part geometry variations and to achieve high efficiency when meeting the stringent quality requirements [4].

Reverse engineering, as a widely used automatic technique in manufacturing for new product/part design, has been introduced in surface modeling for the repair of mechanical components [5–8]. With the aid of RE technologies, a quick and accurate acquisition of the damaged areas of the part surface is attainable and thereby gives an invaluable basis for subsequent operations to bring the part back to a like-new condition. Typically, the 3D optical measurement devices are used to capture the surface geometry of the worn parts in form of 3D data. Then identification and positioning of the part's damaged area can be achieved through a registration operation by comparing the nominal CAD model with the 3D model of the defective part surface [9]. The nominal CAD model is the part's initial design model which reflects its originally intact surface geometry. When a nominal CAD model is not available, a reverse engineering process is required to reconstruct the original surface model based on the 3D model of the damaged surface [10,11].

However in the traditional reverse modeling, reconstruction of the nominal CAD model of the worn part takes consideration of the point clouds in the non-defective regions (intact point clouds) as well as the point clouds in the defective regions (defective point clouds). Since the component after deposited no longer represents its original shape, such reconstruction process by considering both the intact point clouds and
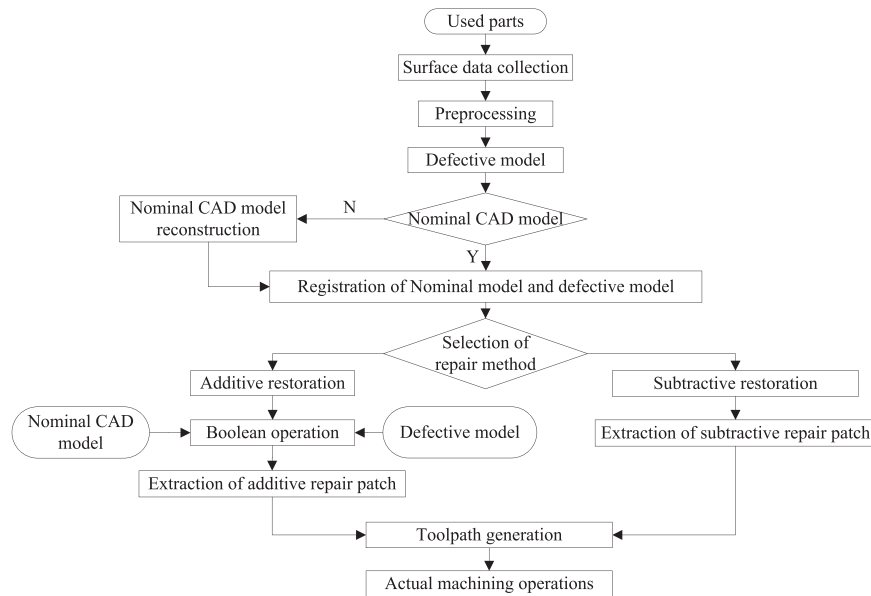
Fig. 1. RE aided remanufacturing framework for worn component.

the defective point clouds of the surface might lead to inaccuracy of model reconstruction. In this work, we use curvature and distance constraint to automatically identify the boundary of the part's damaged area and thereby eliminate these defective point clouds from the Prominent Cross-Section (PCS) based reconstruction process, seeking to achieve for a more accurate nominal CAD model of the part.

With the defective model and the nominal model, a registration operation is required to yield a best-fit position of two models by minimizing the distances between corresponding points [9]. As for registration, iterative closest point (ICP) algorithm and its variants are dominant techniques and widely used for robust rigid registration of 3D data [20–25]. However since the accurate 3D data of the part surface contains point clouds in the damaged area, the best-fitted parts do not match ideally but are in a relative position to each other as close as possible. In our experiment, the registration result of two models by using all the point clouds in the defective model is obviously unsatisfactory and poor as shown in Fig. 1(b). In order to achieve higher accuracy in registration results, a modified ICP algorithm combined with curvature and distance constraints is proposed to eliminate the unreliable correspondences pairs of two models from the registration process.

This paper introduces RE technologies and presents a systematic framework to aid the RE-based remanufacturing processes of worn parts, seeking to improve the reliability and efficiency of manual repair process. The proposed methodology integrates surface data collection via 3D optical devices, nominal model reconstruction, fine registration, extraction of additive/subtractive repair, tool path generation and actual machining process to enable the recovery of worn parts. Considering the point clouds in the damaged area of the part surface, we also focused on developing a more efficient method for reconstruction of the deposited surface of the worn part as well as fine registration of two models for accurate extraction of the repair patch for the damaged area. With the registration results of two models, a suitable repair strategy (i.e., additive or subtractive repair) can be determined for the recovery of the worn part. A CAD/CAM system (such as a CATIA software) is then used to generate tool paths for virtual repair process, based on which numerical control code (such as G-code) can be produced to drive machine tools for an actual repair process.

The rest of the paper is organized as follows. The related work is briefly reviewed in Section 2. Section 3 describes the framework of the proposed approach and some key steps. Section 4 and Section 5 give the implementation of the proposed reconstruction and registration

methods, respectively. Section 6 discusses the case study and experimental results. Section 7 summarizes the conclusions of the paper and discusses the future research directions.

2. Related work

The RE technologies can enable an easy acquisition of damaged areas of the damaged part and provides an invaluable basis for the implementation of recovery operations that are necessary to bring the part back to a like-new condition. A perusal of current studies [5–7,10,11] have introduced RE technologies to aid the remanufacturing process of worn parts/products. However, when RE technology is used for application, two difficulties inherent in the RE-aided process need in-depth studies to enhance efficiency and reliability.

A first group of researches has tacked the re-modeling of deposited surfaces of components where the original geometry has been damaged or missing. Based on 3D scanning data of the damaged surface, Wilson et al. [8] proposed a Prominent Cross Sections based algorithm to facilitate semi-automated reverse engineering and geometric reconstruction of a component. Considering parametric and geometric continuity of free form surface modeling, Yilmaz et al. [7] reconstructed the nominal surface model of the damage area by using the cross-section curves obtained from the polygonal model. A similar study was presented by Bagci [5] where the process of CAD model reconstructed from damaged and broken parts was explored. Ruan et al. [12] introduced a feature inducement technique to extract the features from the point clouds of a worn die and thereby resume the original basic feature morphology of the part's surface.

A second line of work looked into registration process of two models (i.e., the reconstructed CAD model and the defective one) aiming to obtain the accurate extraction of the repair patch for the defective area. Among those studies, one group introduced feature extraction methods [13–16] to approximately matching the two models especially in the case that point clouds are easily detected with obvious features. However, feature extraction is just an expedient solution by reducing the number of points for feasible registration and they do not truly solve the problem. Another group strived to formulate an optimization transformation to achieve a best-fit positon between two models through an iterative procedure, such as genetic algorithm [17], motion approximation [18], simulated annealing [19,20], etc., which is capable of exploring the search space of candidate solutions. Among those iteration methods, iterative closest point (ICP) algorithm [21] and its