Computer-Aided Design 45 (2013) 829–842

Contents lists available at SciVerse ScienceDirect

Computer-Aided Design

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

# Decomposing scanned assembly meshes based on periodicity recognition and its application to kinematic simulation modeling

Tomohiro Mizoguchi[a,*], Satoshi Kanai[b]

[a] Department of Computer Science, College of Engineering, Nihon University, 1 Nakagawara, Tokusada, Tamuramachi, Koriyama, Fukushima, 963-8642, Japan

[b] Graduate School of Information Science and Technology, Hokkaido University, Kita-14, Nishi-9, Kita-ku, Sapporo, 060-0814, Japan

ARTICLE INFO

*Keywords:*
X-ray CT scanning
Assembly
Periodicity recognition
Geometric synthesis
Kinematic simulation

ABSTRACT

Along with the recent growth of industrial X-ray computerized tomography (CT) scanning systems, it is now possible to non-destructively acquire the entire meshes of assemblies. This technology has the potential to realize an advanced inspection process of an assembly, such as estimation of their assembly errors or examinations of their dynamic behaviors in motion using a model reflecting real assembled situations. However, to realize the process, it is necessary to accurately decompose the mesh and to extract a set of partial meshes, each of which corresponds to a single part, from the entire meshes of assemblies measured from the CT scans. Moreover, it is required to create models that are ready for dynamic behavior simulations.

In this paper, we focus on CT scanned meshes of gear assemblies as examples, and propose beneficial methods for establishing such advanced inspections. We first propose a method that accurately decomposes the mesh into partial meshes, each of which corresponds to a single gear, using periodicity recognitions. The key idea is first to accurately recognize the periodicity of each gear, then to extract sets of topologically connected mesh elements where periodicities are valid, and finally to interpolate points in plausible ways from an engineering viewpoint to the area where surface meshes are not generated, especially the contact area between parts in the CT scanning process. We also propose a method for creating kinematic simulation models which can be used for a gear teeth contact evaluation using extracted partial meshes and their periodicities. Such an evaluation of teeth contacts is one of the most important functions in kinematic simulations of gear assemblies for predicting the power transmission efficiency, noise and vibration. The characteristics of the proposed method is that (1) it can robustly and accurately recognize periodicities from noisy scanned meshes, (2) it can estimate the plausible boundaries of neighboring parts without any previous knowledge from single-material CT scanned meshes, and (3) it can efficiently extract partial meshes from large scanned meshes containing millions of triangles in a few minutes. We demonstrate the effectiveness of our method on a variety of artificial and real CT scanned meshes.



## 1. Introduction

Mechanical products, especially those used in power transmission machinery, such as gear trains, bearings, ball screws, and chain sprockets, are composed as assemblies consisting of a set of parts. Since such assemblies are typically covered by housings, it is difficult to observe any assembly errors of any part or the dynamical behavior of their internal motions from outside, as shown in Fig. 1 (left). If one could capture the source of the assembly errors or the internal motions of the assemblies without any disassembling, this would enable advanced inspections which could greatly contribute to performance improvements of mechanical products.

On the other hand, industrial X-ray CT scanning systems have been developing rapidly, and it is now possible to non-destructively capture the volume model or the triangular mesh model of a whole assembly including all the parts placed inside the housings, as shown in Fig. 1 (center). However, such a model cannot be directly used for inspections of assemblies, because the portions of an individual part are not yet identified and separated. If the source of the assembly errors has to be investigated, the spatial position and orientation of each part should be identified. And if the behavior in motion has to be examined, the model of each part and their contact relations should be identified, kinematic or multi-body dynamic simulation models need to be

* Corresponding author. Tel.: +81 24 956 8748.
*E-mail addresses:* mizo@cs.ce.nihon-u.ac.jp (T. Mizoguchi), kanai@ssi.ist.hokudai.ac.jp (S. Kanai).

0010-4485/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cad.2011.02.001

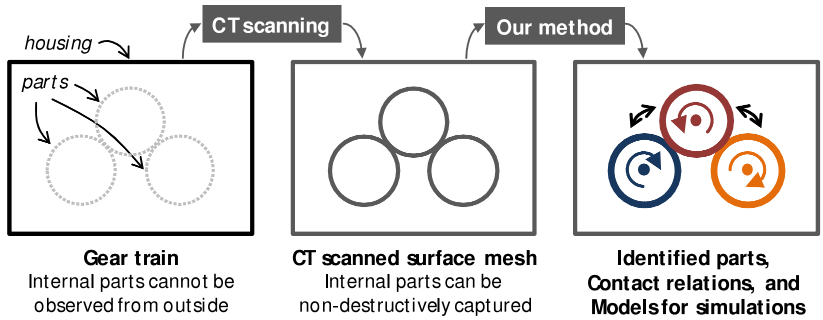


**Fig. 1.** An overview of our research.

created, and then the simulations must be performed. Hence, to achieve such advanced inspections of assemblies, it is necessary to extract a set of separated triangular mesh data, each of which corresponds to a single part, from their CT scanned data and to create models which can be used for estimating the assembly conditions and simulating the motions, as shown in Fig. 1 (right).

The problems become very difficult when we deal with single-material assemblies. Although the entire surface meshes of the assemblies can be acquired by the CT scan, the boundary information between parts cannot be clearly captured in the meshes. Therefore, using current methods, we cannot decompose the assembly mesh into a set of models, each of which corresponds to a single part, in straightforward way.

In this paper, we focus on the periodicities on the surfaces of assembly components, and propose beneficial methods that enable the advanced inspections of mechanical products based on periodicity recognitions. We first propose an automatic method that decomposes a CT scanned surface mesh of an assembly of parts into separated partial meshes, each of which corresponds to a single part, from a surface mesh of an assembly (subsequently referred to as "an assembly mesh") based on periodicity recognition. Our method recognizes a set of part portions having rotational periodicities from a CT scanned assembly mesh. Then, using the periodicities, the original part boundaries which cannot be captured by the CT scanning are estimated in a plausible way from an engineering viewpoint, and the assembly mesh is decomposed into separated parts along the boundaries. Our method enables the accurate decomposition of an assembly mesh composed of a single material, in which previous methods failed. And it also enables the generation of partial meshes in which some portions of the boundaries are interpolated. In addition, as an application of our mesh decomposition, we propose a new method for estimating teeth contacts of gear trains, which are the most frequently used assemblies in power transmission machineries. Our method can generate models for estimating gear assembly conditions and for performing kinematic simulations of the train, reflecting the real gear train measured by the CT scans.

We deal only with gear trains as examples in this paper, but our method is not limited to them. It can also be used for assemblies in which rotational periodicities exist in the contact area between parts, i.e., power transmissions, such as bearings and chain sprockets.

## 2. Related works

### 2.1. Periodicity recognition

Many algorithms have been proposed for recognizing periodicities in two-dimensional (2D) images. Lin et al. [1] proposed an algorithm that recognizes a translational periodicity in a 2D texture based on the generalized Hough transform. Liu et al. [2] proposed an algorithm that recognizes a variety of periodicities, including translations, rotations, and reflections, based on crystallographic theory. Müller et al. [3] proposed an algorithm for extracting a translational periodicity from a 2D façade image of a building by subdividing the image and evaluating the mutual information between the subdivided images. Musialski et al. [4] proposed an algorithm for detecting regular structures on the 2D façade images and using detected structures for repairing the images by propagating them and removing unwanted contents. However, such algorithms cannot be easily extended to 3D meshes.

Periodicity recognitions have strong relations with symmetry detections in the sense that they both find pairs of local shapes that can be closely matched to each other under certain transformation class. Recently, symmetry detections have gained much attention, and many algorithms have been proposed in the computer graphics field [5–7]. However, these algorithms aim only at detecting pairs of congruent regions and their transformations, and they cannot extract the periodicities.

As for 3D periodicity recognition, Liu et al. [8] proposed an algorithm that extracts a single region from the periodically displaced ones in a 3D mesh of a relief. However, this method requires user interactions for the extraction, and it cannot extract the parameters defining their periodicity. Pauly et al. [9] proposed an algorithm that could discover a class of periodicities defined by a combination of translations, rotations, and uniform scaling. The algorithm was based on computations of transformations under which pairs of local coordinate systems around the points can be matched, their voting to a transformation space, grid fittings in transformation space for sets of voted points, and the simultaneous registration in 3D space. However, the algorithm needs to evaluate a huge number of local transformations between a point pair for stably discovering periodicities on large and noisy scanned data; therefore, it needs a long computational time for such data. Bokeloh et al. [10] proposed an algorithm for detecting a set of congruent regions on 3D scanner data by analyzing feature lines. However, it cannot explicitly detect the parameters defining the periodicities that regions form. Zheng et al. [11] proposed an algorithm for consolidating 3D scans of buildings by detecting and utilizing large-scale repetitions. However, it requires user interactions for detecting repetitions, especially from significantly noisy, incomplete, and outlier-corrupted scans.

Li et al. [12] proposed an algorithm for detecting a wide class of approximate symmetries from B-rep CAD models by extracting characteristic points and analyzing their connectivity. The detected symmetries were then used for estimating design intents from B-rep models [13]. However, the symmetry detection algorithm proposed in [12,13] may fail to accurately detect symmetries in the case of noisy CT scanned meshes. Moreover, the method cannot explicitly compute the parameters defining the periodicities such as rotational axes, basis angles, and translational basis vectors.