Available online at www.sciencedirect.com

ScienceDirect

Journal of Computational Design and Engineering 2 (2015) 183–194

www.elsevier.com/locate/jcde

Thickness and clearance visualization based on distance field of 3D objects

Masatomo Inui, Nobuyuki Umezu*, Kazuma Wakasaki, Shunsuke Sato

Ibaraki University, 4-12-1 Nakanarusawa, Hitachi, Ibaraki 316-8511, Japan

Received 28 January 2015; received in revised form 14 April 2015; accepted 15 April 2015
Available online 28 April 2015

Abstract

This paper proposes a novel method for visualizing the thickness and clearance of 3D objects in a polyhedral representation. The proposed method uses the distance field of the objects in the visualization. A parallel algorithm is developed for constructing the distance field of polyhedral objects using the GPU. The distance between a voxel and the surface polygons of the model is computed many times in the distance field construction. Similar sets of polygons are usually selected as close polygons for close voxels. By using this spatial coherence, a parallel algorithm is designed to compute the distances between a cluster of close voxels and the polygons selected by the culling operation so that the fast shared memory mechanism of the GPU can be fully utilized. The thickness/clearance of the objects is visualized by distributing points on the visible surfaces of the objects and painting them with a unique color corresponding to the thickness/clearance values at those points. A modified ray casting method is developed for computing the thickness/clearance using the distance field of the objects. A system based on these algorithms can compute the distance field of complex objects within a few minutes for most cases. After the distance field construction, thickness/clearance visualization at a near interactive rate is achieved.

Keywords: Inscribed spheres; Spatial coherence; Parallel computation; Axis-aligned bounding box (AABB); Modified ray casting; GPU

1. Introduction

Thickness and clearance are basic parameters in product design. The thickness of individual walls and ribs is important for calculating allowable stresses and strains in functional analysis. In general, modern products are designed to be lightweight by reducing the wall thickness by as much as the required structural strength will permit. Thickness evaluations are important in other design tasks, such as for the shape of the insulator that shields the noise of an automobile engine. The insulator shape must have a sufficient and constant thickness across its surface to reduce the volume of transmitted sound.

Part thickness is important from the viewpoint of manufacturability. In injection molding, hot melted plastic material is forced into a mold cavity so that it cools and hardens to take the shape of the required part. It is difficult to insert this plastic material into very thin wall shapes. If the wall thickness is large and not uniform, local depressions (sink marks) may appear because of the excessive shrinkage of thicker regions during the cooling process [1,2]. To assist the machine designer, some CAD systems provide part thickness visualization functions [3–5].

The thickness of the complementary shape of a part should correspond to the clearance around the part. Sufficient clearance between engine components is necessary for cooling their surfaces using air flow. Moreover, clearance affects the accessibility of cutting tools and fixtures to the part surface during the machining process. Clearance evaluation is an important process for automobile safety. The international regulations state that exterior surface parts that could be contacted by a sphere of radius 50 mm must have a roundness of greater than R2.5 [6,7]. Detecting the sphere contact shape is equivalent to identifying part surfaces with a clearance of greater than 100 mm.

In this paper, we propose a novel method for visualizing the thickness and clearance of three-dimensional (3D) objects in a polyhedral representation. The proposed method employs the distance field of an object for the visualization. Consider a solid object in a box-like space. The 3D distance field of the object is a uniform cell decomposition of the space where at each cubic cell

*Corresponding author. Tel. +81 294 38 5262.
E-mail address: umezu@mx.ibaraki.ac.jp (N. Umezu).
Peer review under responsibility of Society of CAD/CAM Engineers.

http://dx.doi.org/10.1016/j.jcde.2015.04.001

(voxel) in the space, the distance from the center of the voxel to the closest point on the object surface is recorded. In addition, other properties such as the identification number of the closest polygon may be recorded in the voxel. The usage of recorded distance values depends on whether the voxel is internal or external to the object. A distance field with internal voxels is used for thickness visualization, whereas clearance visualization is realized using a distance field with external voxels.

The distance field of a polyhedral object can be obtained via iterative computation of the distance between the center of each voxel and the surface polygons. Polygons on the object surface can be classified into groups according to their proximity. For each group, an axis-aligned bounding box (AABB) that tightly encloses the polygons is defined [8]. Using an AABB tree, i.e., a hierarchical structure of boxes, polygons that are sufficiently close to a given voxel can be selected. Similar sets of polygons are usually selected as close polygons for close voxels. On the basis of this spatial coherence, a novel parallel algorithm is designed in order to compute the distances between a cluster of close voxels and the polygons selected by the culling operation so that the fast shared memory mechanism of the graphics processing unit (GPU) is fully utilized.

Thickness t of a 3D object at point $\boldsymbol{p}$ on the surface is defined as the diameter of the maximum inscribed sphere $\boldsymbol{S}$ contacting the surface at $\boldsymbol{p}$ (see Fig. 1) [3]. Similarly, clearance c at $\boldsymbol{p}$ is defined as the diameter of the maximum circumscribed sphere $\boldsymbol{T}$ externally contacting the surface at $\boldsymbol{p}$. The thickness/clearance of objects can be visualized by distributing points on the visible surface of the objects and painting them with a unique color corresponding to their thickness/clearance values. A novel method, namely, modified ray casting, is developed for computing the thickness/clearance at each surface point. Ray casting is a typical method for visualizing 3D scalar fields. In regular ray casting, a line of sight (ray) through the object is assigned for each pixel. Pixel color is determined by accumulating values in the scalar field along the ray. In our modified method, each ray is cast in the same way as in the regular method until it reaches a point on the object surface. Then, the ray turns in a direction perpendicular to the surface and proceeds into the distance field to detect the first peak value in the field that corresponds to the radius of the maximum inscribed or circumscribed sphere contacting the surface at that point.

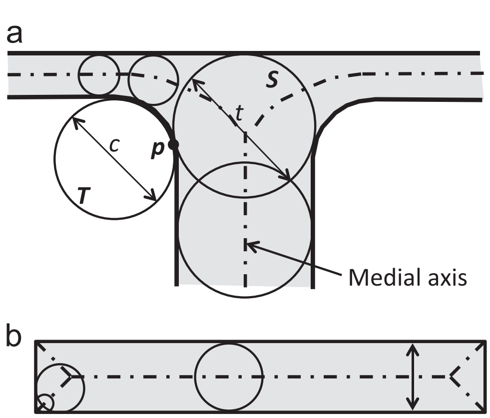

Fig. 1. Thickness/clearance definitions in the sphere method.

The remainder of this paper is organized as follows. Section 2 provides some definitions of thickness and clearance for 3D objects. In addition, it briefly reviews previous studies on distance field computation and thickness/clearance visualization. Section 3 summarizes the contributions of the present study. Section 4 describes a parallel distance field computation algorithm and its implementation using Compute Unified Device Architecture (CUDA) [9], an industry-standard GPU computation environment. Further, it discusses the use of shared memory on the basis of spatial coherence of the distance field. Section 5 describes the modified ray casting method for visualizing the thickness/clearance of objects. Some methods for improving the visualization performance are also discussed. Section 6 presents thickness/clearance visualization results for sample objects. Using the parallel processing capability of the GPU, a distance field with around 80 million voxels can be computed within a few minutes at a sufficiently high speed for practical use. After the distance field is obtained, the thickness/clearance of an object can be visualized at a near-interactive rate by using our modified ray casting algorithm. Finally, Section 7 summarizes our findings and concludes the paper.

2. Related studies

2.1. Thickness/clearance definitions and analysis

In mechanical drawing, thickness is defined as the distance between points on two opposite parallel surfaces. This definition is not suitable for objects with complex curved surfaces. The two major methods for defining the thickness of a 3D object are the ray method and the sphere method [1,3,10]. In the ray method, the thickness at a point $\boldsymbol{p}$ on a surface is given by using a ray originating from $\boldsymbol{p}$ in a direction opposite to the local outward normal. The Euclidean distance d between $\boldsymbol{p}$ and another point $\boldsymbol{q}$ corresponds to the thickness where $\boldsymbol{q}$ is an intersection point between the ray and the surface immediately opposite to the object (see Fig. 2). This definition is ambiguous if the two surfaces containing $\boldsymbol{p}$ and $\boldsymbol{q}$ are not parallel, because the thickness values at $\boldsymbol{p}$ and $\boldsymbol{q}$ become different.

The sphere method always returns consistent results. In this method, the thickness at a point $\boldsymbol{p}$ on a surface is given by the diameter of the maximum inscribed sphere contacting the surface at $\boldsymbol{p}$ (see Fig. 1(a)). Since the locus of the center of the maximum inscribed sphere corresponds to the medial axis of the object (dashed lines in the figure) [11], the thickness at a surface point corresponds to twice the distance between the point and the medial axis. In general, the thickness given by the sphere method is consistent with the mechanical drawing definition of thickness for a plate-like shape, except at its corners, where the diameter of the

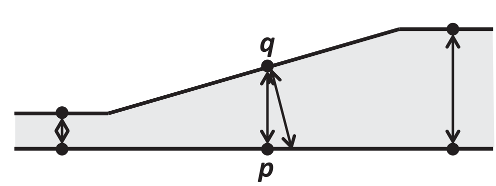

Fig. 2. Thickness definition in the ray method.