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Direct construction of a four-dimensional mesh model from a three-dimensional object with continuous rigid body movement

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Abstract

In the field of design and manufacturing, there are many problems with managing dynamic states of three-dimensional (3D) objects. In order to solve these problems, the four-dimensional (4D) mesh model and its modeling system have been proposed. The 4D mesh model is defined as a 4D object model that is bounded by tetrahedral cells, and can represent spatio-temporal changes of a 3D object continuously. The 4D mesh model helps to solve dynamic problems of 3D models as geometric problems. However, the construction of the 4D mesh model is limited on the time-series 3D voxel data based method. This method is memory-hogging and requires much computing time. In this research, we propose a new method of constructing the 4D mesh model that derives from the 3D mesh model with continuous rigid body movement. This method is realized by making a swept shape of a 3D mesh model in the fourth dimension and its tetrahedralization. Here, the rigid body movement is a screwed movement, which is a combination of translational and rotational movement.

Keywords: Four-dimensional mesh model; Three-dimensional mesh model; Fourth dimension; Rigid body movement

1. Introduction

In the field of design and manufacturing, there are various applications that represent the time change of a three-dimensional (3D) object. They are realized by preparing time-series data of 3D objects, giving movement operation to an initial state, or by interpolating among different states as shown in Figures 1(a), 1(b) and 1(c). However, these methods are insufficient to represent spatio-temporal changes of 3D objects' shapes, positions and orientations continuously and with high accuracy. Therefore, the four-dimensional (4D) mesh model and its modeling system have been proposed [11]. The four-dimensional model enables the representation of dynamic states of 3D objects as a static geometric entity in a higher-order space of space-time extension as presented in Figure 1(d). For example, it helps to solve problems of collision avoidance between 3D objects including deformation and motion. Another example is representing the continuous process of workpiece transformation in five-axis machining using the 4D mesh model [6]. However, the construction of a 4D mesh model is realized with a time-series 3D voxel data based method that is memory-hogging and requires longer computing time.

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The objective of this study is to propose another approach of constructing a 4D mesh model using a 3D mesh model with rigid body movement. This method enables construction of a 4D mesh model by decreasing the number of vertices, tetrahedra and creation-time more than in the existing method.

At first, this paper describes the related works and the overview of the 4D mesh model and its modeling system. Then, the proposed method of constructing the 4D mesh model is explained in detail. Finally, a comparison with the time-series voxel data based method is reported.

2. Related studies and our previous works

In general, the representation of the time change of a 3D object is realized by preparing time-series data of 3D objects,

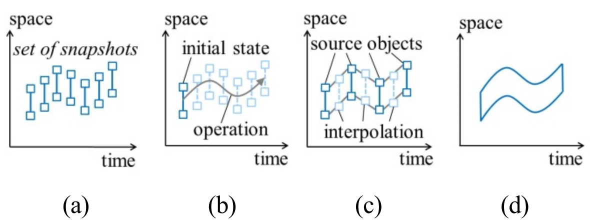

Figure 1. Several approaches of representing time change of a 3D object (space is reduced to 1D): (a) time-series data, (b) initial state and operation of time change, (c) interpolation, (d) 4D model.

giving movement operation to an initial state, or by interpolating among different states. An example of preparing time-series data of 3D objects is the 3D Video [9]. 3D Video is a medium that records a real time-varying 3D object using several cameras from several perspectives. The object's 3D shape is reconstructed using a volume intersection method, and finally, the constructed 3D models are colored by applying the real camera images.

Several physics simulations and machine tool simulations are realized by giving movement operation to an initial state. The state is updated in sequence for each unit time. In the physics simulations, the behavior of a 3D object is determined by the given "force" that is the factor of time change. Recently, physics simulation can be implemented easily into a computer using physics engines like PhysX [13] and Havok [4]. As well as in the machine tool simulations, the movement of a machine tool is driven by operation commands like G-code [5].

An example of interpolating among different states is morphing of a 3D polygon model [7]. Morphing is a technique to change a source object gradually through intermediate objects into a target object. It is realized by constructing the correspondence map among the meshes of the source object and the target object, and computing interpolating points between both objects.

As explained above, the current approaches of representing the time change of a 3D object are realized by preparing a set of static states. They only have discrete information along the time axis and cannot describe the time change continuously with high accuracy. Furthermore, since the information along the time axis is discrete, problems can occur on collision detection among several objects. Therefore, we proposed the 4D mesh modeling and its modeling system. In our previous works [6, 11, 12], a 4D mesh model is constructed from time-series 3D voxel data. Voxel is a simple way to represent 3D objects' shapes and it is also possible to apply higher dimensional Marching Cubes algorithm to construct a 4D mesh model. However, dealing with high-resolution voxel models consumes a large amount of memory.

3. Overview of four-dimensional geometric modeling

3.1 Four-dimensional mesh model

In this study, the fourth dimension (4D) is a 4D Euclid space that includes three-dimensional space and one-dimensional time. Figure 2 shows the four topological elements of 4D topologies: vertices, edges, faces and cells. A cell is a 3D subspace in a 4D space and the simplest cell is a tetrahedron. A pentachoron is a 4D simplex that is bounded by five tetrahedral cells. In addition, a 4D cube is called a hypercube and consists of 16 vertices, 32 edges, 24 faces and 8 cells. A 4D mesh model is defined as the 4D object model that is bounded by tetrahedral cells. As shown in Figure 3, 3D models are obtained by extracting the cross-section of a 4D mesh model.

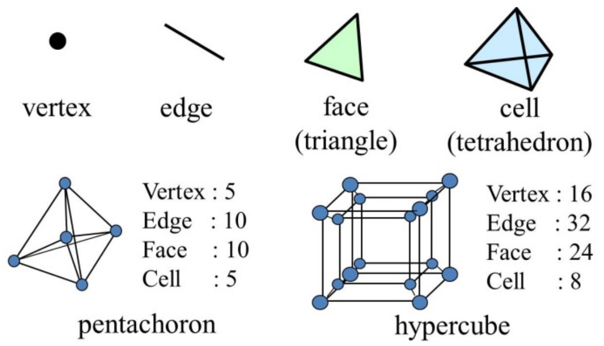

Figure 2. Four elements of 4D topologies and the basic 4D shapes.

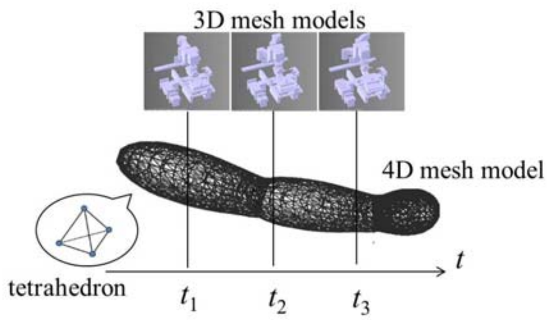

Figure 3. 4D mesh model representation.

3.2 4D mesh modeling system

Figure 4 describes the flow of the current 4D mesh modeling system. Time-series 3D voxel data are needed to construct a 4D mesh model (Figure 4 A), and for weaving from the 3D voxel models to a 4D mesh model, the 4D Marching Cubes algorithm [12] is used (B and C). The 4D Marching Cubes algorithm is an extension of the Marching Cubes algorithm [8] to 4D, and it is based on a higher dimensional isosurfacing algorithm [3].

There are various applications to manage the 4D mesh model (D, E, F and G). It is possible to project a 4D mesh model into 3D and visualize it as a 3D envelope model (D). The 3D envelope model is constructed by applying the Ball-Pivoting algorithm [2] to the 4D mesh model's vertices that is projected into the 3D space. In addition, cross-section extraction from the 4D mesh model by hyper-plane cutting is also possible (E). It is realized by applying the Marching Tetrahedra algorithm [10] to each tetrahedral cell of the 4D mesh model. Employing the collision detection method between 4D objects (F), a method of collision resolution by shape deformation for collision avoidance between moving objects is also proposed (G). The 4D collision detection method is an extension of collision detection method using AABB tree in 3D [17].

As mentioned above, the construction of a 4D mesh model

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