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Junction-aware shape descriptor for 3D articulated models using local shape-radius variation

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ABSTRACT

An articulated model is composed of a set of rigid parts connected by some flexible junctions. The junction, as a critical local feature, provides valuable information for many 3D semantic analysis applications such as feature recognition, semantic segmentation, shape matching, motion tracking and functional prediction. However, efficient description and detection of junctions still remain a research challenge due to high complexity of 3D articulated deformation. This paper presents a new junction-aware shape descriptor for a 3D articulated model defined by a closed mesh surface. The core idea is to exploit the local shape-radius variation for encoding junction information on the shape boundary surface, where the shape-radius at each point on the surface is the radius of corresponding medial balls within the shape. The presented descriptor is typically computed using a center-surround filter operator, which calculates the Gaussian-weighted average of shape-radius in the neighborhood of each point on the surface. Our descriptor is robust to articulation and can reflect the junction feature well without any explicit shape decomposition or prior skeleton extraction procedure. The experimental results and several potential applications are proposed for demonstrating the effectiveness of our method.

1. Introduction

Non-rigid shape analysis [1,2] has been receiving growing attention in many applications in computer vision, computer graphics, pattern recognition, etc. Non-rigid shapes are ubiquitous in the world and, due to their physical properties, can undergo variant deformations [1]. One simplified strategy to non-rigid shape analysis is based on *articulated models* [2–5], which assumes that the non-rigid shape is composed of a set of rigid parts connected by some flexible junctions (or named *joints/hinges* in some literature [2,6]). Each of the rigid parts has a certain degree of freedom to move, and junctions are relatively small compared with parts connected.

The junction, as a critical local feature, provides valuable information for analyzing 3D articulated models. Many applications of 3D semantic analysis such as feature recognition, semantic segmentation, shape matching, motion tracking and functional prediction, can benefit from automatic detection of junctions. For instance, detection of junctions and parts can improve the performance of shape segmentation of 3D articulated models [7,8]. In medical applications, some visual tasks such as vessel

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tracking may rely on junction extraction results, which can facilitate diagnosis and understanding of pulmonary vascular diseases [9]. In molecular structure analysis, many flexible molecules can be regarded as 3D articulated objects with special hinge/junction sites [6], where identifying such hinge sites is a fundamental problem for protein functional prediction and structure comparison. However, efficient description and detection of junctions still remain a research challenge due to the high complexity of 3D articulated deformation.

To address this issue, this paper presents a new junction-aware shape descriptor for a 3D articulated model defined by a closed mesh surface. To encode junction information on the shape boundary surface, the core idea is to exploit the local *shape-radius* variation, where the shape-radius [10,11] at each point on the boundary surface is the radius of its corresponding medial balls within the shape. Our algorithm consists of the following steps. First, the local shape-radius at each vertex of mesh surface is approximated using the classical ray-shooting technique, which associates volumetric information of the shape to the mesh surface. Then we setup a neighboring range for each vertex on the mesh and calculate the difference of local shape-radius within this range to measure the mount of their variance. Finally, a center-surround filter operator, which calculates the Gaussian-weighted average of shape-radius variance, assigns descriptive value to each vertex as its junction-aware descriptor value. One advantage of the presented descriptor is that it is insensitive to articulation deformation and can reflect the junction feature well without any explicit shape decomposition or prior skeleton extraction procedure. The experimental results and several potential applications are proposed for demonstrating the effectiveness of our method.

The main contributions of our work can be summarized as follows.

- A junction-aware shape descriptor is presented for 3D articulated models, which is defined as local shape-radius variation for encoding junction information at each point on the boundary surface.
- A center-surround filter operator is designed for quantifying local shape-radius variation, which calculates the Gaussian-weighted average of shape-radius in the neighborhood of each point on the surface.
- Several potential applications, such as initial junction extraction and handle loop approximation, are proposed for demonstrating the capability and effectiveness of our method.

2. Related work

There are several possible approaches to solve junction detection/extraction of 3D models. One type of approaches is based on shape structure analysis [6,12], which is often used in protein structure analysis. If given a pair of proteins, their junction positions can be found through structure alignment of pairwise proteins [6]. If given a single protein without comparing with others, its junction positions can be predicted with the help of additional chemical information [12]. However, protein structures and additional non-geometric information are not explicitly available for general 3D models in computer vision and computer graphics.

Another type of approaches is based on skeleton extraction (e.g. [13,14]). Those approaches first extract the topological skeleton of a 3D model and then identify its junctions and branches based on further skeleton analysis. However, skeleton extraction is often sensitive to perturbation and noise on the object's boundary, while robust skeleton calculation is not trivial. In addition, skeleton extraction only induces the rough junction positions, while indication of final junction regions still needs to be relocated on the boundary surface. Several robust skeleton extraction methods [11,13] may provide a prior reference for the purpose of junction detection, but this remains a separate research topic. In contrast, our method directly highlights the junction regions on the boundary surface without requiring any prior skeleton extraction procedure.

The third type of approaches is based on shape segmentation. After dividing a 3D model into meaningful parts, the intersection curves where two or more parts meet (referred as "cuts" in some literature) can assist to find the candidate junctions. However, most of segmentation approaches have to face the same question of how to define parts or part boundaries [7,11,15]. The classical part-type segmentation techniques are to analyze the geometric structure of an individual shape in order to detect its parts or part boundaries (e.g. [7,8,11]). In essence, there is a strong connection between part-partitioning and skeletonizing [8,15]. When using part-type segmentation to assist junction identification, it will be a type of "chicken-or-egg" dilemma, since the definition of a part implies the identification of clear-cut junction. In contrast, our method produces a junction-aware shape descriptor without any explicit shape segmentation procedure.

The fourth type of approaches is based on shape descriptor. Our method also falls into this type. A shape descriptor is a concise representation of the shape that expresses some specific properties [4,10]. A simple realization of junction detection can be based on measuring the local surface properties of shape boundary, such as curvature [16] and gradient [17]. However, such measurements are limited by their local surface nature and are very sensitive to local surface noise. There have been some extra efforts to develop new shape descriptors for detecting important regions or features on boundary surfaces, such as distinctive regions [18,19] and salient regions [16,20]. However, most of the shape descriptors are surface-based measurements, which do not explicitly consider the volumetric information inside 3D shapes. The work most related to ours is the *shape diameter function* (SDF) [10,11,15] presented by Shamir et al. The SDF is a scalar function defined on the boundary surface of a 3D shape, but it provides a link between the local volume of the shape and its boundary through mapping volumetric information onto the surface boundary. In essence, the shape diameter is approximated instead of computing the actual medial axis. As a shape descriptor, the SDF is pose-invariant. Another existing volume-oriented surface