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Learning to segment and unfold polyhedral mesh from failures

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ABSTRACT

Folding planar sheets to make 3D shapes from is an ancient practice with many new applications, ranging from personal fabrication of customized items to design of surgical instruments for minimally invasive surgery in self-folding machines. Given a polyhedral mesh, unfolding is an operation of cutting and flattening the mesh. The flattened polyhedral *nets* are then cut out of planar materials and folded back to 3D. Unfolding a polyhedral mesh into planar nets usually require segmentation. Either used as a preprocessing step to simplify the mesh and provide semantics or as the result of unfolding to avoid overlapping, the segmentation and the unfolding operations are decoupled. Consequently, segmented components may not be unfoldable and unfolded nets usually provide no semantic meaning and make folding difficult. In this paper, we propose a strategy that tightly couples unfolding and segmentation. We show that the proposed method produces unfoldable segmentation that resembles carefully designed paper craft. The key idea that enables this capability is an algorithm that learns from failed unfoldings.

1. Introduction

Making 3D shape from planar sheets is an ancient practice with many new applications, ranging from personal fabrication of customized items [1], which is fueled by the recent maker movement, to design of specialized instruments in self-folding machines [2] mostly due to the advances in active materials. One of the prevailing methods for creating 3D objects from planar materials is “unfolding and folding” [3].

Unfolding involves cutting a given polyhedral mesh into surface patches and then flattening them. To ensure that a surface patch can be flattened, existing methods [4,5] either approximate the patch by developable surfaces or ensure that the patch forms a *net*, i.e., a patch that can be cut and flattened by rotating its facets along one of the incident edges without overlapping with other facets [6]. The flattened patches are then cut out of planar materials and folded back to 3D.

Either cutting a polyhedral mesh into nets or approximating with developable surfaces, segmentation of the mesh (a process of breaking a mesh into multiple components) is usually involved; either before the unfolding algorithm is applied or as a product of the unfolding algorithms. Segmentation before unfolding is used as a preprocessing step to provide simplicity, as well as semantics [7,5]. As shown in Fig. 1, segmentation is also a common technique used by paper craft designers. In the literature, shape segmentation is usually done without considering foldability [8,9]. Consequently, surface patches produced by shape segmentation may still be cut into multiple nets or approximated by multiple developable surfaces which lose the semantic meaning and make folding and assembly less intuitive thus time-consuming.

Segmentation can also be produced in order to avoid overlapping in the nets [10]. However, these nets often provide little shape information. Examples of these nets produced by the existing methods can be found in Figs. 9 and 10. In both scenarios, segmentation and unfolding operations have been decoupled.

In this paper, we propose a strategy that produces polyhedral nets by tightly coupling the edge unfolding and surface segmentation operations. Our objective is to algorithmically produce nets that resemble carefully designed paper craft such as those shown in Fig. 1. Fig. 2 shows an example output of the proposed method. We show that the proposed method naturally provides semantic segmentation of the input mesh by unfolding the entire mesh multiple times. Even though most likely, all of these unfoldings will contain overlaps, the proposed method learns from these failures and identifies parts that may be unfolded into valid nets.

Existing shape segmentation methods rely heavily on shape features, such as curvature and geodesic distance. On the contrary, the proposed method creates the segmentation directly from information obtained from edge unfolding, therefore, ensures that every component in the segmentation can be unfolded into *a single net* and maintain its semantics. An overview of the proposed method can be found in Fig. 6 and we will discuss the details in

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Fig. 1. A commercial paper craft designed by KitRex [11] that shows segmented parts with anatomic meanings.

Fig. 2. *Top row*: the "Dancing Children" statue (3000 triangles) is segmented into 16 parts by the proposed method. Most of these parts corresponds to the heads, torso, legs of the model. The unfolded nets are shown in the middle. *Second row*: nets and the folded parts. *Third row*: a crafted paper model, which is about 30 cm wide, 11 cm deep and 22 cm tall. *Bottom row*: an optimization method proposed by Takahashi et al. [12] segments the same model into 21 nets that do not provide semantic information.