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# Rigidity controllable as-rigid-as-possible shape deformation

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ABSTRACT

Shape deformation is one of the fundamental techniques in geometric processing. One principle of deformation is to preserve the geometric details while distributing the necessary distortions uniformly. To achieve this, state-of-the-art techniques deform shapes in a locally as-rigid-as-possible (ARAP) manner. Existing ARAP deformation methods optimize rigid transformations in the 1-ring neighborhoods and maintain the consistency between adjacent pairs of rigid transformations by single overlapping edges. In this paper, we make one step further and propose to use larger local neighborhoods to enhance the consistency of adjacent rigid transformations. This is helpful to keep the geometric details better and distribute the distortions more uniformly. Moreover, the size of the expanded local neighborhoods provides an intuitive parameter to adjust physical stiffness. The larger the neighborhood is, the more rigid the material is. Based on these, we propose a novel rigidity controllable mesh deformation method where shape rigidity can be flexibly adjusted. The size of the local neighborhoods can be learned from datasets of deforming objects automatically or specified by the user, and may vary over the surface to simulate shapes composed of mixed materials. Various examples are provided to demonstrate the effectiveness of our method.



## 1. Introduction

Shape deformation is a fundamental research area in computer graphics. For character animation, skeleton based methods are widely used [1,2]. Such methods however need the users to take extra effort to build the skeletons. Alternatively, some deformation methods [3,4] take cages (simplified geometry enclosing the deforming shapes) as proxies to deform the shapes. Again efforts are needed to build cages.

Compared with skeleton and cage based deformation methods, surface based deformation methods are more intuitive and more flexible to model a variety of shapes, with no need to cope with extra proxies. Laplacian deformation methods [5–8] have been explored extensively for surface based deformation. The difference between the Laplacian coordinates of the deformed and the original shapes is minimized to keep the local geometric details. However, both the positional and rotational constraints for the deformation handles are required for these methods to work. As shown in [9], positional and rotational constraints need to be assigned *compatibly* to avoid artifacts. This is non-trivial and requires additional effort/expertise from the user.

Another general approach to keep geometric details is to deform shapes locally rigidly, just as rotating and translating shapes globally rigidly would not change their geometry. This principle is modeled as an as-rigid-as-possible (ARAP) energy which has been widely used in geometric processing. Based on this energy, Sorkine et al. [10] present a mesh deformation method. Only positional constraints need to be specified at deformation handles. The local rotation of the deformed surface can be estimated automatically during the iterative optimization. This makes interactive modeling much easier and substantially reduces the effort of modeling tasks. The ARAP deformation effectively preserves geometric features and distributes distortions uniformly, which leads to more visually pleasing deformation results than previous methods. The ARAP deformation formulation has also been integrated into various applications in geometry processing. The ARAP deformation method has recently been improved for efficiency [11] and effectiveness [12].

The mechanism of the traditional ARAP deformation [10] is to keep geometric features by deforming the shape locally rigidly. To distribute distortions uniformly over surfaces, local transformation consistency is enforced based on 1-ring neighborhoods of vertices. As shown in Fig. 1, the 1-ring neighborhoods of adjacent vertices share a single edge, so the consistency

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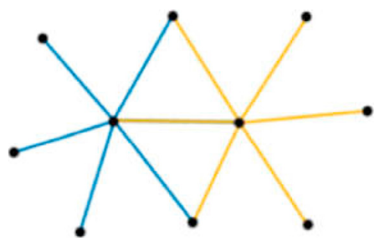

**Fig. 1.** The single overlapping edge of two adjacent 1-ring vertex neighborhoods.

constraint of neighboring rigid transformations is relatively weak. As a result, ARAP deformation results behave as if they are made of soft plastic material.

In this paper, we further explore the ARAP energy. Our key observation is that expanding local neighborhoods will enlarge overlapping areas between adjacent vertices which helps to enhance the coherence of local rigid transformations. As a result, the size of local neighborhoods provides a feasible way to control the appearance of deformation. The larger the size is, the better the local geometric details would be kept, or in other words, the material will look more rigid. By varying this parameter, the appearance of deformation ranges from softer plastic material with smaller local neighborhoods to harder material such as iron. The former is elastic and flexible, whereas the latter is more rigid and harder to bend/stretch. Another advantage of such enhanced rigid transformation consistency is it reduces the variability of local rigid transformations, and hence the optimization will converge with fewer iterations.

Real-world objects are often composed of different materials. Our approach allows such situations to be well simulated by varying the neighborhood sizes across the objects to indicate desired stiffness. Shapes with different local neighborhood sizes can be effectively optimized in a unified framework.

The contributions of this work are summarized as follows:

- We propose a rigidity controllable deformation method by using ARAP deformation with adjustable neighborhood sizes. By using a local neighborhood size suitable to the material, our method produces more natural deformation than state-of-the-art methods.
- Our unified framework allows varying local neighborhood sizes across the surface, simulating objects made of materials with different stiffness. Realistic deformation results are obtained for such cases.
- In addition to user specified neighborhood sizes, we also develop an automatic method to set neighborhood sizes by analyzing a collection of deforming objects, such that the neighborhood sizes are adapted to local stiffness.

We review the most related work in Section 2. The detailed algorithm is described in Section 3. Results and discussions are presented in Section 4. Finally, limitations and future work are given in Section 5.

## 2. Related work

Shape deformation is an active research area in computer graphics with a large amount of related research work. For complete and detailed surveys please refer to [13–15]. In this section, we review the work most related to ours. In order to simulate realistic shape deformation, the pioneer research work [16,17] deforms the shapes according to the physical laws. These physically based methods however are computationally intensive and the parameters derived from physical rules cannot be adjusted intuitively.

To generate visually pleasing deformation results, geometric details should be preserved after the shape is deformed. One typical approach is to preserve the Laplacian differential coordinates [5–8] during the shape deformation. These differential coordinates based methods need the user to specify compatible positional and rotational constraints for deformation handles. As shown in [18], incompatible constraints will introduce artifacts. Popa et al. [19] deform the shape with different material properties based on the deformation gradient method. Again, rotational constraints of the deformation handles should be assigned. Our method allows materials with different stiffness to be simulated, while only requiring positional constraints at handles which makes the modeling procedure much easier. For human body deformations, Murai et al. [20] propose a sophisticated mathematical model to learn parameters for simulating deformation dynamics of soft human tissues. Compared with this work, our work uses a simpler model and can deal with general shapes.

Another approach to preserving geometric details is to keep deformation rigidly. Global rigid transformation while being distortion free is not suitable when non-rigid deformation is involved. Deforming shapes locally rigidly keeps geometric details and makes less distortion. This concept has been modeled as the as-rigid-as-possible (ARAP) deformation energy, which has been widely used in geometric modeling, such as shape interpolation [21,22] and 2D shape manipulation [23]. Sorkine et al. [10] propose a 3D mesh deformation method by using this ARAP technique. This state-of-the-art work often deforms shapes with visually pleasing results. Optimizing the ARAP energy in the $L_1$ norm instead of the traditional $L_2$ norm tends to distribute the distortions sparsely to fewer places thus keep geometric features better for most areas [24]. Zohar et al. [12] augment the ARAP energy with a rotation difference term to improve smoothness of relative rigid rotations (SR-ARAP). Gao et al. [25] blend several reference shapes with the ARAP energy for data-driven morphing. The ARAP based shape optimization framework has also been used for shape registration [26] and parametrization [27]. Chao et al. [28] present a continuous ARAP energy formulation. Based on optimizing ARAP energy in the 2-ring neighborhood, Gao et al. [29] propose an approach to data-driven shape deformation. For animation of articulated shape characters, the ARAP energy is integrated into the linear skinning deformation method [30]. The ARAP energy has also been applied to dynamic shape reconstruction [31,32]. Yang et al. [33] consider adjusting deformation stiffness using different neighborhood sizes. Their method however is based on voxels, which suffers from high computational costs when the grid is dense, or is unable to represent deformations at fine scales if the grid is coarse. Our method works directly on meshes which also avoids the need of converting between meshes and voxels. We also propose a method to automatically learn adaptive neighborhood sizes. Recent progress has also been made to speed up the ARAP deformation with GPU acceleration [11] and the subspace technique [34] for interactive editing. In this paper, we focus on improving the deformation effectiveness.

## 3. Algorithm

Similar to traditional ARAP deformation, we assume that an input model is provided with a set of handles. The user then moves the handles to desired locations and the algorithm produces a deformed model which satisfies the handle constraints and keeps geometric details. The fundamental spirit of the ARAP deformation is to deform shapes locally rigidly. The traditional ARAP approach interprets the local area as 1-ring neighborhoods. Adjacent 1-ring neighborhoods share a single common edge. This edge constrains the consistency or smoothness of rigid rotations between adjacent transformations. Instead of using 1-ring neighborhoods, we

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