Adaptable Geometric Models for Handling Deformable Objects

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Abstract

We present a method to estimate parameters of a geometric model of deformable objects for robotics applications. We achieve this by implementing a formulation with dynamics of the As-Rigid-As-Possible model and optimizing its physical parameters. Our approach is validated with both simulated and real objects.

Introduction

Deformable objects are essential in various fields such as robotics, computer graphics, and physical simulation. Accurate estimation of their physical parameters enables reproducing realistic behaviors in virtual environments and can be fundamental in applications such as the manipulation by robots. This work proposes a method that combines advanced simulations with shape measurements of the real object to estimate these parameters. The methodology is based on the use of the ARAP (As-Rigid-As-Possible) algorithm [1], which enables surface deformation computation while preserving local rigidity as much as possible. We optimize key physical parameters of a dynamic version of ARAP, related to the mass and stiffness of the object. The resulting adaptable model is capable of representing objects with diverse physical properties.

Adaptable Geometric Model

An application was initially developed in C++ using the ARAP implementation in the Libigl library [2], enabling interactive simulations of deformable objects using meshes [3]. This application allows the selection of mesh vertices and the assignment of control groups to define handle points (i.e., the points at which the object is being grasped) and fixed points. Additionally, the influence of gravity [4] was studied by adjusting the parameters already implemented in the library to analyze their effect on the observed deformations.

Our method for parameter estimation used a random initial mass matrix, which was then optimized using the Ceres Solver [5] with numerical derivatives. A parameter (S) related to the stiffness of the object, which directly affects model quality, was also optimized. The optimization was carried out using a ground-truth mesh, by minimizing the error between the ARAP model's mesh and the ground-truth mesh. This adjustment allows the model to achieve more realistic results and represent objects with different mass and stiffness.

After completing the simulation tests, an experimental validation phase was carried out using real objects. A piece of fabric was used (see Figure 1), to which 12 ArUco markers were attached. These markers allow tracking of their 3D positions after deforming the fabric, using an RGB-D camera. Based on this data, a simulated mesh was created in Blender replicating the layout of the ArUco markers observed on the fabric at rest. In this phase, the simulated mesh was assigned the 3D rest positions, and the handle points' positions were defined according to the deformation observed experimentally. From this setup, the ARAP algorithm was applied using the initial guess of the parameters. The parameters were then optimized using Ceres [5], this time using, as ground truth, the 3D positions of the markers captured after the real deformation of the object.

Experimental Results

Figure 1 shows the per-vertex error, computed as the Euclidean distance between corresponding vertices in the ground-truth mesh and the reconstructed mesh. The first two images show a simulated toroid, and the next two the real mesh reconstructed from experimental data. For both cases, the left mesh shows the error before optimization, and the right mesh after optimization.

As shown, the non-optimized meshes exhibit substantial errors. After optimization, the reconstructed meshes closely match the ground-truth geometry, resulting in significantly lower error values, which are nearly uniform and minimal across the entire surface.

Figure 2 shows, for the real object, the RMSE obtained before and after optimization, plotted against the stiffness parameter ‘S’. Each blue dot corresponds to the initial guess of the value of S for a given experiment and each green dot shows the optimized value returned by Ceres. Lines connect initial and final values for each experiment, illustrating the parameter evolution. A clear drop in RMSE confirms the effectiveness of the optimization. However, final ‘S’ values vary across experiments due to simultaneous optimization of both stiffness and mass; different combinations can yield similar deformations. Figure 3 shows an error heatmap between the ground truth and non-optimized simulation of the real object, and circles with radius proportional to the mass matrix value at each vertex. For an initial ‘S’ value of 0.75, the central area shows the highest errors and the largest mass changes, indicating local mass adjustment where needed.

Conclusions

A robust methodology has been developed for the estimation of physical parameters in the modeling of deformable objects, validated both with virtual and real objects. The optimization of the model parameters has enabled effective adjustment of mass and stiffness, significantly improving the accuracy of the simulations. Future steps to be addressed include the validation with more diverse objects and configurations. This methodology has the potential to be used for applications such as motion planning for robots manipulating a deformable object.

Acknowledgements

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REFERENCES

[1]. SORKINE, O. and ALEXA, M. As-Rigid-As-Possible Surface Modeling. Eurographics Symposium on Geometry Processing, 2007, pp. 109-116.

[2]. LIBIGL. As-Rigid-As-Possible Deformation. https://libigl.github.io/tutorial/#as-rigid-as-possible

[3]. MICHIDK. Interactive ARAP. GitHub repository. https://github.com/michidk/Interactive-ARAP

[4]. JACOBSON, A. Algorithms and interfaces for real-time deformation of 2D and 3D shapes. Doctoral thesis. University of Toronto, 2013. https://www.cs.utoronto.ca/~jacobson/images/alec-jacobson-thesis-2013-compressed.pdf

[5]. CERES. Ceres Solver: A Large-Scale Non-linear Optimization Library. ceres-solver.org

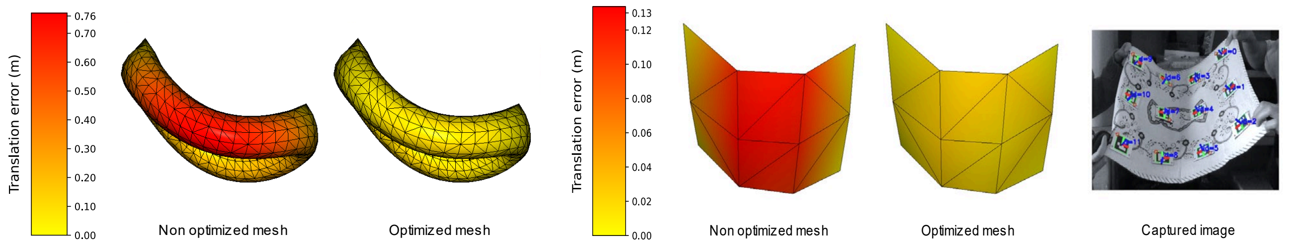

Figure 1. Per-vertex error before and after optimization (left: simulated mesh; center: real mesh) and picture of the fabric used for real experiments (right).

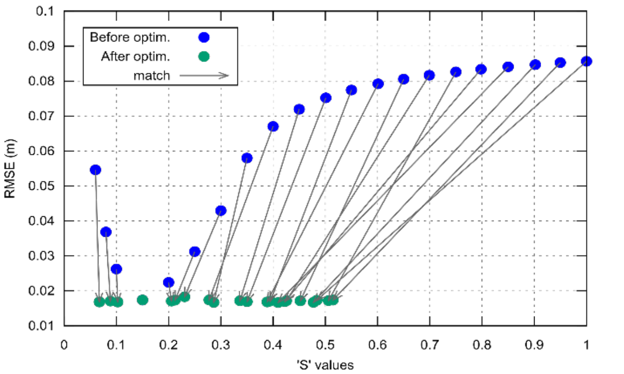

Figure 2: RMSE as a function of the values of ‘S’.

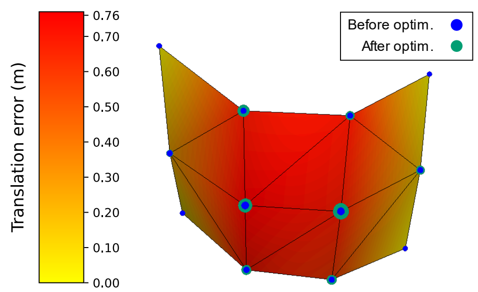

Figure 3: Evolution of the mass matrix per-vertex.