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Constrained space deformation techniques for design optimization☆

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HIGHLIGHTS

- High quality space deformation for design optimization based on MLS approximation.
- High level of modeling flexibility through explicit energy minimization.
- Maintenance of geometric constraints during deformation.

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ABSTRACT

We present a novel shape deformation method for its use in design optimization tasks. Our space deformation technique based on moving least squares approximation improves upon existing approaches in crucial aspects: It offers the same level of modeling flexibility as surface-based deformations, but it is independent of the underlying geometry representation and therefore highly robust against defects in the input data. It overcomes the scalability limitations of existing space deformation techniques based on globally supported radial basis functions while providing the same high level of deformation quality. Finally, unlike existing space deformation approaches, our technique directly incorporates geometric constraints – such as preservation of critical feature lines, circular couplings, planar or cylindrical construction parts – into the deformation, thereby fostering the exploration of more favorable and producible shape variations during the design optimization process.

1. Introduction

Design optimization is a key component of the product development process of automotive industry, aircraft construction, and naval architecture. The overall goal is to discover alternative designs with improved physical or aesthetic properties. The development process typically starts with the creation of an initial prototype using computer aided design (CAD) tools. Subsequent steps generate a polygon surface mesh from the CAD model as well as a volumetric simulation mesh in order to evaluate the physical performance of the design, e.g., based on aerodynamics or structural mechanics simulations. Design variations are then created – either manually or driven by an optimization algorithm – based on performance results during physical simulation.

A challenging task within the optimization process is to develop effective means to create alternate designs. Changing the CAD model directly is typically prohibitive, since repeated surface and volume meshing is highly time-consuming, and for complex geometries might even require manual interaction by an expert. An alternative is to use *shape deformation techniques* to adapt both the surface and the volume mesh of the initial design prototype directly. This way, the design optimization can be performed in a fully automatic and parallel manner, which is of particular importance when using stochastic optimization techniques – such as evolutionary algorithms – which typically require the creation and evaluation of a large number of design variations in order to find a feasible solution. We note that an alternative approach to avoid the costly remeshing of a CAD model is the use of isogeometric analysis [1]. In this work, however, we focus on more traditional design optimization and simulation scenarios.

Even though shape deformation techniques drastically simplify the creation of design variations, their successful application within practical design optimization tasks comes with a number of challenges:

1. Severe defects in the input data or varying element types in the simulation's surface and volume meshes prohibit surface-based

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or mesh-based deformation techniques and typically require space deformation methods.
2. The results obtained from the deformation might not be of sufficient quality, as illustrated in the comparisons of Staten and colleagues [2] and our recent investigations [3,4], which suggest the use of triharmonic radial basis functions (RBFs) for high quality shape deformations.
3. In terms of performance the method might not scale to complex optimization scenarios. For example, the RBFs proposed in [3,4] offer high deformation quality due to their built-in minimization of fairness energies, but the involved dense linear system restrict the method to moderately sized problems.
4. The method might not offer a sufficient level of modeling flexibility, e.g., to simulate inhomogeneous material behavior during deformation. RBFs, which implicitly minimize bending-type energies, fail to simulate stretching-dominant materials.
5. Critical features required for functionality and realization of design prototypes might not be properly preserved during deformation. The typical solution to this wide-spread problem in design optimization is to incorporate additional penalty terms into the cost or fitness function of the optimization process. While this strategy effectively excludes unfavorable designs as the outcome of the optimization process, it still requires the costly creation and evaluation of unfavorable design variations *during* the process since the penalty terms are applied in the fitness or cost function evaluation after the variations have been created and evaluated.

In this paper, we present a shape deformation technique based on moving least squares (MLS) discretization [5] that improves upon existing approaches in virtually all of the above aspects: Since we follow a space deformation approach our method is independent of the underlying geometry representation and highly robust towards defects in the input data. In terms of deformation quality, our method is competitive to global triharmonic RBFs. We drastically improve on the latter in terms of scalability, having to solve sparse linear systems only. By incorporating explicit stretching and bending energies, we offer the same level of modeling flexibility as surface-based methods. Finally, our technique directly incorporates geometric constraints into the deformation, thereby fostering the exploration of more meaningful and producible shape variations during the design optimization process.

We extend our previous work [6] in several key aspects: First, we extend the geometric primitives supported in our constrained deformation method to support cylindrical regions and rigid components. Second, we extend our comparison of subspace deformation techniques to include both global biharmonic and compact Gaussian RBFs, as well as more insightful mean curvature visualizations. Third, in order to make the setup procedure of our deformation method easier for the designer or engineer, we incorporate a technique for the automatic detection of geometric primitives into our system. Fourth, in order to boost the scalability of our constraint deformation, we introduce an alternative formulation of projective constraints ensuring sparsity of the resulting linear system. Fifth, we include additional deformation examples, including a combined volume and surface deformation of a practical CFD setup.

2. Related work

In this paper, we are concerned with high-quality shape deformation techniques for their use in design optimization tasks. Such techniques typically incorporate the minimization of physically-inspired energies in order to perform smooth and physically plausible deformations, as exemplified by *mesh-based variational methods* computing smooth harmonic or biharmonic deformations by solving Laplacian or bi-Laplacian systems [7,8]. The finite element-based FEMWARP technique [7,9], which computes a harmonic deformation, was generalized from tetrahedra to hexahedra in [2], and turned out to be highly successful in comparison to other methods. While the deformations produced by mesh-based variational methods tend to preserve element quality well, they have to be custom-tailored to each mesh type (e.g., tetrahedral or hexahedral), and they depend on the element quality of the underlying mesh.

In contrast, *meshless deformation techniques* avoid these limitations by computing a space deformation $\mathbf{d}: \mathbb{R}^3 \rightarrow \mathbb{R}^3$ that deforms the whole embedding space, thereby implicitly deforming the mesh. Spline-based free-form deformation (FFD) techniques [10] have been widely used in both the graphics and engineering communities [11]. After its initial conception numerous extensions have been proposed, and we refer the reader to the survey papers [12–14] for a more comprehensive overview. However, spline-based FFD does not offer the same degree of fairness as harmonic or biharmonic deformations, and it requires a rather tedious control lattice setup, as we investigate in detail in [4].

In [3] we successfully combined the advantages of meshless approaches and mesh-based variational methods by employing *radial basis functions* (RBFs) for mesh deformation. RBF space deformations can handle arbitrary polyhedral meshes and offer a degree of fairness comparable to mesh-based variational techniques. However, an inherent limitation of this approach is that the implicit energy minimization is built-in by construction and therefore offers no choice in terms of which energy to minimize. Furthermore, due to the global support of their basis functions, the resulting linear systems are dense and therefore limited in terms of scalability.

In this paper, we propose to overcome these limitations by employing *moving least squares* (MLS) methods [5,15] for mesh deformation. These techniques have been successfully used in meshless physics simulation and computer animation, and offer the same high level of deformation quality as RBF deformations, but they also come with increased flexibility with regards to energy minimization. Furthermore, the linear systems resulting from MLS-based discretization are generally sparse and therefore offer a drastically increased level of scalability compared to approaches based on globally supported RBFs.

A rather recent innovation in the development of shape deformation techniques is the integration of additional constraints into the deformation [16], as exemplified by the feature-preserving surface deformation technique of Masuda and colleagues [17], or by the iWires system [18] for deformation of man-made objects. More recently, the latter approach was generalized to component-wise controllers [19], and the work of Habbecke and Kobbelt [20] presents an efficient technique for the linear analysis of non-linear constraint in geometric modeling systems. However, all of the above methods are inherently surface-based. Therefore, their applicability to design optimization tasks is rather limited. A notable exception in this regard is the projection-based technique of Bouaziz and colleagues [21], since it allows for general constraints on arbitrary geometric data sets. We integrate this approach for constraint preservation into our MLS-based space deformation technique, thereby fostering the creation of more feasible design variations during design optimization.

In the following sections we describe our deformation technique in detail, going from the fundamentals to the specifics. We begin with a description of a general deformation model suitable for design optimization (Section 3). We describe our approach to space deformation based on subspace techniques in Section 4, where we also analyze and compare different choices of subspaces. In order to make our technique fully independent from the

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