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Technical Section

Surfacing curve networks with normal control

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ABSTRACT

Recent surface acquisition technologies based on microsensors produce three-space tangential curve data which can be transformed into a network of space curves with surface normals. This paper addresses the problem of surfacing an arbitrary closed 3D curve network with given surface normals. Thanks to the normal vector input, the patch finding problem can be solved unambiguously and an initial piecewise smooth triangle mesh is computed. The input normals are propagated throughout the mesh. Together with the initial mesh, the propagated normals are used to compute mean curvature vectors. We then compute the final mesh as the solution of a new variational optimization method based on the mean curvature vectors. The intuition behind this original approach is to guide the standard Laplacian-based variational methods by the curvature information extracted from the input normals. The normal input increases shape fidelity and allows to achieve globally smooth and visually pleasing shapes.

1. Introduction

Traditionally, digital models of real-life shapes are acquired with 3D scanners, providing point clouds for surface reconstruction algorithms. However, there are situations when 3D scanners fall short, e.g. in hostile environments, for very large or deforming objects. In the last decade, alternative approaches to shape acquisition using data from microsensors have been developed [1,2]. Small size and cost of these sensors facilitate their integration in numerous manufacturing areas; the sensors are used to obtain information about the equipped material, such as spatial data or deformation behavior. Ribbon-like devices incorporated into soft materials [3] or instrumented mobile devices moving on the surface of an object provide tangential and positional data along geodesic curves—see Fig. 2 for an example acquisition setup. In this context, we focus on the resulting problem of surface reconstruction and leave aside all issues related to acquisition and transformation of sensor signals into geometric data.

We address the problem of fitting a smooth surface to given discrete positional and normal data along a network of 3D curves. The goal is to obtain a fully automatic, efficient and robust method producing fair and visually pleasing surfaces consistent with the shape suggested by the input curves. A common practice in shape modeling is to rely on normal vector input in order to enhance shape quality and fidelity. Normal input can be found e.g. as boundary constraints in variational modeling [4–6], as geometric invariants [7], for computing flow-fields guiding the surface construction process, as Hermite data in surface fitting [8,9] or indirectly describing silhouette constraints [10,11] or shading behavior of 2D and 3D shapes [12–14] to cite a few possible applications.

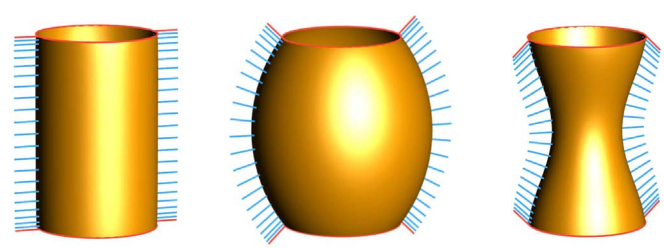

Fig. 1. Influence of input normals: the two circular curves (red) are given as input together with normal vectors of different orientation (red normals). Propagation of the input normals over the surface (blue) guides the computation of three different shapes. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

More generally, surfacing 3D networks is a fundamental problem in geometric modeling. Apart from traditional CAD modeling [15,8,16,9], sketch-based interfaces [17–19] and sketch-based modeling techniques [20–25] have recently become increasingly

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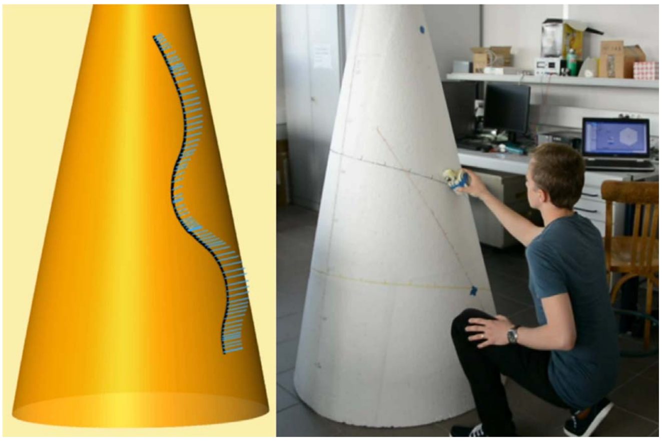

Fig. 2. In this example, we scan curves with normals on the cone using the Morphorider, a small mouse-like device instrumented with microsensors. The position and normal information along the scanned curves can serve as input to our algorithm.

popular in a range of versatile application areas. Even though normal vectors are not part of a typical sketch-based modeler output [26,17,18], recent state of the art [24] in surfacing 3D curve networks however requires estimation of normal vectors along the curve network.

The method we propose is a new mesh-based data-driven variational approach. We show how to generate high quality surfaces faithful to the input data by solving linear systems only. The key insight is the decoupling of normals from positions for the curve-to-patch extrapolation. The method first interpolates positions and normals separately over patches enclosing cycles of curves, then estimates mean curvature values at vertices, and finally optimizes for positions that best match the mean curvature vector formed by the mean curvature value and normal computed in the previous steps. The combination of shape and normal optimization into a compact expression has the advantage of not requiring the usual reformulation of normal constraints into layers of positional boundary constraints.

Contributions: This paper is an extended version of the earlier short paper [27] in which we have first introduced a variational approach for smooth surface modeling to fit a given curve network with surface normals. The main contribution of the earlier short paper was to combine the standard Laplacian with a term based on the estimation of the mean curvature normal. The intuition behind this original approach was to guide the standard Laplacian-based variational methods by the curvature information extracted from input normals. The normal input increases shape fidelity and allows to achieve globally smooth and visually pleasing shapes.

In comparison with the original short paper, this paper provides an expanded discussion of a modified mean curvature estimation used inside our Laplacian-based surface modeling framework that supports the generation of a continuously varying normal vector field. Our mean curvature estimation blends the positional and normal input so that the solution of our optimization conforms to both constraints. Additionally, we propose a simplified and more compact version of the energy functional used to compute a globally smooth surface with constraints along curve network. Most importantly, we provide more results, a convergence analysis and an in-depth comparison of our algorithm with state of the art methods.

2. Related work

Surfacing curve networks: With the advent of sketch-based modeling tools, such as interactive 3D sketching tools [26,28,17,18] or methods inferring 3D curve networks from 2D sketches [29,19], considerable effort has been dedicated to the design of methods for surfacing curve networks originating from sketching tools [20,30–32,24]. The common assumption in these works is that the underlying curve network was created with some design intent, and that the input information is minimal. Rose et al. [20] solve the patch finding problem and compute a developable boundary triangulation. Bessmeltsev et al. [31] interpolate a general 3D network of curve cycles by computing quad-mesh patches whose isolines capture the design flow inherent in the network. Sadri and Singh [32] compute self-intersection-free surface patches based on a flow complex induced by the boundary curves. Both methods compute surface patches individually and do not seek a globally smooth surface across dedicated boundary curves as we do. Pan et al. [24] use rotation-minimizing frames along the curves to estimate normal vector input and construct globally smooth surface patches having a curvature direction field consistent with an orthogonal flow field implied by the boundary curves. This makes sense in the setting of sketch-based modeling where the artist-drawn input represents particular characteristic shape curves, such as representative flow-lines. This is a strong assumption on the input network we do not make; our input curves, in contrast, can have arbitrary shapes (Fig. 9).

n-sided patches: *n*-sided boundary patches—possibly with prescribed tangent ribbons to achieve G^1-continuity across boundary curves—can be computed using transfinite interpolation methods (Coons patches [15], Gregory patches [8], Generalized Bézier patches [9] or subdivision approaches [33]). The first group of methods assumes a pre-segmentation of each input cycle into n curve segments with low-distortion mapping to a convex planar n-sided polygon. Prescribed tangent ribbons must be defined consistently and twists estimated accordingly. Methods in the second group quadrangulate the input cycles with topological guarantees on the extraordinary vertices and approximate the coarse mesh using well-known subdivision schemes. The variational approach of Boier-Martin et al. [34] integrates normal constraints by locally fitting the vertex neighborhood with a quadratic polynomial in order to estimate partial derivatives. However, the integration of normal constraints violates the independence of spatial dimensions of the linear system to solve.

Shading-based variational modeling: Gingold and Zorin [12] modify a given input shape by drawing strokes on a shaded image of the surface. The strokes indirectly impose normal constraints that are solved by modifying the position of the surface along the strokes, while the normals of the surface outside the strokes should not change. In contrast, we impose both positional and normal constraints along input curves, and compute new positions and normals everywhere else.

Variational modeling with normal constraints: The minimum variation surfaces [35] enable direct prescription of normals and principal curvatures along a curve network and may result in high quality shapes; however, the resulting optimization is nonlinear. Thanks to their speed and robustness, linear variational surface modeling and deformation methods have attracted an impressive amount of interest in the past few years, even though they only provide approximate results with respect to nonlinear problems; see the survey by Botsch and Sorkine [36]. We focus on linear methods using normal constraints in addition to standard positional constraints. The boundary constraint modeling methods of Botsch and Kobbelt [4], Jacobson et al. [5], and Andrews et al. [6] prescribe C^k continuity indirectly either by fixing $k-1$ rings of vertices or by adding a ghost geometry. Setting additional rings of