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Surface creation on unstructured point sets using neural networks

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ABSTRACT

We present a new point set surfacing method based on a data-driven mapping between the parametric and geometric spaces. Our approach takes as input an unstructured and possibly noisy point set representing a two-manifold in $\mathbb{R}^3$. To facilitate parameterization, the set is first embedded in $\mathbb{R}^2$ using neighborhood-preserving locally linear embedding. A learning algorithm is then trained to learn a mapping between the embedded two-dimensional (2D) coordinates and the corresponding three-dimensional (3D) space coordinates. The trained learner is then used to generate a tessellation spanning the parametric space, thereby producing a surface in the geometric space. This approach enables the surfacing of noisy and non-uniformly distributed point sets. We discuss the advantages of the proposed method in relation to existing methods, and show its utility on a number of test models, as well as its applications to modeling in virtual reality environments.

1. Introduction

In this paper, we present a new surface design method that can take as input three-dimensional (3D) point sets, and can generate free-form open surfaces through a neural network-based regression algorithm. In this work, point sets of interest can be sparse, unstructured, and unevenly distributed, and devoid of normal vector information. Such point sets frequently arise with the use of new-generation input devices such as 3D optical or magnetic trackers in virtual reality (VR) environments (Fig. 1), where the points are sampled from trackers attached to the users' hands or any part of their bodies. Such point sets are considerably different in nature than the widely studied class of range data, where dense point sets are sampled directly from the surface they represent. In surface design from point tracking, however, one rarely obtains a full and dense coverage of the intended surface. Moreover, point sampling may exhibit significant non-uniformity based on the users' motion speed and their focus on particular regions of the design. The long-term goal of the proposed work is thus to provide industrial surface design algorithms that can operate on tracking data to produce surfaces with controllable aesthetic qualities and associated mechanisms enabling further detailed refinement on the initial data.

As one step toward this goal, we present a neural network-based surface regression method that takes as input open or closed point sets in $\mathbb{R}^3$, and generates free-form surfaces through a parametric embedding and tessellation in $\mathbb{R}^2$. The parametric embedding is achieved through a local neighborhood-preserving method. Once a parameterization of the input point set is computed, a mapping between the parametric coordinates of input points in $\mathbb{R}^2$ and their corresponding 3D design space coordinates is trained on a multilayer, feed-forward, back-propagation neural network. A tessellation created in the parametric domain is then fed to the trained network, which results in the synthesis of a two-manifold surface in the design space. A key advance in the proposed work is that the surface complexity is dictated by the network topology that iteratively minimizes the underfit and overfit to the available data. We focus on the creation of surface patches that capture the underlying geometry intended by the designer in such cases, yet without compromising the surface quality. This approach is in contrast to methods that require the designer to study the underlying point set to decide the degree or functional form of the fitted surfaces. We demonstrate that the proposed approach can be used for creating free-form surfaces from arbitrary point sets, as well as from point sets arising from tracking data. We also present a surface stitching method to enable the creation of watertight and possibly non-manifold shapes in the VR environment, where our patch-based surface creation technique is utilized. We also demonstrate our method's applicability to hole filling on polygonal surfaces. Specifically, our contribution lies in a flexible neural network-based surface creation method from unorganized point sets. This approach utilizes a nonlinear parametric embedding [1] that enables our algorithm to learn a generative mapping from the parametric space to the geometric space. Moreover, the proposed stitching algorithm enables the different surfaces created using our approach to be unified into watertight models.

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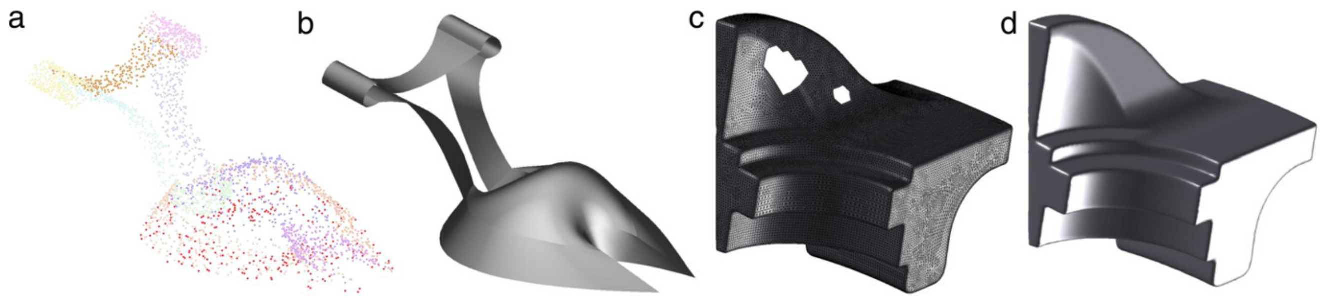

Fig. 1. Applications of our surfacing method. (a–b) Patch-based point set surface regression. (c–d) Hole filling.

2. Related work

In this section, we review the previous work in surface creation, fitting, and approximation of point sets based on the surface representations used, parametric, mesh based and implicit; this is followed by a review of the use of neural networks in this field.

Parametric surfaces: Parametric surfaces are one of the most widely used representations as they enable compact description, and straightforward tessellation with arbitrary resolutions. Gregorski et al. [2] introduced a B-spline surface reconstruction method for point sets. Their approach utilizes a quad-tree-like data structure to decompose the point set into multiple smaller point sets. Least-squares quadratic fitting of each subpoint set is then followed by the degree elevation to B-spline surfaces and blending. Bae [3], focusing primarily on laser-range scanned data, introduced orthogonal coordinate transformations for non-uniform rational basis spline (NURBS) surface fitting. The point set is first transformed into an orthogonal coordinate system, followed by B-spline fitting which is finally converted to NURBS surfaces. Adaptive fitting techniques introduced by Pottmann et al. [4,5] utilize an active contour model which gradually approximates the targeted model shape. This iterative approximation minimizes a quadratic functional composed of an internal surface energy for smoothness and an approximation error for fitting. Lin [6]introduced an iterative NURBS curve and surface fitting methodology to a given point set which is able to interpolate the point set. The major restriction of their approach is that the point set has to be preordered. Following a similar approach, boundary-condition-satisfying NURBS surface fitting is also achieved [7]. The neural network in our method is similar to parametric surface definitions in the sense that it enables arbitrary-resolution tessellation straightforwardly and has a compact definition. However, the proposed method differs from parametric fitting in that the functional form of the surface is dictated by the optimized network topology rather than requiring the user to decide the parameters of the fit. As shown in the following examples, the proposed method can be readily modified to fit a prescribed functional form such as a parametric surface of a given order, when desired.

Mesh-based surfaces: Mesh-based or polygonal surfaces enable a straightforward encoding and rendition of surfaces. In particular, they have been used extensively for surfacing point sets arising from range scanners. In an early work, Hoppe et al. [8] used local linear approximations of the point set to create a mesh-based surface that approximates the point set. The first provably correct mesh-based surface fitting algorithm is presented by Amenta et al. [9,10]. Given a sufficiently dense point sampling from the original surface, the approach guarantees the resulting surface to be topologically correct while interpolating the input samples. Gopi et al. [11] introduced a sampling criterion such that the fitted surface is guaranteed to be topologically correct and also provided algorithms that create mesh-based representations of such point sets [12]. Based on Delaunay tetrahedralization of a given point set, Attene and Spagnuolo [13] introduced a method for closed genus-n triangulation fitting provided that the points are sampled from a real object. In 2005, Kuo and Yau [14] approached the surface fitting problem with a region-growing algorithm that gradually adds new triangles to an initial triangulation starting from a seed region of the point set. Dey and Goswami [15] presented a mesh-based surface fitting method applicable to noisy point sets as long as the noise level is within a specified threshold. Many mesh-based surface fitting algorithms typically require a smoothness or fairness criterion to be minimized, which may require considerable post-processing after the initial surface fit [16].

Implicit surfaces: Implicit representations enable compact mathematical descriptions and rapid set operations. However, the tessellation and rendering of such representations is a significant obstacle, requiring specialized algorithms for visualization. Juttler and Felis [17]introduced an approach which results in implicit least-squares reconstruction of spline surfaces tailored toward reverse engineering. A widely used family of implicit surfaces is that of radial basis functions (RBFs). Kojekine et al. [18] used an octree structure to reduce the computational time associated with RBF spline-based volume reconstruction. Ohtake et al. [19] used implicit surfaces as a way to facilitate intersection checks on mesh-based geometries. They also employed a similar approach together with compactly supported RBFs for range scanner point cloud surface fitting. Wu et al. [20] introduced a combined approach in which they use multiple RBFs, where individual RBFs construct seed regions that are coalesced into larger regions through a partition of unity functional. A key drawback of the implicit approaches is the need for specialized visualization mechanisms. Nonetheless, the proposed approach is conceptually similar to RBFs in the way it takes a purely data-driven approach to surface generation. The main advantage of the proposed work is in its ability to generate an arbitrary tessellation directly within the parametric space. This allows an explicit control of the mesh topology and density, and lends itself to a straightforward geometry creation and visualization in the form of a polygonal model.

Use of neural networks: Barhak and Fischer [21]utilized neural network self-organizing maps for two-dimensional (2D) grid parameterization and surface reconstruction from 3D points sets. The result of the neural network is used to create a 3D surface iteratively with the help of a gradient descent algorithm. Similarly, Galvez et al. [22] and He et al. [23] utilized neural networks for parameterization and point ordering, rather then surface creation. Khan et al. [24] introduced an approach for constructing surfaces from boundary curves that are required to be planar. Their approach addresses the boundary-to-surface learning problem rather than the point-to-surface learning problem. Krause et al. [25] implemented a neural gas neural network [26] for approximating a point set with disconnected triangles. These triangles do not necessarily span the whole surface, and additional post-processing is required to ensure connectivity and watertightness of the final surface. The method presented in this paper differs from their approach in that the network output in