Computers & Graphics 74 (2018) 44–55

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Special Section on SMI 2018

Surface reconstruction of incomplete datasets: A novel Poisson surface approach based on CSRBF

Jules Morel[a,b,*], Alexandra Bac[b], Cédric Véga[c]

[a] French Institute of Pondicherry, 11 Saint Louis Street, Pondicherry 605001, India
[b] Laboratoire des Sciences de l'Information et des Systèmes, 163 Avenue de Luminy, Marseille 13288, France
[c] Laboratoire dInventaire Forestier, Institut National de LInformation Géographique et Forestière, 14 rue Girardet, Nancy 54000, France

ARTICLE INFO

Article history:
Received 27 April 2018
Revised 11 May 2018
Accepted 14 May 2018
Available online 17 May 2018

Keywords:
Surface reconstruction
Approximation
Radial basis functions
Poisson surface
Terrestrial LiDAR scanning

ABSTRACT

This paper introduces a novel surface reconstruction method based on unorganized point clouds, which focuses on offering complete and closed mesh models of partially sampled object surfaces. To accomplish this task, our approach builds upon a known *a priori* model that coarsely describes the scanned object to guide the modeling of the shape based on heavily occluded point clouds. In the region of space visible to the scanner, we retrieve the surface by following the resolution of a Poisson problem: the surface is modeled as the zero level-set of an implicit function whose gradient is the closest to the vector field induced by the 3D sample normals. In the occluded region of space, we consider the *a priori* model as a sufficiently accurate descriptor of the shape. Both models, which are expressed in the same basis of compactly supported radial functions to ensure computation and memory efficiency, are then blended to obtain a closed model of the scanned object. Our method is finally tested on traditional testing datasets to assess its accuracy and on simulated terrestrial LiDAR scanning (TLS) point clouds of trees to assess its ability to handle complex shapes with occlusions.

1. Introduction

The reconstruction of 3D surfaces from scattered data has received increasing attention with the emergence of new close-range 3D acquisition technologies, such as laser scanning devices (LiDAR), close-range photogrammetry and time-of-flight cameras. The dense 3D point clouds thus acquired accurately describe object surfaces (e.g., millimeter resolution for laser scanning). Such scanning processes have a wide range of applications: urban reconstruction and modeling, architecture, artifacts modeling, quality control for production, and medical imaging. However, despite their accuracy, the data acquired by these sensing technologies share common constraints, such as non-homogeneous sampling, occlusion and noise. In view of their characteristics and complexity, dedicated algorithms are required to segment, model and reconstruct objects of interest from raw point clouds. Terrestrial laser scanning (TLS) technology is broadly used in forest studies. TLS enables 3D forest structures to be acquired as point clouds in record time [1], with applications ranging from ecology (allometric relationships,[1] and growth modeling carbon storage assessment) to forestry (forest monitoring, sustainable development) and industry (harvest planning, sawmill optimization). However, the features of such data are even more challenging with respect to reconstructing models and extracting information (e.g., more challenging than classic applicative data, such as urban environments or isolated objects, because the clouds are extremely dense, inhomogeneous, noisy and present large occlusions). These constraints arise both from the remote sensing technology and from the complexity of forest environments. The TLS point cloud sampling rate may vary from one scanner to another, and the spherical geometry of the sensor results in irregular sampling density. Moreover, the combination of TLS geometry and the vegetation itself (branches, leaves, low vegetation) results in large and numerous occluded areas that expand both in size and number far from the sensor. Noise contributes additional confusion at surface extremities and in foliage. Therefore, data obtained from a given tree have different characteristics from the base up to the crown. Forest measurements from TLS data also suffer from object-specific limitations. Stems bark can

---

* Corresponding author at: French Institute of Pondicherry, 11 Saint Louis Street, Pondicherry 605001, India.

E-mail address: jules.morel@ifpindia.org (J. Morel).

[1] Allometry consists of a set of general relations derived from a large compilation of forest measurements. It provides an estimate of the tree structure according to a few given parameters, such as the diameter at breast height (DBH, diameter of the stem 1.30 m above the ground) and the tree height.

https://doi.org/10.1016/j.cag.2018.05.004

be rough and therefore produce highly uneven surfaces. Moreover, the non-trivial topology of branches and the intricate occlusions produced by these branches are highly challenging for point cloud processing. Finally, let us note that LiDAR scanning of trees may be affected by wind and thus create multiple scan alignment issues. All these artifacts induce specific point cloud distortions and generate crooked objects. Therefore, in the context of LiDAR data, reconstruction is necessary to handle partially described objects. To overcome the data distribution characteristics inherent to TLS point clouds, especially for data acquired in forests, our idea was to rely on *a priori* knowledge about the forest elements expressed as geometrical models. This paper presents a novel surface reconstruction method that is specifically designed for the reconstruction of partially described objects based on 3D point clouds. We address this challenge by introducing a novel surface reconstruction method based on a Poisson scheme, building upon sturdy approximating basis functions. On the basis of this innovation, our algorithm lets us integrate *a priori* models of occluded areas, expressed using basis functions, to describe partially tubular objects. This approach provides good estimates of missing data and enables complete reconstruction of forest objects. This algorithm was tested and validated against "classic" datasets and on occluded almost-tubular shapes and tree sections. In Section 2, we present a short literature review of surface reconstruction and tree modeling from TLS samples.

2. State of the art

Pioneering works on surface reconstruction from raw point clouds date to the late nineties and are usually classified as explicit or implicit according to the underlying model (see [2–4] for complete surveys). There are two types of explicit surfaces, parametric and meshes, both of which have been investigated in this context. Parametric surfaces, such as B-splines [5,6] and NURBS [7], entail determining a 2D parameter space together with a set of associated control points. Such surfaces are controlled by these points but not as an approximation or interpolation. Therefore, complex surfaces are not easily representable, and parameterization is a complex issue for scattered data, especially in the presence of noise, inhomogeneity and occlusions. In [8], the authors define polynomial splines over locally refined parameter spaces in any dimension and thus successfully reconstruct sharp features and details from point clouds. However, although the approach performs well on terrain data, its parametric nature, as well as its complexity, limit its application to data from complex scenes. Triangular mesh reconstruction received substantial attention through Delaunay triangulation, alpha shape reconstruction and Voronoi diagrams [9–12]. However, scanning devices, such as LiDAR scanners, produce dense, noisy and potentially occluded point clouds that cannot be accurately modeled by meshes. The successive remeshing required to obtain an adequate model multiplies the cumbersome computations. Moreover, the inhomogeneity of sampling leads to unbalanced meshes, with larger polygons far from the sensor, tiny polygons close to it (where the point density can reach 1 million points/m^2) and stretched polygons in occluded areas.

Therefore, the unstructured, nonplanar nature of point clouds makes implicit surfaces a key modeling tool. Moreover, such models structurally smooth the noise by approximating the input points and are tolerant to inhomogeneity and limited occlusion. Implicit surface reconstruction is the process of finding a function that best fits the input data. However, the implicit representation of a surface needs to be post-processed to be visualized. Marching cube [13,14] is the best-known method to generate a triangulated surface from the implicit representation of the surface. Because the surface is extracted as a level set of an implicit function, the resulting mesh is guaranteed to be a watertight manifold.

Computing implicit functions from point clouds as an approximate of the signed distance function has been extensively studied [15]. However, such approaches prove to be unstable in the presence of nonuniform sampling. The moving least-squares method (introduced in [16], see [17] for a complete survey) addresses this problem but struggles in the presence of missing data, as noted in [2]: the large spatial support of basis functions required near holes spoils the reconstruction. Another class of methods, namely, global reconstruction methods, was proposed by Carr et al. [18]. These approaches are based on radial basis functions (RBFs) and take advantage of their approximating properties. RBFs are positive definite basis of functions and hence guarantee approximation feasibility (see [19,20] for more details). The benefits of modeling surfaces with RBFs are broadly recognized [21–24]. However, polyharmonic RBFs have global support; hence, reconstruction entails inverting dense ill-conditioned matrices. To mitigate this problem, further works focused on compactly supported radial basis functions (CSRBFs) (either used directly [25] or as blending functions between local reconstructions [26–28] or both [29]). The finite support of such functions enables faster filling of the interpolation matrix [30], which simultaneously becomes sparse. Matrix inversion can thus be accelerated by using a direct sparse matrix solver (see Morse [31] for a summary of the advantages of CSRBF over classic RBF). A different approach takes advantage of both global and local fitting schemes by approximating the field of estimated normals through Poisson reconstruction [32]. Owing to the representation as a Poisson problem, this method is robust to nonuniform sampling, noise, outliers and to a certain extent, missing data. These qualities make it a choice method for surface reconstruction from TLS point clouds. However, for computational reasons, implicit surfaces are computed and expressed in a basis of functions obtained by convolution of a box-filter with itself. Unfortunately, this basis is not positive definite (unlike radial basis functions) and thus it does not have sufficient approximation properties to express any *a priori* information about occluded areas. While these surface reconstruction methods have proven to produce sharp models from point clouds, none is able to fill the large gaps created by occlusion in LiDAR point clouds acquired in forests.

To solve this problem and extract the information needed in forestry, scientists rely on a common assumption: a woody tree structure is assumed to be a network of quasi cylinders. Thus, the tree structure, branching organization and branch size distribution are modeled through so-called quantitative structure models that summarize this information by describing the tree components in hierarchical order as a stack of elementary building blocks. This approach has been widely explored. Côté et al. [33] proposed an architectural model combined with a skeletal curve approach to retrieve the tree structure and allometric relationship to build the branching structure and further assess the amount of foliage. Dassot et al. [1] introduced a semi-automatic approach to model tree architecture using cylinders and to estimate tree parameters, such as tree volume. Raumonen et al. [34] introduced a method involving clusterization and segmentation of the point cloud, followed by reconstruction of the tree architecture using cylinders. They combined this geometric and hierarchical information into the concept of quantitative structure modeling (QSM). A similar cylinder-based tree-reconstruction method was proposed by Hackenberg et al. [35] using a sphere-following approach to progressively reconstruct the tree structure from the ground to the apex. Switching from tree-level reconstruction to plot-level reconstruction is a challenging task. Intermingling crowns and occlusions due to branches and leaves in the signal path makes it difficult to accurately segment trees. Raumonen et al. [36] used a clusterization approach to detect tree bases, followed by a distance-based expansion procedure to allocate the remaining clusters to the detected trees. Tao et al. [37] used clustering and shortest-path algorithms