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Applications of mesh parameterization and deformation for unwrapping 3D images of rock tunnels

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ABSTRACT

This paper presents analysis on two 3D mesh to 2D map strategies applied to unwrap images of rock tunnels and facilitate visualization of large datasets. First, we examined mesh parameterization algorithms which are used in computer graphics to convert a 3D mesh model to a 2D representation.

We found that while these methods were automatic and could provide 2D maps with minimal metric distortion (ie: conservation of lengths in 3D when mapped to 2D), they exhibited twisted shapes and were not intuitive to interpret. Second, we proposed two novel approaches, combining mesh deformation algorithms, which are used in computer animation to reshape a 3D mesh to resemble a 3D plane, and projection onto a 2D plane. We found that while these methods required user interaction and introduced a greater amount of metric distortion, their outputs were fairly intuitive to interpret. To compare the relative merits of mesh parameterization and mesh deformation and projection, the different strategies are applied to a 8.2 m wide by 41 m long by 6.7 m high subsection of a mining tunnel. The metric distortion produced was calculated and their respective output 2D maps are presented and discussed.

1. Introduction

Terrestrial laser scanning (TLS) has enabled high-resolution three-dimensional (3D) imaging of underground tunnels in the form of point clouds, which are unstructured collections of points where each point represents the 3D Cartesian coordinates (x, y, z) of the location where the laser beam has illuminated the surface. Surface reconstruction algorithms can then be used to connect individual points to produce a triangulated mesh which conforms to the rock face. These triangulated meshes have been used to facilitate fracture analysis (Mah et al., 2011; Lato and Vöge, 2012; Fekete et al., 2010; Lai et al., 2014), extraction of surface roughness (Mah et al., 2013; Lai, 2013; Lai et al., 2014; Mills and Fotopoulos, 2013), mapping shotcrete thickness (Lato and Diederichs, 2014; Fekete et al., 2009), and deformation analysis (Van Gosliga et al., 2006; Lemy et al., 2006).

Analysis and interpretation of the hundreds of thousands elements which compose a typical triangular mesh requires dedicated hardware with specialized software for visualization. Such equipment is not always readily available, especially underground. It would therefore be beneficial if a 2D representation could be created from the 3D triangulated mesh to allow (near) real-time interpretation in operational conditions, an approach akin to unwrapping acoustic televiewer images (Paillet et al., 1990) for quick inspection. Additionally, it would be useful to have an unfolded 3D tunnel mesh with minimal distortion to make 2D figures for engineering reports.

While many TLS instruments acquire 2D photographs concurrently with 3D data to produce colored point clouds, these photographs are not bidirectional mappings. Any changes made to the 2D photographs, such as adding markings for highlighting specific features, cannot be mapped back to the 3D data. Similarly, analysis which encodes information through color (ie: fracture analysis (Mah et al., 2011; Lato and Vöge, 2012; Fekete et al., 2010; Lai et al., 2014)) in the 3D triangulated mesh cannot be transferred to the 2D representation. Yet, for certain applications such as engineering reports, transferring data attributes from analysis performed on the 3D triangulated mesh unto a 2D representation would be more intuitive to understand and easier to visualize. Unfortunately it has been mathematically proven that very few surfaces can be transferred from 3D space into 2D space without metric distortion (lengths in 3D are not preserved in 2D) and some cannot even be transferred without being cut into pieces first (Kreyszig, 1991).

This paper investigates if existing methods for computing a bidirectional mapping between a 3D mesh model and a 2D

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representation would generate a realistic mapping with minimal distortion. Once existing methods have been examined, an innovative strategy combining mesh deformation, the act of changing the shape of an existing mesh, and projection from 3D space onto a 2D plane, is proposed for creating bidirectional mappings between the 2D and 3D representations of underground tunnels. Fig. 1 is a flowchart of the methods presented in this paper. To discuss their relative merit, with an emphasis on how they can be used in practice, they are applied onto the same subsection of the mining tunnel show in Fig. 2. The main contributions of the paper are: (1) the first comparative study on the relative merit of different methods for unfolding 3D tunnel meshes taken with a TLS instrument and (2) a novel strategy specifically designed for unfolding tunnel meshes so that a bidirectional mapping between the original mesh and the corresponding 2D representation can be obtained. Our approach allows for both the final unfolded tunnel mesh to be intuitively interpreted as a 2D image and the transfer of data attributes between the 2D and 3D representations.

2. Mesh parameterization theory

2.1. Metric distortion

In the field of computer graphics and geometry processing, surface parameterization is used to convert an arbitrary surface into a domain space. When the surface in question is a 3D mesh and the domain space is any 2D shape, the process is known as mesh parameterization. The output of mesh parameterization is typically a unit square known as a uv-map (Sheffer et al., 2006) where each coordinate (x, y, z) from the vertices of the 3D mesh is associated with a coordinate (u, v) in the uv-map. During the process of computing a uv-map, metric distortion (Sheffer et al., 2006; Floater and Hormann, 2005) occurs because there is almost always a loss of information when moving from a higher to a lower dimensional space. Only perfect cylinders (such as borehole acoustic televiewer images), cones and flat planes can be transformed from 3D to 2D (and vice versa) without metric distortion (Kreyszig, 1991; Sheffer et al., 2006; Floater and Hormann, 2005; Hormann et al., 2007). An intuitive view of metric distortion can be gained from considering the many methods of generating a 2D map of the Earth. For example, the common Mercator projection draws the Earth onto a rectangle but exaggerates the size of certain countries, an example of area distortion. Despite this distortion, the original 3D positions can still be recovered through the longitude and latitude which is analogous to recovering the original 3D position on a mesh through the uv-map.

Let p be a point on the surface of the input 3D mesh and let q be the corresponding point in some domain Ω. To quantify metric distortion, differential geometry examines the effects of moving q by an infinitesimal amount, Δ, on the corresponding point p. Differential geometry describes these effects through a special matrix known as the Jacobian which can be decomposed into two singular values σ_1 and σ_2 (a rigorous derivation can be found in Appendix A). Since these singular values represent the lengths of the semi-axes of an ellipse, when they are both equal to one there does not exist any distortion since a circle drawn in the parameter domain will remain a circle when transformed onto the 3D space. Thus, different combinations of these singular values yield varying amounts of metric distortion.

Sections 2.2 and 2.3 describe two mesh parameterization algorithms which automatically compute uv-maps through the minimization of metric distortion.

2.2. Least squares conformal mapping (LSCM)

Developed by Lévy et al. (2002), the least squares conformal mapping (LSCM) aims to minimize the Cauchy-Riemann equations (Gamelin, 2001) in a least squares sense. For the purposes of mesh parameterization, a conformal mapping f satisfies the Cauchy-Riemann conditions which are:

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial y}, \quad \frac{\partial u}{\partial y} = -\frac{\partial v}{\partial x} \tag{1}$$

In general, however, there are no conformal mappings for piecewise linear functions such as triangulated meshes. To circumvent the problem, Lévy et al. (2002) defined the conformal energy per triangle t, E_t, as:

$$E_t = (\sigma_{1,t} - \sigma_{2,t})^2 \tag{2}$$

The minimization of conformal energy for all triangles in a mesh leads a discrete conformal mapping which is a close approximation to a conformal mapping for a smooth surface. The equation to minimize is:

$$\sum_{t \in T} E_t A_t \tag{3}$$

where T is the set of triangles in the mesh and A_t is the each area of triangle t. Thus Eq. (3) satisfies Eq. (1) and leads to a linear system which can be solved in a straightforward manner. The solution of Eq. (3) yields the coordinates (u, v) for every vertex.

2.3. Angle based flattening (ABF and ABF++)

Sheffer and Sturler (2001) observed that a 2D triangulation is uniquely defined by the corner angles of each triangle. Using this observation, they reformulated the mesh parameterization

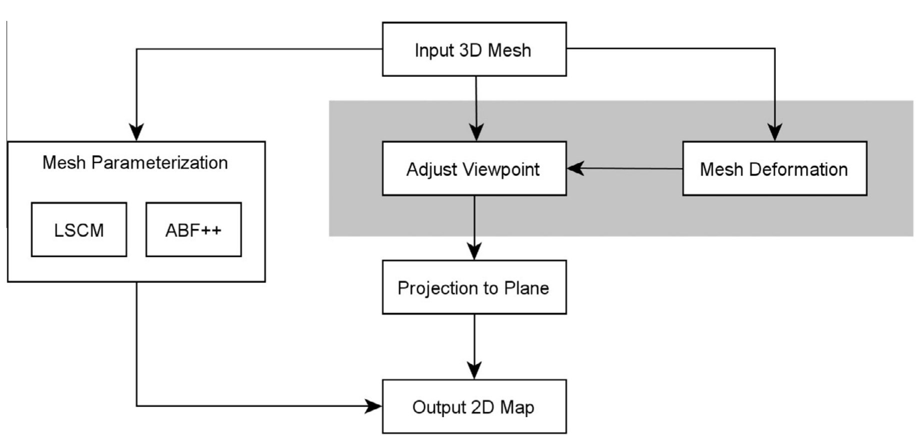

Fig. 1. Flowchart of the methods presented in this paper. Methods which require user interaction are contained within the gray box.