Computers & Graphics 000 (2017) 1–11

Contents lists available at ScienceDirect

Computers & Graphics

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

Special Issue on SMI 2017

Shape from sensors: Curve networks on surfaces from 3D orientations

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ARTICLE INFO

Article history:
Received 3 April 2017
Revised 19 May 2017
Accepted 25 May 2017
Available online xxx

Keywords:
Curve networks
Shape acquisition
Surface reconstruction
Inertial sensors
3D sketching

ABSTRACT

We present a novel framework for acquisition and reconstruction of 3D curves using orientations provided by inertial sensors. While the idea of sensor shape reconstruction is not new, we present the first method for creating well-connected networks with cell complex topology using only orientation and distance measurements and a set of user-defined constraints. By working directly with orientations, our method robustly resolves problems arising from data inconsistency and sensor noise. Although originally designed for reconstruction of physical shapes, the framework can be used for “sketching” new shapes directly in 3D space. We test the performance of the method using two types of acquisition devices: a standard smartphone, and a custom-made device.

1. Introduction

Curve networks play an important role in CAD and often serve for conveying designs [13,32]. At the same time, well-defined curve networks are used for automatic inference of underlying surfaces by minimizing fairing energy or using methods with prescribed degree of continuity.

Recent research in sketch-based modeling and virtual reality produced tools and devices for intuitive design of 3D curves (Fig. 3). These tools and devices attempt to overcome some of the limitations of the traditional CAD approach—designers can sketch curves directly, either on a flat screen or via a 3D interface. Although intuitive, these methods are targeted toward design of new shapes and are not suitable for reconstruction of existing real-world shapes.

We present a novel framework for acquisition of 3D curves using orientations measured by inertial sensors. While the idea of sensor shape reconstruction is not new, we present the first method for creating well-connected networks of curves on surfaces using only orientation and distance measurements and a small set of user-defined constraints. We address three main challenges that arise when working with sensor data.

- **Unknown positions**. Sensors measure local orientations of the surface—no absolute positions in the world space nor relative positions of two adjacent sensors are known.
- **Inconsistent data**. Intersecting curves often provide conflicting data, for instance two different normals for the same point in the world space.
- **Sensor noise**. Raw data from inertial sensors is noisy and needs to be pre-processed prior to reconstruction.

Our approach differs from standard curve acquisition and reconstruction methods in the fact that we formulate all algorithms in terms of orientations. This way, we can leverage consistency of reconstructed curves with respect to user-defined topological constraints. By working directly with orientations, our framework robustly resolves all above challenges in two steps. We first filter the acquisition noise by combining pre-filtering of the raw orientations in the quaternion space with a spline-based smoothing in the group of rotations (Section 4). We then introduce a curve-based Poisson reconstruction method, which transforms the pre-filtered orientation samples into a smooth and consistent curve network by satisfying in particular the user annotated topological constraints (Section 5). To enable a thorough evaluation and comparison with respect to ground truth data (Section 6), we use two physical objects fabricated from digital models: the LILIUM (Fig. 1) and the CONE (Fig. 15).

To demonstrate our framework, we use a *dynamic acquisition* setup, where we suppose the data are measured by a single moving node of sensors. We test and compare two types of devices: a standard smartphone, and a custom-made prototype for measuring orientations and distances (Fig. 10). Nevertheless, the algorithms presented in this paper are not limited to these devices; they are also applicable in a *static acquisition* setup, such as a grid/mesh of sensors [39,41] or instrumented materials [19].

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http://dx.doi.org/10.1016/j.cag.2017.05.013
0097-8493/

Please cite this article as: T. Stanko et al., Shape from sensors: Curve networks on surfaces from 3D orientations, Computers & Graphics (2017), http://dx.doi.org/10.1016/j.cag.2017.05.013

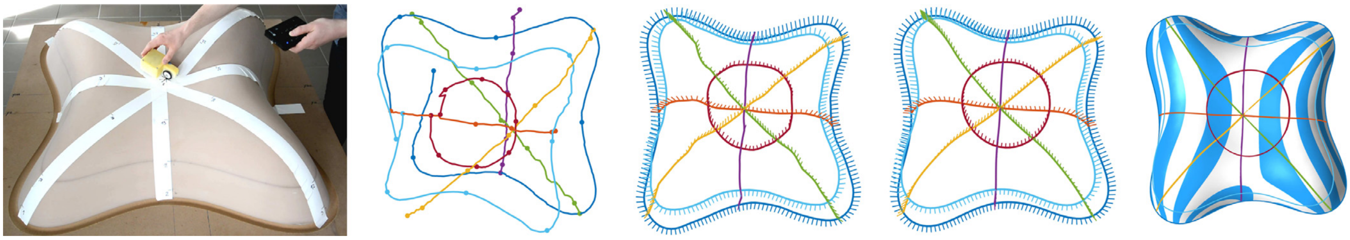

Fig. 1. Surface of the LILIUM is scanned by acquiring orientations along curves using a sensor-instrumented device (left). Naive integration of the scanned data fails to close the network (middle left). Reconstructing the network by solving a Poisson system resolves topological problems but yields noisy and inconsistent normals (middle). Filtering orientations prior to Poisson reconstruction gives a consistent network (middle right) available for surface fitting (right). See the accompanying video for the acquisition setup.

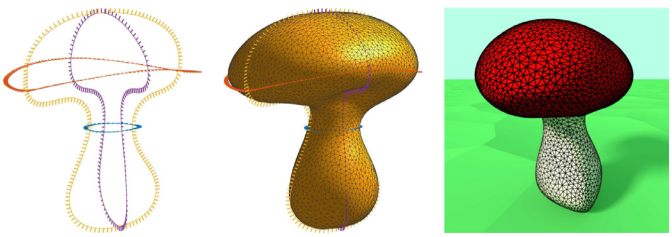

Fig. 2. The MUSHROOM network created from scratch entirely with a smartphone. Curve lengths were estimated from acquisition time. The surfacing was computed using the method of Stanko et al. [43] with soft positional constraints. .

The primary application of the presented framework is reconstruction of existing shapes. Our setup provides a valuable alternative to traditional shape acquisition methods (3D scanners, depth images). Unlike most 3D scanners, which often use cameras and lasers, inertial sensors are independent from light conditions, material's optical properties and scale of the scanned object. They render the acquisition possible outdoors or underground, and can also be used for large and/or moving objects; imagine acquisition of underground pipes [38], or an instrumented sail moving in the wind (Fig. 20). Possible applications include smart materials and structural health monitoring.

A major advantage of our approach is its generality. No special device is required for data acquisition; in fact, any sensor-instrumented device could be used for the task, thus making 3D acquisition accessible to everyone with an ordinary smartphone. Even though originally designed for reconstruction, our framework can also be used for design by "sketching" new shapes from scratch (Fig. 2).

2. Related work

Shape from curves. The problem of generating shapes from collections of curves has been well studied in CAGD (Computer Aided Geometric Design) and all standard techniques can be found in Farin [16]. In the recent years, the interest in this problem was re-ignited due to its applications in sketch-based modeling [2,5,24,33,44] and in virtual reality (VR) systems [17]. Inspired by years of research in CAGD, the *surface from curves* paradigm is invaluable for shape design in modern sketching and VR systems. Recently, Arora et al. [4] have studied issues with accurate design of shapes in the existing VR systems. Their study suggests that users struggle even with simple tasks (drawing a closed circle) when sketching in three dimensions. A system like ours can help in solving such accuracy and consistency issues.

Although equally important, the problem of *reconstruction* of existing physical shapes from a collection of curves received less attention. 3D scanners usually provide large amounts of data and tend to ignore intrinsic structure of the scanned shape. Alternatively, objects can be defined by their characteristic curves as often done in perception and sketch-based modeling. Cao et al. [12] detect characteristic curves in noisy point clouds, then use these curves for surface reconstruction. The use of inertial measurement units (IMUs) for shape acquisition might provide a good alternative in situations for which the optical methods do not yield proper results, positioning sensors along object's characteristic curves. Milosevic et al. [31] introduced SmartPen, a low-cost system for capturing 3D curves, which combines an IMU with a stereo camera (Fig. 3 middle). By combining a stereo camera with a sensor unit, their system is a mixture of traditional 3D scanners and our shape from sensors setup. However, SmartPen's sensors only serve for determining device's orientation needed for estimating relative position of the tip of the pen. Much like traditional point-cloud scanners, the system relies on visual input to get 3D position of the device in world space; this limits size of the scanned object. A recent example of curve acquisition device is the commercially available 01 [25], a dimensioning tool with an IMU and a laser (Fig. 3 right). Usage of this device for 3D curve reconstruction has yet to be demonstrated experimentally.

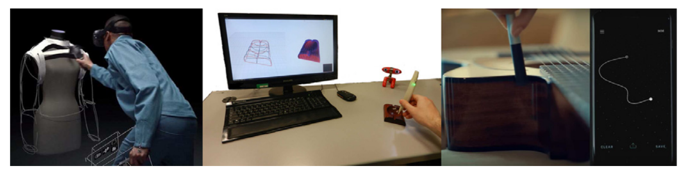

Fig. 3. Recent curve acquisition devices that use inertial sensors. Left to right: Tilt Brush [17], SmartPen [31] and 01 [25].

Shape from sensors. The use of sensors for shape acquisition was first explored by Sprynski [41]. Instead of measuring absolute position of surface points of the scanned object in the world space, the reconstruction algorithms need to be formulated in terms of orientations provided by sensors, and geodesic distances between points of measurement. Curves are represented using natural parametrization and reconstructed via numerical integration. Surfaces are defined via geodesic interpolation [42] or using parallel ribbons of sensors [39]. Huard et al. [23] introduced method for computing smooth patches from a given piecewise geodesic boundary curve. Hoshi and Shinoda [21] reconstruct the target surface using two families of sensors placed in orthogonal directions. Hermanis et al. [19] construct sensor-instrumented fabric and compare the reconstruction results with Kinect data. Antonya et al. [3] use an array of sensors for real-time tracking of human spine.

Attitude estimation and filtering. Attitude control has been studied extensively in aeronautics where accurate algorithms are indispensable for correct estimation of vehicle's orientation with respect to celestial objects [30]. Noise in data is usually reduced using a Kalman filter—specific approaches depend on the representation used for orientations [15], such as unit quaternions, a representation well-known in the graphics community [40]. Markley et al. [29] describe a classical algorithm for computing means in the group SO(3). Average rotation is defined as the minimizer of weighted penalty function, and the corresponding unit quaternion

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