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A robust channel network extraction method combining discrete curve evolution and the skeleton construction technique

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ABSTRACT

The automatic mapping of drainage networks from terrain representation has been an interesting topic in hydrological and geomorphological modeling. However, the existing methods often suffer from high sensitivity to terrain noise or lose significant stream branches and accurate channel paths. In this paper, we propose a contour-based framework in drainage network extraction. The proposed framework incorporates discrete curve evolution (DCE) to eliminate the noise influence by dynamically segmenting the contour lines (CLs) into valley bends, and to detect the valley feature points. The skeleton construction technique is then applied to distill more accurate channel paths in complex terrain. Finally, a linking step is undertaken to generate the channel network. The proposed method was tested on a series of elevation datasets, with varied resolution, region size, and local relief. The experiments verified that the proposed method can achieve highly accurate channel networks and is robust, even in regions with high-contrast relief, and/or in cases with significant terrain noise and irregularities.

1. Introduction

Channel networks are significant landscape features in the description of terrain surfaces, and they serve as fundamental layers in geomorphological and hydrological applications. Due to data availability and the ease of implementation, gridded digital elevation models (DEMs) have been widely used in terrain analysis. Furthermore, channel network extraction from gridded DEMs has become a popular approach [46,50]. Jasiewicz and Metz [14] divided the DEM-based methods into channel initiation methods, valley recognition methods, and a combination of both [21]. Some researchers have also categorized the existing methods as hydrology-based and morphology-based methods [23].

The hydrology-based algorithms usually use DEMs to calculate the flow direction and catchment number of each cell, and determine a channel with specific criteria. Most of the methods within this category are based on the D8 flow direction algorithm [15,28]. The main associated channelization criteria for the D8 algorithm are the contributing area threshold [28], the contributing area and the slope threshold [25], the stream order threshold [32], and the contributing area and stream length threshold (included in TauDEM). Moreover, the limitations of the initial D8 approach have been overcome by a number of improved versions employing multiple flow directions (MFD) [8,11,35,42] or other drainage input [47]. However, the hydrology-based algorithms always fail to derive topologically correct streams in a landscape with changing dissection patterns [23]. In order to handle spatial change, numerous morphology-based methods [4,13,24,34,43] have been proposed to delineate channel networks using topographic curvature rather than flow directions and channelization criteria. Methodologies based on terrain morphology have also been developed to map valley networks for large areas with spatially variable dissection or landforms that lack spatial integration [22].

Recently, with the availability of very high resolution topographic data obtained by airborne laser scanning, new methods [16,17,31] have been proposed to directly detect channels rather than delineating the likely channel location based on topographic features, even in flat and engineered landscapes [30,20]. There have also been methods developed to identify channel networks by incorporating remotely sensed imagery to provide more reliable stream information [40,38].

However, DEM-based methods can be sensitive to DEM errors [16] and/or limited by the imperfect assumptions on the behavior of water flow controlled by surface morphology [44]. Compared to the DEM-based algorithms, there are relatively fewer methods that can obtain the hydrological parameters and map the drainage systems from contour elevation data. In fact, the contour-based models are particularly suitable for hydrological applications and other geophysical processes driven by gravity [26,48,37]. Flow nets derived from contour lines (CLs) can explicitly reproduce the way that water and

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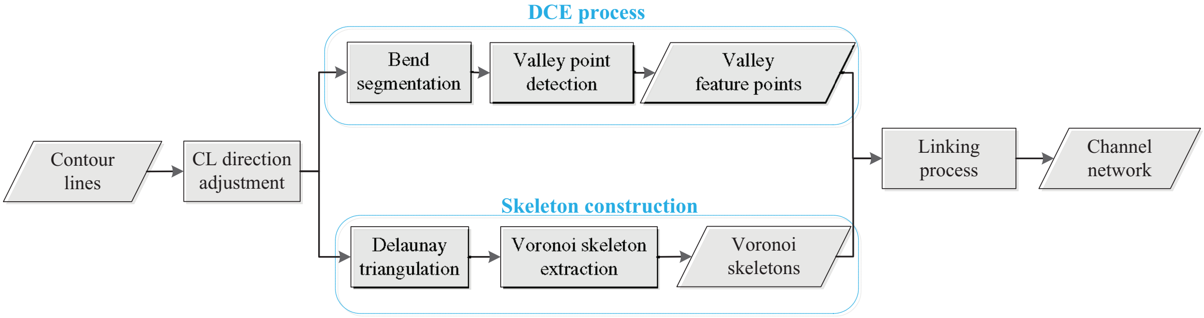

Fig. 1. The framework of the proposed method.

sediments flow on the land surface [27]. In addition, for historical landscapes, contour elevation data remain the only available data source [12]. Therefore, the exploration of extracting landform features from CL data is also necessary for hydrological applications.

Based on a Delaunay triangulation built from CLs, skeleton construction techniques have been proposed to extract the landform features by using "flat triangles" [41] or "crust and skeleton extraction" [9]. However, the skeleton construction methods usually fail to create topologically correct drainage systems, due to the lack of connectivity. Another category of methods are the pure contour-based methods. Earlier examples of the pure contour-based methods are TOPOG [29] and TAPES-C [10], but these methods require a high degree of user involvement. Ai [1] utilized the geometric bends contained in the CLs as the key for drainage network construction. More recently, Rulli [36] proposed a physical watershed partitioning method by tracking flow lines moving from upslope to downslope. The pure contour-based methods are, however, sensitive to vector noise and terrain type [27], which limits their application.

In this study, we propose a contour-based framework that combines the skeleton construction technique with discrete curve evolution (DCE) [18] for the extraction of topologically preserved channel networks. In Ai [1], the CL bends were viewed as projected fragments of valley channels in a 2D plane, which is in accordance with human identification of morphometric features when interpreting a contour map. The use of the relationship between the geometric bends contained in CLs and terrain topological structure is the key idea of this paper. Inspired by the idea, DCE is applied to dynamically segment the contour lines (CLs) into geometric/valley bends, and to detect the valley feature points with respect to CL noise and distortion. In order to distill more accurate channel paths in complex terrain, the Voronoi skeletons (or medial axes) are then extracted from the Delaunay triangulation built from the CLs. A linking step is finally undertaken to generate the complete drainage network.

The remainder of this paper is organized as follows. The methodology is detailed in Section 2, while the experimental results and comparisons with other methods are presented in Section 3. The discussion is given in Section 4. Finally, the conclusions are drawn in Section 5.

2. Methodology

The method used in this study is composed of four major components: (1) dynamic CL bend segmentation with DCE; (2) valley feature point detection; (3) Voronoi skeleton extraction; and (4) drainage network generation. The workflow of the method is shown in Fig. 1.

2.1. Dynamic bend segmentation with discrete curve evolution (DCE)

DCE was developed by Latecki and Lakämper [18]. The main idea of DCE is a stepwise elimination of the vertices with the smallest contribution to the shape of a polygonal curve. The elimination process is conducted by a relevance measure K. In every evolution step of DCE, two consecutive line segments, s_1 and s_2, incident to a vertex v with the smallest K, are substituted by a single line joining their endpoints, where K is given as

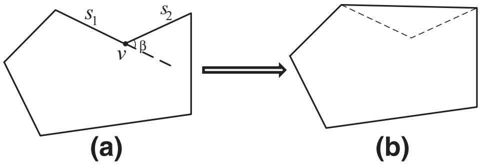

Fig. 2. The elimination of a vertex v with the smallest relevance measure, where its two adjacent line segments, s_1 and s_2 in (a), are substituted by a single line segment, as shown in (b).

$$K(s_1, s_2) = \frac{\beta(s_1, s_2) l(s_1) l(s_2)}{l(s_1) + l(s_2)} \tag{1}$$

where $\beta(s_1, s_2)$ is the turn angle at the common vertex v of segments s_1 and s_2, and l is the length function. Fig. 2 illustrates the elimination process. The higher the value of $K(s_1, s_2)$, the larger the contribution of the vertex v to the shape of the polygonal curve [19,2]. The stepwise elimination of vertices with the smallest shape contribution results in a sequence of simpler polygons from the original curve. The remaining vertices on the simplified polygons are therefore a hierarchical partitioning of the input curve into curve segments.

Given each of the input CLs as an original input curve, a bend is then defined as a segment (part) of the original CL which is enclosed by two endpoints of a convex or concave part (with positive or negative curvature towards the trace direction) in the simplified polygons. In order to guarantee that a bend selected from one side of a CL exactly corresponds to a valley bend[1], a tracing direction along the CL is chosen, usually from the left to the right side (or a set clockwise direction for closed CLs). Fig. 3 illustrates a CL shape in a few stages of evolution. The (red) outer polygons represent the CL simplified by DCE. The green parts indicate the area of the obtained valley bends. These valley bends are obtained by the endpoints of the concave parts on the simplified polygons at different stages. Traditionally, bend acquirement using the convex or concave parts on the original CL is sensitive to CL noise and distortion. The use of DCE-simplified polygons therefore allows us to mitigate the influence of noise and distortion before obtaining the bends. Since CLs are not always closed, as with the endpoints of an open CL, no relevance measure can be computed as there is only one adjacent line segment. We regard these endpoints as the fixed points which will not be eliminated in the DCE process.

We can see from Fig. 3 that the green parts at different stages of DCE indicate that a big bend may contain small bends. This is consistent with the property of self-similarity and the fractal properties, in

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[1] The concave part corresponds to a valley bend, while, conversely, the convex part corresponds to a ridge bend.