Geomorphons - a new approach to classification of landforms

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Abstract—**We introduce a novel method for classification and mapping of landforms based on the idea that the Earth's surface can be described by the two complementary measures: relief-independent, local spatial pattern and the magnitude of the relief itself. The first of these two measures is sufficient to classify and map the landforms. At the core of the method is the concept of geomorphon (geomorphologic phonotype). A geomorphon is a relief-invariant, orientation-invariant, and size-flexible abstracted elementary unit of terrain. It is expressed in terms of local ternary pattern that encapsulates morphology of surface around the point of interest. Geomorphons enable terrain analysis without resorting to differential geometry. A collection of 498 different geomorphons constitutes a comprehensive and exhaustive set of all possible morphological terrain types. This set includes both standard elements of the landscape, as well as unfamiliar forms rarely found on natural terrestrial surfaces. Geomorphons are both terrain attributes and landform types. This reduces the task of landform mapping to the identification of geomorphons by their labels across the site of interest. We describe the fundamental ideas behind the geomorphon concept. We also give an example of how a map of a standard landform types can be constructed using geomorphons.**

I. INTRODUCTION

Earth's surface can be viewed as a mosaic of various landforms - physical features having a characteristic, recognizable shape and produced by natural causes [1]. Classification of those landforms into landform types and ability to auto-segment a given landscape into constituent landform types are important tasks with applications to many scientific disciplines [2]. This is because, as fundamental units of Earth's surface, landforms provide boundary conditions for processes of interest in geomorphology [3,4], pedology [5], vegetation [6] or ecology [2,7], and hydrology [8,9] - to name just a few.

A high interest in auto-segmentation of landscapes (hereafter referred to as landform mapping or simply as mapping) has led to a significant number of proposed methods to address this problem. From geomorphic point of view landform mapping may be based on the following principles: the morphologic, the genetic, the chronologic, and the dynamic [2]. So far, all existing proposals for auto-mapping have been based on morphologic principle. Numerous approaches to implementation of morphologic principle have been proposed; a brief comparative summary of these methods, from different technical perspectives, can be found in the Introduction section of [10]. All auto-mapping techniques, regardless of the details, consist of the following two steps: (a) description of landform elements in terms of numerical features, and (b) semantic assignment (giving landform-like names to specific sets of features). The first step is almost universally achieved by means of differential geometry; slope gradients and different types of curvature are calculated as features encapsulating local morphology of the surface. Generally, those features are calculated from a DEM using a moving square window of a fixed size. The mapping based on such features is scale-dependant [11]; changing the size of the pixels and/or the size of the moving window produces a different map.

In this paper we introduce a novel approach to landform mapping, one that departs significantly from *all* existing methodologies. The focus of this paper is on the step (a) – description of landform elements, although we also present an example of implementation of step (b) which is necessary to produce an actual map. The method has two core components that together set it apart from all existing methods. First, it does not utilize differential geometry; instead, it generalizes an image analysis concept of local binary patterns (LBP) to a new, terrain analysis concept of local ternary patterns (LTP). This breaks with traditional, calculus-based approach to characterization of landforms in favor of a digital-based approach. Second, the new method does not use a fixed-scale window to extract information about the surface; instead, it utilizes a line-of-sight neighborhood as introduced by [12] to achieve flexibility in sizes of mapped landforms.

II. Methodology

In image analysis the LBP operator [13] is a simple yet very efficient texture operator which assigns an 8-tuple pattern of 0s and 1s to a focus pixel by thresholding pixels in the 3 x 3 neighborhood with the value of the focus pixel. We observe that description of Earth's surface can be achieved by two complementary measures: local spatial pattern (different from, but analogous to, the LBP) and the magnitude of the relief itself. This is because we expect that relative differences in elevations between a focus pixel and its neighbors are statistically independent from the absolute elevation of the focus pixel. Through such factorization we can achieve a significant simplification in the way the landforms are characterized as the local spatial patterns are sufficient for landform classification.

A. Local ternary patterns

In order to characterize a relief-independent morphology of surface patch we use a *ternary* (rather than binary) local operator that assigns an 8-tuple pattern (consisting of three symbols "-", "0", or "+") to the focus pixel. The pattern arises from a comparison of a focus pixel with its eight neighbors starting from the one located to the east and continuing counterclockwise. For example, a tuple {+,-,-,-,0,+,+,+} describes one possible pattern of relative measures {higher, lower, lower, lower, equal, higher, higher, higher} for pixels surrounding the focus pixel. It is important to stress that the neighbors are not necessarily an immediate neighbors of the focus pixel in the grid, but rather the pixels determined from the line-of-sight principle along the eight principal directions.

Characterization of the local surface by the line-of-sight principle was proposed in connection with the notion of *terrain openness*. For detailed description of this principle we refer to the paper by [12]; here we note that this principle relates surface relief and horizontal distance by means of so-called zenith and nadir angles along the eight principal compass directions. The ternary operator converts the information contained in all the pairs of zenith and nadir angles into the ternary pattern (8-tuple). The result depends on the values of two parameters: search radius (L) and relief threshold (d). The search radius is the maximum allowable distance for calculation of zenith and nadir angles. The relief threshold is a minimum value of the line-of-sight angle (zenith or nadir) that is considered significantly different from the horizon. Comparison of the angles with the threshold results in assigning the value of "-", "0", or "+" to each principal direction. Using larger values of L and d is tantamount to terrain classification from a higher and wider perspective, whereas using smaller values of L and d is tantamount to terrain classification from a local point of view. The advantage of using the line-of-sign based neighborhood instead of grid-based neighborhood becomes clear by observing that, in principle, choosing an infinitively large value of L should result in identification of landform type regardless of its size. In practice, by using larger values of L, we can simultaneously identify landform types on a wider range of sizes than it would be possible with the grid-based neighborhood thus achieving size flexibility (see Fig. 1).

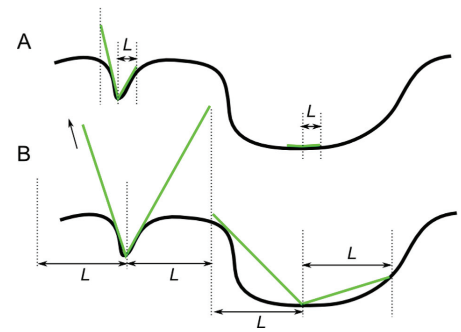

Figure 1. Detecting landforms at different scales with the line-of-sigh principle. (A) Smaller value of search radius L results in detection of locally-determined landforms. (B) Larger value of search radius L results in simultaneous detection of landforms on several sizes.

B. Geomorphons

There are $3^8 = 6561$ possible ternary patterns (8-tuplets). By eliminating patterns that are results of either rotation or reflection of other patterns we are left with a comprehensive and exhaustive set of 498 patterns. We refer to these patterns as *geomorphons*; geomorphons constitute a comprehensive and exhaustive set of idealized landforms that are independent of the size, relief, and orientation of the actual landform. Note that geomorphons are terrain features *and* landform types at the same time. Thus, in our method, mapping of landforms (or, at least their preliminary mapping) is achieved in a single step of calculating geomorphons for each pixel in the DEM. Certainly, mapping all 498 different landform types is unnecessary, but in most real landscapes only a small fraction of all theoretically possible geomorphons are actually present (see the next section).

Using geomorphons to map landscapes has a number of desirable properties. First, it does not require calculation of differential geometry-based terrain parameters with infinite number of possible values. This eliminates (or reduces) the need for an additional set of heuristic rules connecting those values to

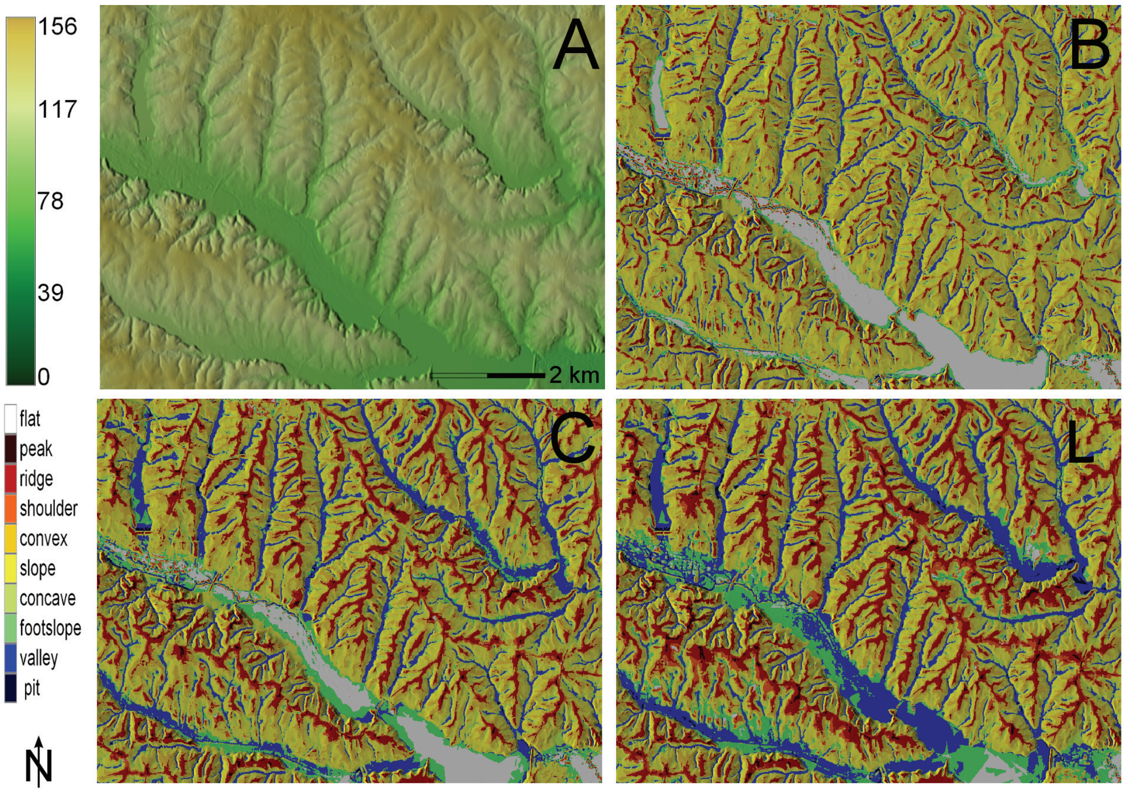

Figure 2. Geomorphons-based mapping of landforms in the south-west portion of the "North Carolina" test site. (A) Visual rendition of the DEM; (B) Map created using L = 100 m and d= 1°; (C) Map created using L = 300 m and d= 1°; (D) Map created using L = 1000 m and d= 1°.

landform types. Second, due to quantization introduced by the ternary operator, the method establishes a finite, absolute set of possible landforms so no landform is too rare to be found. Third, geomorphons are calculated using a scale-flexible procedure, making possible simultaneous recognition of the same landforms having different sizes.

TABLE I. GEOMORPHONS FOR MOST POPULAR TERRAIN FORMS

	SL	SH	VL	CN	FL	RI	FS	CV	PK	PT
A	+++ ○ ○ −−−	−−− ○ ○ ○○○	+++ ○ ○ +++	+++ + + −−−	○○○ ○ ○ ○○○	−−− ○ ○ −−−	+++ ○ ○ ○○○	−−− − − +++	+++ + + +++	−−− − − −−−
B	+++ ○ + −−−	−−− ○ − ○○○	+++ + ○ +++	+++ + + ○−−	+○○ ○ ○ ○○○	−−− − ○ −−−	+++ + ○ ○○○	−−− − − +○○		

FL - flat; PK - peak; RI - ridge; SH - shoulder; CV - convex slope; SL - slope; CN - concave slope; FS - footslope; VL - valley; PT - pit/depression

III. LANDFORM MAPPING

In order to demonstrate a protocol of generating a map of landform types using geomorphons, we use a standard GRASS GIS "North Carolina" test site [14] represented by a DEM with the 10m/pixel resolution. In this site 50% of all pixels are covered by just 8 different geomorphons, 90% are covered by 36 geomorphons, and 100% of the site is covered by 352 of possible 498 geomorphons. It is clear that the vast majority of terrain in this site consists of a small number of "standard" landform types, while more exotic landform types are exceedingly rare. For the purpose of this paper we have chosen 10 most frequent geomorphones (covering almost 60% of the terrain); their patterns are listed in row A of Table I. They represent the well-known terrain types as named in Table I and their patterns are characterized by a minimum number of transitions between ternary elements (-, o, +) – a reflection of high autocorretion in the landscape depicted by the test site. We have assigned the remaining 40% of the pixels to one of the 10 dominant landform types on the basis of pattern similarity. Row B of Table I show a single example of geomorphon also assigned to a landform type as defined by a prototypical geomorphon shown in row A.

Fig. 2 shows the geomorphon-based maps of landforms. A character of the map depends on the value of L (d is the same for all three maps). Using small value of L results in the map that correctly identifies landforms if their size is $\approx L$; landforms having larger sizes are broken down into components (for example, a broad valley is broken into its smaller size constituent components: flat bottom, footslope, slopes). Using larger values of L allows simultaneous identification of landforms on variety of sizes (for examples, both narrow and broad valleys are identified).

IV. CONCLUSIONS

Geomorphons are a qualitatively new way to classify landforms in order to map them. They use local patterns modeled on the well-know LBP of image analysis but constructed in a way that is applicable to terrain analysis. They also can be though of as an extension of the concept of openness from a terrain attribute, designed to emphasize surface concavities and convexities, to a complete landform classification scheme. Their effectiveness stems from their simplicity – a result of quantization by a ternary operator. They may signal a new trend in tools used for terrain analysis: away from differential geometry and toward digital patterns. Geomorphons make the issue of choosing a most appropriate classification technique somewhat mute as they constitute a universal set of landform types; all what remains to be done in order to generate the map of landforms is to identify geomorphons by their labels across the site. The future research will concentrate on a general methodology for agglomeration of this universal mapping into a smaller number of landform classes as judged to be most appropriate in the context of particular mapping task. Different applications may require different agglomeration protocols. Geomorphons are also useful for mapping terrains, such as extra-terrestrial surfaces, which are characterized by a smaller amount of autocorrelation and may possess landforms not encountered on Earth but present in the exhaustive set of geomorphons. They can also be useful in auto-searches for specific, possibly rare, landforms like cirque glaciers, or craters. The method can identify specific landforms having different sizes. Because the set of possible geomorphons is absolute and set once and for all, each location can be assigned a series of different geomorphons parameterized by different values of L and d. This series represents a multi-scale classification of the focus location.

ACKNOWLEDGMENT

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