Landscape dynamics from LiDAR data time series

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Abstract—**We propose a multidimensional framework for characterization of land surface dynamics based on time series of elevation data acquired by LiDAR technology. The proposed methods integrate line feature, surface and volume analysis. A novel, least cost path approach for coastal dune ridge and dune toe extraction is presented to support automated feature evolution analysis. Per-cell statistics is applied to DEM time series to extract the stable landscape core and map the extent of land surface dynamics. Voxel representation of terrain evolution within space-time cube is explored and used to visualize contour evolution. The framework is applied to analysis of barrier island dynamics using time series of airborne LiDAR data acquired over the past decade. Field-scale elevation change is studied based on terrestrial LiDAR surveys and flow patterns. Impact of terrain modification on flow pattern is investigated using Tangible Geospatial Modeling System.**

I. Introduction

LiDAR sensors are increasingly used for repeated surveys that capture the short-term evolution of landscapes and provide unique insights into land surface dynamics. These surveys produce high resolution, multi-temporal elevation data and new concepts and methods in geomorphometry are needed to study and characterize topography as a dynamic surface.

Traditional methods for investigation of land surface change from LiDAR-based DEMs rely on a relatively straightforward *difference of DEMs* computation, including estimation of volume change [1]. Line features, such as shorelines, ridge lines or channels, extracted from series of DEMs have also been used for quantification of land surface dynamics in terms of horizontal feature migration rates [2]. The high resolution and noisy surfaces that characterize LiDAR-derived DEMs pose challenges for traditional feature extraction methods and are motivation for development of algorithms that combine computational geometry with image processing and machine learning techniques. The Least Cost Path (LCP) approach is emerging as a robust method for extraction of continuous line features from complex, noisy surfaces (see e.g., [3] for stream extraction method from radar-based DEMs based on LCP). These line features then can be used to quantify feature migration and map feature-derived metrics such as storm vulnerability factor [4] or erosion risk index.

Changes in elevation surface can have profound impact on processes such as overland water flow, flooding, soil erosion or solar irradiation and, consequently, on ecosystems and human activities. The high resolutions of airborne and terrestrial LiDAR surveys provide unique opportunities to study these impacts, but little research has been done to date on the simulation of processes using LiDAR-derived time series of DEMs.

In this paper, we introduce a multidimensional framework for terrain evolution analysis that captures spatial and temporal variability of elevation surface based on a time series of 1D line features, 2D elevation rasters, and a 3D space-time cube model. This framework is applied to a dynamic coastal beach and foredune system in North Carolina where the change is driven by wind sand transport, wave induced beach erosion and human intervention such as beach nourishment. We then demonstrate the application of flow tracing for capturing the subtle terrain features and their change from time series of terrestrial LiDAR scans of an agricultural field in the piedmont region of North Carolina. Finally, we conclude with a description of the *Tangible Geospatial Modeling System*, a collaborative environment for investigation of terrain change impacts on topographic parameters and landscape processes.

II. Land surface dynamics from time series of lidar data

A multidimensional framework for characterization of land surface dynamics using time series of elevation data integrates the following approaches:

- *Feature Evolution*: Extracts line topographic features (e.g. shorelines, ridges, channels) from DEMs for each time snapshot and derives dynamics metrics from these features;
- *Surface Evolution: A*pplies a per-cell statistical analysis to time series of raster DEMs resulting in new raster maps that characterize evolution of land surface while preserving the original spatial resolution and detail of the DEM;
- *Space-Time Cube:* creates a voxel representation of elevation evolution with time as third dimension and evolution of contour-based features represented by isosurfaces.

The methodology is based on the open source GRASS GIS [5] tools and algorithms implemented in custom python scripts. The framework is illustrated by examples from the analysis of 100 km of North Carolina barrier islands mapped by 14 airborne LiDAR surveys between the years 1996-2009 acquired at ~ 1-2 year time steps, and represented by 0.5 m resolution DEMs interpolated and smoothed by regularized spline with tension [5][6].

A. Feature evolution

To measure land surface evolution using line features, the salient features are extracted from each DEM and then their 3D migration is tracked, usually along set of profiles. For example, coastal erosion rates are estimated by extracting shorelines from DEMs as mean high water elevation contours and then measuring their displacement along cross-shore profiles. More sophisticated methods are needed for extraction of complex features like coastal dune ridges and dune toes. To ensure a continuous line extraction of these features from LiDAR-based DEMs, we propose a new approach based on the LCP method.

The cost function for a *coastal dune ridge extraction* can be defined as an inverse function of elevation, with the cost of a shorter, lower-elevation path greater than the cost of a slightly longer, higher-elevation path. The following cost function fulfills these conditions and performed well in our tests :

$$J = e^{-bz} \qquad (1)$$

where J is the cost of traversing a raster cell, z is elevation, and b is the tunable parameter. Given the cost surface (1), the ridge is extracted as the least cost path between two given end points of the ridge (Fig. 1a). When compared to traditional methods that rely on curvatures or local extremes along cross-shore profiles, the LCP approach generates continuous ridge line with minimal human intervention.

The cost function for *dune toe extraction* is more complex because the geomorphologically intricate dune toe is more difficult to define quantitatively. It is qualitatively described as the location where the beach meets the foredune. This location can also be conceptualized as the location where the cross shore profile deviates the most from a line connecting the dune ridge and shoreline. By expanding this conceptualization into two-dimensions, a continuous dune toe can be extracted.

First, the elevation of an elastic sheet with boundary conditions at the shoreline and the dune ridge is computed (Fig. 1b). The sheet is modeled as an array of critically damped springs with nodes located at each raster cell. The nodes between the shoreline and dune ridge can move vertically, but not horizontally, and the nodes at the ends of the sheet are fixed to the shoreline and the dune ridge. Two forces act on each individual node: a viscous damping force, which depends on its velocity, and a spring force, which depends on its elevation relative to the elevations of its neighbors. The motion of a node in the raster cell *i, j* is described by the differential equation

$$\frac{d^2 z_{i,j}}{dt^2} + 2\zeta\,\omega_0 \frac{d z_{i,j}}{dt} + \omega_0^2 \Big(\sum_{\langle i,j\rangle} z_{i,j} - 4z_{i,j}\Big) = 0 \qquad (2)$$

where z is elevation, t is time, ω_0 is the angular frequency, ζ is the damping ratio, and brackets indicate a sum over nearest neighbors. This equation can be written as a system of two, first-order ordinary differential equations and solved using standard numerical techniques like Runge-Kutta.

Second, elevation of the sheet and the terrain surface (Fig. 1a) are differenced using map algebra, resulting in a raster map that represents the deviation Δz between these two surfaces (Fig. 1c). Finally, a cost surface is derived using the cost function given by (1) where z has been replaced by Δz and the least cost path approximates the dune toe (Fig. 1d).

Changes in the 3D position of the dune toe and dune ridge are then measured to evaluate the trends in dune evolution (Fig. 2). These continuous line features are also used to assess changes in the storm vulnerability factor (Fig. 1e) that relates the spatially variable storm surge to dune ridge and dune toe position [4][7].

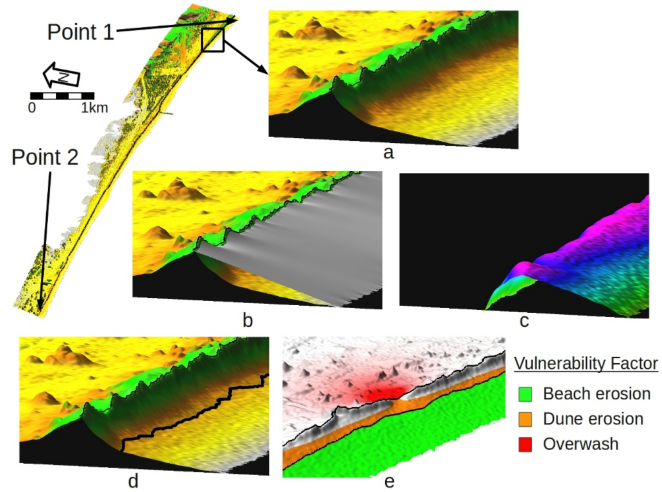

Figure 1. Coastal feature extraction using the LCP method: (a) DEM with extracted dune ridge, (b) DEM with sheet anchored at dune ridge and shoreline, (c) surface showing the elevation difference Δz between the DEM and the sheet, (d) dune ridge and dune toe, (e) vulnerability factor draped over DEM.

B. Surface evolution

To map the spatial pattern of the surface dynamics we have introduced the concept of *core* and *envelope* surfaces (i.e. minimum and maximum elevation measured at each grid cell over the given time period) and *dynamic layer* (the volume bound by the core and envelope), as well as the time of elevation minimum and the time of elevation maximum maps (Fig. 3). These raster maps are derived by simple per-cell statistics applied to time series of DEMs (see [8] for more details and additional metrics). The concept has been specifically designed to map the stable core of the barrier islands and to identify their most dynamic landforms, but it can be applied to other types of evolving landscapes, such as migrating dune fields, eroding hillslopes and streams, and active debris flows.

By applying line feature extraction to the core and envelope the space within which the given line feature evolved can be mapped. For example, shorelines extracted from the core and envelope define a *shoreline band* within which the shoreline evolved during the given period (Figs. 2, 3). Additional metrics that provides quantitative information about mass redistribution within the evolving landscape has also been derived [6].

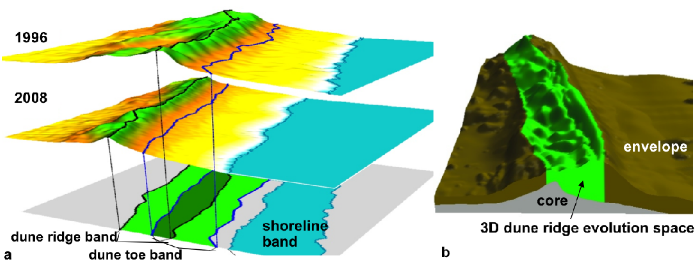

Figure 2. Change in the dune ridge, dune toe and shore line between the years 1998 and 2008: (a) respective evolution bands, (b) 3D ridge evolution space.

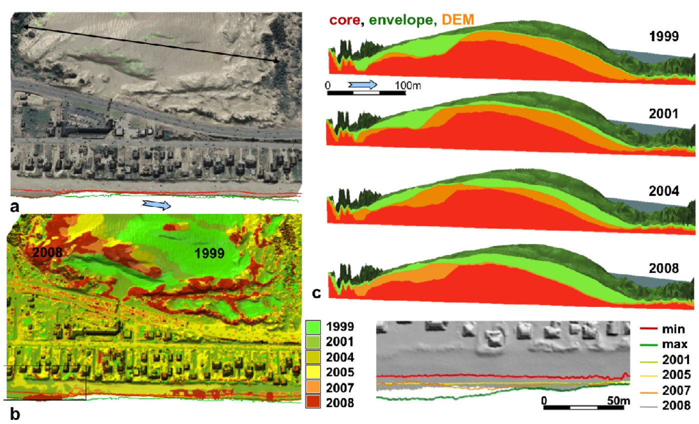

Figure 3. Raster-based analysis of coastal terrain dynamics: (a) 2008 DEM with orthophoto and shoreline band, (b) time of elevation maximum map draped over a 2008 DEM, (c) cross-section through core, envelope and migrating dune surfaces. Inset shows detail of shoreline band with actual shoreline positions.

C. *Land surface dynamics in space-time cube*

The analysis based on time series of DEMs outlined above handles evolution over time as discrete landscape snapshots. To apply the full power of analysis based on differential geometry land surface evolution can be represented as a trivariate function

$$z = f(x, y, t) \qquad (3)$$

where the third dimension is time and elevation is the modelled variable. Elevation evolution is then represented as a voxel (3D raster) model interpolated from time series of LiDAR point cloud using trivariate interpolation. To visualize evolution of selected contours $z=c_i$ in space-time cube, isosurfaces $c=f(x,y,t)$ are extracted from the voxel model (Fig. 4). Spatio-temporal gradients (fastest change in elevation vectors) can also be derived using partial derivatives of the trivariate interpolation function.

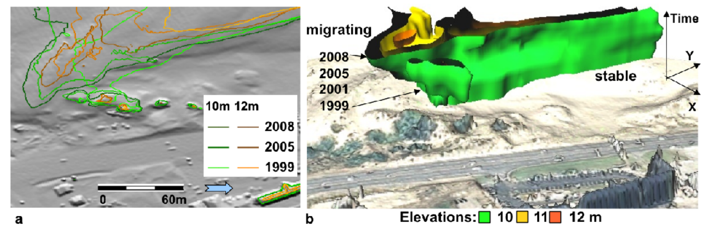

Figure 4. Elevation evolution in space-time cube: (a) limited, but hard to interpret set of contours z=10,12 m for the years 1999, 2005, 2008, (b) space-time isosurfaces derived from 1999, 2001, 2004, 2005, 2007 2008 point data, equivalent to z=10,11,12 m contours stretched in the vertical time dimension.

III. Impact of land surface changes on processes

Change in topography can significantly influence landscape processes such as flooding or runoff. The magnitude of elevation change does not always translate into the magnitude of impact, and location and geometry of the elevation change can play a more important role. Application of process-based simulations to series of real-world or designed DEMs provides opportunities for investigation of relationships and interactions between the change in elevation surface geometry and water or mass flow patterns.

A. *Flow accumulation change due to evolving land surface*

Land surface change is more subtle in sustainably-managed inland watersheds than on dynamic coasts or in disturbed landscapes exposed to extensive erosion and gullying. To study impact of small elevation changes on overland flow, we performed repeated terrestrial LiDAR surveys of an agricultural field that captured elevation surface at cm resolutions (Fig. 5). *D-inf* flow tracing and particle sampling simulations were then applied to the 20 cm resolution DEM series to identify changes in micro-topography, such as breaches in micro-ridges created by tillage that can redirect the overland flow (Fig. 5).

B. *Geodesign*

Although real world LiDAR data time series are becoming more common, laboratory systems can provide us with rapidly generated series of DEMs with different configurations of terrain features and structures.

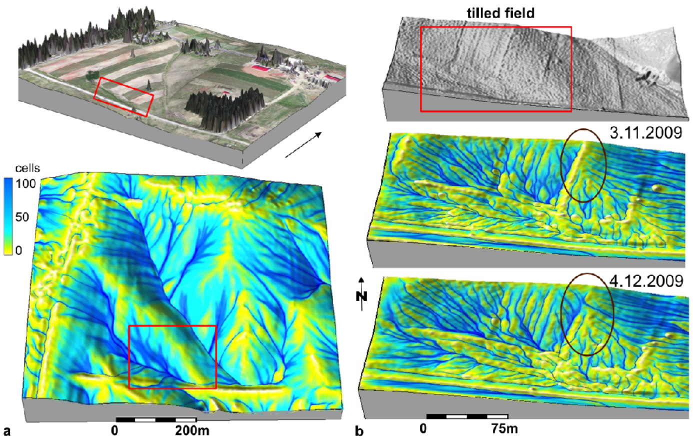

Figure 5. Flow tracing in a small watershed that includes tilled field modeled (a) at 1m resolution from DEM derived from airborne LiDAR data, and (b) at 0.20 m resolution from DEMs derived from terrestrial laser scanner.

This is particularly useful in design studies that examine the impact of elevation changes on surface processes. For this purpose, we use an exploratory *Tangible Geospatial Modeling System* (TanGeoMS) [9] that consists of a flexible landscape model, a 3D laser scanner, and a projector (Fig. 6). The laser scans a 3D clay model, which can be readily modified by hand. The impact of terrain modifications on a selected parameter (e.g. slope, water flow, insolation) is then projected as a color map on the surface of the model. The capability to easily change the terrain surface, including models of built structures, coupled with full power of GIS, facilitates collaborative exploration of landscape design and terrain change impact on processes, such as overland water flow (Fig. 5) or coastal flooding [9].

IV. Conclusions

We have introduced a methodology for comprehensive analysis of land surface dynamics by integrating 1D feature extraction, 2D raster-based per-cell statistics and 3D modeling within the space-time cube. An important component of this methodology is robust extraction of coastal topographic features from high resolution DEMs using LCP approach. The concept of the stable core, dynamic envelope and other per-cell statistics measures provide detailed information about the form and rate of coastal terrain change for research and management applications. The space-time cube concept is still at exploratory stage, but we have shown its feasibility and potential for visual and geometry-based analysis of elevation evolution. Flow tracing has been applied as an effective tool for identification of subtle changes in micro-topography captured by terrestrial LiDAR. The presented case studies demonstrate that high spatial and temporal resolution of modern 3D mapping technologies coupled with advanced GIS tools bring new opportunities to study topography as a dynamic surface and explore the feedbacks between evolution of landforms and landscape processes.

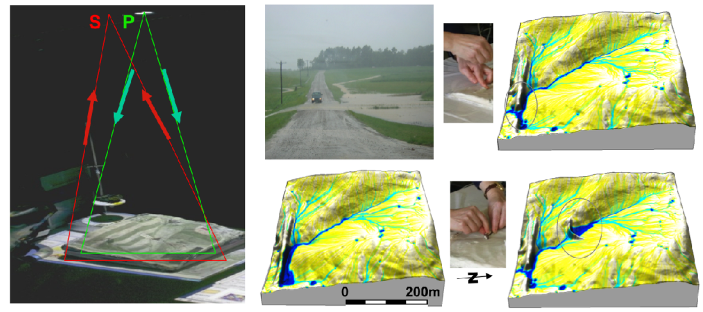

Figure 6. Tangible Geospatial Modeling System: a model is scanned to create a DEM while GIS data are projected over the model; simulation of overland flow exploring impact of road breach and a check-dam on flow pattern.

Acknowledgment

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