Measuring fractal trends in rock surface roughness at the outcrop scale

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ABSTRACT
The evolution of dynamical systems formed by the complex interaction of distinct processes over time has been offered as an explanation for the existence of the many temporal and spatial fractal signals evident in nature. This theoretical framework provides a useful context for understanding the role of gradual and catastrophic processes such as rockfalls, landslides and other mass movements in geomorphology, and their contribution to landforms which approach fractal roughness over broad scaling ranges. The main purpose of this study is to investigate techniques for modeling scale dependent roughness using terrestrial laser scanning (TLS) point cloud data, namely multiresolution analysis by the discrete wavelet transform. The Huckleberry Creek Reservoir spillway in Russellville, Arkansas was selected as a test site for the fractal roughness analysis. The spillway walls, excavated from Pennsylvanian age fluvial Hartshorne sandstone in 1994, were scanned at 2-5 cm point spacing. Point clouds were segmented and interpolated over 2.5D grids for anisotropic roughness analysis by the discrete wavelet transform. The limited spatial extent and inconsistent resolution of the data impose upper and lower bounds on viable measurement scale, but provide the means to bridge the gap between small scale profilometric and coarse scale airborne derived geometric datasets in broad bandwidth surface morphology studies. The implementation of multiresolution analysis presented here provides a novel means for quantitative representation of morphological features useful for characterization and interpretation of distinct rock units.

1 INTRODUCTION

Catastrophic erosional events such as landslides and rockfalls pose a growing threat to life and infrastructure where human activity encroaches on landforms undergoing rapid change. In many cases, access to source areas of interest is limited by the very hazard they pose, making conventional hands-on geologic observations difficult or impractical. Therefore, remote, objective characterization of rock morphology is sought as an interpretive tool to examine surface processes in hazardous or inaccessible environments. Multiscale characterization, which has proven to be useful in many fields of inquiry in the natural sciences was chosen as a basis for the methodological investigation. The use of terrestrial laser scanning (TLS) and other close range remote sensing technologies such as digital photogrammetry has enabled efficient quantitative investigation of morphological phenomena at the outcrop scale, whereas in the recent past data for the same investigation may have been obtained by e.g. labor intensive hand measurements (Andrle & Abrahams, 1989; Feng et al, 2003; Buckley et al, 2008). While scale dependent characterization of roughness has been used to automatically detect landslide scars in digital elevation models (DEM) and describe fracture and fault surface geometry, it has not yet seen comprehensive application to the description of the geometry of whole rock outcrops (Glenn et al., 2006; Candela et al., 2009; Berti et al., 2012). Recent work on scaling in natural scene geometry suggests that the traditional descriptive measures of monofractal dimension or multifractal spectra are imperfectly suited for some tasks such as feature recognition and classification, so alternative descriptors are sought (Brodu and Lague, 2012; Mills and Fotopoulos, 2013). To investigate whether scaling characteristics of rock outcrop geometry record information which may be useful in the interpretation of properties of the rock mass and characterisation of the dynamical systems responsible for its exposure, a novel analytical method was used to process TLS data collected at sedimentary outcrops. Scale and surface angle dependent roughness was estimated using the discrete wavelet transform applied to subsets of outcrop point clouds. The resulting roughness vectors were composed into pseudo-image plots to facilitate visual interpretation. These pseudo-images constitute a template which quantifies the unique form of the surface morphology, enabling its unambiguous and repeatable description and facilitating geological interpretations of roughness.

2 MOTIVATION

The gradual adjustment towards equilibrium between a rock mass's competence and erosive forcing may be conceptualized as a dynamical system displaying self-organized criticality, wherein sporadic adjustments towards equilibrium tend to occur with frequency inversely proportional to their magnitude (Bak et al, 1988). (Stark and Hovius, 2001; Guzetti et al, 2002; Santana et al, 2012). These dynamical systems record fractal signals (such as roughness) on the physical structures they encompass. Many surfaces found in nature are known to exhibit self-similar or self-affine roughness over varying scale ranges (Mandelbrot, 1983; Malcai et al, 1997; Renard et al, 2013).

Surface morphology is closely tied to processes involving rock weathering and erosion. Change in surface height statistics over time has been used to investigate the modes and drivers of landform evolution (Phillips, 1995; Montgomery and Brandon, 2002). Spatial fractal dimension can be conceptualized in several different ways relating to known factors contributing to erosive processes. Fractal dimension in physical space describes the relationship between the surface area and volume of a solid material or the degree of interconnectedness of discontinuities within it. High fractal dimension (D) rock-surface interfaces possess more and larger discontinuities and expose more surface area to weathering processes than low D, which implies faster erosion and greater weakness.

The potential trajectories or modes of transport of detached blocks in a rockfall event are controlled in large part by the complex interaction of the respective geometries of the block and the surface over which it is transported (Fityus et al., 2013). Intuitively, components of slope roughness of much smaller wavelength than the size of a mobilized block will have little influence on its velocity or style of movement compared to larger wavelength roughness or topographic features on its path.

Analyzing the roughness associated with morphological features of given, limited scale bandwidth exposes the possibility of studying in greater detail the causes and styles of hard rock erosion. Likewise, developing more robust numerical representations of roughness will facilitate the automatic recognition of surfaces such as landslide scars or regions of active erosion in remote areas.

3 METHODOLOGY

Spatial data in point cloud format is used to characterize the roughness of natural surfaces. Point clouds typically consist of unordered, irregularly spaced points in 3D space, and constitute the raw observations produced by many remote sensing instruments. Both the anisotropy and measurement scale dependence of surface roughness are measured to provide a comprehensive description of three dimensional roughness.

3.1 Point cloud processing

Interpolated digital surface models are created from a point cloud and used to generate a set of height profiles at varying surface angles relative to the local horizontal direction. The 1D discrete wavelet transform (DWT) is used to decompose each profile into sets of coefficients describing the heights of morphological features corresponding to a limited size range (Daubechies, 1988; Mallat, 1999). The roughness of the morphological features captured at a given combination of size and surface angle is represented by the standard deviation of the corresponding set of wavelet coefficients.

3.2 Data visualisation and simulation

The datasets of scaling, anisotropic roughness scores are arranged and plotted as 2D images. To demonstrate the outcome of the analysis on a known target type, a synthetic point cloud was generated and analyzed in Figure 1. The synthetic surface (shown in Figure 2) consisted of points at 0.01m spacing covering a set of 0.3m ledges, square in cross section, stacked one atop another to simulate an outcrop of a differentially eroded bedded rock. The unitless roughness score was calculated at each pair of 15 surface angles (starting and ending with the horizontal) and 15 feature scales from 0.03 to 0.6m.

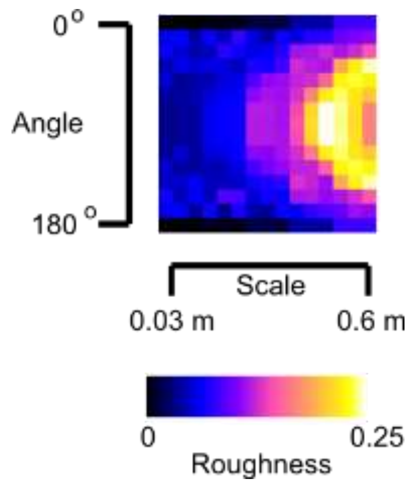

Figure 1. Unitless roughness scores corresponding to surface angle/ feature scale pairs are arranged into a 2D image. Angle value represents degrees from horizontal.

4 CASE STUDY

Point cloud data collected in two scanning campaigns were analyzed. The two rock units, Rock Pens shale and Hartshorne sandstone were selected on the basis of their visibly distinct morphology in outcrop. The Hartshorne sandstone was scanned at its exposure in the Huckleberry Creek Reservoir spillway in Arkansas, US. The Rock Pens shale was scanned at a road cut along U.S. Route 90 outside of Del Rio, Texas.

4.1 TLS data collection

The Pennsylvanian age Hartshorne formation (Figure 3) was deposited in a deltaic environment and is composed of dm to meter scale beds of fine to coarse grained sandstone (Suneson, 1998). Beds exposed in the spillway outcrop take on an angular, blocky habit and form prominent ledges and overhangs. A 7 m high segment of the 15 m high spillway wall was selected for analysis.

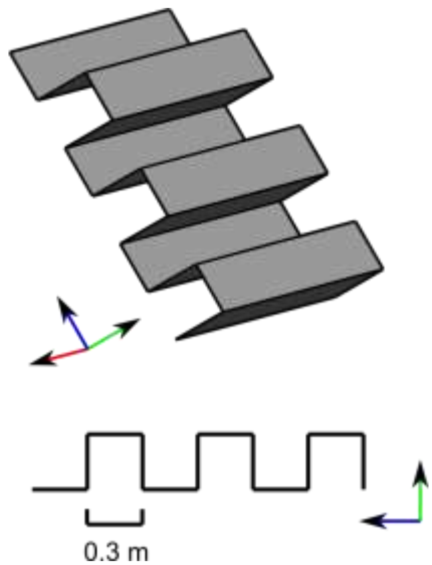

Figure 2. Top: perspective illustration of synthetic surface used to generate analysis in Figure 1. Bottom: cross section through point cloud.

Figure 3. Hartshorne sandstone outcrop, approx. 15 m height.

The upper Cretaceous Rock Pens member of the Eagle Ford group (Figure 4) is an organic rich shale with low, irregular cm-dm scale bedforms at its exposures in the study region (Surles, 1987). The road cut selected stands 7 m high and is devoid of any significant morphological irregularities larger than the bedforms.

Rock outcrop point clouds were obtained by scanning the two outcrops with a Riegl VZ-400 terrestrial LiDAR scanner at a distance of 30m or less. Throughout most of the covered surface of both outcrops, center to center point spacing ranged from 1 to 3cm. Randomly located, partially overlapping spherical subsets (patches) of points 5m in diameter were extracted from the outcrop point clouds for further processing.

Figure 4. Rock Pens shale outcrop, approx. 7 m height.

4.2 Data processing

The anisotropic multiresolution analysis was conducted at 15 profile angles defined by 12º steps from the local horizontal level and 15 physical scales resulting from 3 initial profile resolutions decomposed with 5 levels of the DWT. To enhance the signal to noise ratio for visual interpretation, groups of 10 roughness score vectors were selected at random and stacked. The resulting vectors of roughness scores were flattened into 15x15 pixel images and magnified for visibility. 16 each of the stacked outcrop roughness images were arranged in grids in Figure 5 and 6.

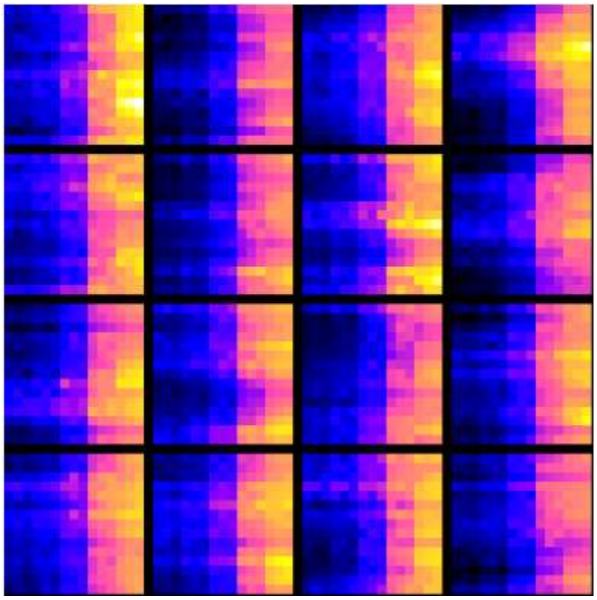

Figure 5. 16 roughness vectors generated from random patches of the Hartshorne sandstone point cloud. Roughness scale increases along the horizontal axis, and angle from the point cloud horizontal direction increases along the vertical.

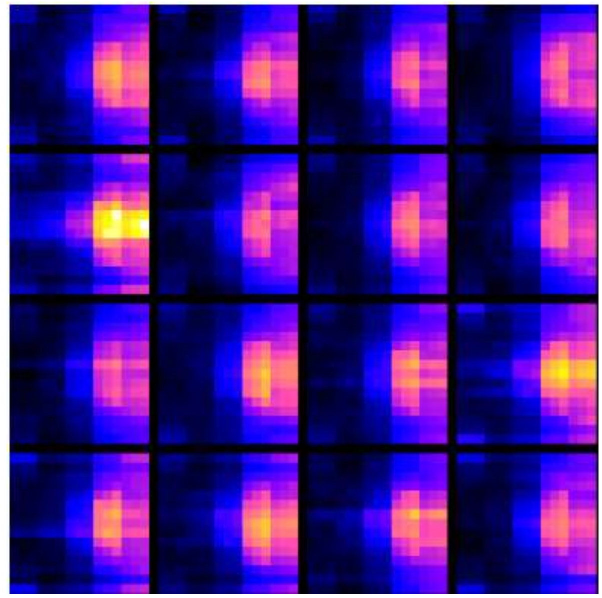

Figure 6. 16 roughness vectors generated from the Rock Pens shale point cloud. Narrow regions of high roughness scores similar to those found in the synthetic point cloud test are present and correspond to bedding in the outcrop.

4.3 Interpretation of roughness plots

The Hartshorne sandstone roughness images (Figure 5) do not possess readily apparent structure after stacking. A monotonic increase in roughness with feature scale but independent of profile angle is observable. Individual patches contribute localized concentrations of angular dependence, but taken as a whole there is no preference for any particular profile angle, demonstrating an overall isotropic surface roughness habit.

Patterns in the Rock Pens shale roughness images (Figure 6) are accentuated by the stacking step. A local concentration of roughness similar to that observed with the simulated surface test case is present in the stacked images, but at a lower scale range, indicating thinner bedforms contributing to the anisotropy.

5 CONCLUSIONS

A strategy for measuring the scale dependence and anisotropy of rock surface roughness is introduced. These characteristics of roughness serve as a basis for making comparisons between rock habits in an outcrop when visualized in a useful format. Furthermore, the roughness scores provide a means to supplement visual inspection of raw point cloud data. The developed analytical technique has diverse potential applications in remote scene inspection and modeling. Current and ongoing research is focused on improved statistical models of surface morphology that will benefit geologists studying surface processes.

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