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New (Digital) Technique for Areal Measurements of Stonewall Surface Roughness

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Abstract: This study revisits a method introduced in the 1990 s that was deployed to measure surface roughness through profiles on rock blocks. Measurements were originally taken directly in the field using a micro-roughness meter or a simple profile gauge. The roughness index was obtained in the "deviograms" method utilizing the standard deviation of differences between 38 adjacent height measurements. The original method used four profiles of depth, each 19 cm in length taken at 5 mm intervals, for each block. A minimum of 10 surfaces are needed to measure the magnitude and scale of roughness, as of boulders. In the current study, this recognized method is applied to a newly introduced method employing the O-IDIP method, which measures areal surface coloration, including standard deviation of lightness and chroma, enabling for roughness estimation. An analysis of the results obtained using both methods conveys similar and statistically significant linear correlations at the 95 and 99% levels of significance. This indicates that the O-IDIP method can be employed for areal measurement of surface roughness and can be deployed on stonewalls.

Keywords: CIE *Lab*, O-IDIP, Quantitative Photography, Deviograms, *RMS* Roughness

Introduction

Many instruments and methods currently used to measure surface properties, including color (Grossi *et al*., 2003), depending on point samples. However, more recent approaches have been developed to quantify areas rather than just points, as on ashlar building surfaces (Thornbush, 2008). The author has shown the usefulness of an integrated (outdoor) digital photography and image processing (O-IDIP) method that considers entire surface areas for color quantification. This research has enabled the development of a soiling index (the TSI by Thornbush, 2014a) based on surface areal measurements of lightness.

Thornbush and Viles (2004) originally introduced the Integrated Digital Photography and Image Processing (IDIP) method, which was subsequently calibrated by Thornbush (2008) for outdoor application as the O-IDIP. Thornbush (2010) discovered that the standard deviation of lightness was indicative of lighting conditions, including cast shadows (especially on a day with clear sky conditions), which were affected by the smoothness or roughness of the surface. This method, which calibrated color using a colorchecker, was more recently applied to measure the greening of walls (Thornbush, 2013).

Most recently, Thornbush (2014b) used the O-IDIP method in two different days in order to test for the effect of outdoor lighting (overcast versus clear sky). As before, histogram-based quantification was derived from images captured on a tripod set close-up in front of a c. 380-year-old wall at the University of Oxford Botanic Garden. A 10-step calibration procedure was employed in the processing of images to make contrast adjustments, in particular. The author discovered that more adjustments were required under

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a clear sky for standard deviation (Std Dev *L*) measurements. Nevertheless, she found that it was possible to employ these measurements (on a comparative basis) in the quantification of surface roughness using this procedure. The technique was not affected by pitting evident on the wall surface, which should have been reflected in the measurements.

In the current study, the O-IDIP is employed again, but this time to ascertain surface roughness associated with changes in color measurement indicative of surface texture (smoothness) or surface roughness. An established manual method already exists based on point sampling along profiles, and this study aims to compare the newly developed (digital) technique with the recognized protocol. By doing so, it is possible to apply a point-based method to areal sampling of surface roughness based on digital photography and image processing.

Surface roughness of rocks were examined in the 1990 s and most of the literature within weathering science dates to that time (from the early 1990 s). More recent work has been published, as for example by Benaissa *et al.* (2010), who investigated the effect of wall roughness (in combination with the appearance of clay) and soil erosion at the fluid/soil interface. Other authors have focused on the surface roughness of metals, such as steel (Sahin and Motorcu, 2004; Onwubolu, 2005; Al-Qawabeha, 2007; Iqbal and Khan, 2010). However, more recent address of surface roughness as concerns rock surfaces and walls in particular is scarce by comparison to these applications.

McCarroll (1991) investigated rock hardness as a measure of weathering through the deployment of a Schmidt hammer to attain rebound (*R*) values. He discovered that weathering and surface roughness are intimately related. So that by measuring one (surface roughness) it is possible to infer the degree of weathering of a rock, such as a boulder; rock wall (Bos *et al*., 2000); rock reservoir (Zhang *et al*., 2001); scarp outcrop (Grab *et al*., 2005); or carbonate caprock (Ellis *et al*., 2011). At the scale of the rock outcrop, it is possible to derive roughness profiles from a laser scanner or through photogrammetry (Haneberg, 2007). This, subsequently, led McCarroll (1991) to develop a detailed method to quantify surface roughness as relevant to weathering studies. Power and Tullis (1991), for instance, explicated the relevance of the topography of rock surfaces as affecting frictional strength, fluid flows (as through joints and fractures), seismicity at faults and more. McCarroll (1992) subsequently examined different scales of surface roughness by varying transect length and measurement interval (as in increments of 5, 10, 15, 20, 25 and 30 mm by McCarroll (1997)) of point measurements across transects rendered on rock surfaces of boulders in his field trials.

An established method used in the measurement of surface roughness was published by (McCarroll and Nesje, 1996). They derived measurements along a profile of standard deviation of the differences between height values. Such a regression approach (in what they termed a "deviogram") was used to calculate the Root-Mean-Square (*RMS*) roughness. Their method was considered to be "automated" due to a software that was provided to automate the calculation of roughness.

Other developments, at that time towards the early 1990 s, in the derivation of surface roughness measurements incorporated laser gauges mounted on a transversing frame (Matsukura and Onda, 1991). Using a laser gauge similarly allowed for the field-based measurement of surface roughness and it was used in a trial run on a gabbro stone monument. More recently, laser scanning of rock surfaces is commonly applied in research. Precision can be improved through reduced noise (as through the use of wavelet denoising methods, Khoshelham *et al*. (2011)) in range measurements, which tend to overestimate the amplitude of laser profiles.

Other researchers have examined wall rock surface roughness in order to assess the impact on slip behavior (Bos *et al*., 2000). Exposure has also been considered, as with Hall *et al*. (2008), who investigated temperature (thermal stress) effects on granular disintegration (relevant for granite in Antarctica). They found (north-facing) orientational effects associated with exposure to solar radiation throughout the day as well as into seasons. Other studies have addressed roughness quantification specifically and their observations have revealed that rock surface roughness increases (at high rates) after just 4-6 months of exposure, with *RMS* values initially 14-32 μm and up to 396-492 μm (Fornós *et al*., 2011). As with the study by Hall *et al*. (2008), these researchers found that surface roughness is affected by widening spaces between rock grains (so, at the grain scale) and their detachment (again, granular disintegration). Finally, X-ray computed tomography was employed (also along with SEM, as by Fornós *et al*. (2011)) in research examining fracture geometry (Ellis *et al*., 2011). These researchers showed that rock properties affecting fracture permeability, such as the preferential dissolution of calcite, leads to

weathering and an unevenness of surfaces and, hence, the development of surface roughness. It is, therefore, important to consider carbonate content, mineral heterogeneity and any spatial patterning affecting the flow path of CO_2-acidified brine. This research has conveyed the relevance of surface acidity to the roughening of surfaces. Biological organisms, microbial as well as higher organisms, can acidify the rock surface, as of the border walls at the University of Oxford Botanic Garden (affected by insects as well as climbing plants, such as ivies). It is recently known, for instance, that incorporating the bacterium *Bacillus sphaericus* in mortar can allow for the "self-healing" of cracks through $CaCO_3$ precipitation in just 40 days from the initiation of cracks (De Belie *et al*., 2014). In this way, acidifying the environment, as through the introduction of bacteria, can release precipitate from $CaCO_3$ walls, which (in addition to pitting, which did not augment surface roughness measured using the O-IDIP method in the way that precipitates visible on the surface, cf. Thornbush, 2014b, Fig. 1a) had the potential to roughen surfaces through its bumpy texture.

Materials and Methods

"Deviograms" Method

Rock surface roughness was measured by McCarroll (1997) using four profiles, each 19 cm long and 5 mm apart, through the application of a micro-roughness meter or a simple profile gauge directly in the field. A roughness index is calculated through the standard deviation of differences of adjacent height measurements. At least 10 surfaces, such as boulders, are needed and "deviograms" are derived and recorded on a spreadsheet program.

O-IDIP Method

Following up on Thornbush (2014b), further research was executed at the University of Oxford Botanic Garden on 15 August 2014. Digital photographs (acquired previously on 24 August 2012) were obtained with a digital camera: FujiFilm Finepix J32 with 12.2 Megapixels (M) with flash off and macro on at 3 M image resolution mounted on a tripod at regular intervals (c. 10 m apart) and at a constant height of 1.5 m above ground level, so that similar wall heights are represented in this field study. The color chart (Gretagmacbeth ColorChecker^{TM} Color Rendition Chart) was used for calibration and the area behind it was measured using depth-gauge profiling (transects), with the chart positioned on blocks located between 0.99 and 1.81 m above the ground.

Specifically, the objective was to use the method deployed by McCarroll (1997) to derive values of *RMS* roughness, as outlined in his article. Specifically, a 150 mm BMI digital caliper with depth measure blade was used to measure surface roughness every 5 mm (which is the smallest increment tested by McCarroll (1997) in the area directly behind where the color chart had been placed at each site. This instrument was calibrated through a zero function and calibrated units were read in mm to two-decimal places, with a measurement resolution of 0.01 mm.

The instrument, mounted each time on a transparent ruler against the wall, measured depth through numeric digital output every 5 mm up to 19 cm. In this way, a total of 38 samples were acquired for each profile, for a total (for four profiles) of 152 depth measurements for every block, for a total of 12 sites (out of 18 sites used in the previous study by Thornbush, (2014b), totaling 1,824 measurements. It was not possible to gain access (due to a grown vegetation cover on the walls) to every site included in the previous study and Sites 8-9, 11-12, 14 and 18 had to be omitted. Most of the sites (12 out of 18, two-thirds or 67%), however, are considered here in order to establish the comparability of these two methods.

Results

Of the 12 sites revisited in this study, seven (Sites 1-7) were to be compared with previous photographs taken in an overcast sky condition and the remaining (five: Sites 10, 13 and 15-17) sites were photographed previously under a clear sky. Comparisons were made of the O-IDIP results (for % Mean *L*, % Std Dev *L* and % Median *L*, respectively) and calculated *RMS* roughness values (Fig. 1).

These results convey a negative (linear) correlation, with increasing O-IDIP results leading to a reduced *RMS* roughness. A Pearson correlation coefficient test subsequently performed to test the strength of these correlations showed strong negative correlations of % Mean *L* and % Median *L* with *RMS* roughness (Table 2). It is noteworthy here that the % Mean *L* and % Median *L* are strongly positively correlated, with $r = 0.95$, so that either measure can be used to quantify surface roughness based on histogram-based outputs for the CIE *Lab* color space. Table 1, which contains a summary of these results, is provided to supplement information already provided by Thornbush (2014b, Table 1).

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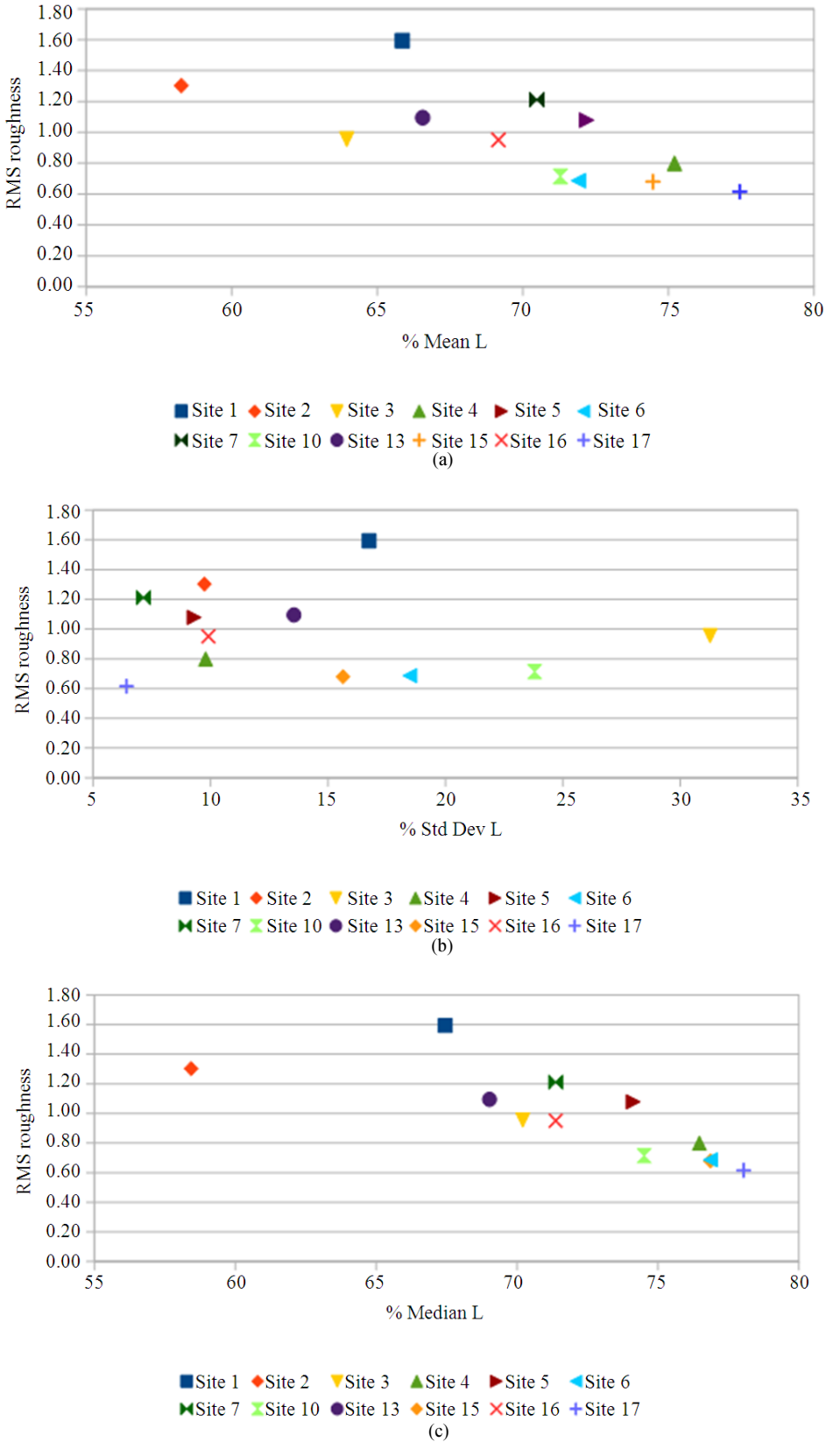

Fig. 1. Comparisons of the O-IDIP and *RMS* roughness methods for 12 sites

Table 1. Summary of results

Sites (Orientation: Facing)	Height[a]	Mean[b]	Standard deviation	RMS roughness
1 (West)	1.06-1.45	7.63	7.26	1.59
2 (West)	1.14-1.52	4.99	1.82	1.30
3 (West)	1.44-1.81	4.27	1.58	0.96
4 (West)	1.35-1.73	2.60	0.86	0.80
5 (West)	1.01-1.37	3.27	1.96	1.08
6 (West)	0.99-1.38	3.38	0.87	0.69
7 (West)	1.07-1.40	3.26	1.65	1.21
10 (North)	1.22-1.50	3.12	0.73	0.71
13 (North)	1.04-1.44	2.86	1.07	1.09
15 (North)	1.35-1.62	2.98	1.01	0.68
16 (North)	1.21-1.48	2.72	1.07	0.95
17 (North)	1.02-1.37	1.99	0.79	0.62

a. Measured (lowest and highest) block height in m above ground level; b. The average was based on 152 measurements (four profiles with 38 sampling points) per block. Measurements were made digitally in mm

Table 2. Pearson correlation coefficient results

	O-IDIP versus *RMS* roughness		
O-IDIP results	Coefficient of determination (r^2)	Correlation coefficient (r)	Two-tailed probability
% Mean *L*	0.48	-0.69	0.01246824[a]
% Std Dev *L*	0.01	-0.12	0.70564463[b]
% Median *L*	0.60	-0.78	0.00303757[a]

a. Statistically significant; b. Not statistically significant

Discussion

The findings of this study convey that % Median *L* and % Mean *L* are (respectively) the strongest linear correlations with *RMS* roughness. These correlations are both negative, so that lightness values increase (both mean and median values), as surface roughness is reduced, which indicates that the lightness of the surface is actually diminished with increasing surface roughness. It is expected that weathering thereby augments surface roughness and reduces its brightness. This is evident because of cast shadows, particularly in bright daylight (under a clear sky), rendering a greater darkness on uneven surfaces.

It is surprising, however, that % Std Dev *L* values are not the most correlated with surface roughness, as predicted by Thornbush (2010) due to lightness variations associated with cast shadows, which should be particularly pronounced on roughened surfaces in the advanced stages of weathering. Sites 1-7 were located along a west-facing wall and Sites 10-17 on a north-facing wall. Aspect (orientation) could, therefore, have affected the results and the strength of the correlations, particularly of % Std Dev *L* values. However, the level of lighting on north- and west-facing walls is known to be similar (generally less illuminated than south-and east-facing walls situated in the northern hemisphere). A reduced contrast would be expected on surfaces with these orientations and this could be affecting the spatial trends. It is evident, for instance, from Fig. 1 that there are differences in the range of the data based on location, whether west- or north-facing. Comparatively, there is less of a data spread (and lower average values) across *RMS* roughness (in all three O-IDIP measures) for sites facing north (and photographed under a clear sky).

This could be a product of microclimate and/or associated plant growth, with temperatures on a north-facing exposure experiencing less thermal stress than all other aspects (Hall *et al*., 2008). Thermal stress indicates that heating-cooling is affecting the wall and this is evident particularly on the west-facing border wall (in comparison to the north-facing wall). This would promote more physical weathering of the surface, in addition to any chemical weathering attributable to the climbing plants evident at these sites (on the west-and north-facing walls), which could acidify the wall surface, as is evident with the appearance of precipitates most notable towards the west-facing wall on the north-facing section of the border wall. However, it is not possible to differentiate between the impacts of outdoor lighting conditions and site location (aspect) in the current study.

Further research is needed to test whether wall aspect or outdoor lighting conditions is (independently) chiefly responsible for differences in the spread of data. Moreover, this study did not take into consideration any piecemeal repair (patchwork) of the wall, which would affect the age of the blocks, their weathering and their roughness. Moreover, it was assumed that all blocks are of the original stone (Headington freestone, Arkell (1970; Horsfield, 2011)).

Fig. 2. Encrustation visible at Site 2 (west-facing), where average *RMS* roughness was relatively high

It is noteworthy that encrustation evident at some sites (Site 2, appearing in Fig. 2) could enhance surface roughness. Also, pitting could augment depth values and Thornbush (2014c) previously observed that pit depth actually decreased (westwards) along this border wall (see her Fig. Iib). Finally, more sites would have helped to elucidate the strength of the correlation between the different methods.

Conclusion

An interesting finding in this study is that % Std Dev *L* is not most strongly correlated with *RMS* roughness. Rather, both % Mean *L* and % Median *L* show stronger negative correlations with measured roughness using an established profile-based technique. Another discovery is this negative linear correlation, which suggests that a roughening of surfaces reduces image lightness measured using a histogram-based approach, such as the O-IDIP method. Both walls sampled in this study faced relatively shady (north-and west-facing) aspects and perhaps this affected the results, especially as the data points were less spread out for measured roughness at north-facing sites that were more often devoid of direct sunlight and thermal stress. Another consideration is the outdoor condition across the days when photographs were taken, representing an overcast versus clear sky, with the latter also producing less spread in *RMS* roughness values and more consistent results.

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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