Inferring texture from shadows

[1]J. Iaquinta, [2]C. Łukianowicz

[1]French Public Works Research Laboratory, Division for Metrology and Instrumentation, 58 Boulevard Lefebvre, F-75015 Paris (France),
Email: iaquinta@lcpc.fr

[2]Department of Mechanical Engineering, Technical University of Koszalin, Raclawicka 15-17, PL-75620 Koszalin (Poland),
Email: czel@tu.koszalin.pl

Abstract. *Fast and robust sensors are often needed to determine surfaces texture in the range of about ten micrometers or so, up to several millimeters. Profiling systems, even able to discriminate between nanometers, cannot guarantee a result representative of a wide area (unless scanning it completely). Other techniques proved to be also static and/or restrained to a strict laboratory environment. A more global approach, taking advantage of the shadow-hiding phenomena observable in the back-scattered radiation field, is therefore suggested. Experiments conducted to validate the measuring principle on surfaces of known roughness are described, and recommendations for an operational set-up are given.*

Keywords: Surface texture, light back-scattering, shadow-hiding, global approach.

1. Introduction

In the fields of industry, space, medicine or civil engineering, the quantitative characterization of surface texture relies on the statistical processing of data obtained from profilometers. The relevance of such measurements is conditioned by the narrowness of the probe (that collects lines relief) and by the pitch. Besides severe limitations in terms of detectable features [1], the representativeness of the derived parameters may often be questionable [2], and scanning a large area is time consuming [3]. Moreover, using a high-resolution device (such as an atomic force microscope or a scanning tunneling microscope) is not necessarily appropriate since this information is too rich in regards of the actual need, yet cumbersome or tedious (in particular when samples have to be especially prepared and brought in the laboratory) and expensive.

Actually, it would be beneficial to find a contact-less method allowing a global determination of texture in a real-time acquisition. Basically, instead of operating instruments providing as accurately as possible profiles from which mean parameters are numerically derived after, we advocate to use a large light beam and study the scattering pattern to get directly roughness characteristics intrinsically averaged on the whole illuminated zone. In essence this concept is close to a volumetric approach where light would replace material (i.e., in a patch test, texture depth is given by the diameter of an area formed with a known volume of calibrated spheres poured onto the surface under study and spread in circle until all the voids are filled).

The first part of this paper describes the shadow-hiding opposition effect, and the relationship with texture is illustrated through numerical modeling results. The second section is related to an experimental validation of the measuring principle against coated abrasive sheets. Finally, the advantage of such measurements and the potential contribution of a smart sensor for the in situ assessment of surface texture are discussed.

2. Theoretical basis

Opposition effect

Opaque surface asperities cast shadows that are visible at large phase angles (i.e., when the viewing direction is far from that of illumination), but close to the zero phase angle they are hidden by lighted grains themselves (Fig. 1). The result is a non-linear increase of brightness for rough surfaces, when the scattering angle approaches the exact back-scattering direction [4]. This phenomenon is usually known as shadow-hiding, opposition or “hot-spot” effect.

Surface texture index

Light scattering by rough surfaces has already been studied with a physically based numerical model including a representation of the shadow-hiding effect [5]. Back-scattered intensity was found to be strongly related to surface texture: the larger the roughness, the wider the hot-spot (Fig. 2). Such features contributing to small angle scattering [6], a perpendicular incidence of the beam on the target is suitable to extract information from reflectances [7]. A normalization avoids single-scattering albedo mismatch, making it insensitive to the nature of the scatterers, so that the behavior is identical for different materials having the same roughness.

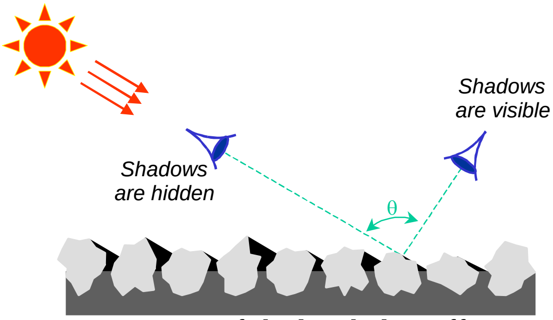

Fig. 1. Because of shadow-hiding effects a scene appears brighter when seen from a direction close to that from which it was lighted (there is no visible shadow).

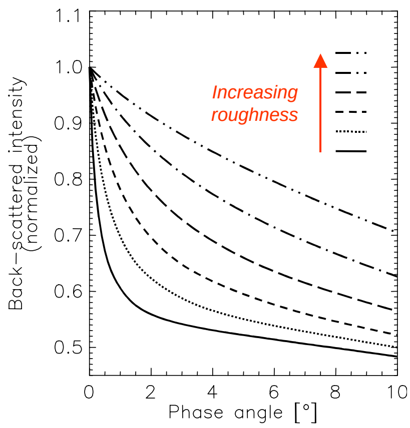

Fig. 2. Example of computed back-scattered intensity (normalized to unity) as a function of the phase angle θ, for surfaces of the same material but with different roughness levels.

The slope D of the curve is given by the derivative of the normalized back-scattered intensity I_n (dimensionless quantity) with respect to the phase angle θ (between incident and emergent directions). Let the texture index T_i (Eq. 1) be the inverse of this derivative at angle θ=0° with the opposite sign to account for the decrease of the function $I_n(\theta)$:

$$1/T_i = -D = -\left[dI_n(\theta)/d\theta\right]_{\theta=0} \tag{1}$$

Numerical simulation

Synthetic reflectances were generated with the soil bi-directional reflectance factor model[1] for different configurations and a vertical incidence of light on the surface. Numerous optical and textural characteristics were considered (cf. [5] for more details) from mirror-like condition to very rough surfaces, and single scattering albedo related to visible and near-infrared regions. Texture indices were computed by picking among these data sets values starting from θ_{min}=0° (Fig. 3a) and in the range of 0 to 3° (Fig. 3b).

The relationship between the calculated texture indices and the actual roughness parameter is linear, whatever the other surface properties. Single scattering (carrying shadow-hiding effect) dominates at visible, whereas multiple scattering contribution increases at near-infrared. At large wavelengths, the consequence is a slightly wider hot-spot peak and an overestimation of T_i which is independent of the roughness itself but more obvious when the latter is large (any slope miscalculation being reported on T_i). Furthermore, the coherent back-scatter mechanism attributed to a constructive interference between multiply scattered rays [8] is negligible when reflectivity is low. Hence, the retrieval of texture should be easier at small wavelengths.

[1] S-BdRF is a freeware, available from the authors, that can be used by anybody for purely research purposes

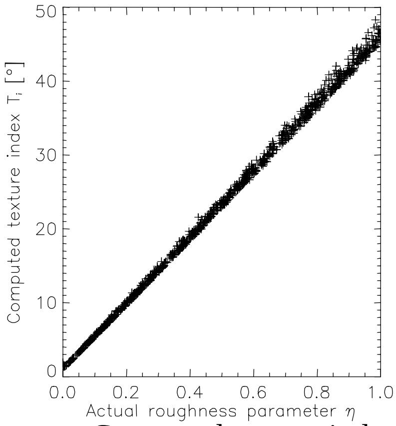

Fig. 3a. Computed texture index T_i as a function of the actual surface roughness parameter η, for θ_{min}=0.

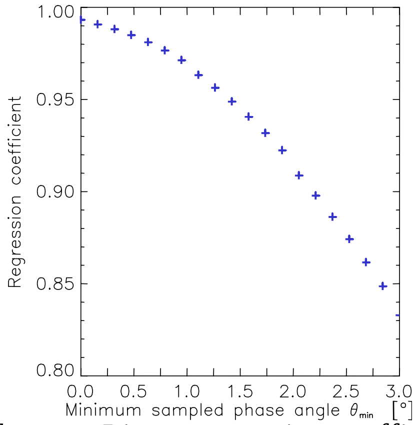

Fig. 3b. Linear regression coefficient as a function of the minimum sampled phase angle θ_{min}.

The accuracy of the estimation and the linear regression coefficient decrease as the minimum sampled phase angle θ_{min} increases. When there is a lack of data at small phase angle, the first difficulty is to normalize the reflectance. The second problem is related to the calculation of the slope: as noticeable on Fig. 2 not considering data below about 1.5° may lead to erroneous interpretations for narrow hot-spot features.

3. Experimental study

The idea was to evaluate the angular distribution of light back-scattered by coated abrasives of known roughness characteristics.

Samples

Among the standards for coated abrasives, that of FEPA (Federation of European Producers of Abrasives) was chosen since in this standard a grit determines a range of grain dimensions subjected to tight tolerances[2]. For instance in the F180 definition no more than 3% by mass of the grit can have a particle size > 90 µm, and at least 94% must be > 53 µm. Unfortunately, it proved difficult to get samples in the whole range of 12 to 2500 (grain size of 1815 to 8.4 µm, respectively), as the roughest or smoothest items are not very common, so only a few typical abrasive sheets[3] were considered. Samples coming as 9×11 inches sheets were glued on stiff aluminum plaques painted in black, to prevent the corrugation and undesirable reflections.

Measurements

The angular distribution of scattered light was acquired with a bench suited for measuring the properties of retro-reflectors (employed on road signs) at the French Public Works Research Laboratory. A halogen lamp projects a 17 cm diameter circular spot on the target placed 10 m away (perpendicularly to beam incidence), and a photodetector is driven along a vertical axis. By construction, the smallest possible phase angle is about 1/3°, therefore the normalization had to be made (arbitrarily) by using other available values.

Results

An example of data obtained with this bench over the smooth abrasive sheets is shown on Fig. 4 (with normalization at 1.5° for sake of clarity of the graph). The two curves and their slopes are easily differentiable even if the particle size disparity between P1200 and P600 samples is less than 10 µm.

[2] http://www.fepa-abrasives.org
[3] The authors are grateful to Carborundum Schleifmittelwerke GmbH (Germany) for kindly providing the samples

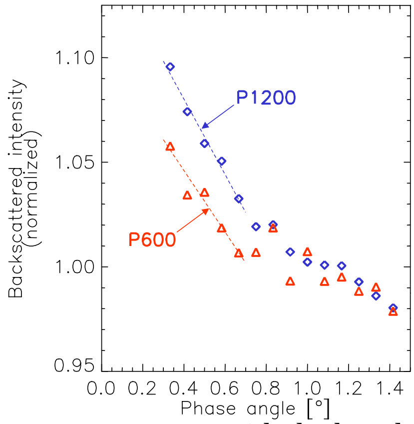

Fig. 4. Measurements with the bench for retro-reflectors over the P1200 (diamonds) and P600 (triangles) samples.

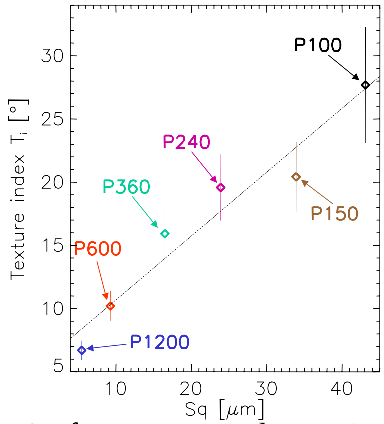

Fig. 5. Surface texture index retrieved from reflectance data as a function of the actual RMS value.

Computed texture indices are presented on Fig. 5 as a function of the actual S_q (i.e., quadratic mean of the deviations from the mean, as defined in the EUR 15178 EN report). The contact measurements were completed at the Technical University of Koszalin using a T 8000 stylus instrument (Hommelwerke GmbH, Germany) where the angle of the diamond tip was 90° and its radius 5 μm. The reference value for the normalization was taken at 1°. The agreement is good and the trend is similar to the previous simulations. However, because of the weak back-scattered light, a high amplification was necessary, resulting in a poor signal-to-noise ratio in particular for wide peaks, so that the standard deviation increases with roughness.

4. Summary and conclusions

The shadow-hiding opposition effect offers a powerful tool to determine texture because the angular distribution of back-scattered radiations carries information about surface conditions. A numerical sensitivity study allowed us to understand the phenomena, and to define a texture index possibly derived from reflectance data. The measuring principle was validated through experiments where retrieved roughness and actual surface characteristics favorably compare.

We can put forward several results: i/ small wavelengths are most appropriate, ii/ achieving measurements at θ=0° is paramount (which requires a beam-splitter), iii/ otherwise if data are available close enough a different normalization allows to compensate for the lack of value at angle zero but with a lesser accuracy (and the same reference angle will have to be maintained for further comparisons).

These results are encouraging, and it seems realistic to think about a true “roughness-meter”, that is to say an instrument providing directly an integrated information about the roughness of a given surface, and not statistical parameters derived off-line from a more or less detailed cartography. However, there is still work to do, particularly to identify the external parameters of influence, quantify the imprecision and the limits, before concluding about the behavior of the method in another using environment.

With this kind of approach, the characterization of surfaces becomes contact-less and global: this is essential for monitoring the transportation infrastructures by means of probes onboard vehicles. Indeed, a single acquisition is sufficient to estimate actual roughness characteristics intrinsically averaged over the whole illuminated area. By comparison, a profilometer would provide a series of height data, and texture parameters computed using already accumulated information necessarily correspond to the stretch road behind.

Acknowledgements. The authors are especially thankful to Bruno Hanocq (Division for Road Operation, Signalling and Lighting) for operating the measuring facilities at the French Public Works Research Laboratory.

References

[1] Anamalay R. V., T. B. Kirk, and D. Panzera, Numerical descriptors for analysis of wear surfaces using laser scanning confocal microscopy. *Wear*; 181-183 (2): 1995, 771-776.

[2] Whitehead S. A., A. C. Shearer, D. C. Watts and N. H. F. Wilson, Comparison of two stylus methods for measuring surface texture. *Dental Materials*; 15 (2): 1999, 79-86.

[3] Morrison E., A prototype scanning stylus profilometer for rapid measurement of small areas. *International Journal of Machine Tools and Manufacture*, 35 (2): 1995, 325-331.

[4] Hapke B., W. D. DiMucci, R. Nelson, and W. Smythe, Cause of the hot spot in vegetation canopies and soils: shadow-hiding versus coherent back-scatter. *Remote Sensing of the Environment*; 58: 1996, 63-68.

[5] Iaquinta J., and A. Fouilloux, Modeling of light scattering by rough surfaces with relevance to pavements monitoring sensors. *Optics and Lasers in Engineering*; 41: 2004, 687-702.

[6] Bennett J. M., and L. Mattsson, Introduction to surface roughness and scattering. Optical Society of America, Washington D. C.; 1989.

[7] Iaquinta J., and A. Fouilloux, A differential scattering probe for monitoring road surfaces. *Measurement Science Review*; 3: 2003, 17-20.

[8] Nelson R. M., W. D. Smythe, B. W. Hapke, and A. S. Hale, Low phase angle laboratory studies of the opposition effect: search for wavelength dependence. *Planetary and Space Science*; 50 (9): 2002, 849-856.