Paper and board surface roughness characterization using laser profilometry and gray level cooccurrence matrix

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SUMMARY: Image texture analysis tool gray level cooccurrence matrix was implemented to assess surface topography of eight commercial paper and board samples varying considerably in roughness. Height data for individual specimens were acquired by confocal laser profilometer. Strong linear relationship was found between the texture measures "Correlation" and "Energy" derived from gray level cooccurrence matrix on one hand and ISO topography descriptors Rq and Ra on the other. Correlation of these data to those obtained with a conventional roughness method – Bendtsen – was only a rough one. The applied technique can also be used for determination of paper formation and quantification of print mottling.

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Surface topography, apart from affecting substrate's look and feel, plays an extremely important role in various paper-converting applications, one of them being printing. For example, in gravure printing, requirements for a high smoothness/low roughness are especially demanding. Here, due to a close contact between the hard printing form and the paper during the ink transfer operation, depressions in the paper surface exceeding the size of a screen dot cell (50-150 µm in diameter) are very likely to cause a well-known "missing dots" phenomenon (Wågberg, Johansson 1993). Different conventional as well as digital, non-impact, printing techniques can be applied for printing electronic components (Pekarovicova et al. 2008) and researchers have suggested that one of the important criteria for a paper based substrate used is its smoothness on a number of different length scales (O'Neill, Preston 2010). Apart from influencing the absorption of ink into the paper, paper smoothness is also one of the key parameters affecting the paper and print gloss (Xu et al. 2005).

In general, surface topography assessment methods can be divided into direct and indirect ones. Traditionally, paper smoothness/roughness has been assessed indirectly with air flow-based instruments, such as Bekk, Bendtsen or Parker Print Surf (PPS), which measure average distance between the paper surface and the reference plane. While the PPS method attempts to simulate the situation in a printing nip, the other two do not. These techniques, although giving a rough estimate of the paper surface topography, suffer from several well documented drawbacks, such as the inability to provide information about the spatial variation of surface non-uniformity.

Today a large number of sophisticated methods for the surface analysis of paper are available (Preston 2009; Chinga-Carrasco 2009). For example, atomic force microscopy (AFM) has frequently been implemented to obtain either micro- or nano-scale surface topography information (Xu et al. 2005) while confocal laser scanning microscopy (CLSM) enables a three-dimensional surface imaging (Auran 1998; Muck et al. 2009). Mechanical and optical (laser) profilometers – accompanied by image processing tools – enable both visualization of paper surface topography and its detailed numerical assessment. While with mechanical profilometers a fine point stylus traverses the sample surface, in optical devices the profile is recorded using a laser beam without any physical contact between the stylus and the surface. In confocal laser profilometer, the distance to the surface is measured by focusing a light spot on it. These methods were extensively used for paper surface characterization (Gooding et al. 2007; Chinga et al. 2007; Sung, Keler 2008). Once the surface profiles, i.e. the height data points, have been recorded, one can analyze these data statistically to extract characteristic descriptors of the sample surfaces, such as arithmetic average of absolute values (Ra), root mean squared roughness (RMS or Rq) and others, specified e.g. in standard ISO 4287/2000 (2000). It is also possible to evaluate surface topography characteristics separately in different components or scales instead of obtaining a single roughness index, for instance by performing power spectrum analysis on the acquired data (Singh 2008). Another approach, discussed in this article, is implementation of the texture analysis tool Gray level cooccurrence matrix (GLCM), which generates several statistical parameters related to the surface topography. This method, although well known in various technical fields, has not yet been widely used for assessing paper roughness.

Texture analysis and GLCM

Although surface properties of a material such as its smoothness/roughness, graininess, periodicity, homogeneity, directionality and others can be intuitively related to the corresponding digital image texture, it is extremely difficult to define this term formally. While Russ (1999) characterized image texture as a descriptor of local brightness variation from pixel to pixel in a small neighborhood through an image, IEEE standard (1990) describes it as an attribute representing the spatial arrangement of the gray levels of the pixels in a digital image region.

Texture analysis has been extensively used in a variety of applications, such as medical imaging, remote sensing (Randen 1997; Van de Wouwer 1998) and paper inspection (Iivarinen, Visa 1998) and the implemented methods mainly differ in the way how textural features have been extracted. Apart from the structural, model-based and transform-based techniques (Bharati et al. 2004), one of the most frequently used statistical texture analysis methods is based on computation of the GLCM. This matrix – also known as the gray level spatial dependence matrix – is a table that keeps track of how often different combinations – pairs – of pixel intensity (gray level) values in a specific spatial relationship and distance occur in an image. From this matrix, it is possible to compute various first- and second order statistical parameters or texture measures. In contrast to first order statistics, such as standard deviation or variance, second order statistics provide information about the spatial relationships of image pixels, i.e. image texture.

In their original article on GLCM, Haralick, Shanmugam and Dinstein (1973) proposed 14 texture measures to be extracted from the matrix. These can be classified into one of the three groups. The first one – contrast group – contains measures, such as contrast (also known as variance or inertia), dissimilarity and homogeneity, that use weights related to the distance from the GLCM diagonal. Members of the second group are related to orderliness; parameters such as angular second moment, energy (also referred to as uniformity), entropy and maximum probability are used to assess how regular (orderly) the pixel values are within an image. The third group consists of statistics measures derived from the GLCM, e.g. GLCM mean, variance and correlation (Hall-Beyer 2010). Measures in each group describe one aspect of the image texture and do not necessarily correlate to the measures from the other two categories. In practice, usually only a small subset – four or five – of the texture measures are computed and used.

Goal of our study was to compare values of several statistical measures obtained from GLCM with those of traditional roughness parameters for a set of paper and board samples differing in surface roughness. Topograhical data were acquired using confocal laser profilometer.

Materials and Methods

In our research, the surfaces of eight paper and board samples of varying grades and a considerable range in roughness were investigated (*Table 1*). In addition to three inkjet papers, two multipurpose graphic papers and one newsprint paper, two board samples were tested. While one was a normal coated board sample, surface of the specimen designated as Brd2 was characterized by having periodic, oval-shaped elevated indentations (see *Fig 2*) that were made during an industrial board making process. *Table 1* contains basic information about the samples and their Bendtsen roughness data. Note that the Pap6 data are not listed together with those for other paper samples; this was done to ease the comparison of roughness values with the surface topography results presented in *Table 3*, as explained below.

Topographical measurements were performed at the KCL, Finland, with the confocal laser profilometer NanoFocus μScan (NanoFocus 2010). Measuring range of the instrument (sensor) is 1 mm, vertical resolution 0.1 μm, spot size 1.5 μm and measuring frequency 850 Hz. The sensor module is mounted on a solid platform and the sample is positioned on a highly precise computer controlled

Table 1. Paper and board samples used in the study.

Sample code	Description	Basis weight, g/m^2	Thickness, μm	Roughness (Bendtsen), ml/min
Pap1	Inkjet paper A	110	125	79
Pap2	Inkjet paper B	87	110	314
Pap3	Inkjet paper C	114	133	205
Pap4	Multipurpose graphic paper A	91	110	262
Pap5	Multipurpose graphic paper B	103	140	272
Brd1	Coated board	339	478	1100
Pap6	Newsprint paper	61	100	810
Brd2	Board with periodic markings	200	338	1980

x/y stage with measurable area 100 x 150 mm and resolution 0.5 µm.

Two-dimensional (2D) measurements for paper and board samples were made with the following settings: dimensions of the tested samples were 10 mm x 10 mm, x- and y-resolutions were set to 5 and 20 µm, respectively (*Fig 1*), scanning speed was 3 mm/s. Only with sample Brd2, which showed visual, large-scale markings, settings were somewhat different: dimensions were 20 mm x 20 mm, x-and y-resolutions were 20 and 60 µm with scanning speed 12 mm/s. A large number – typically 1 million – of data points were thus obtained containing information about the sample topography. The collected height data in micrometers were stored in a text file and the subsequent digital image processing and statistical treatment were performed using MATLAB® (MathWorks 2010) and ImageJ (Rasband 2010) software.

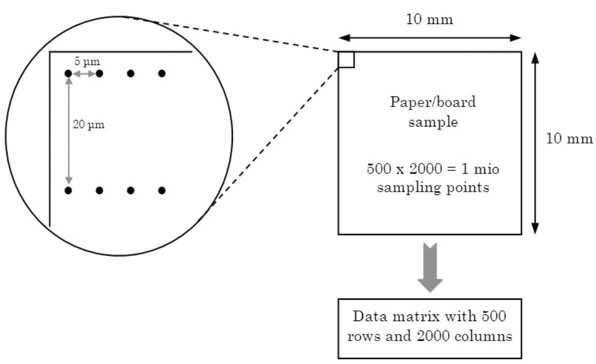

Fig 1. Data sampling details for measuring surfaces of paper and board samples using laser profilometer.

Results

Surface of the studied paper and board samples can conveniently be visualized using pseudocolored height maps obtained from the 2D measurements (*Fig 2*). Color indicates the degree of depression or elevation at that particular sample location. To enable easier topography comparison, the scale is the same for all eight specimens, ranging from a dark blue (valleys: 40 µm below the surface) to a vivid red (peaks: 40 µm above the surface).

Matrices (GLCM tables) created from the original topography data for Pap1 and Brd1 samples are shown in *Table 2*. Since the size of the GLCM is determined by the number of the gray levels of the corresponding image – its bit depth – this number was, to reduce the required computation time, prior to GLCM extraction decreased from 32-bit to 3-bit, i.e. to eight values (1 to 8). Scaling of the original images was done according to the following criteria: values that were lower than -20 µm were mapped in all eight scaled images to the value 1, those above +20 µm were mapped to the value 8 while the remaining values were linearly transformed to the values 2 to 7. Computation of individual values of the entries in GLCM was then performed as follows (see the top table). Element in the first row and the first column – element (1-1) – contains the value 1171 since this is the number of instances in the scaled Pap1 image where two horizontally adjacent pixels both have values 1 and 1. Element GLCM (1-2) contains the value 280 because there are 280 instances where two horizontally adjacent pixels have the values 1 and 2, respectively. The algorithm scans the input image for other (i-j) pairs and records the sums into the corresponding matrix fields.

Table 3 summarizes topography parameters for paper and board samples computed from 2D measurements. Values for four standard statistical parameters – descriptors – defined in ISO 4287/2000 together with four texture measures derived from GLCM are listed. Corresponding equations are given in the Appendix.

Table 2. GLCM tables for samples Pap1 (top) and Brd1 (bottom).

	1	2	3	4	5	6	7	8
1	1171	280	0	0	0	0	0	0
2	280	13825	2725	0	0	0	0	0
3	0	2717	94599	13009	0	0	0	0
4	0	1	12923	306917	27901	0	0	0
5	0	0	4	27733	362257	15893	0	0
6	0	0	0	0	15752	99309	1110	1
7	0	0	0	0	2	1095	2489	3
8	0	0	0	0	0	0	4	0

	1	2	3	4	5	6	7	8
1	18474	3460	44	0	0	0	0	0
2	3459	45413	9772	44	0	0	0	0
3	44	9731	120457	19798	49	1	0	0
4	0	84	19744	208961	26544	37	0	0
5	0	1	75	26456	226856	21088	17	1
6	0	0	0	59	20968	139814	9251	6
7	0	0	0	0	19	9192	48564	2098
8	0	0	0	0	1	13	2082	9323

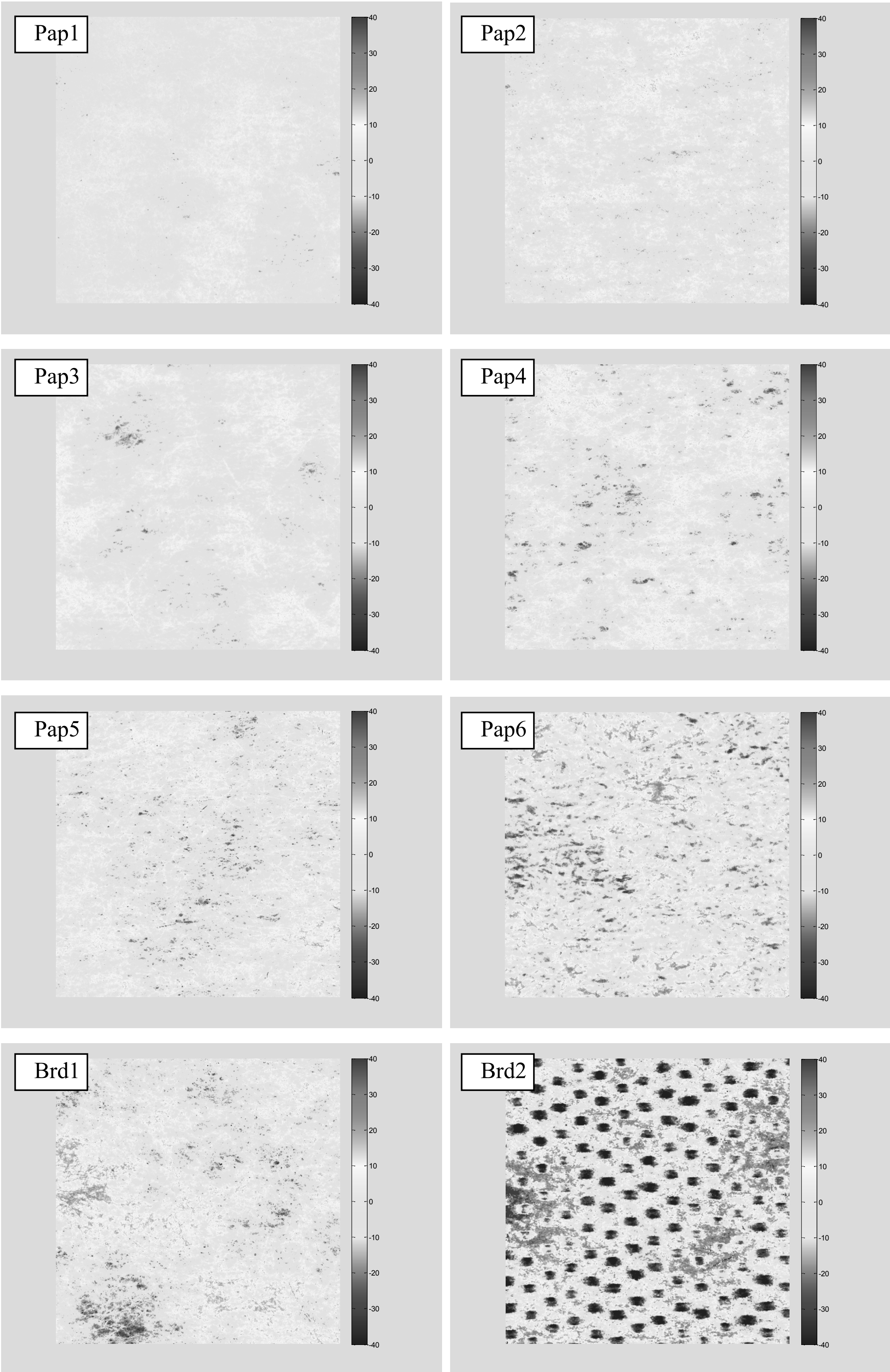

Fig 2. Color maps of paper and board surfaces.

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Table 3. Values for ISO statistical descriptors and GLCM-derived texture measures.

Sample code	ISO topography descriptors*				ISO topography descriptors**			
	Rq	Ra	Rv	Rp	Contrast	Correlation	Energy	Homogeneity
Pap1	3.72	2.95	-35.11	30.39	0.119	0.882	0.321	0.941
Pap2	4.87	3.88	-27.27	18.92	0.161	0.900	0.231	0.919
Pap3	4.98	3.96	-30.04	17.51	0.121	0.928	0.246	0.939
Pap4	6.11	4.85	-34.83	28.29	0.148	0.939	0.194	0.926
Pap5	6.30	4.96	-48.32	53.29	0.179	0.930	0.180	0.911
Brd1	8.03	6.36	-47.83	38.83	0.185	0.954	0.137	0.908
Pap6	8.89	7.15	-38.47	49.83	0.166	0.966	0.125	0.917
Brd2	17.17	13.49	-67.30	105.01	0.252	0.977	0.086	0.879

* Rq = Root mean square (RMS) roughness; Ra = Arithmetic average of absolute values; Rv = Maximum valley depth; Rp = Maximum peak height. All values are given in micrometers.
** For definitions see text.

Discussion

In any GLCM table, the main diagonal elements (red entries in *Table 2*) represent pairs of pixels in the original – or, in our case, scaled – image with no difference in their values (1-1, 2-2, 3-3 etc.). If these numbers are high, then the image does not show much contrast: most pixels are identical to their neighbours. On the other hand, if the texture of an image is non-uniform, gray levels of pixel pairs will always be different, so the values of the co-occurrences will distribute widely over the matrix (Chen 1998). When comparing Pap1 and Brd1 GLCMs it is clear that the former one is characterized by having a large number of pixel value combinations 4-4 and 5-5. This means that this sample image is dominated by pixels whose values differ only slightly from zero micrometers which is an indication of a highly uniform, flat surface of this paper sample. On the other hand, Brd1 GLCM contains a higher number of other same-value combinations (3-3, 6-6, etc.) as well as a considerable number of horizontally adjacent pixels that differ in values by 2, e.g. 4-2, 6-4, 3-5, etc., which is again a sign of a more uneven surface than in the case of the sample Pap1 where almost no such combinations of pixels were found.

Values for the four texture measures derived from GLCM for the investigated paper and board samples are in accordance with the above discussion. For instance, parameter *Energy* – also known as *Uniformity* – provides the sum of the squared elements in the GLCM and is 1.0 for a constant image. A gradual, almost monotonous decrease in *Energy* values – and therefore the substrate surface uniformity – from Pap1 to Brd2 correlates very well with an increase in both ISO topography descriptors Rq and Ra. Similarly, texture parameter *Correlation* which is a measure of how correlated a pixel is to its neighbour over the whole image increases correspondingly. The other two texture measures – *Contrast* (measures the intensity contrast between a pixel and its neighbour over the whole image) and *Homogeneity* (defines the closeness of the distribution of elements in the GLCM to the GLCM diagonal) – do not show such a good agreement with Rq and Ra. Since during the data sampling procedure distances among data points in x-direction were not the same as those in y-direction, all calculations were based on a horizontal adjacency of pixel pairs, i.e. considering the pixel of interest and the pixel to its immediate right. However, if other directions (45°, 90° or 135°) or larger distances between two pixels were specified when calculating GLCM, these correlations might become more apparent. Nevertheless, it is evident from *Table 3* that low *Contrast*, low *Correlation*, high *Energy* and high *Homogeneity* correspond to uniform gray level distribution, i.e., indicate a uniform, smooth paper surface.

If one ranks the investigated samples according to the values of their ISO roughness descriptors Rq or Ra (*Table 3*) – they both exhibit the same trend – it therefore seems plausible to conclude that the surface of the coated board sample Brd1 is smoother than that of the newsprint paper Pap6. Comparison of data from *Tables 1* and *3* also reveal that conventional papermaking methods for determining smoothness/roughness such as Bendtsen can not be directly compared to either standard ISO topography descriptors or GLCM based texture measures. This was to be expected, as Bendtsen and similar air leak methods measure substrate's surface indirectly and are known for their lack of adequate accuracy and precision, especially in comparison to the other two techniques implemented in the study. As *Table 1* shows, based on Bendtsen values eight samples can be separated only very roughly into three distinctive groups – first one containing a single inkjet paper Pap1 with the highest smoothness, second one consisting of paper samples Pap2 to Pap5 and third one containing the newsprint paper (Pap6) and both board samples (Brd1 and Brd2) with the roughest surface.

Conclusions

Texture of a paper or board substrate may result from physical surface properties such as roughness and can be seen as a spatial non-homogeneity of the corresponding digital image pixels. In the present study, surface topography of paper and board samples was assessed by the image texture analysis tool GLCM after obtaining raw topographical data using confocal laser profilometer. The study confirmed that the texture measures derived from GLCM, especially *Correlation* and *Energy*, can be used for accurately assessing paper surface topography. An additional benefit of the presented method lies in its ability to take into account spatial relationships among the image pixels. Since the method can also be applied for assessing paper formation as well as for determination of print unevenness (mottling) – for both applications, various image analysis-based commercial solutions already exist, e.g. Verity 2010 and DOMAS 2010 – we hope that in the future it will be used more frequently in paper- and graphic arts research and industrial settings.

Appendix

Equations for the four ISO topography descriptors (surface roughness parameters) are as follows (BS EN ISO 2000):

R_q = Root mean square $R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}$

R_a = Arithmetic average of absolute values

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i|$$

R_v = Maximum valley depth $R_v = min_i\, y_i$

R_p = Maximum peak height $R_p = max_i\, y_i$

Four GLCM-derived texture measures were computed using the following equations (MathWorks 2010):

$$Contrast = \sum_{i,j}|i-j|^2 p(i,j) \quad [5]$$

$$Correlation = \sum_{i,j}\frac{(i-\mu i)(j-\mu j)p(i,j)}{\sigma_i \sigma_j} \quad [6]$$

$$Energy\ (Uniformity) = \sum_{i,j} p(i,j)^2 \quad [7]$$

$$Homogeneity = \sum_{i,j}\frac{p(i,j)}{1+|i-j|} \quad [8]$$

where μ, σ and *p(i,j)* denote mean, standard deviation and probability occurrence of a normalized GLCM pixel pair *i* and *j*, respectively.

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