Illumination : a directional filter of texture ?

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This paper uses theory, simulation, and laboratory experiment, to show that directional illumination, used during the image acquisition process, acts as a directional filter of three dimensional texture. It is shown that the directional characteristics of image texture are not intrinsic to the physical texture being imaged, as they are affected by the direction of the illumination. This result has important implications for texture classification schemes: as many use directional characteristics for discrimination purposes. Variation of illuminant direction is shown to significantly affect a common texture measure : the Laws' L5E5 operator [1].

1. Introduction

Texture classification normally involves three processes. First, the subject texture must be illuminated and its image acquired. Second, feature operators are applied to the digitised image to produce a set of feature images. It is these images that provide the numerical descriptions of the textures. Third, a set of discriminant rules (for instance, a set of statistically derived discriminant functions) are applied to classify the image into texture classes.

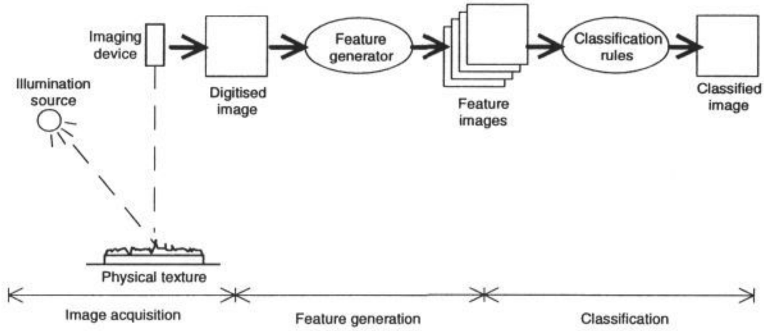


Figure 1 - The texture classification process

Much work has been published on the last two processes of texture classification (i.e. the feature generation and discriminant stages). But surprisingly few researchers have reported investigations into the effects of variations in the first process; i.e. variations in the image acquisition stage [2]. Of particular interest to the authors is the effect of rotating the illuminant round the scene. A number of papers do describe *"rotation invariant"* texture classification schemes, but surprisingly, they do not consider the effect of the rotation of the illuminant direction [3-9]. This paper examines the effect that the direction of the illuminant has on the directional characteristics of image texture. First, it presents an image model of three-dimensional texture, which predicts that an imaging process, that uses directional lighting, acts as a directional filter of texture. Second, it uses results from simulations and laboratory experiments, to examine the response of image texture to changes in illuminant tilt. Third, it presents results obtained from a commonly used texture measure, as a function of illuminant tilt.

2. An image model of three-dimensional texture

This section a presents model of the image of an illuminated three-dimensional texture; based on theory developed by Kube and Pentland [10]. Kube and Pentland's paper essentially applies a simplified version of the Lambertian surface reflectance model to an expression for the power spectral density of the fractal height-map. The theory is split into two parts. *Case 1* considers the situation where the illuminant vector is not perpendicular to the reference plane of the surface texture - allowing the Lambertian reflectance model to be linearised and used in the frequency domain. *Case 2* considers the situation in which the direction of illumination is perpendicular, or close to the perpendicular. Here the quadratic term becomes significant and cannot be ignored. The theory becomes complex, involves additional assumptions and does not yield an expression as a function of either illuminant slant or tilt. Hence only case 1 will be considered here.

2.1. A frequency domain model of image texture

The following theory assumes :

(i) a Lambertian surface (i.e. perfectly diffuse reflection),
(ii) an orthogonal camera model,
(iii) a constant illuminant vector over the scene, and
(iv) a viewer-centred co-ordinate system, in which the reference plane of the surface is perpendicular to the viewing direction.

The normalised image intensity $I(x,y)$ of the surface $V_H(x,y)$ is

$$I(x,y) = \mathbf{n} \cdot \mathbf{L} = \frac{-p\cos\tau\sin\sigma - q\sin\tau\sin\sigma + \cos\sigma}{\sqrt{p^2 + q^2 + 1}} \tag{1}$$

where

$\mathbf{n}$ = the unit vector normal to the surface at the point (x,y)

$$p = \frac{\partial V_H}{\partial x} \qquad q = \frac{\partial V_H}{\partial y}$$

$\mathbf{L} = (\cos\tau.\sin\sigma, \sin\tau.\sin\sigma, \cos\sigma)$ is the unit vector towards the light source τ and σ are the illuminant vector's *tilt* and *slant* angles as defined below.

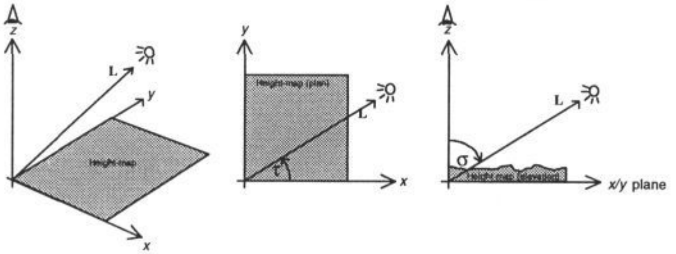


Figure 2- Definition of axis and illumination angles

Now in a departure from [10] and without loss of generality, choose a new axis (x',y',z) which is rotated τ about the z axis such that the projection of $\mathbf{L}$ onto the x-y plane will be parallel to the x' axis. In this new axis system the expression for intensity simplifies to

$$I(x,y) = \mathbf{n} \cdot \mathbf{L} = \frac{-r\sin\sigma + \cos\sigma}{\sqrt{r^2+t^2+1}} \tag{2}$$

where

$$r = \frac{\partial V_H}{\partial x'}, \text{ and } t = \frac{\partial V_H}{\partial y'}$$

Taking the MacLaurin expansion yields

$$I(x,y) = (-r\sin\sigma + \cos\sigma)\left[1 - \frac{(r^2+t^2)}{2!} + \frac{9(r^4+t^4)}{4!} \ldots\ldots\right] \tag{3}$$

Now if the surface slope angle is less than 15°, then $r^2, t^2 << 1$; and the quadratic and higher order terms may be neglected. Note that the error introduced by this approximation for a slope angle of 15° is 3.5%. With this approximation (3) becomes

$$I(x,y) = (-r\sin\sigma + \cos\sigma) \tag{4}$$

which is simply the mean, plus a linear contribution of the surface gradient, measured in the direction of the illuminant's tilt angle.

Now the partial derivative operator $\frac{\partial}{\partial x'}$ is a *linear* operator [2], and in the frequency domain may be represented by :

$$\mathcal{F}\left[\frac{\partial V_H}{\partial x'}\right] = i\omega\cos(\theta - \tau)F_H(\omega,\theta) \tag{5}$$

where

ω is the angular frequency of the Fourier component

θ is its direction w.r.t. the x-axis

$\mathcal{F}[g(x,y)]$ is the two-dimensional Fourier transform of $g(x,y)$, and

$F_H(\omega,\theta) = \mathcal{F}[V_H(x,y)]$

Now, from (4)

$$I(x,y) = -\frac{\partial V_H}{\partial x'}\sin\sigma + \cos\sigma \tag{6}$$

Hence if the mean is ignored, the Fourier transform of the image intensity is :

$$\begin{aligned} F_I(\omega,\theta) &= \mathcal{F}\left[-\frac{\partial V_H}{\partial x'}\sin\sigma\right] \\ &= \left[-i\omega F_H(\omega,\theta)\right]\left[\cos(\theta - \tau)\right]\left[\sin\sigma\right] \end{aligned} \tag{7}$$

This is similar to the result presented in [10], except that (i) it is more general, in that it does not assume a fractal surface, and (ii) it contains simpler trigonometric terms, which enable the directional effect of lighting to be more easily understood.

2.2. Implications of the model for the directional characteristics of images

If the surface texture is isotropic, and the slant angle of the illuminant is held constant, then (7) above, predicts that the image texture will be :

$$F_I(\omega,\theta) = \cos(\theta-\tau).k \tag{8}$$

where k is a constant.

That is, the frequency components of a texture in the same direction (θ) as the tilt angle of the illumination (τ) will be accentuated compared with those components at right angles to this illumination. Thus it implies that an image forming process using directed illumination acts as a *directional filter* of texture. Such an effect is likely to have important implications for texture classification schemes. It implies that the directional properties of image texture are not intrinsic to the surface, but that they are considerably affected by variation in illuminant tilt. This is unfortunate, as the majority of texture feature sets used in classification and segmentation exploit directional characteristics.

3. The tilt angle response of image texture

The above theory has important implications for texture classification of three-dimensional texture. However, many assumptions were made during its derivation. This section therefore, uses simulation and laboratory experiment to further investigate the predicted effects.

3.1. Simulation

An isotropic fractal surface was generated and illuminated synthetically ($\sigma = 50°$ & $\tau = 0°$). Figure 3 shows a polar plot of the FFT of the resulting image texture, in which each point on the graph represents the sum of the magnitude coefficients in one direction (i.e. for one value of θ : the angle of the frequency component).

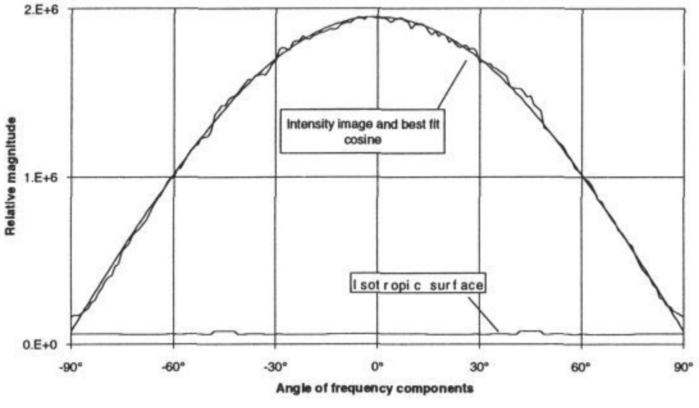
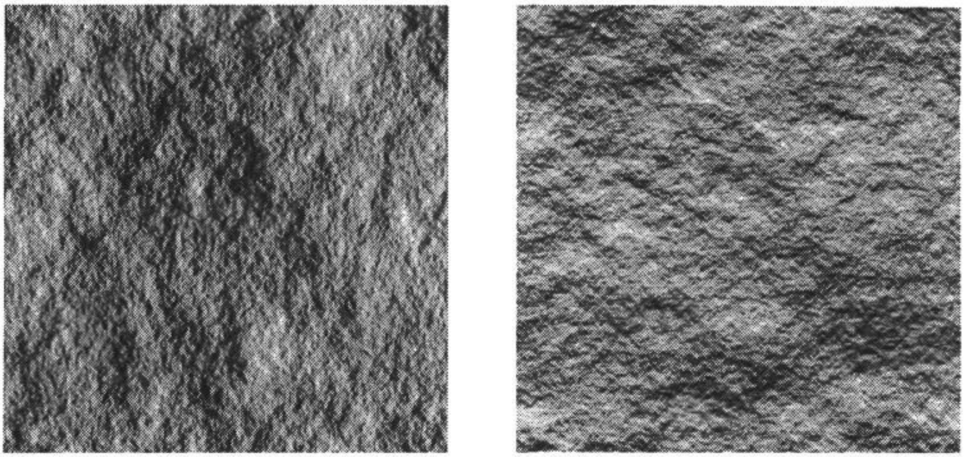


Figure 3- Polar frequency plot of image texture ($\tau = 0°$), and corresponding best fit cosine (original surface also shown).

The directionality in the image is clearly evident in the polar plot shown above, especially when the graph is compared to the almost flat plot of the original surface. As predicted by the image model, the polar response is greatest in the direction of the illuminant tilt, and it follows a cosine function closely. However, these data do not illustrate the effect of variation in illuminant tilt angle : figure 4 shows images for illuminant tilt angles of 0° and 90°. The effect on these images could not be described as dramatic but is clearly discernible. However, in the frequency domain the response to a change in tilt is much more obvious, as shown in the polar plots of figure 5.



τ = 0° τ = 90°

Figure 4 - Intensity images showing the effect of changing the illuminant tilt angle (τ).

τ = 30° τ = 90°

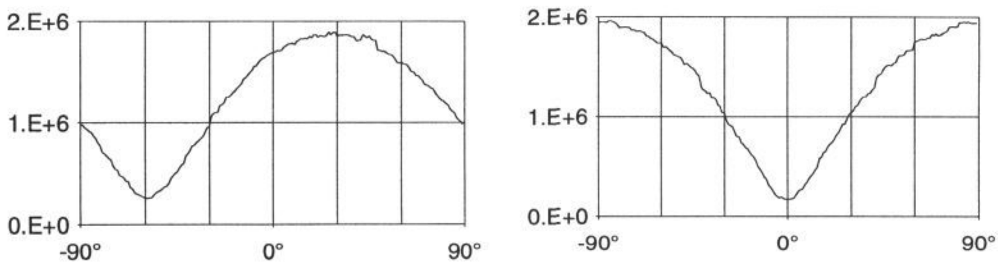


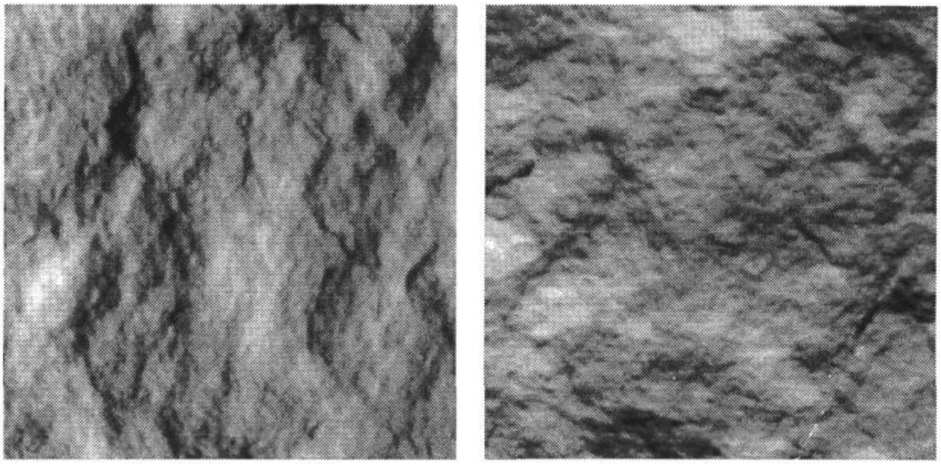
Figure 5 - Polar frequency plots of image texture showing the effect of variation in illuminant tilt (τ). Axes are as figure 3.

The above demonstrate that in simulation the tilt angle responses of images of isotropic topologies closely follow the directional characteristics predicted by the model. These results are not surprising as the synthetic surface had an average slope angle of 8.6° - and the effect of the quadratic and higher order terms neglected in the model would be small. The next section therefore, presents results of laboratory experiments using real examples of three-dimensional texture.

3.2. Laboratory experiment - four physical textures

In this section, results of laboratory experiments are presented using real textures. The textures were sprayed matte white to eliminate any albedo texture and to provide an approximately Lambertian reflectance characteristic. The texture sample was mounted perpendicularly to the camera's line of sight at a distance of

3.3m, and illumination was provided by a 500W lamp 1.6m from the subject. The position of the illumination was varied in terms of tilt and slant angles and all other parameters were kept constant. Two images of the test texture are shown below.



"rock1" (τ = 0°) *"rock1" (τ = 90°)*

Figure 6 - Images of the test texture "rock1" at two angles of illuminant tilt.

The illuminant's tilt angle (τ) was varied in 10° steps over 180°. Four examples of the polar plots of the two-dimensional spectra of *rock1,* are shown in figure 7. As predicted, illuminant tilt clearly has a considerable impact on directionality of image texture *rock1* (note that the angular position of the magnitude peak follows τ). What is perhaps more surprising however is the similarity of the above plots to those obtained via simulation. Compare for instance the τ = 30° plot above with that of figure 5; both resemble a raised cosine, and both have clear minima within a few degrees of -60°. These empirical results therefore

(i) show that image texture directionality is not an intrinsic characteristic, and
(ii) support the $\cos(\theta - \tau)$ relationship between illuminant tilt and image texture.

These phenomena complicate the task of texture classification; as many texture measures used in such schemes, exploit directional characteristics of texture. Hence the next section examines the effect that changes in illuminant tilt angle have on the output of one texture measure, which is popular in the literature.

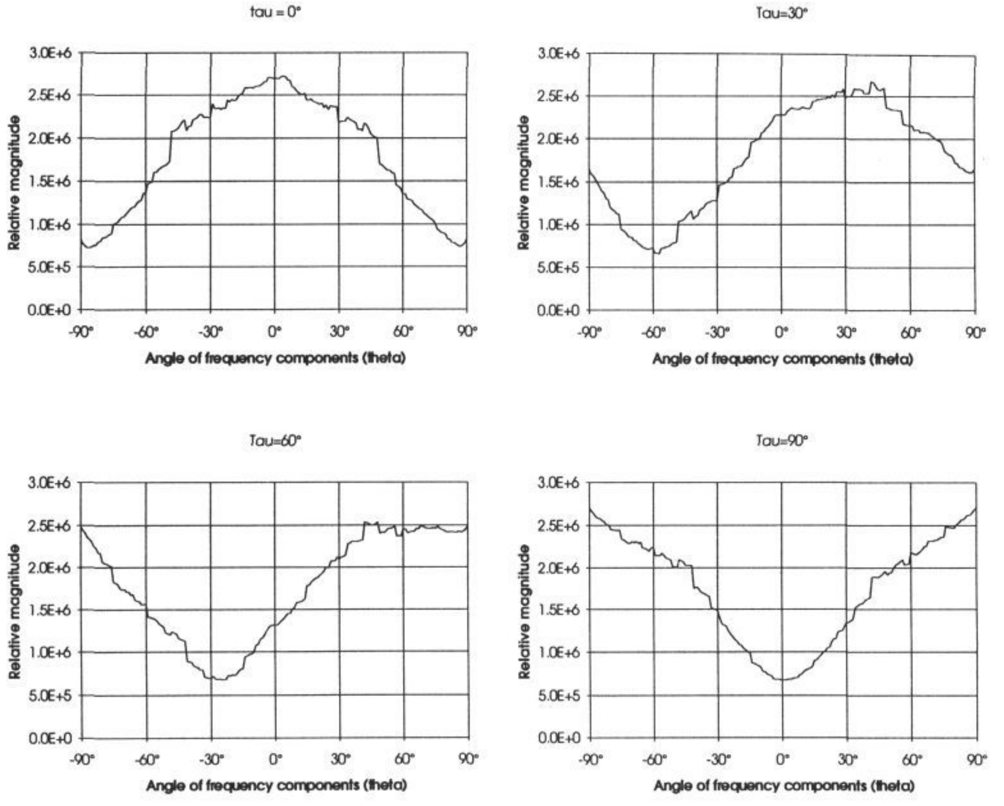


Figure 7 - Effect of illuminant tilt angle on image directionality (rock1)

4. The effect of variations in tilt angle on Laws' texture measures

This section presents the results of laboratory experiment into the effect of variation in the illuminant's tilt angle on the output of Laws' L5E5 texture measure. This texture measure comprises the 5×5 mask shown in figure 8, followed by a a *mean square* macro statistic [1].

-1	-2	0	2	1
-4	-8	0	8	4
-6	-12	0	12	6
-4	-8	0	8	4
-1	-2	0	2	1

Figure 8 - Laws' L5E5 mask

Figure 9 shows the results obtained by processing images of four textures, taken at a range of illuminant tilt angles, with the Laws' L5E5 operator. They show that the Laws' L5E5 operator's mean output, is affected by variation in illuminant tilt.

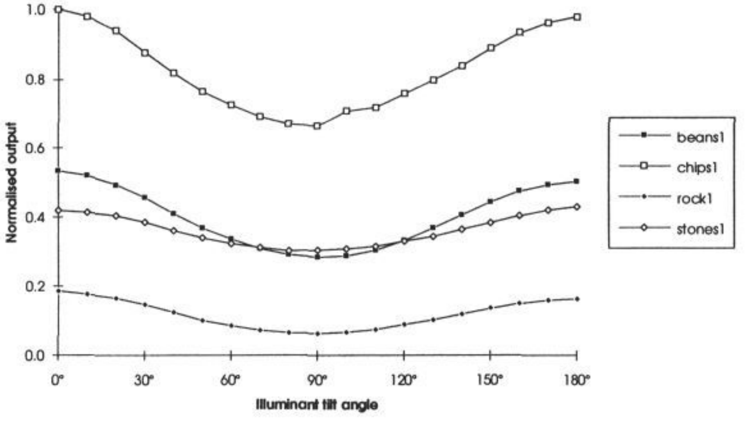


Figure 9 - Observed effect of tilt angle variation on L5E5 mean output

The behaviours of feature means is obviously important for classification and segmentation purposes, but they do not provide sufficient information to allow the likely effects to be assessed. What is required is the behaviour of the distributions. A small variation in mean due to change in illuminant tilt may be very significant for distributions of large variance, but insignificant those of small variance. Hence, the figure 10 shows distributions of L5E5 for two textures under two lighting conditions.

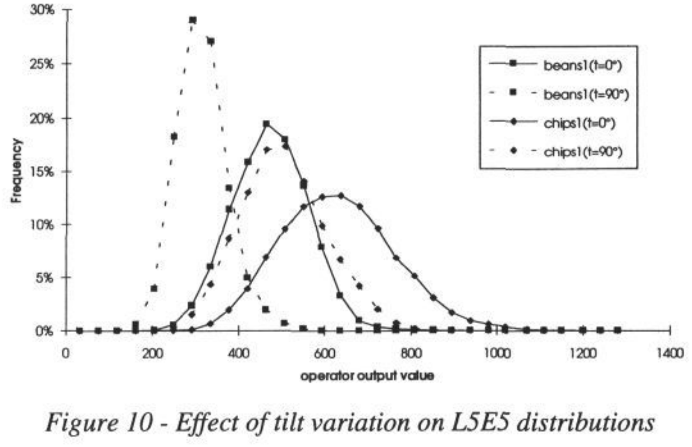


Figure 10 - Effect of tilt variation on L5E5 distributions

Assuming equal prior probabilities, the maximum likelihood classifier trained under an illuminant tilt of 0° would have a decision surface at approximately L5E5 = 580. That is half way between the *beans1*(τ=0°) and *chips1*(τ=0°) distributions (solid line graphs). However, the dashed graphs show the result of changing the tilt to 90° : the mean of *chips1* is now clearly to the left of L5E5 =

580, and so the majority of this class at $\tau=90°$ would be incorrectly classified. Thus changes in the illuminant's tilt have been shown to significantly affect the output of Laws' L5E5 operator. Experiments with the other Laws' operators gave similar results. Experiments with co-occurrence and fractal dimension based texture operators also gave similar results.

5. Conclusions

This paper has presented the results of an investigation into the effect that variation in illuminant tilt angle, has on image texture. To summarise :

(i) Results from theory, simulation and physical experiment show that the directional characteristics of image texture are not intrinsic — but that they are heavily dependent upon illuminant tilt.

(ii) The linear image model (7) predicts a cosine relationship : $\cos(\theta - \tau)$ for the directional characteristics of images of isotropic texture, and this is supported by the results of simulations and laboratory experiments.

(iii) Variation in the illuminant tilt angle was shown to significantly affect the output of the Laws' L5E5 operator.

The above points seem obvious, but, to the authors' knowledge, have not been systematically investigated and reported before.

The image model presented in this paper is currently being used to derive a set of filters that when applied to the raw texture images, compensates for the effects of variation in illuminant tilt.

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