$2\frac{1}{2}$D texture mapping: real-time perceptual surface roughening

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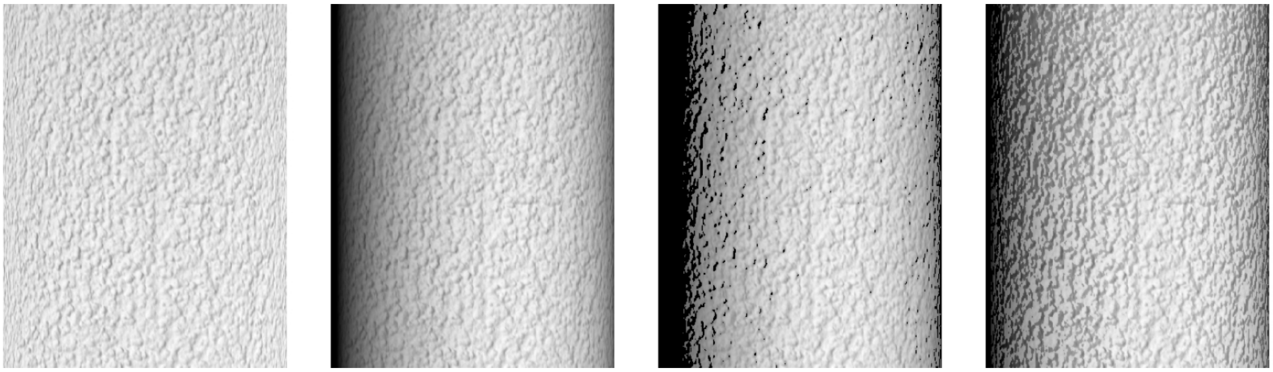

Figure 1: Cylinders with an orthogonally-projected plaster texture. In the first cylinder the texture is only warped, while in the second we have added diffuse shading as is conventionally done for texture-mapped Lambertian surfaces. In the third, the blackshot was modified, and in the last one the luminance values were remapped according to the texture-contrast function ($2\frac{1}{2}$D texture mapping) presented in this paper. Out of the four approaches, ours gives the best sense of surface relief.

Abstract

We applied fundamental perceptual and physico-mathematical studies to a fast method for luminance remapping of 2D texture maps which enhances perceived surface roughness in comparison with conventional 2D texture mapping. The fundamental physical mechanism underlying the method is the fact that texture contrast increases as the incident illumination tends towards grazing for rough matte surfaces, actually "exploding" near the shadow edge [Pont and Koenderink 2005]. A psychophysical study by Ho et al. [Ho et al. 2006] confirmed that human observers use texture contrast as a cue for relief-depth or surface roughness. Thus, 2D texture-mapped objects will appear to have a rougher surface if the texture contrast is increased as a function of the local illumination angle. In particular, we increase the bidirectional texture contrast in close accordance with the contrast gradients measured for real objects with rough surfaces. The method presented works well for random textures of locally-matte surfaces if the original texture does not have a contrast that is too high. This modification is in addition to the usual attenuation of the surface irradiance due to the angle of the incident illumination and the computational costs of the technique are similar to that of conventional diffuse shading. This low cost makes it straightforward to implement the technique with real-time shaders which allow interactive rendering on modern graphics hardware.

CR Categories: I.3.7 [Computing Methodologies]: Computer Graphics—Three-Dimensional Graphics and Realism; J.2 [Computer Applications]: Physical sciences and engineering; J.4 [Computer Applications]: Social and behavioral sciences

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1 Introduction

Currently 2D texture rendering techniques are still widely used in real-time rendering systems in which realism is desirable, but the computational costs have to be kept within limits. The standard technique of 2D texture mapping and shading which involves the warping of "wallpaper textures" onto a surface followed by the modulation of the texture values by a parameter dependendent on the direction of the incident illumination results in renderings in which the surface relief appears to be much less than that of real objects with rough surfaces [Dana et al. 1999], as shown in the second image of Figure 1. Texture maps that represent rough surfaces cannot be represented properly due to the illumination- and view-dependent effects of shading, shadowing, interreflections and differential foreshortening. However, in this paper we present a method called "$2\frac{1}{2}$D texture mapping," which approximates local texture shading and shadowing effects using a simple modification of the luminance values of a single standard 2D texture map. This results in the illusion of a surface with enhanced 3D relief (which is why we call it "$2\frac{1}{2}$D," as in Marr's $2\frac{1}{2}$D sketch [Marr and Poggio 1983]), at a computational cost which is similar to that of conventional shading.

The phenomenon that grazing illumination brings out surface relief has been used for a long time by artists, for instance by photographers to capture surface relief of matte rough surfaces [Adams 1981; Hunter and Fuqua 1990], in artwork to draw or paint rough surfaces [Baxandall 1995; Jacobs 1988], in art historical research to analyse brush strokes [Bomford et al. 1990], etc. Surprisingly, this texture-contrast effect has not yet been applied in rendering

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systems, though it can be implemented via simple and fast luminance remapping. This will result in an enhancement of the illusion of surface depth relief, which is currently simulated in real-time rendering systems by using bump-mapping [Blinn 1978]. In bump-mapping, the surface normal at every position of the object is perturbed by values accessed from a texture map. When the perturbed normals are used during shading, they create the appearance of a bumpy or wrinkled surface.

For real-world objects with rough surfaces, the appearance of their texture depends strongly on illumination direction and viewing angle. In particular, for locally-matte materials, their roughness or surface relief will appear most clearly for grazing illumination. Using a simple micro-facet model that assumes locally-Lambertian reflectance, Pont and Koenderink found that the bidirectional texture contrast increases monotonically as a function of the illumination angle to arbitrarily high values ("exploding") near the shadow edge [Pont and Koenderink 2005]. Ho et al. [Ho et al. 2006] studied human perception of surface roughness and found that surfaces appear to be more rough for more shallow illumination due to increased texture contrast (a measure of the width of the luminance histogram), average luminance (a measure of the position(s) of the mode(s) in the histogram), standard deviation of the luminance (another measure of the histogram width) and blackshot (number of shadowed pixels). The average luminance as a function of illumination and viewing angles is described by the bidirectional reflectance distribution function (BRDF) [Nicodemus et al. 1977], and is usually simulated by Lambertian shading in 2D texture mapping for real-time applications. The increase in blackshot as a function of illumination direction can be simulated by simple clipping of the luminance values depending on illumination angle. Modification of the histogram width (e.g. contrast) as a function of local-illumination direction may result in blackshot modification, but will also influence all other pixels in the image.

The micro-facet model of rough, opaque, locally-Lambertian surfaces used in the algorithm of Pont et al. [Pont and Koenderink 2005] assumed a distribution of attitudes which was bounded by micro-facets with an attitude $\Delta\theta$. Those facets, which deviate maximally from the global or fiducial normal on the surface, give rise to local illuminance values which differ from the fiducial value $\cos\theta$ according to $\cos(\theta \pm \Delta\theta)$. The texture contrast was defined as $(\max - \min)/(2 \text{ fiducial})$ for which it was found that the contrast increases with illumination angle and actually exploded near the terminator: $c = \sin\Delta\theta \tan\theta$. Results agreed with texture contrast gradients of real textures, for which the minimum, maximum and fiducial values were defined to be the 5%, 95% and 50% percentiles (defining the fiducial to be the median), in order to get robust measurements.

2 $2\frac{1}{2}$D texture mapping

Conventional 2D texture mapping follows $t'(x, y, \theta) = t(x, y)\cos\theta$ where $t(x, y)$ is the gray-value of a pixel at position (x, y) in the original texture image and $t'(x, y, \theta)$ is the gray-value of the texture-mapped pixel. The global luminance gradient follows Lambertian shading as a function of the local illumination angle with respect to the local surface normal θ [Lambert 1760]. It is clear that in this case, the texture contrast c' is independent of the illumination angle: $c' = (\max\cos\theta - \min\cos\theta)/(2 \text{ median} \cos\theta) = (\max - \min)/(2 \text{ median}) = c$. This might well be one of the main reasons why surfaces rendered using conventional 2D texture mapping techniques appear "flat." Our $2\frac{1}{2}$D texture mapping can be applied in several ways. Based on our micro facet model we can specify one version of the technique with the following equation:

$$t'(x, y, \theta) = t(x, y)\cos(\theta - s\,sign[t(x, y) - m] \arccos\frac{t(x, y) - m}{m}).$$

In this case, m is the median luminance of the original texture and s is a scalar value with which the magnitude of the effect can be scaled (in Figure 1 $s = .09$). The $\cos\theta$ shading term now includes an $\arccos$ term which mimics the deviation of the local facet attitude from the fiducial one ($\Delta\theta$ for the minimum and maximum in the micro-facet model). After this illumination-dependent luminance remapping, we clamp the luminance values to the range 0 to 255. The exact parameters of the algorithm can be varied in order to change the exact shape of the resulting contrast function, the amount of stretching of the gray-values around the fiducial value, the choice of fiducial value, the baseline contrast, etc., as long as the contrast increases steeply towards the shadow edge.

In Figure 3, we show textures of Gaussian random surfaces and their gray-value histograms for real surfaces, for conventional 2D textures maps, and for $2\frac{1}{2}$D texture mapped surfaces. The two rendered sets were mapped with the images of the 40° real surfaces. For all three cases, we show results for low-relief and high-relief surfaces in the first and second rows. It is clear that the histograms for the real and $2\frac{1}{2}$D texture mapped images show bimodal structures that are characteristic for real rough surfaces [Dana et al. 1999], in contradistinction to those of the conventionally mapped textures. These bimodal structures are due to a combination of a shadow and a diffuse mode. At the right of the images in figure 3 we show the texture contrast functions for the Gaussian surfaces. The upper graphs show the median (black line), minimum and maximum (gray lines) values as a function of illumination angle, while the lower ones plot the median and contrast (gray line), which was scaled with regard to the median curve. In the real data we can see that: 1) the median value decreases according to a cosine-like function, 2) the minimum and maximum curves deviate more for higher relief, 3) the contrast increases towards the shadow edge and actually "explodes" just before the terminator. In the conventionally mapped data, all luminance curves decrease and converge while the contrast stays constant. For the $2\frac{1}{2}$D texture mapped images we find curves with the same main properties 1)-3) as for the photographs of the real surfaces.

Since the computational costs of texture-contrast mapping are similar to standard Lambertian shading because the algorithm is simple, it can be implemented in real-time hardware shaders. Figure 2 shows screen shots of a system in which the texture-mapped and texture-contrast-mapped objects can be rotated interactively. Unlike the bump-mapping approach, only a single texture map needs to be accessed to shade the points on the surface of the objects.

3 Discussion and conclusions

The benefit of non-realistic 2D texture mapping techniques is the low computational and memory capacity which is needed by real-time applications. Conventional 2D texture mapping, however, results in flat and non-convincing renderings of surface roughness. In order to solve this problem, we applied results from perception and optics studies to a "cheap" fast luminance remapping method. This method, $2\frac{1}{2}$D texture mapping, mimics the texture contrast gradients and histogram transformations that occur in real-world rough objects, at a cost which is similar to that of standard diffuse shading. This method is therefore suitable for fast real-time applications such as games. We showed quantitative results for real surfaces, 2D mappings and $2\frac{1}{2}$D texture mappings which demonstrate why conventionally 2D texture-mapped objects appear to have less surface relief than our $2\frac{1}{2}$D texture-mapped objects. Furthermore, the

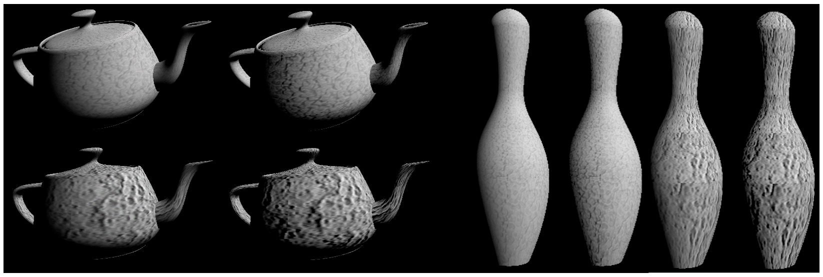

Figure 2: Screen shots of a real-time hardware implementation of our approach, using the Gaussian random texture (the 10° sample) from Figure 3 and a plaster texture from the Curet database. For every object, we show it rendered using conventional 2D texture mapping on the left, and our $2\frac{1}{2}$D texture mapping on the right. The images render at over 100 fps and the objects can be rotated interactively.

psychophysical study by Ho et al. [Ho et al. 2006] provided fundamental perceptual insights which underlie this method: roughness perception was found to be correlated with measures of the width of the luminance histogram such as the texture contrast and standard deviation. In our method, the histogram width was modified as a function of local illumination angle.

Ho et al. [Ho et al. 2006] also found a correlation between blackshot and roughness perception. For comparison, we applied this simple modification by clamping luminance values based on the local-illumination direction, causing the number of shadowed pixels to increase towards the shadow edge to achieve the proper result. The third image of Figure 1 shows an example of our blackshot modification algorithm, which indeed results in an increase of perceived surface roughness, when compared to the conventionally shaded image. However, since only the darkest pixels are remapped to black in this approach, the result looks fairly artificial. Our $2\frac{1}{2}$D texture mapping method applies to the full range of luminance values while at the same time enhances shadows for grazing illumination, resulting in a more realistic rendering of a rough surface.

Today, it is possible to use sophisticated 3D texture rendering techniques because fast computers and large memory are available. In 3D texture mapping approaches, bidirectional texture functions are used in which illumination and view-dependent effects of local occlusions, interreflections, shading, shadows and differential foreshortening play a role. These photometrical effects result in intricate transformations of the gray-value histograms and spatial properties of the textures, for instance of the illuminance flow [Pont and Koenderink 2003]. The absence of such systematical spatial transformations in 2D texture maps causes them to look more like flat "wallpaper textures" instead of rough "3D surface textures". Nonrealistic rendering methods to mimic such spatial modifications will not be able to weigh up to current developments in 3D texture rendering. However, the value of very fast luminance remapping methods for altering material appearance has already been recognized by other researchers [Motoyoshi et al. 2005; Kahn et al. 2006].

In this paper, we have presented a fast, simple method which can be used to enhance the illusion of surface depth relief in 2D texture maps and is based on a physical model and on psychophysical findings. The method modulates the texture contrast gradient, thereby simulating local shading and shadowing effects due to surface roughness. $2\frac{1}{2}$D texture mapping is fast and inexpensive, and is therefore very suitable for real-time rendering systems.

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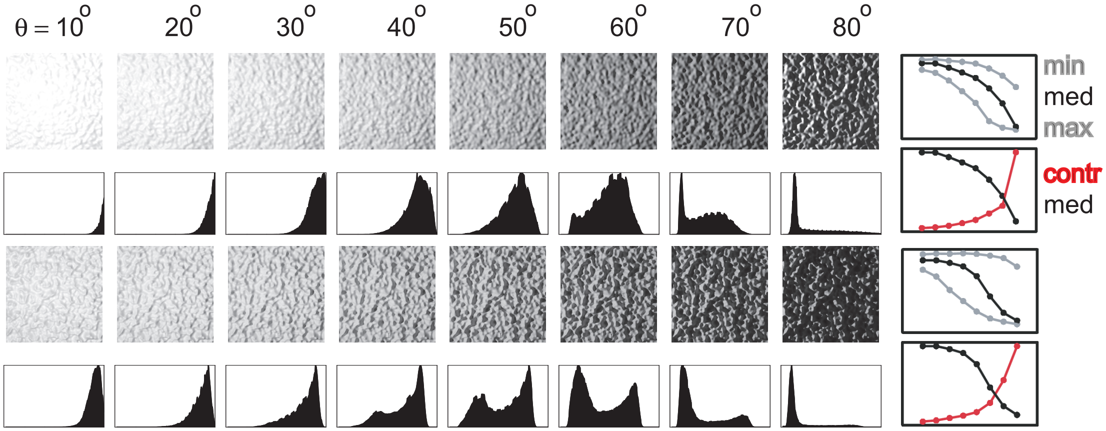

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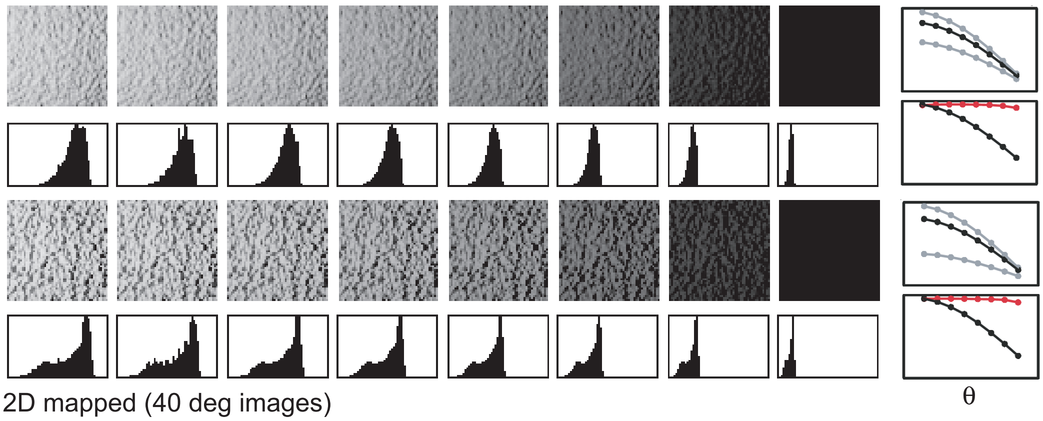
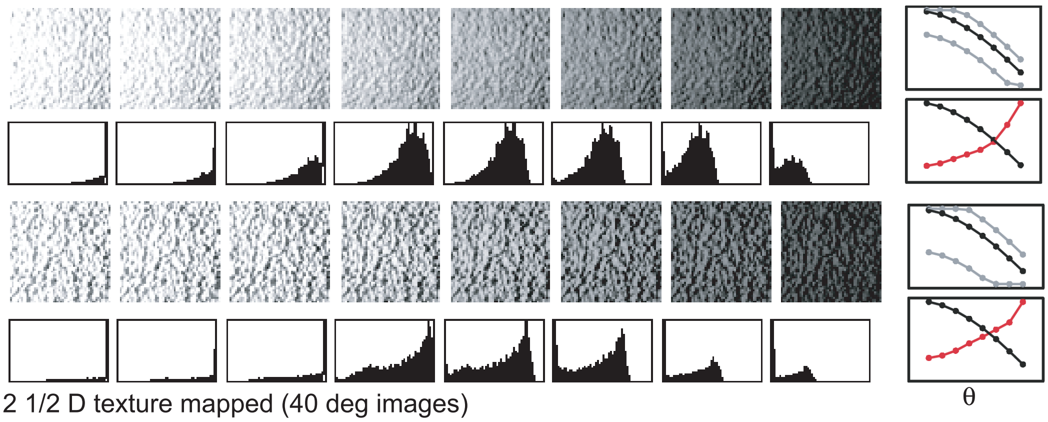


2D mapped (40 deg images)



2 1/2 D texture mapped (40 deg images)

Figure 3: Textures of Gaussian random surfaces for illumination angles ranging from 10 to 80 degrees (from left to right). The first two rows show photographs of two real random Gaussian surfaces 40cm × 40cm in size, which were painted matte white. The first row is of a low-relief surface, the second row of a high-relief surface (on the order of 0.5cm and 1.7cm respectively). The second set shows images generated with standard 2D texture mapping, while the third set uses the approach described in the paper for modifying the texture contrast. The two rendered sets use the 40° photographs from the first set as inputs. At the right we show the texture contrast as a function of incident illumination angle. In each row, the top plot shows the median (black line) in comparison to the minimum and maximum (gray lines). The bottom plot shows the contrast (gray line) against the median (black line).