Determining Wet Surfaces from Dry

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Abstract

Wet surfaces are ubiquitous in our visual experience. Autonomous machines with vision systems will need to identify wet surfaces from dry. Wet surfaces (especially rough, absorbent ones) appear darker when wet. This paper presents the Lekner and Dorf model for describing the darkening caused by wetting. We explain how to use this optics model to transform intensity values of a region of an image to make that region appear wet. We also show how the model can be reversed in order to make a wet part of an image appear dry. It is also shown that this technique can be used to identify wet regions. This identification is contrasted with darkening caused by shadows. Comparisons of the gray-level histograms of these real images show the validity of this approach for distinguishing wet surfaces from dry.

1.0 Introduction

People learn to distinguish between wet and dry surfaces by sight. One visual cue is that wet things look darker. In fact, most materials, especially those with rough and absorbent surfaces, appear darker when wet. Knowledge of the physical model behind this ubiquitous optical phenomena can contribute to computer vision applications capable of distinguishing wet from dry.

The ability of a machine to identify wet surfaces can aid the machine in carrying out its tasks. Robots in an industrial setting may be made safer if they can identify spills of liquids in their operating environment. Exploratory robots would be able to navigate in environments where wet surfaces are a factor. The self-navigating automobile would be able to tell when the roads are wet and slick and alter its speed accordingly.

This paper embarks on the study of wet surfaces in the computing realm. Much theoretical and experimental work remains to be done in optical physics to describe the mechanisms of wet surfaces, but the existing models suggest areas of investigation in computer vision. We will introduce an optical model of wetting and then demonstrate how it can be used to distinguish wet surfaces from dry.

2.0 Background

The modeling of wet surfaces has not been covered in the realm of computer science. Practical optics has not looked at it closely either. Ångstrom proposed a model ([1]) in 1925 that has not significantly changed since that time. Lekner and Dorf (L&D) revised Ångstrom's model in 1988 ([4]) to more closely coincide with the very sparse albedo data available for wet surfaces.

Consider a rough surface covered by a thin film of liquid. A ray of light will not be completely reflected at the air-liquid interface. The light will be diffusely reflected at the rough surface. Some of this light will be at the liquid's critical angle causing it to be totally internally reflected. The probability of the light's absorption by the material increases, therefore less light reaches the viewer and the surface appears darker.

Ångstrom underestimates the fraction of light reflected back at the liquid-air interface. He considers only the light which has been reflected from the surface that is at the critical angle or greater as returning to the surface. Leckner and Dorf account for the reflectivities of both polarizations of the interface of the liquid media and air. They show in [4] that their theoretical results more closely coincide with experimental data.

Twomey, Bohren, and Mergenthaler in [6] (TBM) describe a different darkening mechanism for wetted substances. They examine the case of granulated substances such as sand, dirt, and soil. They describe the darkening phenomenon as arising from the greater degree of forward scattering caused by the replacement of the usual interstitial fluid of air with water (which has a greater index of refraction.) This model will not be used in this work but is mentioned because of the coincidence that the

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L&D model and the TBM have with respect to the experimental data. TBM is suggested by its originators to be more accurate for granular substances. The L&D model will be used in this study because it is computationally less complex and more closely associated with the class of surfaces being examined.

Computer graphics research has examined the rendering of realistic depictions and animations of water (see [7], [3], and their listed references). These models have only addressed the dynamics of gross fluid behavior and have not captured impinging liquids on an absorbent surface. Computer graphics provides little guidance to the computer vision problem of identifying wet surfaces. In addressing this problem we begin with physical optics.

3.0 Optics Model

The L&D revision of Ångstrom's model provides an accurate way of predicting the darkening of a rough, absorbent surface when it is covered by a thin film of water. The model takes as input the dry albedo ((1 - a_d), a_d is the fraction of light absorbed by a dry surface) of the surface, the index of refraction of the impinging liquid (n_l), and the index of refraction of the surface (n_r). The model accounts for the probability of absorption of light by the surface and considers refraction at the air-liquid interface.

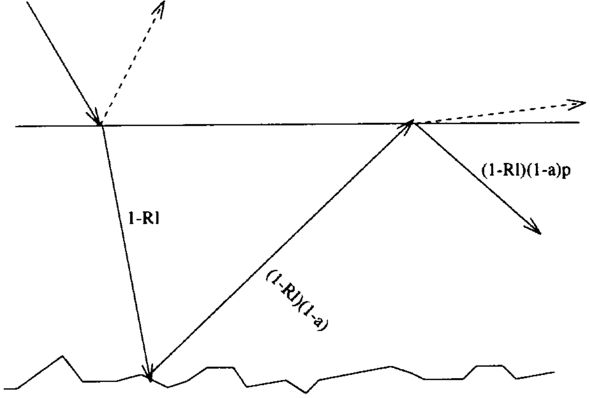


Figure 1: A rough surface covered by layer of water. As the light ray travels through the water to the surface and is inter-reflected its energy is increasingly absorbed.

Figure 1 shows the path of an arbitrary ray of light and the variables that are associated with each phase of the light ray. The rough surface is assumed to be composed of randomly oriented facets that reflect specularly. R_l is the reflectance at the liquid-air interface. The probability of a light ray penetrating the liquid layer to the surface on which the liquid sits is (1 - R_l). The fraction of that light that is absorbed by the surface is a. (1 - a) is the amount of that light that is reflected by the surface. That makes p the fraction of light reflected back at the liquid-air interface. The summation of these probabilities for the total probability of absorption for this light ray is:

$$A = (1 - R_l)[a + a(1-a)p + a(1-a)^2 p^2 + \ldots] \qquad (1)$$

Extracting a and substituting the formula for the remaining sum allows us to write (1) as:

$$A = \frac{(1-R_l)a}{1-p(1-a)} \qquad (2)$$

Ångstrom evaluates p as all of the light reflected at the liquid-air interface for angles of incidence greater than the critical angle. L&D also accounts for both polarizations of the reflected light. [2] (section 1.5) shows the small, but not infinitesimal, contribution of these reflectivities. The complete derivation of p is in [4]. It shows that we can write p in terms of the liquid's index of refraction (n_l) and the average reflectance of an isotropically illuminated surface ($\bar{R}$):

$$p = 1 - \frac{1}{n_l^2}[1 - \bar{R}(n_l)] \qquad (3)$$

From Stern's formulas [5] for the transmission of radiation at an interface we write (n > 1):

$$\bar{R}(n) = \frac{3n^2+2n+1}{3(n+1)^2} - \frac{2n^3(n^2+2n-1)}{(n^2+1)^2(n^2-1)} + \frac{n^2(n^2+1)}{(n^2-1)^2}\log(n) - \frac{n^2(n^2-1)^2}{(n^2+1)^3}\log\left(\frac{n(n+1)}{n-1}\right) \qquad (4)$$

In this model we will assume normal illumination and write the reflectance at the air-liquid interface as:

$$R_l = \frac{(n_l-1)^2}{(n_l+1)^2} \qquad (5)$$

Where a in equation (1) is the fraction of light that is absorbed incident to the surface. Ångstrom assumed that a would be the same whether the surface was wet or dry, but it does not account for the interaction of the surface's index of refraction (n_r) with that of the liquid (n_l). We denote the value of a when dry as a_d. Using equation (4) we write:

$$a_d = 1 - \bar{R}(n_r) \qquad (6)$$

L&D estimate the wet value of a (a_w) in terms of a_d, n_l, and n_r. L&D interpolate between the limiting forms for small and large surface absorption with the equation:

$$a = a_w = a_d(1-a_d)\frac{1-\bar{R}\left(\frac{n_r}{n_l}\right)}{1-\bar{R}(n_r)} + a_d \qquad (7)$$

Calculations from these equations can produce a graph of wet albedo (**1 -** A) as a function of dry albedo (**1 -** a_d). The result of this graph can be seen in Figure 2.

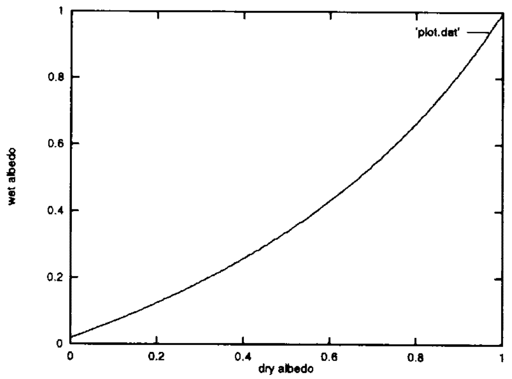


Figure 2: Wet albedo plotted as a function of dry albedo. This is developed from the Lekner & Dorf model. We assume normal illumination, the index of refraction for the surface (n_r) is 2, and the index of refraction for water (n_l) is 1.33.

Notice that the greatest differences between wet and dry albedo occurs for surfaces in the middle range of dry albedo. This is because especially dark surfaces will tend to absorb more light than can be internally reflected, decreasing the effect of wetting; while bright surfaces will tend to reflect much more light than is absorbed by internal reflection also decreasing the effect of wetting. This is a significant characteristic of wetting and can be used to differentiate between darkening mechanisms of other kinds, such as shadows.

3.1 Reversing the Optics Model

The L&D model discussed above shows how to generate the wet albedo from the input of dry albedo (and other factors). The process can be reversed to allow the calculation of dry albedo from wet. This will be used when we discuss transformations and the wet darkening mechanism's contrast from the dry surface. In equation (7), let:

$$C = \frac{1 - \bar{R}(\frac{n_r}{n_l})}{1 - \bar{R}(n_r)} \qquad \textbf{(8)}$$

Using (**8**) we rewrite (**7**) as:

$$Ca_d^2 - (C+1)a_d + a_w = 0 \qquad \textbf{(9)}$$

This is a quadratic in a_d and we can write:

$$a_d = \frac{(C+1) \pm \sqrt{(-C-1)^2 - 4(C)(a_w)}}{2C} \qquad \textbf{(10)}$$

This is the reverse of the L&D optics model, except that we need to know whether to carry out addition or subtraction with this equation. Figure 2 plots wet albedo as a function of dry albedo. The new equation is dry albedo as a function of wet albedo. We choose subtraction because it generates the dry albedos to correspond with the wet albedos to produce the same curve displayed in Figure 2.

4.0 Applying the Optics Model

The L&D model of darkening caused by wetting takes as inputs the dry albedo (**1 -** a_d) and the indices of refraction for the surface and the liquid (n_r and n_l respectively). In order to use this model with images in the real world some assumptions and conversions must be made. The current model depends on **albedo**, which is the ratio of incident light over the returned intensity. The albedo is a value between zero and one, zero being totally dark and one being totally reflected. Digitized images record intensity not albedo. To use the wetting model the intensity data must be normalized to a representative albedo.

The Lambertian model describes a surface as randomly oriented facets. We assume that each recorded pixel intensity corresponds to a surface which has a particular associated albedo. The pixel values represent the intensity of reflected light. If we assume the image is uniformly illuminated then we can assume a constant intensity for incident light. Dividing the pixel intensities by this constant yields a normalized number between 0 and 1 that is treated as the albedo at that pixel. This value is used as an input to the L&D model. The maximum intensity of a pixel within an image will be the divisor that normalizes the intensity values to albedos. This is based on the assumption that the pixel is a facet which exhibits total reflectance. This value proves to be most accurate with that of the real-world data when the techniques, described below, are applied.

The L&D model can be used to alter a digitized image so that it appears wet or to make a wet image appear dry. This model can also be the basis for determining whether a darkened region of an image is caused by wetting. The following subsections will explain these procedures in more detail.

4.1 Transformations

The L&D model can be used to alter a real-world image so that it appears wet. The intensity of each pixel is divided by the maximum intensity in the image to give an albedo ($1 - a_d$). This will provide a_d as input to the L&D model. Because nearly all surfaces have a index of refraction of 2 this will be the value used for n_r. The index of refraction for water (n_l) is 4/3. The wet albedo can be calculated from the L&D model with the inputs described above. Multiplying the wet albedo by the maximum intensity value, used to normalize the image intensities, results in a new intensity value that corresponds to the wet intensity of that pixel.

The same operations can be applied to make wet portions of an image appear dry. Using the reversal of the L&D model from section 3.1, we use the normalized pixel value as the wet albedo ($1 - a_w$). n_r and n_l are the same as above. The new "dry" intensity value becomes the pixel's intensity in the image. The image will now appear as the surface would if it were not wet. For both processes the relationship among the pixels of the surface's intensity texture is maintained. In an image where there are wet and dry regions of a homogeneous surface, their boundaries disappear when one region is transformed by this process to match the other region.

4.2 Identification

To identify whether a darkened region of an image is caused by wetting we first produce a gray-level histogram of the image. Most homogenous surfaces will produce a bimodal curve. The intensity values of the two peaks will be those associated with the dark and light segments of the image respectively. The image is segmented into these two fragments. The individual gray-level histograms are superimposed on the total image's histogram. The individual curves will match the two peaks of the bimodal curve. To test whether the darker segment is caused by wetting we transform the candidate wet segment using the process described above and compare the new histogram with the one already generated for the light region. A very good match of the two curves will indicate that the candidate wet region exhibits the same darkening effect of the surface when wet. Because darkening caused by wetting is a very distinct effect the candidate wet region can be identified as wet with some certainty.

5.0 Experiments

Three experiments were carried out to demonstrate the use of the L&D model. The first and second experiments examine the synthetic "wetting" and "drying" of an image respectively. The third experiment describes the steps for determining a wet segment from a dry one in an image. Section 6.0 discusses the comparison of histograms on which this approach is based.

The first experiment utilizes the digitized video image of a pool deck (concrete). Figure 3 shows this image. Figure 4 shows the gray-level histogram of the image. The histograms of the dry and wet segments of the surface are also plotted in Figure 4 for comparison. Notice that the bimodal curve of the entire image is an aggregate of the two Gaussian curves of the wet and dry regions. This image is segmented into these two regions, then the dry portion is made to appear wet using the process described above in section 4.1. This image is shown in Figure 5. Figure 6 shows the histograms of this image and the two regions that formerly contrasted. The curves of the formerly dry region have shifted to be like that of the wet. Looking at Figure 5, it appears that the boundary between the wet and dry region has become indistinct. The dry part now appears wet.

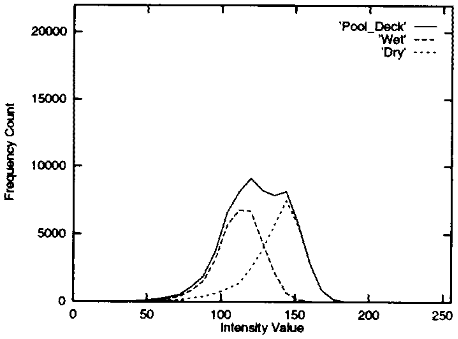
The second experiment also uses the same video image shown in Figure 3. The process for drying uses the reverse of the L&D model as described in section 4.1. Figure 7 is the image with the wet region made to appear dry. Figure 8 shows the respective histograms of that image. As we saw for the "wetting" process, the boundary evident in Figure 3 is indistinct in Figure 7. Figure 8 shows that the synthetically dried portion's histogram matches with the histogram that is dry. The formerly wet region now appears dry both visually and statistically.

The third experiment shows how these transformations are used to identify wet from dry. An image with a shadow that statistically behaves as wetting is analyzed to demonstrate that the wetting phenomenon is distinct from other darkening phenomena. For this experiment, we shadow the image in Figure 3 and map part of the shadow image to the same sample space as the wet region. This image can be seen in Figure 9 with its requisite histograms in Figure 10. Applying the method described above in Section 3.2 we make the dark portion "dry". We then compare the statistics of this region to that of the light (dry) area. Figure 11 is the image. Figure 12 has its histograms.

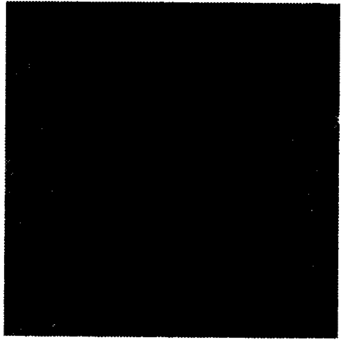
6.0 Discussion

Figure 13 compares the gray-level histograms of the dry segment of the image in Figure 3 with the transformed darkened regions caused by wetting and by shadow. It shows the correlation between the curves for the dry region and the transformed wet region, however, the transformed shadow segment does not exhibit this similarity. This demonstrates the validity of using the transformations developed from the L&D model to identify wet regions. It can also be seen that shadows and darkening caused by wetting are distinct processes.

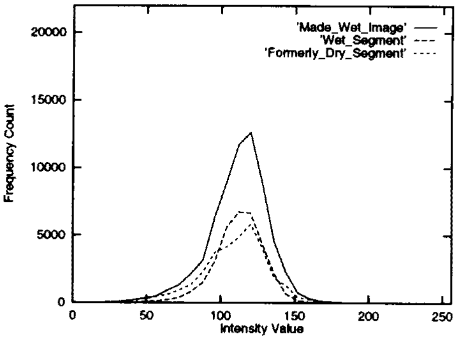
←**Figure 3:** A pool deck surface (concrete)- recorded with a video camera, captured from tape, and digitized to a gray-scale format with intensities from 0 to 255. The right side is dry. The left is wet.



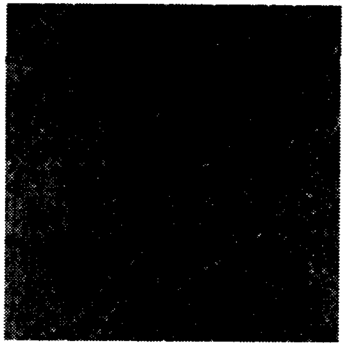
→**Figure 4:** Histograms of the image in Figure 3. The 'Wet' curve is the wet part of the image. 'Dry' denotes the dry segment. Note that their peaks correspond to the bimodal peaks for the whole image.



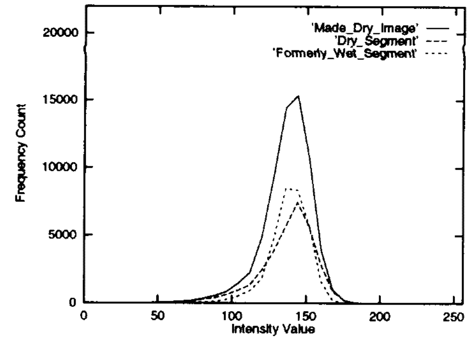
←**Figure 5:** The image of Figure 3 with the dry side transformed to appear wet. Note that the surface appears homogeneous and the boundary is indistinct.



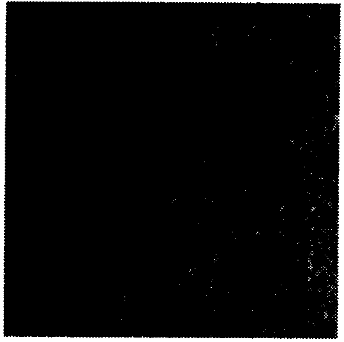
→**Figure 6:** The histograms for this image show a shift towards the actual wet curve. 'Wet_Segment' is actually wet while 'Formerly_Dry_Segment' has had the "wetting" transformation applied to it.



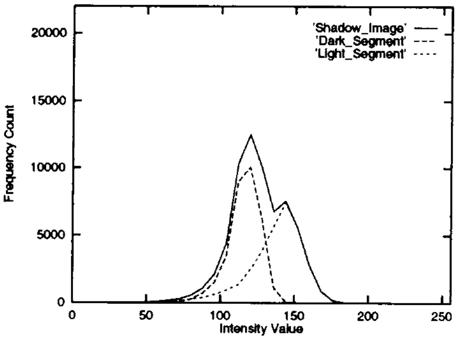
←**Figure 7:** The image of Figure 1 with the wet portion transformed to appear dry. Note that the surface appears homogeneous and the boundary is somewhat indistinct.



→**Figure 8:** The histograms of the image in Figure 7. The 'Formerly_Wet_Segment' has shifted to coincide with the 'Dry_Segment'.

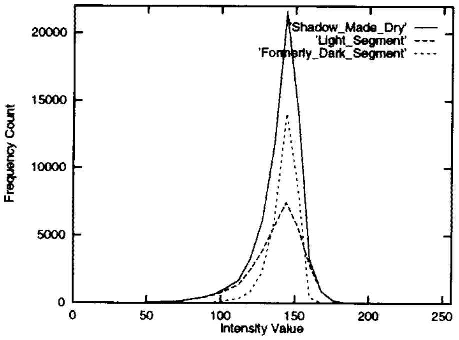


←**Figure 9:** This image was created by mapping the image with a shadow to the space of the wet portion in Figure 3. This is to ensure the same sample space for analysis.



→**Figure 10:** The histogram of Figure 9. Comparison with Figure 4 shows that the peaks of light and dark match with those of dry and wet.

←**Figure 11:** The image of the pool deck with the "drying" transformation applied to the shadowed segment. A boundary is visible and the different regions are distinct.



→**Figure 12:** The gray-level histograms of Figure 11. The value at the peaks of the 'Light_Segment' and the 'Formerly_Dark_-Segment' match.

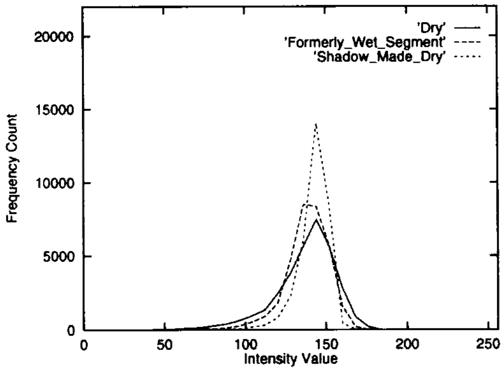


Figure 13: Comparison of a 'Dry' histogram with wet and shadowed segments transformed to appear dry.

Figure 14 is a theoretical comparison of both darkening mechanisms. It was found that the shadow in our image attenuated all the available light. The line in Figure 14 shows that each pixel's available light is reduced by a constant amount. The curve in Figure 14 shows that wetting (which affects albedo) impacts intensity values in a non-linear way. Applying the drying transformation to a wet segment has an expected effect. If the process does not "dry" as expected this indicates that the region's darkening was most likely not caused by wetting.

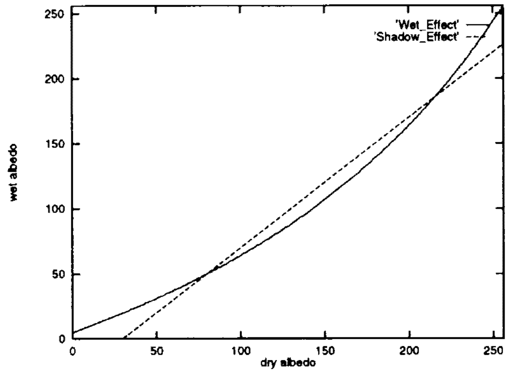


Figure 14: The formulation of intensities from the L&D model and from shadowing. Shadows linearly attenuate the illumination of a surface. Wetting causes changes in albedo.

Certainly, there are cases where the algorithm can be fooled, but the same can be said for the human visual system. One such case would be that of two different surfaces where one appears, statistically, to be the wet region of another. This kind of problem will require more examination, but that is the purpose of the introduction of this approach. It is our hope that the initiation of this topic will lead to further research and new applications.

7.0 Future Work

This paper has presented an approach to identifying a wet region on a surface by using knowledge of the darkening mechanism of wetting on a certain class of surfaces. A quantitative examination of this approach applied to many different images is left to be done. The current model is also extensible to identification of different liquids by determining the index of refraction of an impinging fluid. The L&D model can accomplish this with the *a priori* knowledge that a dark region is caused by wetting. Utilizing the L&D model, our approach works well but many other visual cues remain to be examined. Morphology, dynamics, and color are other considerations to be explored especially as the weaknesses of the above approach become apparent.

8.0 Conclusion

We have developed some useful tools from the L&D physical model of wet optics. Methods of transforming real world images to make dry surfaces appear wet or wet surfaces appear dry have been demonstrated. We have also shown how to use the L&D model to identify wetting in an image (as opposed to shadowing). The exciting part of this work has been to carry out computer vision tasks based on well-understood physical models of the actual world. Understanding the underlying causes of certain visual effects can be of great help in identifying those effects when observed.

9.0 References

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