A Model for Simulating the Photographic Development Process on Digital Images

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ABSTRACT * +

In this paper we present a model for the simulation of the photographic development process for use on computer generated and other digital images. The model provides us with a tone reproduction operator based on photographic principles that mimics the creation process of black and white photographic prints. We focus on four characteristics of photographic materials: density response, spectral sensitivity, resolution and granularity. These characteristics are described quantitatively using empirical data thus making the simulation of the response of actual photographic materials a straight forward application of the model. The result of the simulation is a device independent image of floating point values between 0 and 1 which represent shades of gray on a linear scale. This image can be quantized for display on a given output device.

CR Categories and Subject Descriptions: I.3.3 [Computer Graphics]: Picture / Image Generation; I.3.7 [Computer Graphics]: Three-dimensional Graphics and Realism; I.4.9 [Image Processing] : Applications

Additional Keywords and Phrases: Photography, Tone Reproduction, Digital Effects, Post-processing, Simulation.

1 INTRODUCTION

Since its inception, one of the major goals of computer graphics has been the quest for photorealism in the synthesis of computer generated imagery. The field has utilized a photographic metaphor to achieve this goal where renderings are produced by following the path of visible radiation from a virtual scene, through a camera and onto a film plane. This process can be viewed as a large simulation problem, where the tracing of the light in the scene can be divided into the three stages: a simulation of the distribution and reflection of light within a scene, the capture and focus of this light by a camera model, and the translation of captured radiance values to quantized pixel values for producing a displayable image.

Over the past decade, a great deal of research in image synthesis has focused on the first stage. This research has resulted in a wealth of shading techniques, reflection models and illumination algorithms. Advances in the second stage have resulted in realistic camera models, far more sophisticated than original pinhole models, that are based on an accurate treatment of lens optics[1,2].

The rendering process is not complete, however, until the third stage is considered. The results produced by the first two stages provide us with representative illuminance values at each pixel, but give no indication of how these values should be interpreted or translated to produce an appropriate image. Taking an ad-hoc approach in this stage can lead to extremely misleading results especially in rendering scenes with different levels of contrast[3].

This third phase, known as the *tone reproduction problem*, involves the definition of a response function that converts representative illuminance values to appropriate tones for final display. Recent research efforts in this area have concentrated on simulating the response of the human visual system [3,4,5,6] (usually in conjunction with a given output device) thus faithfully reproducing how the eye would perceive a given virtual scene.

There are instances, however, where visual accuracy may not be the desired goal. Looking again to photography, the famed photographer Ansel Adams viewed photography as an expression not of what one sees, but instead, how one interprets what one sees. His philosophy of “artistic visualization” has the photographer mentally visualizing the final print based on what is seen and using the controls of photography to realize his or her vision.[7]

In this paper, we approach the tone reproduction problem by modeling the response of photographic materials. Such a model can provide the computer graphic artists with the means to interact with images using the same controls that photographers have learned to use so effectively. With the increased use of computer generated elements in images and film, this model also becomes essential in the seamless composition of computer graphic elements with real scenes recorded on film.

Although the mechanism of photographic image formation operates independently of the human visual system, photographic engineers have spent over a century designing photographic materials that have optimal response for human viewing, even under a variety of circumstances and viewing conditions (e.g. slide film is designed to take into effect the fact that the resultant image will be viewed in dark surroundings [8]). With a generalized photographic

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model, one will be able to take advantage of the knowledge derived from years of photographic film design and apply it to computer generated imagery.

Our model is designed to mimic the process by which actual photographs are created. As such, we rely heavily on the existing photographic process and on photographic data commonly available for existing photographic materials. In order to clearly illustrate this process, we focus on the generation process of black and white positive prints. Although all photography is based on the same fundamental concepts, the discussions below are specific to black and white print photography. Issues regarding the extension of the model to color photography are discussed in Section 7.

Our paper proceeds with a summary of the process by which photographic prints are created. The photographic data used by the model is described in Section 3, followed by a full description of our model in Section 4. In Section 5, we provide some implementation details. We conclude by showing some results of the application of the model on computer generated images and by a giving a discussion of future work.

2 PHOTOGRAPHIC IMAGE FORMATION

Photographic images are the result of the chemical interaction of silver halide with radiant energy to produce metallic silver [9].

Photographic materials consist of microscopic silver halide grains embedded in a gelatin (*photographic emulsion*). When exposed to radiation, these grains undergo an invisible chemical change to form a *latent image*. This latent image becomes realized during the chemical development process, where fractions of grains adequately exposed to the radiation transform to metallic silver thus creating a visible density. The conversion from silver halide to metallic silver is a binary one (i.e. a grain is either silver halide or metallic sliver) with the threshold for the change being dependent upon the chemical developer used and the time of processing.

Both photographic film and photographic paper comprise an emulsion. In film, the emulsion is mounted in a transparent support, whereas, with paper, the emulsion is spread on a paper base.

2.1 Photographic Print Formation

In print photography (Figure 1), the illumination from a scene is captured by a camera and focused onto the plane of photographic film. Once processed, this film produces a negative image where dark areas represent regions of high illuminance. This negative is then placed into a printer/enlarger, where light is shown through it onto photographic paper. The printing process acts as a second reversal procedure and re-establishes the relationship of light and dark that exists in the original scene. Once developed, the processed paper results in the final print.

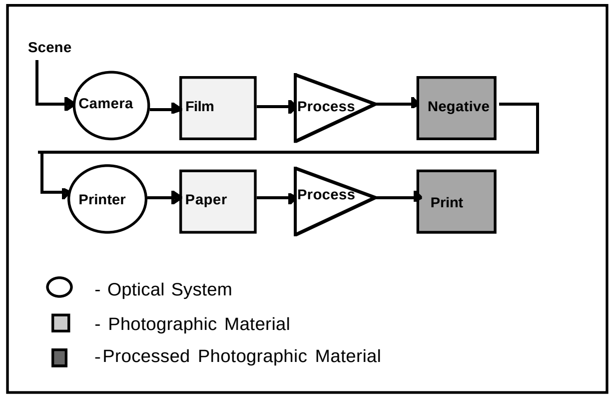


Figure 1 - Block diagram of the print photography process

2.2 Exposure and Density

In describing the response of photographic materials, a given emulsion is said to produce a *density* as a response to a given *exposure*.

Exposure is defined as the product of the irradiance incident upon the photosensitive surface (I) and the time during which the surface is exposed (t).

$$E = It \tag{1}$$

Photographic exposure data is generally given in photometric rather than radiometric units. Photometric units take into account the response of human visual system by weighting the power at each wavelength by its corresponding value in the luminosity function[10]. In Equation 1 above, I is usually given as an illuminance value (in lumens/m^2 or lux) and exposure is given in lux-sec.

In cases where the incoming flux is a continuous spectral distribution, which is usually the case, the exposure is given by the integral:

$$E = \int E_\lambda d\lambda = \int I_\lambda t d\lambda \tag{2}$$

where E_λ is the exposure at wavelength λ, I_λ is the illuminance at wavelength λ and t is the time of exposure.

The definition of exposure is concerned only with the product of illuminance by time, and does not discriminate between the contributions of the individual components. Because of the chemical nature of the process, this definition breaks down at very low values of I or t. This breakdown is known as the *reciprocity law failure* and must be considered when trying to capture low luminance scenes (as in the case of astronomical photography).

The measured response of a photographic material is given in density. Density is a unit less, logarithmic measure that indicates the opacity of an emulsion that results from processing.

Density comes in two flavors. Transmission density is used in describing the response of photographic film. It is defined as:

$$D_T = \log_{10} 1/T \tag{3}$$

where T is a transmission value, between 0 and 1, that gives the ratio of light transmitted through an emulsion to the quantity of light incident to it.

Reflective density, used for describing the response of photographic papers, indicates the quantity of light that is transmitted through the emulsion and reflected off the paper base. It is defined as:

$$D_R = \log_{10} 1/R \quad (4)$$

where R is the ratio of the light reflected off the paper base to the light incident to it.

3 SENSITOMETRY

The quality of an image is directly related to the quality of the emulsions that comprise the film and the photographic paper used in creating the image. For over a century, photographic scientists have been concerned with the measurement and study of the response of photographic emulsions to radiant energy. This science, called *sensitometry*, provides us with empirical measures that can be used to quantify the characteristics of an emulsion [11]. In our analysis, we consider four characteristics of the emulsion: density response, spectral sensitivity, resolution, and granularity.

3.1 Density Response

On a macroscopic level, emulsions have a non-linear response to radiant energy. This relationship is customarily illustrated by an emulsion's *characteristic curve* (Figure 2), a plot that relates input exposure to output density.[1]

The gradient of the characteristic curve in its straight line section is an important characteristic of an emulsion as it defines the change in density due to a given change in log exposure. This measure, termed *gamma*, is analogous to gain measures in other display systems and acts as a gauge for the contrast range of an emulsion. It is important to note that although gamma measures the slope of the curve in its linear portion, it really describes the non-linearity of an emulsion's response as the characteristic curve is plotted on a log-log scale.[8] Recall that density is already a logarithmic measure.

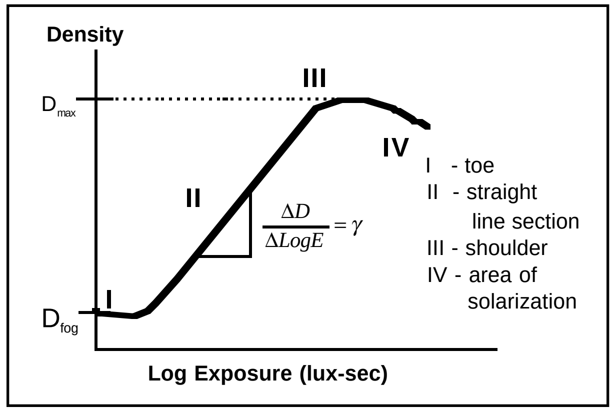


Figure 2 - A Typical Characteristic Curve

Sensitivity of an emulsion is indicated by its speed. A higher speed emulsion is more sensitive to light than a lower speed emulsion. Speed is defined as

$$SP = K / E_m \quad (5)$$

where K is a constant and E_m represents the exposure necessary to produce a density of m units above the fog density. Current standards for the speed of photographic materials define K = 0.8 and m = 0.1 for photographic films [12], and K = 1000 and m = 0.6 and for photographic papers[13].

The density response of a processed emulsion depends not only on the nature of the emulsion, but on also development conditions (i.e. developer solution, temperature, time of development). Consequently, the shape and positioning of a characteristic curve, and thus its gamma, speed, and density scale , will also vary based on these conditions.

Note that for photographic papers, the density reported in the characteristic curve represents transmission density whereas with photographic papers, reflection density is recorded.

3.2 Spectral Sensitivity

Untreated, silver halide grains are only sensitive to the blue and ultraviolet wavelengths of the spectrum. Specially formulated dyes that extend the responses of the grains to longer wavelengths are injected into emulsions in order to the increase the spectral sensitivity to include the rest of the visible spectrum.

The spectral sensitivity of an emulsion is very often expressed by means of a *spectral response curve* which provides a measure of relative sensitivity of the emulsion to each wavelength in the spectrum. Figure 3 shows the spectral response curves for three film types with different spectral sensitivities: panchromatic (sensitive to entire visible spectrum), orthochromatic (sensitive to green and blue light), and blue-sensitive (untreated).

[1] The characteristic curve is also known as the D-Log E curve or the H & D Curve (after Hurter and Driffield who introduced its use in 1890).

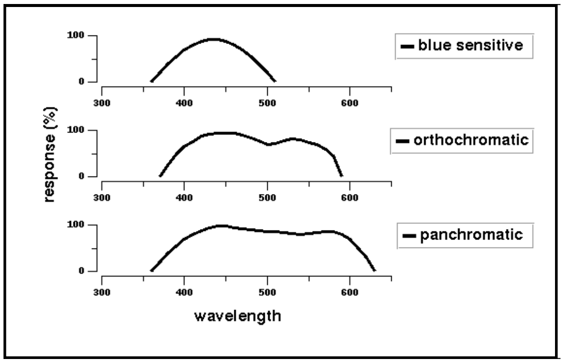


Figure 3 - Spectral response curves for three types of film with different spectral sensitivities (after [7])

3.3 Resolution

The resolution of an emulsion defines its ability to clearly reproduce the spatial detail of the scene being recorded on it. Internal scattering of light between the grains within an emulsion, causes a degradation of the recorded image. A point source ray of light incident to a film's surface, rather than producing a single transmitted ray, will instead produce a distribution of light. This distribution, termed the *point spread function (PSF)*, is instrumental in determining the resolution of an emulsion. Assuming the film to be isotropic, the point spread function is rotationally invariant.

The *line spread function, A(x)*, which is defined by:

$$A(x) = \int_{-\infty}^{\infty} PSF(x, y)\, dy \qquad (6)$$

gives the scattering response to an infinitesimal line of light. This function can be determined by measuring the response to a knife-edge exposure. Since most films can be considered isotropic, this function serves as a primary means for obtaining the PSF of an emulsion.

Although the macroscopic response of an emulsion is non-linear (as is evident by the characteristic curve), the internal scattering of light due to the microscopic grains can be modeled as a linear system and the response due to scattering determined by performing a convolution of the input image with the point spread function[14]. In the frequency domain, the effect of the scattering is given by the *modulation transfer function (MTF(ω))* which is the Fourier transform of the line spread function (Figure 4). The MTF can be determined directly from the line spread function, measured using the response of a sinusoidal exposure input, or calculated mathematically using Monte Carlo methods. [16]

A numerical measure for an emulsion's resolution is its resolving power. This measure, expressed in cycles/mm, is an estimate of the finest detail that can visibly be observed on the photographic material[17]. Its value can be roughly inferred from the MTF by determining the frequency at which the modulation transfer function falls to 0.1 (*f* in Figure 4).

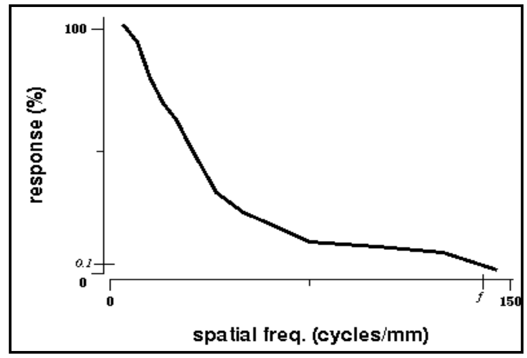


Figure 4 - Modulation Transfer Function (MTF) of a typical emulsion (after [15]).

3.4 Graininess and Granularity

Graininess is the visual perception of the non-uniformity in a uniformly exposed emulsion due to the random placements of the grains within it. Since grains in an emulsion are microscopic in nature, graininess for most emulsions is observable only upon magnification. The graininess becomes more apparent as the magnification of an exposed emulsion is increased.

The objective measure of graininess is called *granularity* and can be determined by examining the micro structure of an emulsion. Using the traces obtained a microdensitometer, fluctuations in density of a uniformly exposed emulsion can be measured and recorded. These measurements can be used to statistically model the grains within an emulsion and provide a measure for the granularity.

The *root mean square (rms)* deviation provides an indication of the uniformity of a sample and is obtained by computing the differences in density from a mean over an entire photographic sample. Assuming N independent sample points in a trace, the rms is calculated as:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(\Delta D_i)^2 \qquad (7)$$

where ΔD_i is the deviation from the density mean of the *i*th sample point.

Although the rms is a natural choice for a measure of granularity, it is ineffective as an absolute measure as its value depends upon the area of the aperture used in making the measurement. Selwyn developed a classic measure based on his observation that for large aperture areas (with respect to grain size), the product of the square root of the rms by the area of the aperture is constant. The *Selwyn granularity*, is given by:

$$G = \sqrt{(2A)}\,\sigma \qquad (8)$$

where A is the area of the scanning aperture and σ the square root of the rms density fluctuation.

Analysis of microdensitometer traces of many films has indicated that the density fluctuations of processed emulsions tend to follow a Gaussian distribution[15], although the above definitions hold for any probability distribution assumed.

Granularity, and as a result graininess, is also dependent on the density level of a sample. Experiments have shown granularity to be approximately proportional to the cube root of the density[11].

4 SIMULATION MODEL

In this section, we present our model for the photographic processing of photographic materials. The model is based on emulsion characteristics expressed using the sensitometric measures mentioned above.

Like the process described in Section 2.1, our full model is a two-step process whereby film development is simulated first, followed by a simulation of the printing process. In the summary below, we describe the simulation of the processing of a single photographic material, i.e. a single step of our full model. An image will have to run through the described process twice with the first run resulting in a virtual negative. This simulated negative is then used during the second simulation run which results in a simulated print.

In an attempt to base our model solely on reported photographic data, we assume ideal processing conditions and ignore adjacency effects[11] that may occur during processing. The H & D curves used by the simulation should be carefully chosen to reflect appropriate sets of processing conditions and materials.

The model is an extension of a computation model developed by Kelly[18] and is presented as a pipeline of image processing modules (Figure 5). Each module performs a given image processing operation and passes the result to the next module in the pipeline. The pipeline takes as input a color image where each pixel represents the illuminance values at given sample wavelengths as detected on the film plane. The pipeline can be separated into three stages.

During the first stage, the wavelength based illuminance values are converted to exposure values. This stage consists of three modules. The **expose** module converts the illuminance values to exposure by multiplying each pixel by a time value. This time parameter represents the amount of time the photographic material is exposed. After passing through this module, the image is still a color image with each color channel giving the exposure at a given sample wavelength. These color channels are merged in the **spectral sensitivity** module where the image is filtered by a spectral response curve and exposure integrated over the wavelengths to produce a single channel of exposure data per pixel. Resolution is modeled by the **internal scattering** module which makes use of an emulsion's MTF to spatially filter the image and approximate the effects of scattering due to grains within an emulsion.

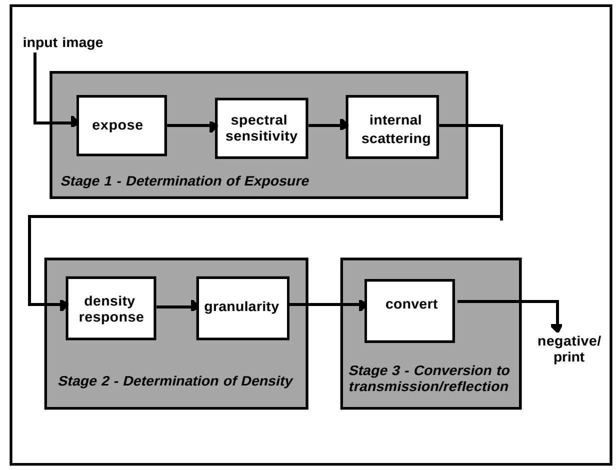


Figure 5 - Simulation pipeline for a single processing step

During the next stage of the pipeline, density values are determined. The **density response** module uses a characteristic curve to determine density from the exposure values calculated in the first stage. To simulate film grain, these density values are stochastically modulated using Gaussian noise in the **granularity** module. The deviation at each pixel is based upon a Selwyn Granularity value, the size and magnification of the image, and the density value at the pixel.

During the third and final stage, density values are converted to transmission values (for film) or reflection values (for papers) by the **convert** module. The conversion is done by directly applying the definitions of density as presented in Section 2.2.

After passing through the pipeline, the resulting image consists of floating point values between 0 and 1 that represent transmission or reflectance values. This is a convenient final format as it provides us with a device independent solution which can then be quantized for a given output device. The only caveat is that the output device will have to be adjusted to display these values on a photometric linear gray scale[8].

A table summarizing the various modules of the pipeline is given in Table 1.

5 IMPLEMENTATION

We have implemented our model into a system called the Virtual Darkroom (VDR). VDR takes a rendered image as input and allows for user specification of the parameters required by the simulation pipeline modules. Sensitometric curves are specified to the system as sampled functions with curve values between sample points determined by linear interpolation. These curves can be intuitively created using graphical input tools provided by VDR.

MODULE	PARAMS	OUTPUT UNITS	OUTPUT RANGE	RGB?
Input Image	–	lux/λ	10^{-3} - 10^{4}	Yes
Expose	time (sec)	lux-sec/λ	10^{-3} - 10^{4}	Yes
Spectral Sensitivity	spectral response curve	lux-sec	10^{-3} - 10^{4}	No
Internal Scattering	MTF	lux-sec	10^{-3} - 10^{4}	No
Density Response	H & D Curve	density	0 - 3	No
Granularity	Selwyn Granularity magn, size	density	0 - 3	No
Convert	–	trans or reflect	0 - 1	No

Table 1- Summary of Simulation Pipeline Modules

Implementing the model itself can be most easily performed using an image processing library that supports a rendering chain paradigm. Our initial implementation was written using the ImageVision library[19] and we are currently in the process of re-implementing the system using Java.

Physically based illuminance values are expected as input to the simulation pipeline. Certain renderers (such as RADIANCE[20]) will output these values. However, for images produced by renderers that do not, a conversion from the pixel values to illuminance values needs to be made. VDR performs a simple linear scaling from 0 to a user supplied maximum to make this conversion. (More sophisticated, non-linear mappings may be required if the image had been optimized for display on a particular output device such as a CRT[8]).

Similarly, the illuminance that falls on the surface of photographic paper during the printing process must also be estimated. Much like a camera, a printer/enlarger is a complex optical system whose properties highly affect the quality of the final print. VDR simplifies this estimation by using a simulated negative as a transparency map ignoring any optical effects that may occur during the printing process. The intensity and spectral distribution of the light source used in printing is supplied by the user.

Most renderers provide only three channels of color data per pixel (usually in RGB color space). VDR performs spectral filtering (as is required by the spectral sensitivity module) in XYZ color space, converting the spectral response curves to XYZ triplets and then using these XYZ components as scale factors for the corresponding spectrally dependent exposure values. Note that pixel values must also be converted to XYZ space. (See [10] for details on these conversion). The integration over the range of wavelengths is approximated by summing the results of the scaling operation.

6. RESULTS

In our examples, we focus on the effects due to the characteristics of the film. Representative data from data sheets of actual films are used. In all the examples, the paper being simulated uses data from a medium grade paper with gamma of 1.67 and speed of 250.

In figure 6, the effects of film speed on the contrast of the final image is illustrated. The original image is processed using data from films with speeds of 100, 200, and 400 with exposure time for each of the images remaining constant.

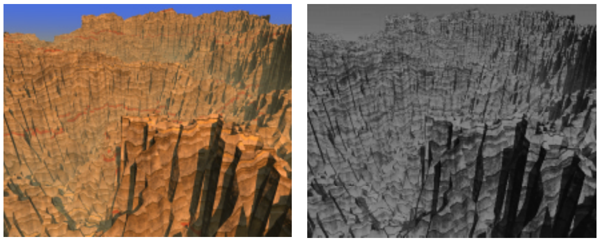
(a) Original image (b) Simulated 100 speed film

(c) Simulated 200 speed film (d) Simulated 400 speed film

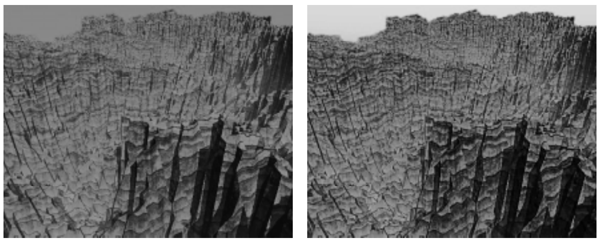
Figure 6 - Effects of film speed

Figure 7 illustrates the effects of a film's spectral sensitivity on the final image. In this example, an artistic challenge is to properly expose the image as to maintain the brightness of the scene yet at the same time, emphasize the detail in the rocks. Attempts using a panchromatic, orthochromatic and untreated film are shown with exposure time chosen so that the mountain is properly exposed. Because of the extended spectral sensitivity in the panchromatic and orthochromatic films, it is difficult to capture the bright blue sky in its full brilliance without running the risk of overexposure of the mountain area. With the untreated, blue-sensitive film, this is not a problem since the majority of the film's sensitivity lies in the blue range of the spectrum. Increasing the exposure as to capture the detail in the rocks, an area to which the film is not very sensitive, will only result in the overexposure of the sky. When processed, the sky appears white in the final print, thus given a feeling of brilliance. This kind of image is indicative of many old time landscape photographs taken before the introduction of sensitizing dyes that extend the spectral sensitivity of an emulsion.

The effects of granularity are illustrated in Figure 8. The figure shows three magnifications of an image, all processed using the same granularity value. As the magnification of the image increases, the graininess in the image becomes more apparent.



(a) original scene (b) Using panchromatic film



(c) Using orthochromatic film (d) Using blue sensitive film

Figure 7 - Effects of spectral sensitivity

Using the MTF to model the resolution can be useful when degradation of an image is required (e.g. when compositing computer generated elements with existing photographic images.) The combination of MTF filtering and the addition of grain produces a more striking degradation which results in a more photographic look to computer generated imagery. Figure 9 shows a magnified portion of the image presented in Figure 8 processed with and without MTF filtering. The MTF used is exaggerated to illustrate the effect. Grain is added in Figure 9c to complete the simulated photographic look.

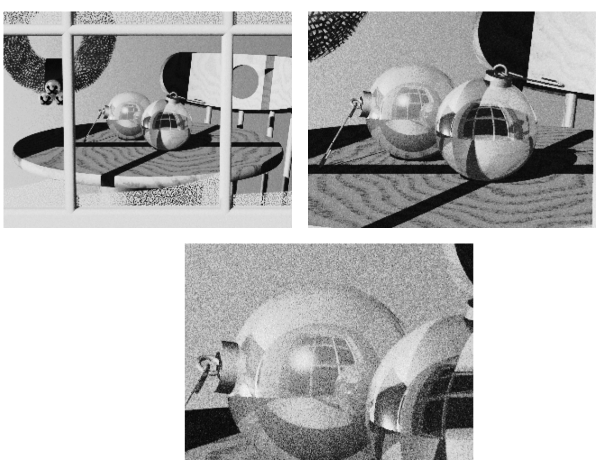


Figure 8 - Simulation of grain

7 CONCLUSION

We have presented a practical model for the simulation of photographic processing for use on digital images. The model makes use of empirical sensitometric data commonly reported in film and paper data sheets, thus making the simulation of the response of actual photographic materials a straightforward exercise.

7.1 Discussion

The simulation model essentially describes a tone reproduction operator for digital images. It is not, however, meant as a replacement for other tone reproduction operators that are based on the response of the human visual system. The eye's response to light generally differs from that of photographic materials thus leading to different goals of the operators that mimic the response of each. In fact, taking Adams' idea of artistic visualization to an extreme, the tone reproduction operators that mimic the response of the eye should be used *in conjunction with* that which models photographic response. In this scenario, tone reproduction operators that mimic the response of the visual system can be used to generate a rendering of what a photographer *sees* when viewing a virtual scene, whereas the photographic model presented can be used to realize the photographer's artistic vision in the final print.

7.2 Future Directions

The natural next direction for this work would be to extend the model to color photography. Color photography, although based on the same fundamental principles, does provide an additional set of challenges. Photographic materials for color photography consists of three emulsion layers, each layer sensitive to different portions of the visible spectrum. During development, the silver is converted to dyes that acts as color filters that absorb red, blue, and green light.[21] As a result, the number of parameters needed to simulate the color development process will triple as each emulsion layer of the material will have its own unique set of sensitometric data associated with it. (Note that this is true not only for the spectral response and characteristic curves, as would be expected, but also for the resolution and granularity parameters)[9]. The simulation for producing color prints also provides an additional challenge as the inter-reflections of light between emulsion layers of color paper should be considered [21].

Although our model produces predictable results, we have no quantitative measure of its effectiveness in reproducing the photographic qualities of an image. The next step in our investigation will involve the validation of our model by both visually and computationally comparing a simulated print of a virtual scene with carefully created photographs of an equivalent real-world scene.

Our model and system assumes a priori knowledge of the photographic materials to be simulated. In practical situations where computer generated elements are composed with existing photographic images, the details of the film stock used is very often unknown . An interesting extension to this work would be a reversal of the model as to obtain the model parameter values from scanned negatives and prints. This is especially true with grain modeling as the accuracy of grain matching during compositing is critical in the creation of computer generated special effects for motion pictures. Our model considers each emulsion characteristic independently. However, when analyzing and modeling emulsions at the grain level, the interdependencies between the characteristics should be considered (see [14] for a complete treatment). Additional research in this area would prove to be a valuable addition to the model.

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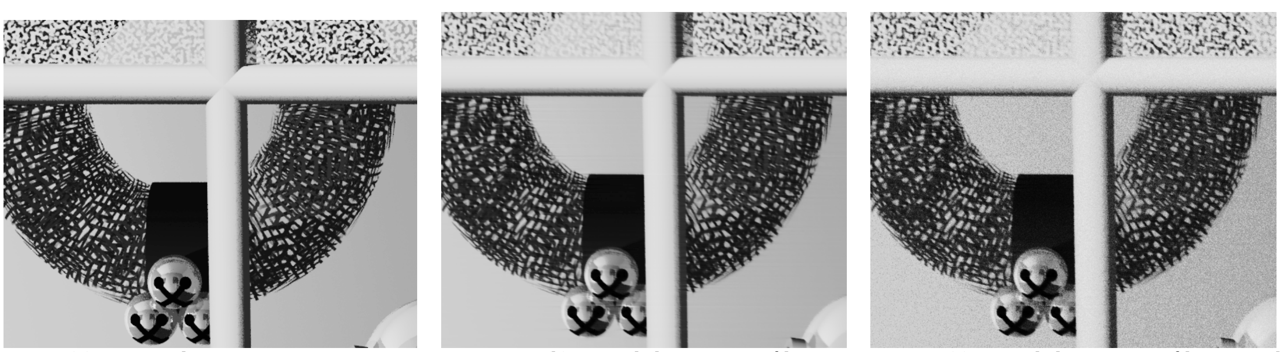

(a) Original image (b) Degraded using MTF filtering (c) Degraded using MTF filtering with grain

Figure 9 - Using the simulation model to degrade an image