

Recovering High Dynamic Range Radiance Maps from Photographs

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ABSTRACT

We present a method of recovering high dynamic range radiance maps from photographs taken with conventional imaging equipment. In our method, multiple photographs of the scene are taken with different amounts of exposure. Our algorithm uses these differently exposed photographs to recover the response function of the imaging process, up to factor of scale, using the assumption of reciprocity. With the known response function, the algorithm can fuse the multiple photographs into a single, high dynamic range radiance map whose pixel values are proportional to the true radiance values in the scene. We demonstrate our method on images acquired with both photochemical and digital imaging processes. We discuss how this work is applicable in many areas of computer graphics involving digitized photographs, including image-based modeling, image compositing, and image processing. Lastly, we demonstrate a few applications of having high dynamic range radiance maps, such as synthesizing realistic motion blur and simulating the response of the human visual system.

CR Descriptors: I.2.10 [Artificial Intelligence]: Vision and Scene Understanding - *Intensity, color, photometry and thresholding*; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism - *Color, shading, shadowing, and texture*; I.4.1 [Image Processing]: Digitization - *Scanning*; I.4.8 [Image Processing]: Scene Analysis - *Photometry, Sensor Fusion*.

1 Introduction

Digitized photographs are becoming increasingly important in computer graphics. More than ever, scanned images are used as texture maps for geometric models, and recent work in image-based modeling and rendering uses images as the fundamental modeling primitive. Furthermore, many of today's graphics applications require computer-generated images to mesh seamlessly with real photographic imagery. Properly using photographically acquired imagery in these applications can greatly benefit from an accurate model of the photographic process.

When we photograph a scene, either with film or an electronic imaging array, and digitize the photograph to obtain a two-dimensional array of "brightness" values, these values are rarely

true measurements of relative radiance in the scene. For example, if one pixel has twice the value of another, it is unlikely that it observed twice the radiance. Instead, there is usually an unknown, nonlinear mapping that determines how radiance in the scene becomes pixel values in the image.

This nonlinear mapping is hard to know beforehand because it is actually the composition of several nonlinear mappings that occur in the photographic process. In a conventional camera (see Fig. 1), the film is first exposed to light to form a latent image. The film is then developed to change this latent image into variations in transparency, or *density*, on the film. The film can then be digitized using a film scanner, which projects light through the film onto an electronic light-sensitive array, converting the image to electrical voltages. These voltages are digitized, and then manipulated before finally being written to the storage medium. If prints of the film are scanned rather than the film itself, then the printing process can also introduce nonlinear mappings.

In the first stage of the process, the film response to variations in exposure X (which is $E\Delta t$, the product of the irradiance E the film receives and the exposure time Δt) is a non-linear function, called the "characteristic curve" of the film. Noteworthy in the typical characteristic curve is the presence of a small response with no exposure and saturation at high exposures. The development, scanning and digitization processes usually introduce their own nonlinearities which compose to give the aggregate nonlinear relationship between the image pixel exposures X and their values Z .

Digital cameras, which use charge coupled device (CCD) arrays to image the scene, are prone to the same difficulties. Although the charge collected by a CCD element is proportional to its irradiance, most digital cameras apply a nonlinear mapping to the CCD outputs before they are written to the storage medium. This nonlinear mapping is used in various ways to mimic the response characteristics of film, anticipate nonlinear responses in the display device, and often to convert 12-bit output from the CCD's analog-to-digital converters to 8-bit values commonly used to store images. As with film, the most significant nonlinearity in the response curve is at its saturation point, where any pixel with a radiance above a certain level is mapped to the same maximum image value.

Why is this any problem at all? The most obvious difficulty, as any amateur or professional photographer knows, is that of limited dynamic range—one has to choose the range of radiance values that are of interest and determine the exposure time suitably. Sunlit scenes, and scenes with shiny materials and artificial light sources, often have extreme differences in radiance values that are impossible to capture without either under-exposing or saturating the film. To cover the full dynamic range in such a scene, one can take a series of photographs with different exposures. This then poses a problem: how can we combine these separate images into a composite radiance map? Here the fact that the mapping from scene radiance to pixel values is unknown and nonlinear begins to haunt us. The purpose of this paper is to present a simple technique for recovering this response function, up to a scale factor, using nothing more than a set of photographs taken with varying, known exposure durations. With this mapping, we then use the pixel values from all available photographs to construct an accurate map of the radiance in the scene, up to a factor of scale. This radiance map will cover

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