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Evidence theory for high dynamic range reconstruction with linear digital cameras ☆

Benjamin Bringier *, Alexandre Bony, Majdi Khoudeir

XLIM-SIC Laboratory, UMR CNRS 7252, University of Poitiers, France

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With the advent of the digital camera, a common popular imaging processing is high dynamic range (HDR) that aims to overcome the technological limitations of the irradiance sensor dynamic range. In this paper, we will present a new method to combine low dynamic range images (LDR) for HDR processing. This method is based on the theory of evidence. Without a prior knowledge of the sensor intrinsic parameters and no extra data, it allows to locally maximizing the signal to noise ratio over the entire acquisition dynamic. In addition, our method is less sensitive to object or people in motion into the scene that are causing ghost-like artifacts with the conventional methods. This technique require that the camera be absolutely still between exposures or need a translational alignment. Simulation and experimental results are presented to demonstrate both the accuracy and efficiency of our algorithm.

1. Introduction

Most camera systems, if not all, present technical limitations which affect the image acquisition quality. On a conventional photography (LDR), the most visible one is the lack of the irradiance dynamic range between natural scenes which produces over or under-exposure depending on the choice of the exposure time. In order to overcome this limitation, the solution commonly used was a combination of photographs acquired at different exposure times to achieve a high dynamic range image (HDR) [1]. But it is really democratized with the arrival of the digital camera [2]. A increase of the irradiance dynamic range is also possible through a variation of the ISO value [3], or for indoor photographs, the power of the light source [4]. In the field of digital photography, the second technological limitation for the irradiance is the data quantization. However, the HDR imaging methods may be used to decrease the quantization step [4,5].

To combine a series of image acquisitions to accurately match an HDR image corresponding to the irradiance variations, it is absolutely necessary to estimate the irradiance value for each pixel in every image. Several methods have been published to determine the irradiance response curve of the acquisition system [6,7], the ratios between the exposure times [8] and more complex transformation from cameras [9]. Then, the HDR algorithms would use a weighted average for each pixel to estimate irradiance value. The weighting function enables to limit the noise acquisition and remove over and under-exposed values resulting from long and short exposure times. The first weighting functions suggested in the literature does not have recourse to additional information in relation to the sensor. Only the response curve is necessary to determine the most appropriate weighting function [2,8,7,10] or more simply a hat function to limit the extreme values [6]. To improve the results, weighting functions which use a noise and acquisition model are proposed [11–13,3]. These provide significant improvements in the visual quality of HDR images and the opportunity to use ISO variations [3]. However, these are much more complex to implement as a noise model and the sensor intrinsic parameters are needed (number of electrons per photosite, shot noise, quantization noise, read noise, etc.). Furthermore, the use of all the estimated irradiance values may be problematic in the instance of very high dynamic range. Indeed, it is essential to use a large number of different acquisitions or significant ratio between various exposure times to acquire a very high irradiance dynamic range. An error of a single quantization step for the lowest exposure time is bound to be very prejudicial for the estimation of low irradiance value. Fig. 1 shows the evolution of the irradiance estimation error or the size of the quantization step depending on the exposure time. This error is far more important than the image dynamic range in case of the longest exposure time. In addition, viewing HDR images typically use a tone mapping algorithm which compresses the dynamic, on the one hand and increases the visual errors for low irradiance value on the other [14–18].

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* Corresponding author.
E-mail address: benjamin.bringier@univ-poitiers.fr (B. Bringier).

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Last, but not least, if an object or person moves during the various acquisitions, *ghosts* appear in the HDR image. These artefacts are more or less visible subject to the object's irradiance, the exposure times and the weighting function. Many algorithms are proposed to remove the *ghost* artefacts in the final result [19–21].

In this paper, we propose a new approach to combine the estimated irradiances for each image based on the theory of evidence [22,23]. Our method consists in estimating the most probable irradiance value for each pixel, according to the predictions of each acquisition time. Furthermore, our method is more robust to noise acquisition or *ghosts* following the rejection of the least plausible estimates. It is thus possible to obtain a signal to noise ratio (SNR) which is almost identical across the entire irradiance dynamic range from a large image number. Unlike the last weighting methods, it is not necessary to use a noise model and the intrinsic sensor parameters to obtain an HDR image without noise. Our method is very simple to implement and requires no intervention on the part of the user.

This article is broken down into four distinct parts. After a brief presentation of the image formation model, the first one introduces the weighted average method of creating HDR images. In a given case of noise free, we indicate the best irradiance estimate with the theory of quantization. Then, we introduce our new method for creating HDR images and demonstrate, in this section, that our approach by the theory of evidence can easily use the weighting functions of the weighted average methods. Finally, we evaluate the performance of our method using simulations and real acquisition examples. In the case of linear digital camera, we demonstrate the performance of our method even though no information relating to the sensor is available. Finally, we demonstrate that our method directly remove the *ghosts* on a real acquisition.

2. Image formation model and irradiance estimation

A digital camera is used to convert the light flow into digital values usable by a computer [24]. In a typical image formation model, image irradiance E received by the sensor is related to scene radiance L:

$$E = L\frac{\pi}{4}\left(\frac{d}{h}\right)^2 \cos^4\phi = Lk \tag{1}$$

where h is the focal length of the imaging lens, d is the diameter of its aperture and ϕ is the angle subtended by the principal ray from the optical axis. Additional optical effects may alter this relationship but these, are calibrated separately. If the imaging system is ideal,

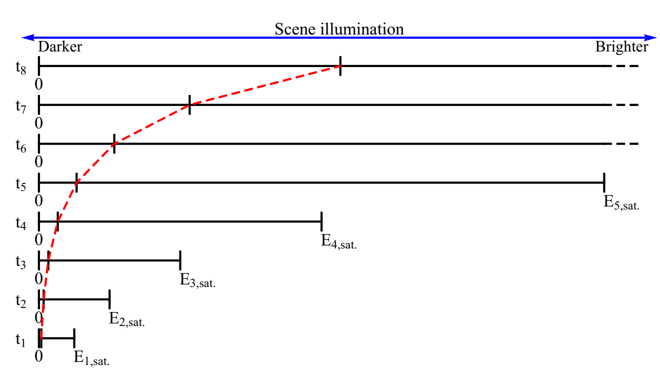

Fig. 1. Schematic representation of irradiance captured dynamic range for different values of exposure time t_u when the ratio is $\chi = 0.5$ and $E_{u,sat.}$ represent the acquisition saturation. The dotted red curve represents the irradiance estimation error if an error of one quantization step occurs with $Q = 4$ bits, as a function of exposure time t_u.

the irradiance E expressed in units of electrons per second is converted into photoelectrons by the image sensor in proportion to the exposure time t:

$$I = min\left\{\frac{Et}{g} + I_0 + n, I_{max}\right\} \tag{2}$$

where g is the sensor gain which is based on ISO value, I_0 is a constant offset representing the black point, I_{max} is the maximum number of electrons that can be captured and n is the signal and gain-dependent sensor noise. Numerous analog and digital processing are applied to the number of electrons I to obtain a numerical value M:

$$M = f(I) \text{ with } 0 < M < 2^Q - 1 \tag{3}$$

where $f()$ is a response function of the acquisition system and Q is the number of bits for quantizing information. For mono-CCDs [25], this function is linear. However, additional processing need to be added in order to obtain a color image such as demosaicing, white balance and data compression. Within the framework of our study, we consider that each image pixel has three linear and independent sensors where only the noise n can alter the measurement. To model the essential properties of noise, we treat the noise as a zero-mean random variable, the variance of which comes from three independent sources [3]:

$$Var(n) = \frac{Et}{g^2} + \frac{\sigma^2_{read}}{g^2} + \sigma^2_{ADC} \tag{4}$$

where the first term represents the Poisson distribution of photon arrivals. The other terms represent the readout noise and the analog to digital conversion noise (ADC) which are independent of the scene. Image-dependent noise can be estimated from multiple or a single images [26,27]

When the function $f()$ is known, it is possible to overcome the irradiance range limitations of photographic sensors in terms of dynamic range [2,6,8] or quantization step [5,4]. The idea is to combine a series of U images where exposure time t_u or gain g_u is changed at a fixed or variable ratio $\chi = \frac{t_u}{t_{u+1}}\ \forall u$. For each given image u and each pixel, the aim is to estimate an irradiance value $\widehat{E}_u$ that would produce a frame of discernment $\theta^- = \left\{\widehat{E}_1, \widehat{E}_2, \ldots, \widehat{E}_U\right\}$ where $\widehat{E}_u = \frac{g}{t_u} f^{-1}(M_u)$ and $M_u\ \forall u, (M_u \geqslant 0\ \wedge\ M_u < 2^{Q-1})$ are not a over or under-exposed value. The combination of these values should limit the impact of noise n on the estimated irradiance $\widehat{E}$.

3. Weighted average method and irrradiance quantization

The traditional method (*WA*) combines the LDR estimated irradiance values $\widehat{E}_u$ of the frame of discernment θ^- with a weighted average:

$$\widehat{E}_{WA} = \frac{\sum_u \omega(M_u) \times \widehat{E}_u}{\sum_u \omega(M_u)} \tag{5}$$

where $\omega(M_u)$ is a weighting function intended to reduce the noise and to exclude the limit values. There are several functions available in the literature and a review of weighting schemes is proposed in [13,12] for linear and logarithmic domains. In the case of noise free acquisition, the estimated irradiance is a function of the weighting function and ratio χ between exposure times (Fig. 2). When $\chi = 0.5$ and $U = 2$, half estimated irradiance values are dependent on the weighting function ω. When $\chi > 0.5$ and for a same U, the number of possible solution for the final estimated irradiance values is far more important. However, these values are highly dependent on the weighting function ω. For a noise free case, the problem of the weighted average method arises from combining