Variable Exposure Time Imaging for Obtaining HDR Images

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Keywords: Computational Photography, HDR Image, Exposure Time.

Abstract: In this paper, we propose a novel imaging method called variable exposure time imaging for obtaining HDR images from single image capture. In this method, we control exposure time pixel by pixel. Thus, each pixel in an image taken by this imaging method is obtained under different exposure time. We call this image variable exposure image. By using the variable exposure image, we can synthesize a high dynamic range image efficiently, since we can optimize the exposure time pixel by pixel according to the input intensity at each pixel. Experimental results from the proposed method show the efficiency of the proposed imaging method.

1 INTRODUCTION

Obtaining high dynamic range images is very important in many computer vision applications. However, the dynamic range in natural scenes is much wider than the dynamic range of ordinary cameras. If the maximum intensity of the input scene is over or under the dynamic range of the camera, over exposure or under exposure occurs as shown in Fig.1.

In order to avoid the over exposure and under exposure problems, several methods have been proposed for obtaining high dynamic range (HDR) images from ordinary cameras (Burt and Kolczynski, 1993; Debevec and Malik, 1997; Mann and Picard, 1995; Aggarwal and Ahuja, 2001; Schechner and Nayar, 2001). In these methods, multiple images are taken by an ordinary cameras under different exposure parameters, and these images are combined so that a single HDR image is obtained. Although these methods are useful, several image captures are required for obtaining a single HDR image. Thus, they are not appropriate for obtaining HDR images in dynamic scenes, where objects move during multiple image captures.

Another way to obtain HDR images is to modify the imaging system of cameras, so that we can obtain HDR images from a single image capture. For this objective, some new imaging methods were proposed recently. In these methods, the exposure of imaging systems is controlled pixel by pixel by using special devices, such as LCD and LCoS (Nayar and Mitsunaga, 2000; Nayar et al., 2003; Mannnami et al., 2007). By using these methods, over exposure and under exposure can be avoided, even if the dynamic range of input scene is very wide. Although these methods can obtain HDR images from a single shot, the systematic delay of exposure control exists in these methods, since they compute the exposure pattern of the current image frame by using the image obtained in the previous image frame. As a result, rapid changes of dynamic range in the scene cannot by suppressed in these methods.

(a) Over exposed image (b) Under exposed image

Figure 1: The over exposure and under exposure.

In this paper, we propose a new imaging method which we call *variable exposure time imaging*. In this imaging method, each pixel in an image sensor stops its exposure when the integrated intensity in the pixel becomes higher than a threshold value. Thus, the exposure time of each pixel varies according to the input intensity. In this method, not only an observed intensity, but also an exposure time are recorded pixel by pixel. Therefore, we can obtain information of input light not only from observed intensity, but also from exposure time in each pixel. From the obtained exposure time and intensity in each pixel, an HDR image

Uda, S., Sakaue, F. and Sato, J.
Variable Exposure Time Imaging for Obtaining HDR Images.
DOI: 10.5220/0005719101180124
In *Proceedings of the 11th Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP 2016) - Volume 3: VISAPP*, pages 120-126
ISBN: 978-989-758-175-5

can be obtained efficiently from a single image capture.

2 EXPOSURE MODEL

We first consider the exposure model of digital cameras. Considering the light field in the scene, cameras can be regarded as recorders of light rays. Let $L(u,v,t)$ be a 3-dimensional continuous light field, where (u,v) denotes 2D position on the image plane and t denotes time. Note that, the light field in general consists of the position, orientation and time of light rays, and thus it is 5D. However, we in this paper consider ordinary 2D cameras, and thus we do not consider orientation of light rays. Hence, $L(u,v,t)$ indicates integrated intensity of a set of light rays which go through a point (u,v) on the image plane at time t.

By using the light field $L(u,v,t)$, an intensity $I(x,y)$ obtained by the camera at pixel (x,y) in a single frame time can be described as follows:

$$I(x,y) = \int_0^T \int_{y-\frac{1}{2}}^{y+\frac{1}{2}} \int_{x-\frac{1}{2}}^{x+\frac{1}{2}} L(u,v,t)dudvdt \quad (1)$$

where T is an exposure time in a single frame. If $L(u,v,t)$ is constant during the exposure time, e.g. observed scene is static, Eq.(1) can be rewritten as follows:

$$I(x,y) = T\int_{y-\frac{1}{2}}^{y+\frac{1}{2}} \int_{x-\frac{1}{2}}^{x+\frac{1}{2}} L(u,v,0)dudv \quad (2)$$

Then, Eq.(2) can be described as follows:

$$I(x,y) = TE(x,y) \quad (3)$$

where, $E(x,y)$ is an intensity obtained in a unit time as follows:

$$E(x,y) = \int_{y-\frac{1}{2}}^{y+\frac{1}{2}} \int_{x-\frac{1}{2}}^{x+\frac{1}{2}} L(u,v,0)dudv. \quad (4)$$

Hence, $E(x,y)$ is considered as the intensity of input light. In an ordinary camera, the exposure time T is constant for all the pixels, and thus observed image intensity $I(x,y)$ is proportional to the input light intensity $E(x,y)$ as follows:

$$I(x,y) \quad \propto \quad E(x,y) \quad (5)$$

By changing the exposure time T, the range of intensity in obtained image changes. For example, if T is small, a dark image is obtained as shown in Fig.2 (a), and a bright image is obtained if T is large as shown in Fig.2 (b). In Fig.2 (a), the intensities of indoor part are very dark, and they do not include enough information. In Fig.2 (b), the intensities of outdoor part are saturated, and they also do not have enough information. This is because the brightness of outdoor scene in fine day is more than 100,000 lx, while the brightness of indoor scene is just about 500 lx. As shown in these images, it is difficult to obtain sufficient information from an image taken by a constant exposure time. Thus, we next propose a new imaging method, which controls the exposure time pixel by pixel.

(a) Image taken under short exposure time (b) Image taken under long exposure time

Figure 2: Difference of obtained image under different exposure time.

3 VARIABLE EXPOSURE IMAGING

As described in the previous section, the observed image intensity is proportional to the input light intensity in the ordinary cameras. In this section, we propose a new imaging model, in which the observed image intensity is not proportional to the input light intensity. In this imaging method, the exposure time for each pixel changes adaptively in order to obtain the magnitude of input light intensity accurately without suffering from over exposure and under exposure.

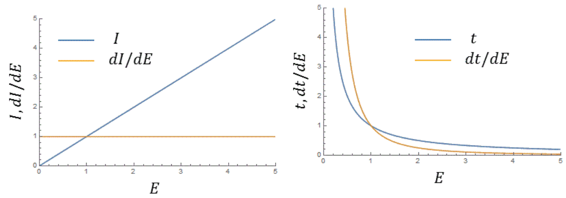
In this imaging model, observed intensity can be described as follows:

$$I(x,y) = \int_0^T \int_{y-\frac{1}{2}}^{y+\frac{1}{2}} \int_{x-\frac{1}{2}}^{x+\frac{1}{2}} R(x,y,t)L(u,v,t)dudvdt \quad (6)$$

where $R(x,y,t)$ indicates a transmittance of each pixel. If $R(x,y,t) = 1$, the input light is accumulated to the image pixel, and if $R(x,y,t) = 0$, the input light is not accumulated to the image pixel. We control $R(x,y,t)$ pixel by pixel according to the input light $L(u,v,t)$ of each pixel in a single exposure time T, i.e. in a single frame. By using the variable exposure imaging, we can control temporal exposure pattern at each pixel in each frame.

3.1 Variable Exposure Time Imaging

We next consider variable exposure imaging for obtaining HDR images from single shot images. In



(a) Ordinary camera (b) Variable exposure time camera

Figure 3: The relationship between the input intensity E and the measurements in the ordinary camera and the proposed variable exposure time camera. The blue lines show image intensity I in (a) and exposure time T in (b). The red line in (a) shows the resolution $\frac{dI}{dE}$ of image intensity I in the ordinary camera, and the red line in (b) shows the resolution $\frac{dT}{dE}$ of exposure time T in the proposed camera.

this imaging method, we accumulate input light at each pixel, so that the accumulated image intensity at the pixel becomes a certain constant value. This is achieved by controlling the transmittance $R(x,y,t)$ at pixel (x,y) as follows:

$$R(x,y,t) = \begin{cases} 1 & I(x,y,t) < I^{\theta} \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where I^{θ} is a threshold, and $I(x,y,t)$ is the accumulated image intensity at pixel (x,y) up to time t as follows:

$$I(x,y,t) = \int_0^t \int_{y-\frac{1}{2}}^{y+\frac{1}{2}} \int_{x-\frac{1}{2}}^{x+\frac{1}{2}} R(x,y,t)L(u,v,t)dudvdt. \tag{8}$$

Then, we record the time t as the exposure time $T(x,y)$ of pixel (x,y), when $R(x,y,t)$ changes from 1 to 0. In this imaging method, we control the exposure time $T(x,y)$ of each pixel, so that the accumulated image intensity $I(x,y)$ is under the threshold value I^{θ}. Thus, the over exposure does not occur in this method. The intensity of input light is measured as the exposure time unlike the standard camera. That is the exposure time $T(x,y)$ is inversely proportional to the intensity of input light $E(x,y)$ as follows:

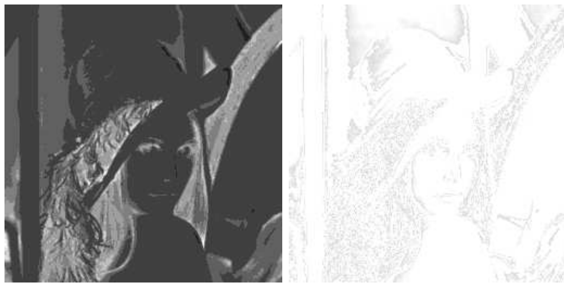
$$T(x,y) = \frac{I^{\theta}}{E(x,y)} \tag{9}$$

Thus, unlike the ordinary cameras shown in Eq.(5), the proposed imaging model measures the input light intensity $E(x,y)$ according to the following relationship:

$$T(x,y) \propto \frac{1}{E(x,y)} \tag{10}$$

The blue lines in Fig. 3 (a) and (b) show the relationship between the input light intensity E and the measurement I in the ordinary camera and the measurement T in the proposed camera. While the measurement I is proportional to the input E in the ordinary camera, the measurement T is nonlinear to the input E in the proposed camera. The red lines in Fig. 3 (a) and (b) show the resolution of measurements in both cameras, that is $\frac{dI}{dE}$ in the ordinary camera and $\frac{dT}{dE}$ in the proposed camera. As shown in these images, the resolution of the proposed camera is large for small input intensity, and is small for large input intensity, while the resolution of the ordinary camera is constant regardless of input intensity. This property of the proposed camera enables us to capture small difference in low input intensity avoiding the saturation of high input intensity.

In the proposed method, the observed image intensity $I(x,y)$ becomes constant I^{θ} in an ideal case. However, it is actually not, since the exposure time is finite and both the exposure time and the image intensity have quantization errors. Therefore, we record both the observed image intensity $I(x,y)$ and the exposure time $T(x,y)$ simultaneously. From these recorded informations, we can reconstruct HDR images efficiently as we describe in the next section.



(a) Exposure time image (b)Variable exposure image

Figure 4: Output of variable exposure camera: (a)Exposure time image and (b)variable exposure image.

Fig. 4 shows an example output from the variable exposure imaging. The left image shows exposure time and the right image shows observed image intensity which we call a variable exposure image. In the exposure time image, the brightness of each pixel shows the exposure time of the pixel. In the variable exposure image, almost all pixels have similar intensity to I^{θ}, which indicates the exposure time for each pixel is controlled appropriately. In addition, bright area in exposure time image corresponds to dark area in variable exposure image. It indicates that exposure time becomes large, when the power of input light ray is small.

3.2 HDR Image Reconstruction

We next consider the recovery of HDR images from the exposure time image $T(x,y)$ and the variable exposure image $I(x,y)$.

The HDR image reconstruction is equivalent to the estimation of image $E(x,y)$ obtained in a unit time. In a static scene, the relationship among the HDR image $E(x,y)$, the exposure time image $T(x,y)$ and the variable exposure image $I(x,y)$ can be described as follows:

$$I(x,y) = T(x,y)E(x,y). \tag{11}$$

Therefore, the HDR image $E(x,y)$ can be estimated as follows:

$$E(x,y) = \frac{I(x,y)}{T(x,y)} \tag{12}$$

Although the proposed method is similar to the existing pixelwise exposure control methods (Nayar et al., 2003; Mannnami et al., 2007), the actual behavior of the proposed method is very different from that in the existing methods especially in dynamic scenes. In the existing pixelwise exposure control methods (Nayar et al., 2003; Mannnami et al., 2007), the exposure time of each pixel is constant, and the reflectance of LCoS or transparency of LCD is controlled in each pixel. On the contrary, the proposed method controls the exposure time of each pixel. As a result, the exposure time of the proposed method is smaller than that of the existing methods. Thus, the motion blur of the proposed method is much smaller than that of the existing method in dynamic scenes. Also, the existing methods have systematic delay of controlling LCoS or LCD. That is, the exposure of each image pixel is controlled one frame after the image capture. This systematic delay problem is especially serious when the observed image is saturated. If the observed intensity is saturated, we need several frames to control LCoS or LCD for obtaining unsaturated image, since we do not know how large is the input intensity if the observed image is saturated. On the contrary, the proposed imaging method requires just a single capture for obtaining HDR images, since the exposure time of each image pixel is controlled, so that the accumulated image intensity of each pixel becomes I^{θ}. These properties of the proposed method enable us to decrease the motion blur and the delay of intensity control in observed images, when we observe moving objects. Thus, the proposed method provides us better results in dynamic scenes.

3.3 Structure of Variable Exposure Camera

In order to realize our new imaging model, we combine an LCoS (Liquid Crystal on Silicon) device with two image sensors, i.e. main image sensor and measuring image sensor, as shown in Fig.5. The LCoS device can control the input light of the main image sensor, and thus by controlling the LCoS device we can control the exposure time of each image pixel. The

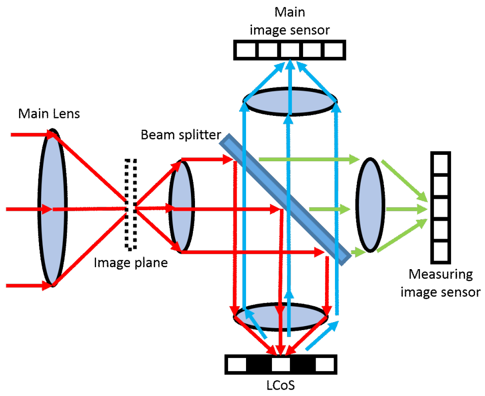


Figure 5: Variable exposure camera by combining digital micro-mirror device and image sensor. The DMD control exposure time of the image sensor pixel by pixel.

Figure 6: Variable exposure camera. It consists of an LCoS device and two image sensors.

exposure time is controlled according to the measurement results of the measuring image sensor. The observation result of the main image sensor is the variable exposure image.

We next explain the detail of our variable exposure camera. At first, input light rays pass through an image plane and a relay lens. After that, the rays are split into two ways as shown in Fig. 5. One is the direction to the measuring image sensor and the other is the direction to the LCoS device. The light rays directed to the image sensor are received by the measuring image sensor. Observation results of this sensor are reflected to the displaying patterns of the LCoS device. Each pixel on the LCoS device, main image sensor, and measuring image sensor corresponds to each other. Therefore, the exposure time of a pixel on the main image sensor can be controlled by changing the reflectance of a corresponding pixel on the LCoS device. Then, the observed result of the measuring image sensor is used for controlling the LCoS device.

Note that the sampling frequency of the measuring image sensor and the LCoS device is much higher than the main image sensor. Therefore, we can con-

(a) (b)

Figure 7: Observed images taken by an ordinary camera with long exposure time (a) and short exposure time (b).

(a) (b)

Figure 8: Variable exposure image (a) and exposure time image (b) taken by the variable exposure camera.

trol the exposure time of the main image sensor with a sub-frame speed.

Fig. 6 shows a prototype of the variable exposure camera. In this camera, the frame rate of the measuring image sensor is 10 fps, and it is much higher than the frame rate of the main image sensor which is 1 fps. The two sensors are synchronized to each other, and the image acquisitions of these two sensors start at the same time.

4 EXPERIMENTAL RESULTS

In this section, we show experimental results from the proposed HDR imaging method.

We first show results from a static scene. Fig. 7 (a) and (b) show images taken by an ordinary camera. As shown in this figure, the long exposure time is good for indoor scenes, but it is over exposure for outdoor scenes. On the contrary, the short exposure time is good for outdoor scenes, but it is under exposure for indoor scenes. Thus, we cannot observe both indoor scenes and outdoor scenes simultaneously in ordinary cameras.

Fig. 8 (a) and (b) show the variable exposure image and the exposure time image obtained from our variable exposure camera. As shown in the exposure time image, the exposure time of each pixel is controlled according to the input light intensity at each pixel. The HDR image obtained from these observations of the variable exposure camera is shown in Fig. 9. As shown in this figure, we can observe both

Figure 9: HDR image obtained from the variable exposure camera.

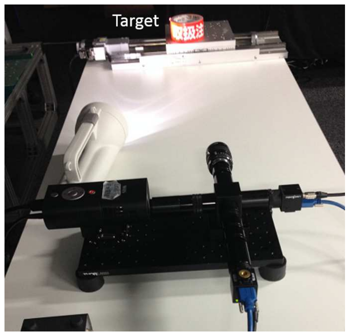


Figure 10: Experimental environment.

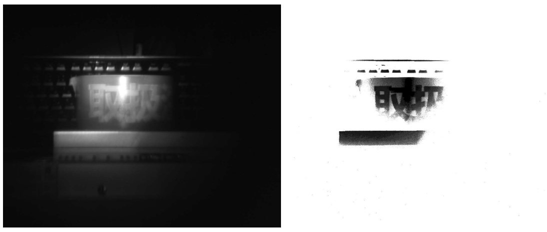
indoor and out door scenes in the image obtained from the variable exposure camera.

We next show results from a dynamic scene, where we have moving objects in the scene. Fig. 10 shows experimental settings. The target object is set on a moving stage and it was moved horizontally by the moving stage. In order to widen the dynamic range of input scene, a strong light source illuminated the scene partially. As a result, the observed intensity changed drastically depending on the position of the moving object. Fig.11 (a) and (b) show images taken by an ordinary camera. The left image was taken with long exposure time and the right image was taken with short exposure time. In these images, dynamic range of the camera is not sufficient, and thus, over exposure and under exposure occurred. In addition, motion blur exists in the case of long exposure time as shown in Fig. 11 (a).

In order to obtain HDR image of the scene, we took images by using the proposed variable expo-

(a) (b)

Figure 11: Observed images taken by an ordinary camera with long exposure time (a) and short exposure time (b).



(a) (b)

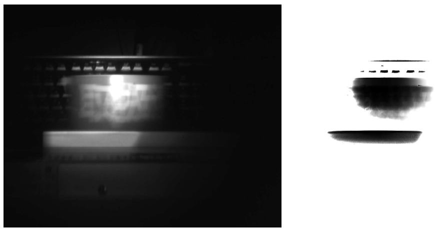
Figure 12: Variable exposure image (a) and exposure time image (b) taken by the variable exposure camera

Figure 13: The HDR image obtained from the variable exposure camera.

sure time camera. For comparison, the reflectance of LCoS was controlled as proposed in (Mannnami et al., 2007) to obtain HDR image with constant exposure time.

Fig. 12 shows observed images taken by the variable exposure time camera. The left image is a variable exposure image and the right image is an exposure time image. As shown in Fig. 12 (b), the exposure time is short at large input intensity pixels, and the exposure time is long at small input intensity pixels. As a result, the over exposure is suppressed in the captured image as shown in Fig. 12 (a). From these two images, an HDR image was computed by the proposed method. The obtained HDR image is shown in Fig.13. For representing HDR images, we used tone mapping with logarithm operation in this paper.

For comparison, the HDR image was obtained by using the existing method (Mannnami et al., 2007), in which the reflectance of LCoS is controlled pixel by pixel in a constant exposure time. The exposure time is same as that of the main camera of the proposed method, i.e. 1fps. Fig. 14 (a) shows an observed image and (b) shows an LCoS reflectance image obtained from the previous image frame. From these images, an HDR image was computed as shown in Fig.15. As shown in Fig.15, although over exposure and under exposure are suppressed, the motion blur occurs at a target object, since the exposure time is constant and long. On the contrary, the motion blur is suppressed in our proposed method as shown in Fig.13, since the exposure time is controlled in our method and thus it becomes shorter than that of the existing method. These results show that the proposed



(a) (b)

Figure 14: Observations in the existing method (Mannnami et al., 2007). (a) shows observed image, and (b) shows reflectance of LCoS at each pixel, which is obtained from the previous image frame in sequential images.

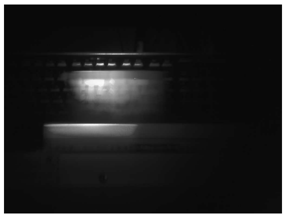


Figure 15: The HDR image obtained from the existing method (Mannnami et al., 2007).

method can suppress not only over/under exposure, but also motion blur in dynamic scenes.

5 CONCLUSION

In this paper, we proposed a novel imaging method for obtaining HDR images from single shot image capturing, which we call variable exposure time imaging. In this image method, we control exposure time of each image pixel according to the accumulated input light intensity at each pixel in a single frame. While the ordinary camera captures input scene intensity as the intensity of observed image, the proposed imaging method captures input scene intensity as the exposure time of each image pixel. We built the variable exposure time camera by using an LCoS and two cameras. The experimental results show that the proposed variable exposure time imaging can suppress not only over exposure and under exposure, but also motion blur in dynamic scenes.

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