Image-Based Relighting with 5-D Incident Light Fields

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Abstract

In this paper, we propose a method for image-based relighting with 5-D incident light fields: 4 DoF of the position and direction and 1 DoF of the color of an incident ray. Specifically, we illuminate a scene with various rays by using a two-layer 5 DoF lighting system consisting of a rear-projection display and a transmissive LC panel, and synthesize images under desired 5-D incident light fields by combining the images captured under those rays. Our proposed method efficiently acquires the required images by using coded illumination; it reduces the number of captured images and the measurement time, and enhances their SNRs. In addition, we propose a method for removing the effects of the black offsets due to the projector and the LC panel in the two-layer setup. The experimental results using the prototype system show that our method enables us to synthesize photo-realistic images of scenes where wavelength-dependent phenomena such as fluorescence are observed.

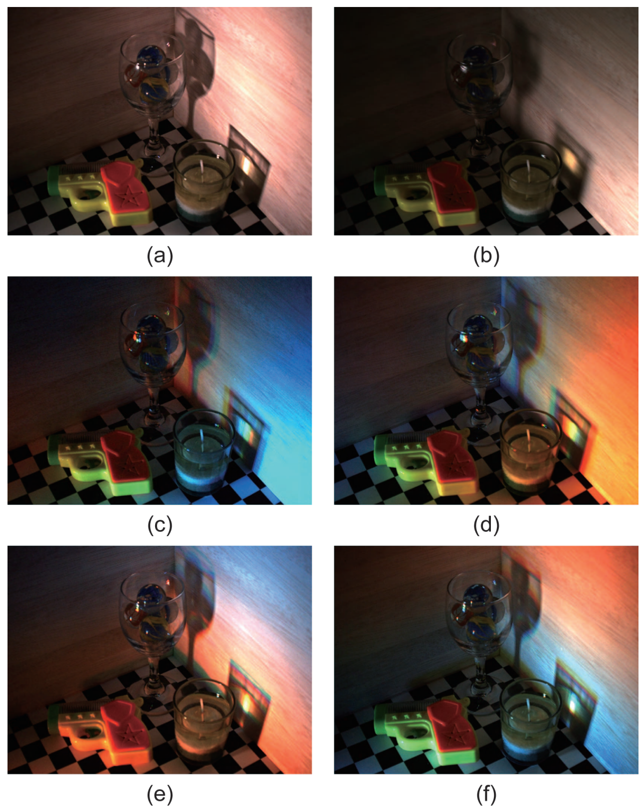

Figure 1. The synthesized images of the first scene by using our proposed method with various 5-D incident light fields.

1. Introduction

Image-based relighting (IBRL) [3] is a technique for synthesizing images of a scene under novel lighting environments by linearly combining the images of the scene captured under various illumination conditions on the basis of the superposition principle of illumination. Although IBRL requires a large number of captured images in general, it enables us to synthesize photo-realistic images since it directly synthesizes novel images from real images without intervening the geometric and photometric modeling of the scene.

In the real world, rays with various wavelengths (colors) propagate from various positions to various directions. Such a lighting environment is called a light field [1], and the amount of ray is described by a 6-D plenoptic function with respect to the position (x, y, z), direction (θ, ϕ), and wavelength λ under the assumption of static scenes and unpolarized rays. The light field in clear media is described by a 5-D plenoptic function. This is because the radiance along a ray remains constant due to negligible absorption and scattering, and then one degree of freedom (DoF) in the position and direction of a ray is redundant.

Unfortunately, however, the conventional methods for IBRL illuminate a scene with low-dimensional slices of 5-D incident light fields. A light stage-based approach [3, 4], a display-based approach [19, 18], and a projector-based approach [20, 24] control the 2-D positions or the 2-D directions (and the 1-D colors) of incident rays. Therefore, they

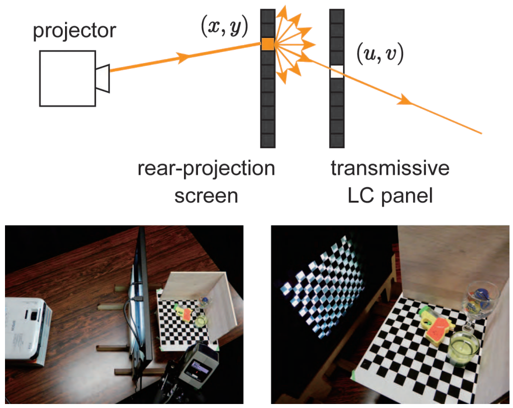

Figure 2. A sketch (top) and a prototype (bottom) of a two-layer 5 DoF lighting system consisting of a rear-projection display and a transmissive LC panel.

cannot synthesize images under 5-D incident light fields, which include point light sources at varying positions and with varying angular profiles and their combinations for example. The existing method for IBRL with 4-D incident light fields [15] controls both the 2-D positions and 2-D directions of incident rays by using a moving projector, but does not take their colors into consideration. Therefore, it cannot synthesize images of scenes where wavelength-dependent phenomena such as fluorescence are observed as shown in Figure 10 (e) and Figure 11 (e). Note that fluorescent materials emit light with longer wavelengths than those of absorbed light [8, 22, 26]. It is reported that fluorescent materials are common and present in 20% of randomly constructed scenes [2].

Accordingly, we propose a method for IBRL with 5-D incident light fields: 4 DoF of the position and direction and 1 DoF of the color of an incident ray (see the synthesized images in Figure 1 and Figure 12 and the supplementary video[1]). Specifically, we use a two-layer 5 DoF lighting system consisting of a rear-projection display and a transmissive liquid crystal (LC) panel as shown in Figure 2, and illuminate a scene by rays propagating from various positions to various directions with various colors. Then, novel images of the scene under desired 5-D incident light fields are synthesized by combining the images of the scene captured under those rays. Our proposed method enables us to synthesize images under rays not only from various positions to various directions but also with various colors. The DoF of the color is important for synthesizing images of scenes where wavelength-dependent phenomena such as fluorescence are observed as shown in Figure 10 (f) and Figure 11 (f).

IBRL using the 5 DoF lighting system has two difficulties; one is that a large number of captured images are required due to high DoF of the lighting system, and the other is that the signal-to-noise ratios (SNRs) of the captured images are small because the radiance of each ray is small. To cope with those difficulties, our proposed method efficiently acquires the required images by using coded illumination, which is used also for image acquisition [19], separating direct and global components [16], shape recovery [13], reflectance recovery [5, 17, 10], and material classification [12, 23]. Specifically, our method reduces the number of captured images by generating multiple rays that do not interfere each other at the same time, and enhances the SNRs on the basis of multiplexed illumination [19].

In addition, the lighting system using a projector and an LC panel has the problem of black offset; they are not able to generate perfect black, even though we set the input to the projector and/or the transmittance of the LC panel to 0. The problem is serious because the offset due to each "black" ray is small but the number of the rays is large. Accordingly, we reveal how the offsets of the projector and the LC panel propagate to the images captured by using the two-layer setup, and then propose a method for removing the effects of those offsets from them.

The main contribution of this study is threefold. First, we achieve IBRL that can synthesize images under desired 5-D incident light fields, *i.e.* rays propagating from various positions to various directions with various colors. We show that our proposed method enables us to synthesize photo-realistic images of scenes which contain fluorescent materials. Second, we propose an efficient method for acquiring the required images by using coded illumination. Our method reduces the number of captured images and the required time for measurement, and enhances the SNRs. Third, we reveal the relationship between the black offsets of the projector and the LC panel and the images captured by using the two-layer setup, and then remove the effects of the offsets from them.

The rest of this paper is organized as follows. We briefly summarize related work in Section 2. A method for IBRL with 5-D incident light fields by using a two-layer 5 DoF lighting system is proposed in Section 3. We report the experimental results in Section 4 and present concluding remarks in Section 5.

2. Related work

3D display:

A number of methods for generating desired light fields have already been proposed in the context of 3D display. For example, Lanman *et al.* [11] propose a 3D display based on the parallax barriers using a two-layer LC panel, and Wetzstein *et al.* [25] extend it by using a multi-layer LC panel and uniform or directional backlighting. Hirsch *et al.* [7] propose a large-scale 3D display by combining a light

[1] https://www.dropbox.com/s/0gkwykv1jx9ws10/supplementary_video.mp4?dl=0

field projector and an angle-expanding screen.

Whereas the objective of the above methods is glasses-free 3D display, *i.e.* generating light fields so that users view the displayed content stereoscopically in real time, our objective is IBRL, *i.e.* illuminating a scene by various rays and combining the images under those rays afterward. Therefore, the methods for glasses-free 3D display are not suited for IBRL. Specifically, the dynamic range of the light fields generated by those methods is limited because the number of images used for temporal multiplexing in real time is limited. In addition, they do not take the black offset due to a projector and an LC panel into consideration because image subtraction is impossible in real-time display.

Lighting simulation with light fields:

As the most closely related work to ours, Masselus *et al.* [15] achieve IBRL with 4-D incident light fields; they control both the 2-D positions and 2-D directions of incident rays by moving a single projector around a scene of interest. Unfortunately, however, their method does not take account of the colors of those rays, and therefore it cannot synthesize images of scenes which contain fluorescent materials. Although they propose a method for efficient image acquisition under the assumption that each ray has local influence, it is not applicable to transparent and translucent materials with non-local influence.

Zhou *et al.* [27] propose a light field projection system for lighting reproduction by using rear-projection projectors and a lens array. Their method controls not only the 2-D positions and 2-D directions but also the 1-D colors of incident rays, and therefore is applicable to scenes with fluorescent materials. Unfortunately, however, their proposed method for real-time lighting reproduction shares the limitations with the methods for glasses-free 3D display: limited dynamic range and black offset.

3. Proposed method

3.1. Two-layer 5 DoF lighting system

As shown in Figure 2, we use a two-layer 5 DoF lighting system; a transmissive LC panel is placed in front of a rear-projection display consisting of a projector and a rear-projection screen. When a ray with an arbitrary color is projected from the projector to an arbitrary point (x, y) on the screen, it is scattered to various directions. Then, we set the transmittance at an arbitrary point (u, v) on the LC panel to 1 and set those at the other points to 0. Thus, the lighting system generates a ray with an arbitrary color and passing through arbitrary points (x, y) and (u, v), *i.e.* a 5 DoF incident ray.

In this study, we divide the rear-projection display and the LC panel into N blocks (*e.g.* $N = 128$) respectively, and control the pixel values of the display and the transmittances of the LC panel in a block-wise manner[2]. Suppose that the projector has L color channels ($L = 3$ in general), the number of rays generated by the 5 DoF lighting system is $L \times N \times N$ (*e.g.* $3 \times 128 \times 128 = 49152$) in total.

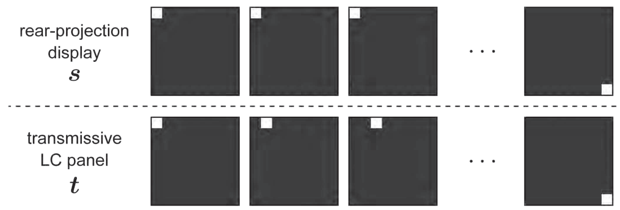

Figure 3. The naive method generates a single ray in turn and captures an image when a scene is illuminated by a single ray. The number of captured images is $N \times N$.

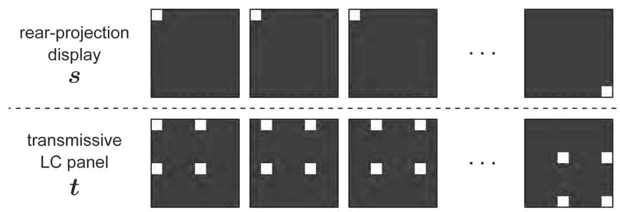

Figure 4. The parallel method generates multiple rays that do not interfere each other at the same time. The number of captured images is $N \times M$, where $M = N/4$ in this example.

3.2. Efficient image acquisition

IBRL requires a large number of images of a scene, each of which is captured when the scene is illuminated by each ray. Accordingly, we propose a method for efficiently acquiring those required images on the basis of coded illumination. Here, we address the 4 DoF of the positions (x, y) and (u, v) followed by the 1 DoF of the color.

Naive method:

Let us denote the intensities of the N blocks of the rear-projection display and the transmittances of N blocks of the LC panel by N-D vectors $\boldsymbol{s}$ and $\boldsymbol{t}$ respectively. Then, the intensities of $N \times N$ rays generated by the two-layer lighting system are represented as

$$\boldsymbol{s} \otimes \boldsymbol{t} \tag{1}$$

by using a direct product $\otimes$ [11]. As shown in Figure 3, the naive method, which generates a single ray in turn, sets one of the elements in $\boldsymbol{s}$ and one of the elements in $\boldsymbol{t}$ to 1 and sets the other elements to 0.

Unfortunately, however, the naive method has two limitations as the resolution of the positions (x, y) and (u, v) of

[2] In this paper, we call the bundle of rays passing through a block on the rear-projection screen and a block on the LC panel "a ray" for the sake of simplicity.

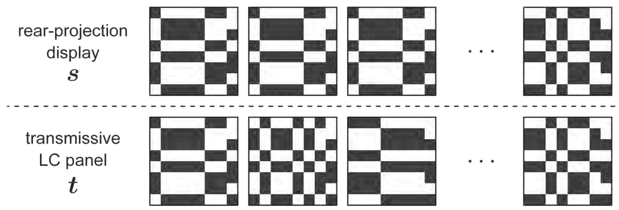

Figure 5. The multiplexed naive method is obtained by multiplexing the naive method. The number of captured images is $N \times N$.

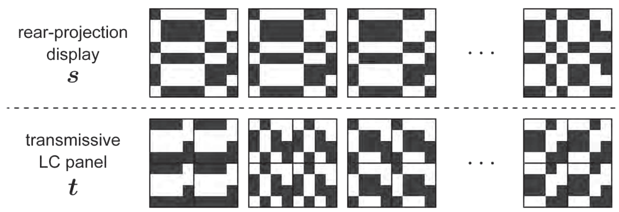

Figure 6. The multiplexed parallel method is obtained by multiplexing the parallel method. The number of captured images is $N \times M$, where $M = N/4$ in this example.

incident rays increases. First, the number of captured images increases as the number of blocks N increases. Second, the SNRs of the captured images decreases as the size of each block decreases, because the radiance of each ray also decreases.

Parallel method: To cope with the former limitation on the number of captured images, we reduce the number of captured images by generating multiple rays that do not interfere each other at the same time. Specifically, we make use of the fact that the 5 DoF lighting system generates redundant rays that do not arrive a scene, and then set the transmittances of multiple blocks to 1 at the same time.

Figure 4 shows an example of the parallel method. Suppose that a scene of interest is located in front of the LC panel and that at most a single ray among the 4 rays arrives the scene, which depends on the distance between the screen and the LC panel, the number of required images is reduced from $N \times N$ to $N \times M$ where $M = N/4$ in this case. The parallel method sets one of the elements in $\boldsymbol{s}$ and multiple elements in $\boldsymbol{t}$ to 1 and sets the other elements to 0. Note that the above parallelization is compatible with the following multiplexing.

Multiplexed parallel method:

To cope with the latter limitation on the SNRs of the captured images, we make use of multiplexed illumination [19] that is a well-known technique for increasing SNRs without increasing the number of captured images and measurement time. Whereas the multiplexed naive method in Figure 5 requires $N \times N$ captured images, the multiplexed parallel method in Figure 6 requires only $N \times M$ captured images. The multiplexed parallel method captures those images under the coded illumination and then decode them.

Specifically, the N-D vector $\boldsymbol{s}$, which represents the intensities of the N blocks of the rear-projection display, is given by the $N \times N$ S-matrix [21] that is constructed from the Hadamard matrix of order $(N + 1)$. For the example in Figure 6, we concatenate the M-D vector $(M = N/4)$ given by the $M \times M$ S-matrix N/M $(= 4)$ times, and obtain the N-D vector $\boldsymbol{t}$, which represents the transmittances of the N blocks of the LC panel. The images taken under the coded illumination are sequentially decoded by using the inverses of the S-matrices in two steps.

5 DoF coded illumination:

Let us denote the intensities of L color channels of a ray projected from the projector by an L-D vector $\boldsymbol{c}$. In a similar manner to the above, we capture images under the multiplexed color and then decode those images. For usual projectors with $L = 3$, we project CMY instead of RGB.

Our proposed method combines the multiplexed parallel method and the multiplexed color, and captures images under the 5 DoF coded illumination represented as

$$\boldsymbol{c} \otimes \boldsymbol{s} \otimes \boldsymbol{t}, \tag{2}$$

where $\boldsymbol{c}$, $\boldsymbol{s}$, and $\boldsymbol{t}$ are described by using the S-matrices with the sizes of L, N, and M respectively. The images taken under the coded illumination are sequentially decoded by using the inverses of the S-matrices in three steps.

3.3. Black offset removal

In general, a small amount of light is projected from a projector and passes through a transmissive LC panel, even though we set the input to the projector and/or the transmittance of the LC panel to 0. Therefore, the images of a scene illuminated by using the 5 DoF lighting system, which consists of a projector and a transmissive LC panel, are contaminated by the black offsets of the projector and the LC panel. The contamination is serious because the offset due to each black ray is small but the number of the rays is large. However, the way of removing the effects of the offsets caused by the two-layer setup is non-trivial, whereas the offsets of a projector or an LC panel can be removed easily by image subtraction.

Accordingly, we reveal how the black offsets of the projector and the LC panel propagate to the images captured by using the two-layer setup, and then propose a method for removing the effects of those offsets from them. Let us denote the offsets of the projector and the LC panel by N-D vectors $\boldsymbol{\delta}$ and $\boldsymbol{\epsilon}$ respectively. Then, the actual intensities of the N blocks of the rear-projection display $\boldsymbol{s}'$ and the actual transmittances of the N blocks of the LC panel $\boldsymbol{t}'$ are given by

$$\boldsymbol{s}' = \boldsymbol{s} + \boldsymbol{\delta}, \tag{3}$$
$$\boldsymbol{t}' = \boldsymbol{t} + \boldsymbol{\epsilon}. \tag{4}$$

Substituting the above equations into the desired intensities of $N \times N$ rays in eq.(1), we obtain

$$\begin{aligned} s \otimes t &= (s' - \delta) \otimes (t' - \epsilon) &(5)\\ &= s' \otimes t' - \delta \otimes t' - s' \otimes \epsilon + \delta \otimes \epsilon. &(6) \end{aligned}$$

Therefore, we can remove the effects of the black offsets by subtracting the two images captured when the input to the projector is 0, *i.e.* $\delta \otimes t'$ and the transmittance of the LC panel is 0, *i.e.* $s' \otimes \epsilon$ from the image captured under $s' \otimes t'$ and adding the image captured when both the input to the projector and the transmittance of the LC panel are 0, *i.e.* $\delta \otimes \epsilon$ to it. Thus, the number of required images becomes $L \times (N+1) \times (M+1)$ in total.

3.4. Image synthesis under novel lighting

We synthesize an image of a scene under a novel lighting environment by linearly combining the acquired images of the scene on the basis of the superposition principle of illumination. Specifically the novel image $\boldsymbol{I}$ is represented by a linear combination of the acquired images $\boldsymbol{B}_{lnm}$ under the ray with the l-th color and passing through the n-th block on the screen and the m-th block on the LC panel as

$$\boldsymbol{I} = \sum_{l=1}^{L} \sum_{n=1}^{N} \sum_{m=1}^{N} w_{lnm} \boldsymbol{B}_{lnm}. \qquad (7)$$

Here, w_{lnm} are the coefficients of the linear combination and computed from a desired 5-D incident light field.

4. Experiments

We implemented the prototype of a two-layer 5 DoF lighting system in Figure 2. We used a cooled CCD camera BU-50C from BITRAN with a linear radiometric response function for HDR image acquisition. We show the results of two scenes; one contains an aroma candle, a water gun, and marbles in a wineglass in Figure 7 (a), and the other contains an empty glass bottle, a tennis ball, and a glass bottle with olive oil in Figure 8 (a). We used two projectors for a rear-projection projector: an EB-S04 from EPSON for the first scene and an MS524 from BenQ for the second scene. Until otherwise noted, we set $L = 3$, $N = 63$, and $M = 15 \simeq N/4$[3], for which the measurement time of our proposed method was about 100 min.

In order to confirm the effectiveness of our proposed method, we compared the following three methods.

- **5 DoF baseline method:**
  This method requires $L \times (N+1) \times (N+1)$ images. We combine the multiplexed *naive* method for the 4 DoF of the positions (x, y) and (u, v) in Figure 5 with the multiplexed color for the 1 DoF of the color, and take account of the black offsets. We consider the images acquired by using this method and the images synthesized from them as the ground truths.

- **Our proposed method:**
  Our method requires $L \times (N+1) \times (M+1)$ images.

[3] The orders for which the Hadamard matrices exist are limited.

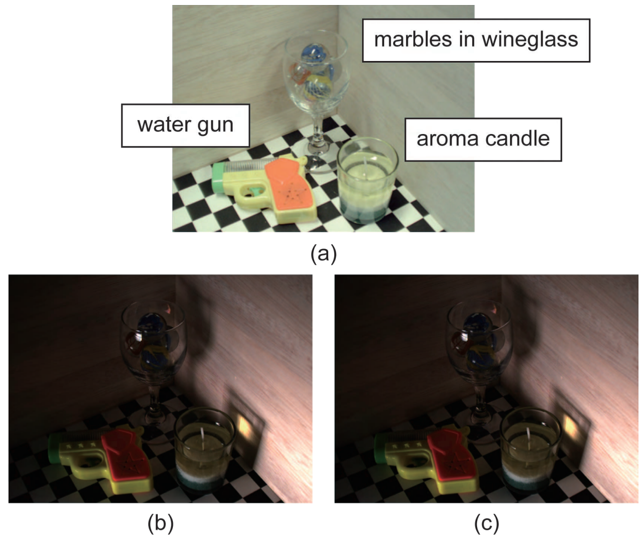

Figure 7. (a) an image of the first scene and the synthesized images from the images acquired by using (b) the 5 DoF baseline method and (c) our proposed method. Note that our method reduces the number of captured images and the required time for measurement by almost a quarter.

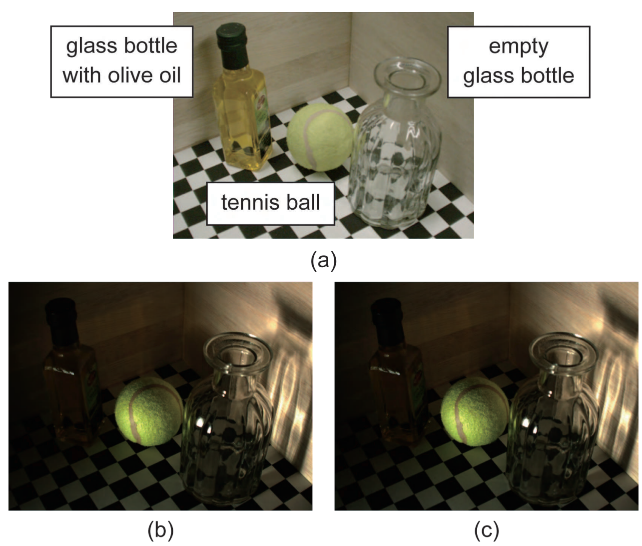

Figure 8. (a) an image of the second scene and the synthesized images from the images acquired by using (b) the 5 DoF baseline method and (c) our proposed method. Note that our method reduces the number of captured images and the required time for measurement by almost a quarter.

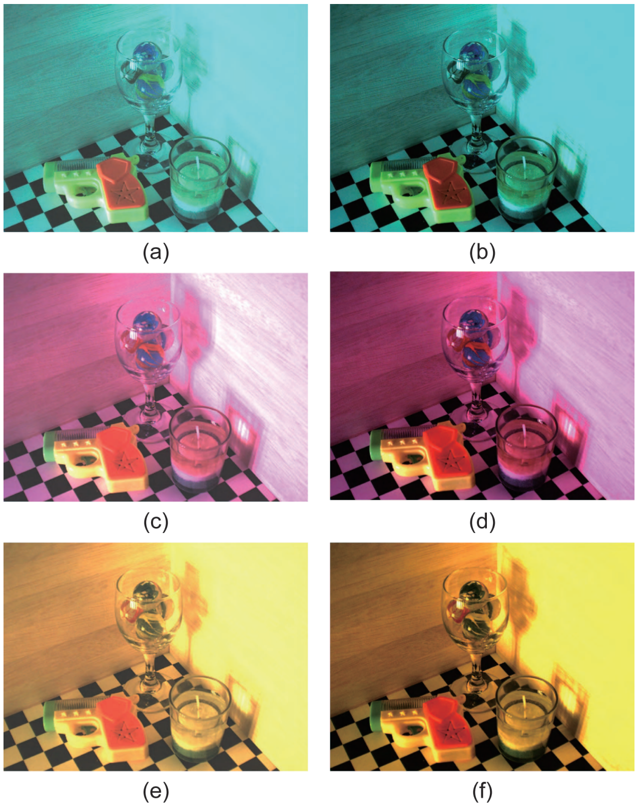

Figure 9. The images of the first scene captured under (a)(b) cyan, (c)(d) magenta, and (e)(f) yellow illumination patterns (a)(c)(e) without and (b)(d)(f) with the offset removal. The pixel values of the all images are scaled by the same factor for display purpose.

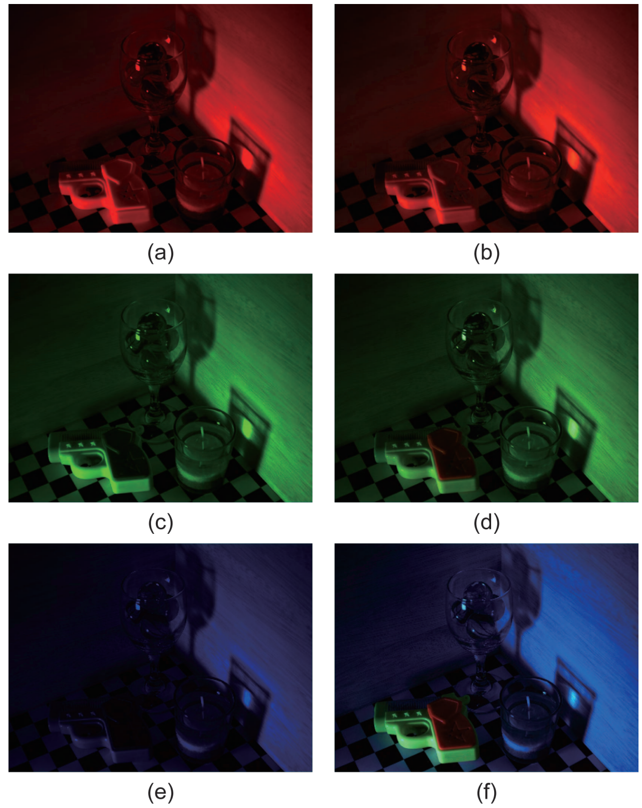

Figure 10. The synthesized images of the first scene under (a)(b) red, (c)(d) green, and (e)(f) blue nearby point light sources from the images acquired by using (a)(c)(e) the 4 DoF baseline method and (b)(d)(f) our proposed 5 DoF method.

We combine the multiplexed *parallel* method for the 4 DoF of the positions (x, y) and (u, v) in Figure 6 with the multiplexed color for the 1 DoF of the color, and take the black offsets into consideration.

- **4 DoF baseline method:**
  This method requires $(N+1) \times (M+1)$ images taken under white light sources. We use the multiplexed *parallel* method for the 4 DoF of the positions (x, y) and (u, v) in Figure 6, and take the black offsets into consideration. We synthesize the images under red, green, and blue light sources from the red, green, and blue channels of the acquired images under white light sources.

Figure 7 shows (a) an image of the first scene, and the synthesized images under a novel lighting environment from the images acquired by using (b) the 5 DoF baseline method and (c) our proposed method. Here, we assume a white nearby point light source. We can see that (c) the synthesized image by using our method is very similar to (b) the ground truth, even though our method reduces the number of captured images and the required time for measurement by almost a quarter. In Figure 8, we can see that the result for the second scene is similar to that of the first scene. The PSNRs of the synthesized images in 16 bit by using our method in Figure 7 and Figure 8 are 53.92 dB and 54.12 dB respectively. Those results show the effectiveness of our method.

Figure 9 shows the images of the first scene captured under (a)(b) cyan, (c)(d) magenta, and (e)(f) yellow illumination patterns (a)(c)(e) without and (b)(d)(f) with the offset removal. We can clearly see that (a)(c)(e) the images without the offset removal are brighter than (b)(d)(f) those with the offset removal. Therefore, the proposed method works well for removing the offsets in the two-layer lighting system.

Figure 10 shows the synthesized images under (a)(b) red, (c)(d) green, and (e)(f) blue nearby point light sources from the images acquired by using (a)(c)(e) the 4 DoF baseline method with white light sources and (b)(d)(f) our proposed 5 DoF method with RGB light sources. Hereafter, we set $L = 3$, $N = 127$, and $M = 31 \simeq N/4$, for which the measurement time of our method was about 430 min. We synthesized the images under (a) red, (c) green, and (e) blue

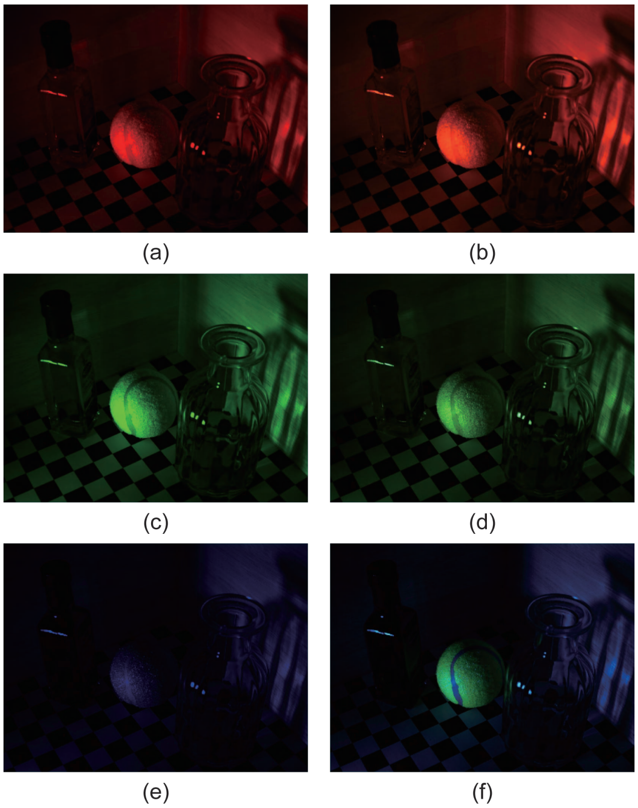

Figure 11. The synthesized images of the second scene under (a)(b) red, (c)(d) green, and (e)(f) blue nearby point light sources from the images acquired by using (a)(c)(e) the 4 DoF baseline method and (b)(d)(f) our proposed 5 DoF method.

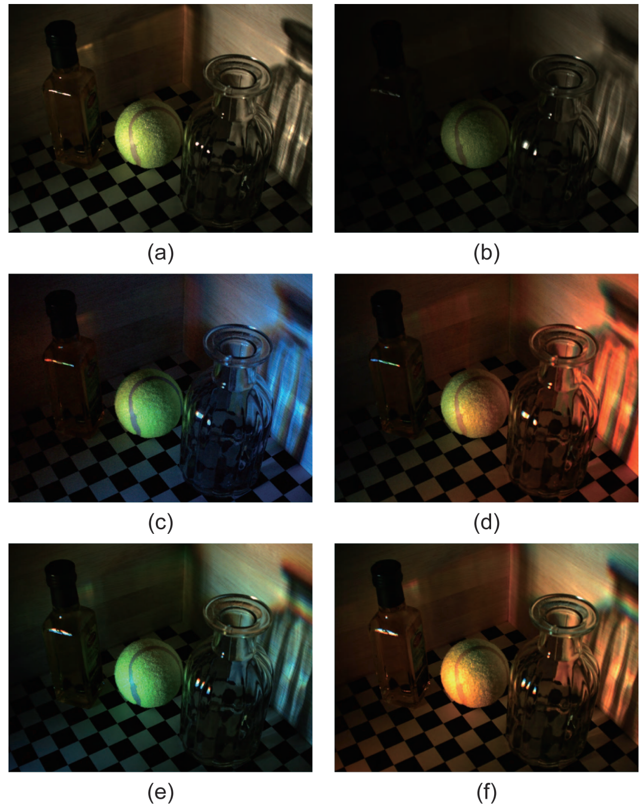

Figure 12. The synthesized images of the second scene by using our proposed method with various 5-D incident light fields.

light sources from the red, green, and blue channels of the acquired images under white light sources. Comparing (e) and (f), we can see that our 5 DoF method can reproduce the appearance of the water gun with fluorescent components, which absorb blue light and emit yellow light and red light, whereas the 4 DoF baseline method cannot. Figure 11 shows that our 5 DoF method can reproduce the appearance of the tennis ball with fluorescent components, whereas the 4 DoF baseline method cannot. Those results clearly show that our 5 DoF method with the 1 DoF of the color is useful for synthesizing images of fluorescent materials.

Figure 1 and Figure 12 show the synthesized images of the first and the second scenes respectively by using our proposed method with various 5-D incident light fields. Here, we assume (a)(b) a white light source and (c)(d)(e)(f) three light sources with red, green, and blue colors. We can see that our method can synthesize photo-realistic images in the framework of IBRL, in particular, the refraction due to the aroma candle in Figure 1 and the caustics due to the empty glass bottle in Figure 12 are remarkable.

5. Conclusion and future work

In this paper, we proposed a method for IBRL with 5-D incident light fields by using a two-layer 5 DoF lighting system consisting of a rear-projection display and a transmissive LC panel. Our proposed method efficiently acquires the required images by using coded illumination; it reduces the number of captured images and the required time for measurement, and enhances their SNRs. In addition, we proposed a method for removing the effects of the black offsets due to the projector and the LC panel in the two-layer setup. Through the experiments using the prototype system, we confirmed that our method is useful for synthesizing photo-realistic images under 5-D incident light fields, in particular, images of scenes with fluorescent materials.

The future work of this study includes the extension to multispectral light sources [9, 6, 14] for increasing the resolution of color. It enables us to synthesize photo-realistic images of scenes where wavelength-dependent phenomena such as refraction, diffraction, interference, and scattering are observed. The extension of the region of interest by using the larger lighting system or multiple lighting systems is also one of the future directions of our study.

Acknowledgments

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