Acquiring Multispectral Light Transport Using Multi-Primary DLP Projector

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***Abstract*— Acquiring the light transport (LT) of a scene is important for various applications such as radiometric analysis, image-based relighting, and controlling appearance of the scene. The multispectral LT, *i.e.* the LT in multiple primary colors enables us not only to enhance the color gamut but also to investigate wavelength-dependent interactions between light and a scene. In this paper, we propose a method for acquiring the multispectral LT by using a single off-the-shelf multi-primary DLP (Digital Light Processing) projector; it does not require any self-built equipment, geometric registration, and temporal synchronization. Specifically, based on the rapid color switch due to a rotating color wheel in the projector, we present a method for estimating the spectral properties of the projector in a non-destructive manner, and a method for acquiring the images of a scene illuminated only by one of the primary colors. We conducted a number of experiments by using real images, and confirmed that our method works well and the acquired multispectral LT is effective for radiometric analysis and image-based relighting.**

***Keywords*— Light Transport, Multispectral Imaging, DLP Projector, Color Switch, Reverse Engineering**

I. Introduction

The relationship between the lighting conditions illuminating a scene and its images taken under those lighting conditions is called *light transport* (LT). The LT describes how the light radiated from a light source interacts with a scene before arriving at a camera. Acquiring the LT of a scene is important for various applications such as radiometric analysis [10], [8], [4], image-based relighting [13], [16], [17], and controlling appearance [14], [3], [1] of the scene.

Conventionally, the LT of a scene is acquired by using projectors or displays with three primary colors, *i.e.* RGB. Unfortunately, however, such sampling in the spectral domain is sparse because the interactions between light and a scene often depend on the wavelength of light. If we can acquire the *multispectral* LT, *i.e.* the LT in N (> 3) primary colors, it enables us to investigate the interactions highly dependent on the wavelength such as refraction, diffraction, interference, scattering, and fluorescence. In addition, multi-primary light sources enhance the color gamut, and therefore make image-based relighting and controlling appearance more accurate.

Accordingly, we propose a method for acquiring the multispectral LT of a scene by using a single off-the-shelf projector. Specifically, we use a single-chip multi-primary DLP (Digital Light Processing) projector in which a color wheel consisting of multiple color filters with different spectral transmittances as shown in Fig. 1 (a) is placed between a white light source and a DMD (Digital Micromirror Device). The color wheel rotates at high speed in front of the light source, and generates various colors by mixing the transmitted lights with different SPDs (Spectral Power Distributions) via time-division multiplexing.

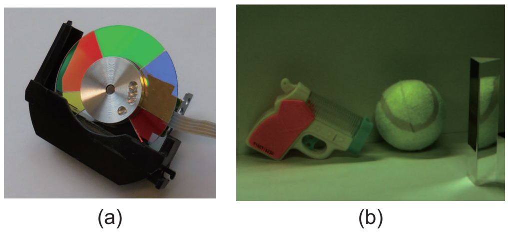

Fig. 1. (a) A color wheel consisting of multiple color filters with different spectral transmittances. (b) A scene where wavelength-dependent interactions of light are observed. See Fig. 7 for the results of direct-global separation.

Compared with the existing technique [18] using multiple projectors with different three primary colors, the advantage of our proposed method using a single projector is that ours does not require geometric registration and temporal synchronization. In addition, compared with the existing techniques [18], [11], [7], [6] using self-built equipments, our method using a consumer projector does not require such an equipment and is easy to implement. On the other hand, the use of an off-the-shelf multi-primary DLP projector has some issues to be addressed. In order to acquire the multispectral light transport by using the projector, its spectral properties such as the SPDs of the N primary colors are necessary. Unfortunately, however, those properties of consumer DLP projectors are not publicly available.

To cope with this problem, our proposed method exploits the rapid *color switch* due to the rotating color wheel of a single-chip DLP projector that is observed when the output light is captured by a sensor with a short integration time. Specifically, we estimate the SPDs of the N primary colors in a non-destructive manner by using a spectral sensor with a short exposure time, and acquire the images of a scene illuminated only by one of the primary colors by using a color camera with a short exposure time. We conducted a number of experiments using real images, and confirmed that our method works well. In addition, we showed that the acquired multispectral LT is effective for multispectral separation of direct and global

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components and image-based spectral relighting.

The main contribution of this study is threefold. First, we propose an easy-to-implement method based on a single consumer multi-primary DLP projector for acquiring multispectral LT; it does not require any self-built equipment, geometric registration, and temporal synchronization. Second, based on the rapid color switch due to the rotating color wheel, we propose a method for estimating the spectral properties of the projector in a non-destructive manner. Third, we propose a simple method for acquiring the images of a scene illuminated only by one of the primary colors on the basis of the color switch, and show that the acquired multispectral LT is effective for radiometric analysis and image-based relighting.

II. Related Work

In this section, we briefly describe the relationship between our proposed method and related work, in particular, research using multi-primary light sources and research on reverse engineering of DLP projectors.

A. Multi-Primary Light Sources

Yamaguchi *et al.* [18] propose a 6-primary projection display by using two 3-primary projectors in which color filters are inserted so that the three primary colors of one projector are different from those of the other projector. They show that the proposed display has wider color gamut than conventional three-primary projectors. Unfortunately, however, their method using multiple projectors requires cumbersome geometric registration and temporal synchronization.

Kauvar *et al.* [7] propose an adaptive color display by using a three-primary projector. The proposed display dynamically choose the three primary colors by combining 6 LEDs with different SPDs in a context-adaptive and user-centric manner. Hirai *et al.* [6] also propose a 6-primary projector by combining a programmable light source in the spectral domain and a DMD for modulating light intensity in the spatial domain.

Park *et al.* [11] propose a method for recovering the spectral reflectance of an object of interest by using multi-primary LED clusters. In order to reduce the number of images required for the spectral reflectance recovery, they make use of the multiplexed illumination in the spectral domain and the low-dimensional linear model for spectral reflectance [12]. They show that the proposed method achieves the spectral reflectance recovery of a moving object at 30 fps.

Compared with the above techniques, our proposed method does not require any self-build equipment. Therefore, our setup using only an off-the-shelf DLP projector is easy to implement.

B. Reverse Engineering of DLP Projectors

Narasimhan *et al.* [9] propose an approach to fast active vision by using a DLP projector. The DMD in a DLP projector controls the intensity of emitted light from the projector by switching mirrors "on" and "off" at high speed. They exploit such temporal dithering of illumination captured by using a high-speed camera. They show that the temporal dithering is useful for various applications such as structured light-based range finding, photometric stereo, separating direct and global components and so on. In our study, we focus more attention on the color switch and does not explicitly take the temporal dithering into consideration.

Han *et al.* [5] propose a method for recovering the spectral reflectance of a moving object by using a three-primary DLP projector. Specifically, they rapidly change the lighting colors illuminating the object on the basis of the color switch, and capture its images by using a high-speed camera. They also make use of the low-dimensional model for spectral reflectance and show that the proposed method achieves the spectral reflectance recovery of a moving object at 100 fps.

Our proposed method is similar to Han *et al.* [5] in the sense that we also make use of the color switch. However, the reverse engineering of the multi-primary DLP projector is far more difficult than that of a three-primary DLP projector; we can directly measure the SPDs of the latter three primary colors by setting the projector input to $(R, G, B) = (255, 0, 0)$, $(0, 255, 0)$, and $(0, 0, 255)$, but cannot measure the SPDs of the former multi-primary colors. This is because the mapping from the projector input (3-D) to the projector output (N-D) is non-trivial when $N > 3$ as described in Section III.A. Therefore, the reverse engineering proposed in the next section is necessary. In addition, our method uses a regular-framerate camera with a short exposure time instead of an expensive high-speed camera.

III. Proposed Method

In this section, we propose a method for acquiring the multispectral LT by using a multi-primary DLP projector. First, we describe the color generation model of single-chip multi-primary DLP projectors. Second, we present a method for estimating the spectral properties of the multi-primary DLP projectors in a non-destructive manner. Third, we present a method for acquiring the multispectral LT, *i.e.* the LT per primary color.

A. Color Generation Model

As described in Introduction, in a single-chip multi-primary DLP projector, a color wheel consisting of multiple color filters with different spectral transmittances rotates at high speed, and generates various colors by mixing the transmitted lights with different SPDs via time-division multiplexing.

Let us denote the number of color filters, *i.e.* the number of the primary colors by N (> 3) and the SPDs of those primary colors by $p_n(\lambda)$ $(n = 1, 2, 3, ..., N)$. Here, λ is the wavelength of light. When we observe the emitted light from the projector with a certain exposure time, its SPD $l(\lambda)$ integrated over the time is represented by a convex combination of those of the primary colors as

$$l(\lambda) = \sum_{n=1}^{N} c_n p_n(\lambda). \tag{1}$$

Here, c_n (≥ 0) are the mixing coefficients of the primary colors. If the exposure time is long enough so that no color switch is observed, the mixing coefficients are determined by the RGB value input to the projector. Note that the mapping from the RGB value (3-D) to the mixing coefficients (N-D) is non-trivial and difficult to estimate when $N > 3$.

The acquisition of the multispectral LT is easy if the spectral properties of a multi-primary DLP projector such as the SPDs $p_n(\lambda)$, the mixing coefficients c_n, and the mapping function are known. Unfortunately, however, those properties of consumer DLP projectors are not publicly available. Accordingly, in the next two subsections, we present a method for estimating the SPDs of the primary colors and a method for acquiring the multispectral LT on the basis of the rapid color switch due to a rotating color wheel.

B. Estimating SPDs of Primary Colors

We use a white image as the input to a multi-primary DLP projector[1], and illuminate a white target object such as a white balance reflectance target. Then, we observe the reflected light on the target object by using spectral sensors such as a spectrometer and a hyperspectral camera. The key idea of our proposed method is that, when the integration time of such a sensor is short enough, *e.g.* 0.1 ms, we should observe the light transmitting only one of the color filters of a color wheel.

Therefore, when we plot a number of SPDs, each of which is observed with a short exposure time, in a certain space, we should see some clusters; the number of clusters is equal to the number of the primary colors and the center of each cluster corresponds to the SPD of each primary color. Hence, we can estimate the SPDs of the primary colors $p_n(\lambda)$ (and the number of primary colors N if necessary) by clustering the observed SPDs.

In our experiments, we map the observed SPDs to the CIE xy chromaticity space. We use the mean shift clustering [2] for estimating the cluster centers in that space.

C. Acquiring Multispectral Light Transport

In a similar manner to the above, we use a white image as the input to a multi-primary DLP projector, and illuminate a scene and a white target object at the same time. Then, we capture their images by using a color camera with a short exposure time.

For the same reason as described above, when we plot a number of RGB values, each of which is observed on the white target object, in a certain space, we should see some clusters; the number of clusters is equal to the number of the primary colors and the center of each cluster corresponds to the observed RGB value of each primary color. Therefore, we can see that the image of the scene corresponding to the cluster center is captured when it is illuminated only by the corresponding primary color. Thus, we can acquire the multispectral LT by using a consumer multi-primary DLP projector.

[1]We assume that all of the primary colors are used when we set the projector input to (255,255,255).

Fig. 2. The closeups of the captured hyperspectral image of a white balance reflectance target at various wavelengths; 450, 500, 550, 600, and 650 nm from left to right.

In our experiments, we map the observed RGB values to the rg chromaticity space, where $r = R/(R+G+B)$ and $g = G/(R+G+B)$. We use the mean shift clustering [2] for estimating the cluster centers in that space.

Note that we need to capture M $(\gg N)$ images so that all of the N primary colors are observed. Taking the sampling in the spatial domain into consideration, we denote the spatial resolution of the LT, *i.e.* the number of the projector pixels (or patches) in our case, by S. We need to capture $S \times M$ images in total although the exposure time per image is short enough. We can use the multiplexed illumination [15] in the spatial domain if necessary.

IV. Experiments

In this section, we show the SPDs of the primary colors and the images of a scene illuminated by those primary colors[2] estimated on the basis of the rapid color switch. In our experiments, we tested two off-the-shelf projectors; an NP-VE282 from NEC and an MS524 from BenQ.

A. SPDs of Primary Colors

We used a white image as the input to the projector from NEC, and illuminated a white balance reflectance target. Then, we captured an image of the target by using a hyperspectral camera from EBA Japan[3] with an exposure time of 0.1 ms. Fig. 2 shows the captured hyperspectral image of the target at various wavelengths. Because this camera is based on a line scanner, different rows of the image have different time stamps. Therefore, a number of SPDs of the emitted light from the projector at different time are included in the single hyperspectral image.

We converted those SPDs into the CIE XYZ values, and plotted them as shown in Fig. 3 (a). We can see that there are 6 linear clusters, *i.e.* the projector has 6 primary colors; it is consistent with the specification document of the projector. The reason why the clusters' shapes are not spherical but linear is that the intensity of the emitted light from the projector is modulated by temporal dithering. In addition, we can see some

[2]Due to limited space, we focus on the LT in the spectral domain and do not consider the LT in the spatial domain, *i.e.* we illuminate a scene by spatially uniform lighting. See Section V.A for spatially nonuniform lighting.

[3]As described in the previous section, we can use other spectral sensors such as a spectrometer.

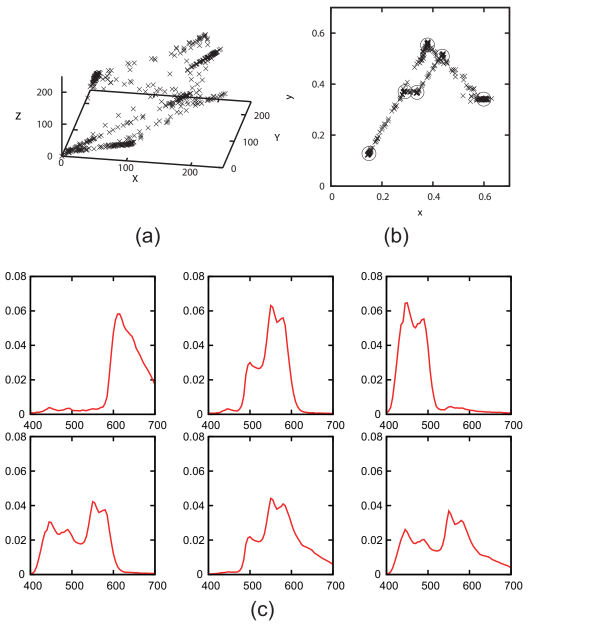

Fig. 3. Reverse engineering of a projector NP-VE282 from NEC; (a) the CIE XYZ and (b) xy values converted from the observed SPDs. A white balance reflectance target illuminated by the projector was captured by using a hyperspectral camera. (c) The estimated SPDs of the 6 primary colors; R, G, B, C, Y, and W from upper left to lower right.

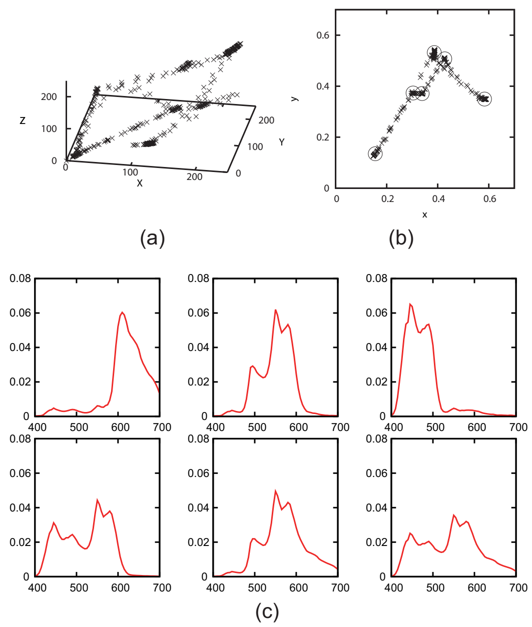

Fig. 4. Reverse engineering of a projector MS524 from BenQ.

outliers corresponding to the light passing through two color filters next to each other within the exposure time.

Then, we converted the above SPDs into the CIE xy values, and plotted them as shown in Fig. 3 (b). Similar to Fig. 3 (a), it is clear that there are 6 clusters, in other words, the projector has 6 primary colors. Here, $\circ$ stands for the center of the cluster computed by using the mean-shift clustering under the assumption of $N = 6$. Fig. 3 (c) shows the SPDs corresponding to the cluster centers. We can see that those SPDs corresponds to 6 primary colors; Red, Green, Blue, Cyan, Yellow, and White from upper left to lower right.

The experimental results on the projector from BenQ are shown in Fig. 4. Fig. 4 (a) and (b) show that the projector has 6 primary colors and Fig. 4 (c) shows that the primary colors are R, G, B, C, Y, and W. Those results are consistent with the color wheel shown in Fig. 1 (a), that was taken from the projector in a destructive manner.

B. Multispectral Light Transport

In a similar manner to the above, we used a white image as the input to the projector from NEC, and illuminated a scene and a white target object at the same time. Then, we captured their images by using a color camera FL3-U3-13E4C-C from Point Grey with an exposure time of 0.1 ms. Because this camera has a global shutter, all pixels in a single image has the same time stamp.

We captured 1000 images and plotted the RGB and rg values observed on the white target in Fig. 5 (a) and (b) respectively. Those results are consistent with those using a hyperspectral camera; the projector has 6 primary colors. Here, $\circ$ stands for the center of the cluster computed by using the mean-shift clustering under the assumption of $N = 6$.

Fig. 5 (c) shows the images of a scene illuminated by the 6 primary colors; R, G, B, C, Y, and W from upper left to lower right. Here, the white target (left) and an X-Rite ColorChecker Passport (right) were captured at the same time. This result qualitatively shows that the proposed method works well. Note that the scales between the estimated SPDs shown in Fig. 3 (c) and the acquired images shown in Fig. 5 (c) are adjusted by using the spectral sensitivity of the color camera calibrated in advance.

The experimental results on the projector from BenQ are shown in Fig. 6. Fig. 6 (a) and (b) show that the projector has 6 primary colors and Fig. 6 (c) shows that the proposed method works well for capturing the images of a scene illuminated by the 6 primary colors. Interestingly, in Fig. 6 (a), we can clearly observe some paths between two clusters caused by light passing through two color filters next to each other within the exposure time. We can see that the order of the color filters in the color wheel is R, G, B, C, W, and Y; it is also consistent with the color wheel shown in Fig. 1 (a).

V. Applications

In this section, we show two applications of our proposed method; one is multispectral separation of direct and global components and the other is image-based spectral relighting.

A. Multispectral Separation of Direct and Global Components

We can combine our proposed method with the separation of direct and global components of a scene by using high-

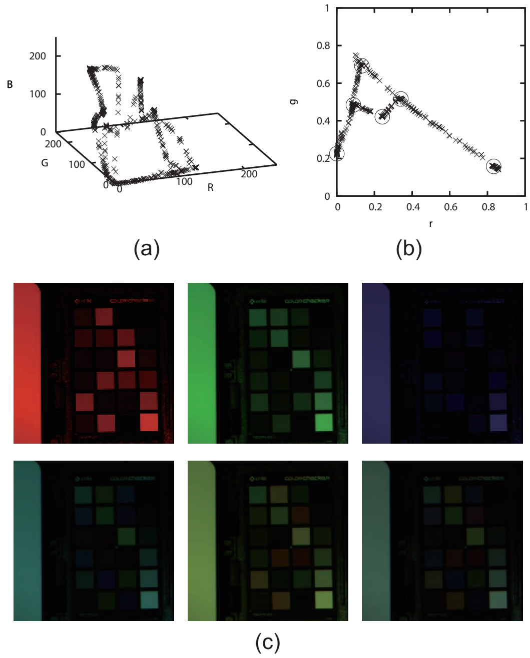

Fig. 5. Multispectral LT using a projector NP-VE282 from NEC; (a) the RGB and (b) rg values of a white balance reflectance target illuminated by the projector and captured by using a color camera. (c) The images of a scene illuminated by the 6 primary colors; R, G, B, C, Y, and W from upper left to lower right.

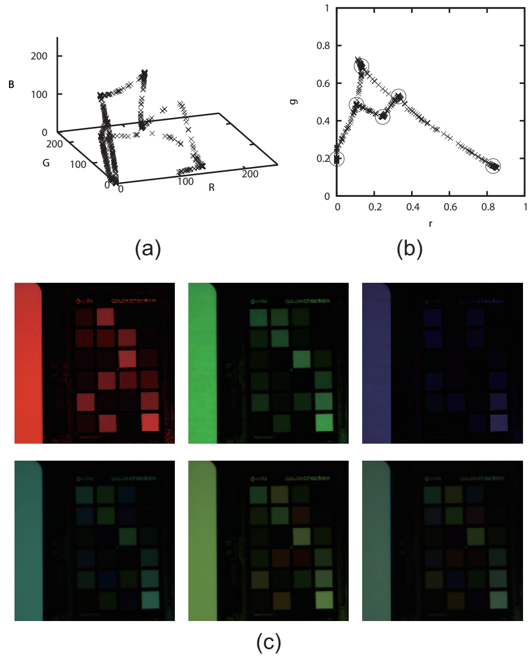

Fig. 6. Multispectral LT using a projector MS524 from BenQ.

frequency illumination in the spatial domain [10], and achieve the direct-global separation in multi-primary colors. Specifically, we used a set of shifted checkerboard illumination patterns in black and white for the input to a projector, and acquired the images of a scene illuminated by the checkerboard patterns in multi-primary colors as shown in Fig. 7 (a). Here, we used 4 checkerboard patterns and their complementary ones for stably separating direct and global components although some artifacts are still visible.

Fig. 7 (b) and (c) show the direct and global components of the scene respectively. Interestingly, the direct components of a toy gun and a tennis ball, in particular those under blue light (upper right) show that they are made of fluorescent materials; they absorb the light with certain wavelengths and emit the light with different (longer) wavelengths [19]. The global components include subsurface scattering of the toy gun, interreflections between the tennis ball and a floor, and so on. More importantly, we can observe that the light refracted by a prism appears at different positions according to the wavelength of light since the refraction coefficient depends on the wavelength.

B. Image-Based Spectral Relighting

We can use the SPDs of the primary colors and the images of a scene under the primary colors acquired by using our proposed method for image-based spectral relighting. Specifically, we synthesized the image of the scene under a novel illuminant SPD by linearly combining those images under the primary colors. Here, the coefficients of the linear combination is computed from the SPDs of the primary colors and the novel illumination.

Fig. 8 shows (a) the images of pastels under the primary colors, (b) the images under a fluorescent lamp, and (c) those under an incandescent lamp respectively. The RMS errors of the synthesized images in the rgb chromaticity space are shown in Table 1. Those results show that the spectral relighting using multi-primary colors ($N = 6$) works better than the conventional one using three primary colors ($N = 3$), but the difference between them is not so large. This is because the SPD of C (Y) is similar to those of B+G (G+R) in the low-end consumer projectors used in our experiments. Emphasizing the difference between the SPDs of the primary colors by using bandpass filters in front of the projector for example is one of the future directions of our study.

VI. Conclusion and Future Work

In this paper, we proposed a method for acquiring the multispectral LT by using a single off-the-shelf multi-primary DLP projector on the basis of the rapid color switch due to a rotating color wheel in the projector. We conducted a number of experiments and confirmed that our proposed method works well and the acquired multispectral LT is effective for radiometric analysis and image-based relighting. Our future study includes the enhancement of the SPDs of the primary colors.

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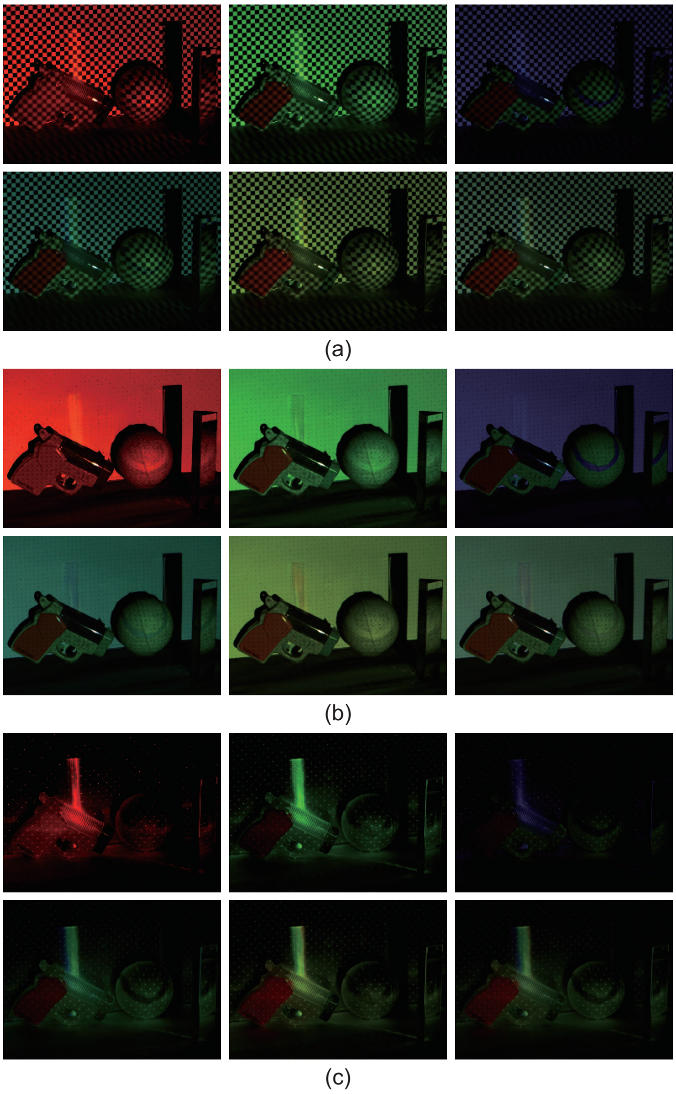

Fig. 7. Multispectral direct-global separation; (a) the acquired images of a scene illuminated by high-frequency illumination patterns in multi-primary colors, (b) the direct and (c) the global components of the scene in multi-primary colors. R, G, B, C, Y, and W from upper left to lower right.

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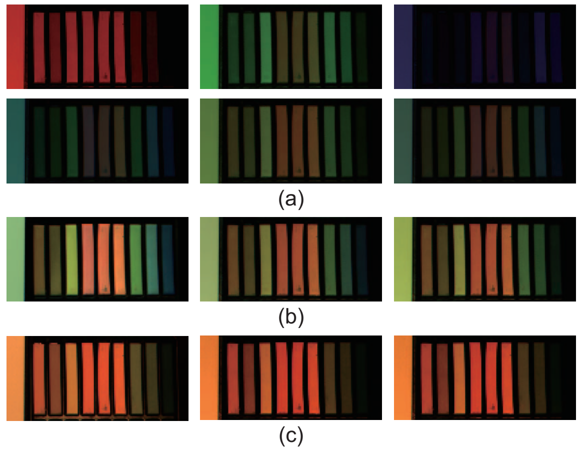

Fig. 8. Image-based spectral relighting; (a) the images of pastels under the primary colors, *i.e.* R, G, B, C, Y, and W from upper left to lower right, (b) the images under a fluorescent lamp, and (c) those under an incandescent lamp. In (b) and (c), the ground truth, the synthesized images when $N = 6$ and $N = 3$ are shown from left to right.

Table 1. The RMS errors of the synthesized images using N primary colors.

Projector	Light Source	N=6	N=3
NEC (NP-VE282)	fluorescent	**0.024**	0.039
	incandescent	**0.037**	0.038
BenQ (MS524)	fluorescent	**0.045**	0.050
	incandescent	**0.044**	0.053

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