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Multispectral Direct-Global Separation of Dynamic Scenes

Moriaki Torii Takahiro Okabe
Kyushu Institute of Technology
okabe@ai.kyutech.ac.jp

Toshiyuki Amano
Wakayama University
amano@sys.wakayama-u.ac.jp

Abstract

In this paper, we propose a method for separating direct and global components of a dynamic scene per illumination color by using a projector-camera system; it exploits both the color switch and the temporal dithering of a DLP projector. Our proposed method is easy-to-implement because it does not require any self-built equipment and temporal synchronization between a projector and a camera. In addition, our method automatically calibrates the projector-camera correspondence in a dynamic scene on the basis of the consistency in pixel intensities, and optimizes the projection pattern on the basis of noise propagation analysis. We implemented the prototype setup and achieved multispectral direct-global separation of dynamic scenes in 60 Hz. Furthermore, we demonstrated that our method is effective for applications such as image-based material editing and multispectral relighting of dynamic scenes where wavelength-dependent phenomena such as fluorescence are observed.

1. Introduction

When a scene is illuminated by a light source, the radiance observed at each point in the scene consists of two components: direct and global [11]. The direct component is caused by the direct illumination from the light source, while the global component is caused by the illumination from the other points in the scene due to interreflection, subsurface scattering, volumetric scattering, and diffusion. Separating direct and global components of scenes is important for various computer vision techniques such as shape recovery, image-based material editing, and improving image quality [11, 6].

In this paper, we propose a method for separating direct and global components of a *dynamic scene* per *illumination color* by using a projector-camera system. The direct-global separation per illumination color, *e.g.* per primary color of a projector, is useful for studying the interactions highly dependent on the wavelength of light: refraction, diffraction, scattering, and fluorescence [2, 18]. Our proposed method enables us to investigate dynamic scenes where such wavelength-dependent phenomena are observed.

It is known that one can separate direct and global components in a scene by projecting high-frequency patterns from a projector, because the global components are low-frequency in general [11]. Therefore, the multispectral direct-global separation of *static scenes* can be realized by projecting several high-frequency patterns with different illumination colors. Unfortunately, however, such a straightforward method is not applicable to *dynamic scenes*, since the frame rates of off-the-shelf projectors are low in general.

The key idea of our proposed method is to exploit both the *color switch* [7] due to a color wheel and the *temporal dithering* [10] due to a DMD (Digital Mirror Device) of a DLP (Digital Light Processing) projector. We make use of such a projector for rapidly changing illumination conditions in a dynamic scene of interest. Then, the image sequence of the scene is captured by using a high-speed camera so that the effects of the rapidly-varying illumination conditions on the scene are observed.

Specifically, our proposed method studies the image sequence of a scene when the input to a DLP projector is a single high-frequency pattern. Note that the output from the projector rapidly changes in both colors and intensities due to the color switch and the temporal dithering even for a single input pattern. Our method uses a reference object, and then does not require temporal synchronization between a projector and a camera. In addition, our method automatically calibrates the projector-camera correspondence in a dynamic scene on the basis of the consistency in pixel intensities, and optimizes the projection pattern on the basis of noise propagation analysis. We make use of the 3D mode in the side-by-side format of a projector, and then achieve multispectral direct-global separation in 60 Hz.

We implemented the prototype setup and confirmed the effectiveness of our proposed method. In particular, we showed that our proposed auto-calibration of projector-camera correspondence and optimization of projection pattern work well. We demonstrated that our method is effective for applications such as image-based material editing and multispectral relighting of dynamic scenes where

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wavelength-dependent phenomena such as fluorescence are observed.

The main contribution of this study is threefold. First, we achieve fast multispectral direct-global separation by exploiting both the color switch and the temporal dithering of a DLP projector. Second, our proposed method is easy-to-implement, because it uses a consumer DLP projector and a consumer high-speed camera, and does not require any self-built equipment. In addition, our method achieves auto-calibration of projector-camera correspondence and does not require projector-camera temporal synchronization. Third, our method is robust, because the high-frequency projection pattern is optimized on the basis of noise propagation analysis.

The rest of this paper is organized as follows. In Section 2, we briefly summarize related work. In Section 3, a method for multispectral direct-global separation of dynamic scenes is proposed. We report the experimental results and the applications in Section 4 and Section 5. We present concluding remarks in Section 6.

2. Related Work

2.1. Direct-global separation

The relationship between the light sources illuminating a scene and its images taken under those light sources is called light transport (LT). The LT reveals where the light radiated from a certain light source interacts with the scene just before arriving at a camera. Acquiring the LT of a scene is important for various applications such as image-based relighting [4, 12, 16, 17] and controlling appearance of the scene [14, 5, 3, 1].

On the other hand, the direct-global separation reveals how the light radiated from a light source interacts with a scene. Nayar *et al.* [11] propose a method for separating direct and global components in a scene by projecting high-frequency patterns from a projector on the basis of the insight that global components are low-frequency in general. Separating direct and global components of scenes is effective for various computer vision techniques such as shape recovery, image-based material editing, and improving image quality.

Gu *et al.* [6] extend the above direct-global separation for a single light source to that for multiple light sources. Specifically, they optimize a set of high-frequency projection patterns in terms of SNR (signal-to-noise ratio) on the basis of illumination multiplexing [15], and then show that it is effective for scene recovery. Mukaigawa *et al.* [9] show that projecting high-frequency patterns is useful also for studying the light transport in scattering media, in particular for decomposing multiple scattering into each bounce component.

In contrast to the above existing methods, we propose a method for separating direct and global components of a dynamic scene per illumination color by using a projector-camera system. As demonstrated in Section 5, multispectral direct-global separation enables applications such as image-based material editing and multispectral relighting of dynamic scenes where wavelength-dependent phenomena are observed.

2.2. Active illumination using DLP projector

In a single-chip DLP projector, a color wheel consisting of three (or more) color filters with different spectral transmittances is placed between a white light source and a DMD. 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. Then, the DMD controls the intensity of the light transmitted from the color wheel by temporal dithering; it switches micro mirrors "on" and "off" directions at high speed.

Narasimhan *et al.* [10] exploit the rapidly-varying illumination intensities due to the temporal dithering, and then propose a method for separating direct and global components of dynamic scenes by using a high-speed camera. They show that the temporal dithering is useful also for fast active vision such as structured light-based range finding and photometric stereo. Unfortunately, however, their method assumes that the illumination color is fixed, and then it cannot separate direct and global components per illumination color.

On the other hand, Maeda and Okabe [8] exploit the rapidly-varying illumination colors due to the color switch of a multi-primary DLP projector, and then propose a method for separating direct and global components of a static scene per primary color of the projector by using a usual camera with a short exposure time. In addition, they propose a method for estimating the SPDs of the primary colors in a non-destructive manner. Unfortunately, however, their method assumes static scenes, and then it is not applicable to objects in motion. Han *et al.* [7] propose a method for recovering the spectral reflectance of a moving object by using a DLP projector and a high-speed camera on the basis of the color switch.

Our proposed method exploits both the color switch and the temporal dithering of a DLP projector, and achieves the direct-global separation of dynamic scenes per illumination color. Our method is not a straightforward combination of the above existing methods based on the temporal dithering [10] and the color switch [8]. In particular, we realize auto-calibration of projector-camera correspondence on the basis of the consistency in pixel intensities. Furthermore, we optimize the high-frequency projection pattern on the basis of noise propagation analysis so that it is robust to noises.

3. Proposed Method

3.1. Principle of direct-global separation

Nayar *et al.* [11] propose a method for direct-global separation of a static scene by using a projector-camera system; it makes use of the properties of global components, *i.e.* they are low-frequency in general, and studies the images of the scene under high-frequency projection patterns. Specifically, their simplest method uses two images; they are captured when a black-and-white checkered pattern or its negative-positive reversed pattern are projected from a projector to the scene.

Let us denote the two output intensities from a projector corresponding to white and black input intensities of a checkered pattern by a and b, *e.g.* $a = 1$ and $b = 0$[1]. The pixel intensities observed at a certain point in the scene are given by

$$I^+ = aL_d + \frac{1}{2}(a+b)L_g, \tag{1}$$

$$I^- = bL_d + \frac{1}{2}(a+b)L_g, \tag{2}$$

where L_d and L_g are the direct and global components at the point, and I^+ and I^- are the larger and smaller pixel intensities observed there when $a > b$ [11, 10]. Therefore, one can compute the direct component L_d and the global component L_g by solving the simultaneous linear equations in eq.(1) and eq.(2), when the pixel intensities I^+ and I^- and the output intensities from the projector a and b are known.

3.2. Multispectral separation of dynamic scene

According to the principle of the direct-global separation described in the previous subsection, the multispectral direct-global separation of static scenes can be realized by projecting at least 6 ($= 3$ primary colors $\times$ 2 negative-positive patterns) high-frequency patterns with different illumination colors[2]. Unfortunately, however, the frame rates of off-the-shelf projectors are low in general, and then the above straightforward method causes motion blur for dynamic scenes. In addition, the temporal synchronization between a projector and a camera is required.

Our proposed method captures the image sequence of a dynamic scene illuminated by a consumer DLP projector by using a consumer high-speed camera, and then studies the effects of the rapidly-varying illumination conditions due to both the color switch and the temporal dithering on the scene. Figure 1 (a) shows the input gray-scale image to a DLP projector which consists of the blocks with different pixel intensities from 0 (the upper left) to 255 (the lower right). Figure 1 (b)(c)(d)(e) shows the example images of the white reflectance standard illuminated by the projector and captured by a high-speed camera, when (a) the gray-scale image is input to the projector. We can see the effects of the color switch in (b)(c)(d) and those of the temporal dithering in (d)(e).

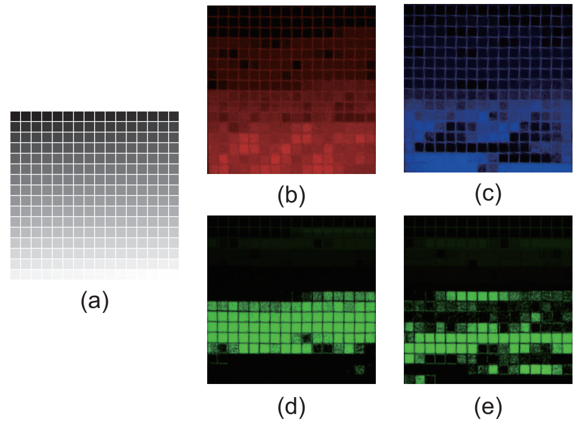


Figure 1. The color switch and the temporal dithering: (a) the input gray-scale image and (b)(c)(d)(e) the example images of the white reflectance standard illuminated by a DLP projector and captured by a high-speed camera, when the gray-scale image is input to the projector.

In our proposed method, the input to a DLP projector is a single high-frequency pattern: a "checkered" pattern with two different gray-scale intensities. Our method captures not only a dynamic scene of interest but also a reference object, *e.g.* the white reflectance standard at the same time as shown in Figure 4. This setup enables us to classify the captured images into the images illuminated only by each primary color of the projector on the basis of the observed colors on the reference object. We assume that the scene is stationary within a single frame of the result image sequence, *e.g.* 1/60 sec in our current implementation. Therefore, our multispectral direct-global separation results in the direct-global separation of a stationary scene illuminated by a single primary color of the projector.

Then, let us consider the N images of a stationary scene illuminated by a single illumination color. In a similar manner to eq.(1) and eq.(2), the pixel intensity I_n ($n = 1, 2, 3, ..., N$) observed at a certain point in the scene is given by

$$I_n = a_n L_d + \frac{1}{2}(a_n + b_n)L_g \tag{3}$$

or

$$I_n = b_n L_d + \frac{1}{2}(a_n + b_n)L_g \tag{4}$$

in the n-th image. Here, L_d and L_g are the direct and global components at the point, and a_n and b_n are the two output intensities from the projector. Although the output inten-

[1]Note that the relationship between the input and output intensities of a projector is not linear in general.

[2]It results in the multispectral direct-global separation in 5 Hz when we use a projector with 30 fps.

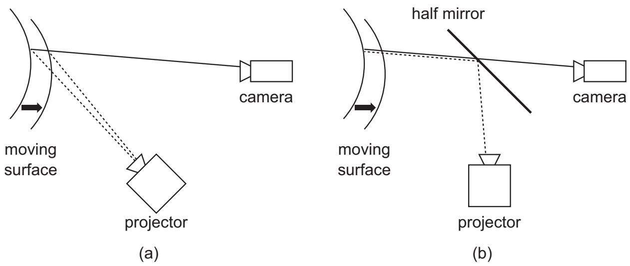


Figure 2. The projector-camera correspondence in a dynamic scene: (a) dynamically varying correspondence and (b) fixed correspondence using a half mirror.

sities a_n and b_n vary due to the temporal dithering, we can estimate those intensities also from the observed pixel intensities on the reference object. Therefore, one can compute the direct component L_d and the global component L_g by solving the simultaneous linear equations in eq.(3) or those in eq.(4), if whether the point is directly illuminated by a_n or b_n is known.

3.3. Auto-calibration of pro-cam correspondence

The multispectral direct-global separation described in the previous subsection suffers from an ambiguity, when the projector-camera correspondence is unknown. As shown in Figure 2 (a), in dynamic scenes, the projector-camera correspondence also varies dynamically. Therefore, we cannot distinguish whether we should solve the simultaneous linear equations in eq.(3) or those in eq.(4). To cope with the problem of such an ambiguity, Narasimhan *et al*. [10] fix the projector-camera correspondence by using a half mirror as shown in Figure 2 (b) and calibrate the correspondence in advance.

In contrast to their method, our proposed method resolves the problem of the ambiguity on the basis of the consistency in pixel intensities. Specifically, we solve the both simultaneous linear equations via the linear least-square method as

$$\min_{\{L_d, L_g\}} \sum_{n=1}^{N} \left[I_n - a_n L_d - \frac{1}{2}(a_n + b_n) L_g \right]^2 \tag{5}$$

or

$$\min_{\{L_d, L_g\}} \sum_{n=1}^{N} \left[I_n - b_n L_d - \frac{1}{2}(a_n + b_n) L_g \right]^2 \tag{6}$$

with the non-negativity constraints: $L_d \geq 0$ and $L_g \geq 0$. Then, we choose the solution with the smaller sum of the squared errors. In other words, our method is based on the insight that the sum of the squared errors is smaller (or larger) for the correct (or wrong) projector-camera correspondence.

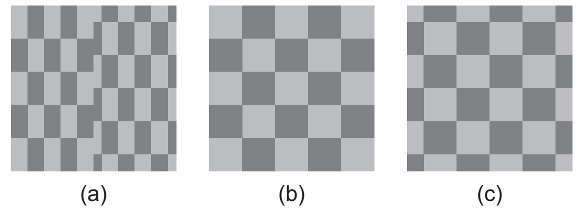


Figure 3. The 3D mode in the side-by-side format: (a) the input image to and (b)(c) the output images from a projector.

Thus, compared with Narasimhan *et al*. [10], our proposed method with the auto-calibration of the projector-camera correspondence does not require any additional equipment such as a half mirror and does not require cumbersome pre-calibration of the projector-camera correspondence. In addition, our method enables us to move a projector and a camera independently during shooting.

3.4. Optimization of projection pattern

The output intensities from a DLP projector, *i.e.* how the output intensities vary due to the color switch and the temporal dithering depends on the input intensities to the projector. Therefore, we can optimize the two input intensities of the checkered pattern in order to separate direct and global components accurately. We take the noises in the observed pixel intensities into consideration, and then optimize those input intensities on the basis of the condition numbers [13].

Specifically, we choose two blocks from the gray-scale image in Figure 1 (a), and denote the pixel intensities observed at the corresponding points on the white reflectance standard in the n-th image by a_n and b_n $(n = 1, 2, 3, ..., N)$. Then, we compute the condition numbers of the following matrices:

$$\begin{pmatrix} a_1 & (a_1 + b_1)/2 \\ a_2 & (a_2 + b_2)/2 \\ \vdots & \vdots \\ a_N & (a_N + b_N)/2 \end{pmatrix} \tag{7}$$

and

$$\begin{pmatrix} b_1 & (a_1 + b_1)/2 \\ b_2 & (a_2 + b_2)/2 \\ \vdots & \vdots \\ b_N & (a_N + b_N)/2 \end{pmatrix}. \tag{8}$$

Those condition numbers tell how much noises in the observations I_n propagate to the unknowns to be estimated L_d and L_g. We compute the condition numbers for all the pairs of the input intensities in 8 bit (from 0 to 255), and then select the optimal pair of the input intensities for which the sum of the condition numbers with respect to RGB colors is minimal. Note that smaller condition number is better.

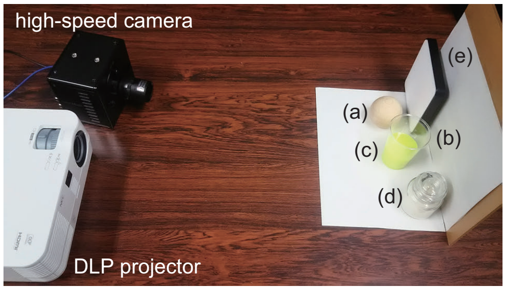


Figure 4. Our setup: the first scene is illuminated by a DLP projector and captured by a high-speed camera: (a) a wood ball, (b) a plastic cup, (c) slime, (d) wax in a bottle, and (e) the white reflectance standard (reference object).

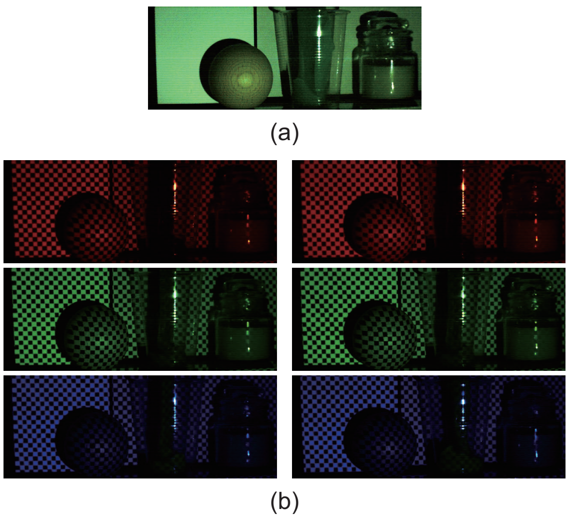


Figure 5. The captured images of the first scene: (a) the image of the scene illuminated by uniform projection pattern and (b) those illuminated by checkered projection patterns.

3.5. Use of 3D mode in side-by-side format

The simplest direct-global separation described in Subsection 3.1 uses two projection patterns; one is a black-and-white checkered patten and the other is its negative-positive reversed pattern. It is known that the simplest method often causes visible artifacts near the boundaries between the blocks of the checkered pattens because the spatial resolutions of a projector and a camera are limited. Nayar *et al*. [11] show that those artifacts can be reduced by using more than two projection patterns, *e.g.* spatially shifted patterns from the original checkered patten.

Accordingly, our proposed method makes use of the 3D mode in the side-by-side format, which is relatively common function even for consumer projectors, and then projects two spatially-shifted checkered patterns in practice. When a single image in Figure 3 (a) is input to the projector, the projector outputs (b) and (c) in turn[3]. Since we can distinguish the two spatially-shifted checkered patterns from the images of a reference object, we can realize the direct-global separation by using spatially-shifted projection patterns in a similar manner to the previous subsections.

4. Experiments

We implemented the prototype setup and achieved multispectral direct-global separation of dynamic scenes in 60 Hz. Please see our supplementary material for the result image sequences.

4.1. Experimental setup

In our experiments, we used a DLP projector NP-VE282 from NEC and a high-speed camera Fastcam Mini UX50 from Photron. The frame rate and the exposure time were set to 10,000 fps and 0.05 ms respectively. We conducted multispectral direct-global separation by using our proposed method for every 166 images, *i.e.* in 60 Hz.

The captured images were classified into the images illuminated only by each primary color, *i.e.* R, G, and B in our current setup by using the mean shift clustering. For solving eq.(5) or eq.(6), we used the images classified into each primary color. As described in Subsection 3.4, we optimized the two pixel intensities of the input checkered pattern, and then set them to 134 and 172.

4.2. Experimental results

Figure 4 shows the first scene which includes (a) a wood ball, (b) a plastic cup, (c) slime, (d) wax in a bottle, and (e) the white reflectance standard (reference object). The slime was running down into the cup during shooting. Figure 5 shows (a) the image of the scene illuminated by uniform projection pattern and (b) those illuminated by checkered projection patterns. We can see that the spatially-shifted checkered patterns with varying illumination colors and intensities are projected to the scene.

Figure 6 shows the result of our proposed method for the first scene: (a) the direct and (b) the global components of a certain frame of the result image sequence and (c)(d) those of another frame. The illumination colors are R, G, and B from top to bottom. We can see that the direct components include the specular reflection components on the cup and the bottle and the diffuse reflection components on the ball and the white reflectance standard. On the other hand, we can see that the global components include the subsurface scattering on the wax and the slime. Interestingly, we can observe that the slime radiates yellow light under blue illumination; it contains fluorescent material which absorbs

[3] In our current setup, the left-eye and the right-eye images quickly switch in 120 Hz. For the sake of simplicity, we do not take account of the nonlinear mapping from the input intensity to the output intensity in this illustration.

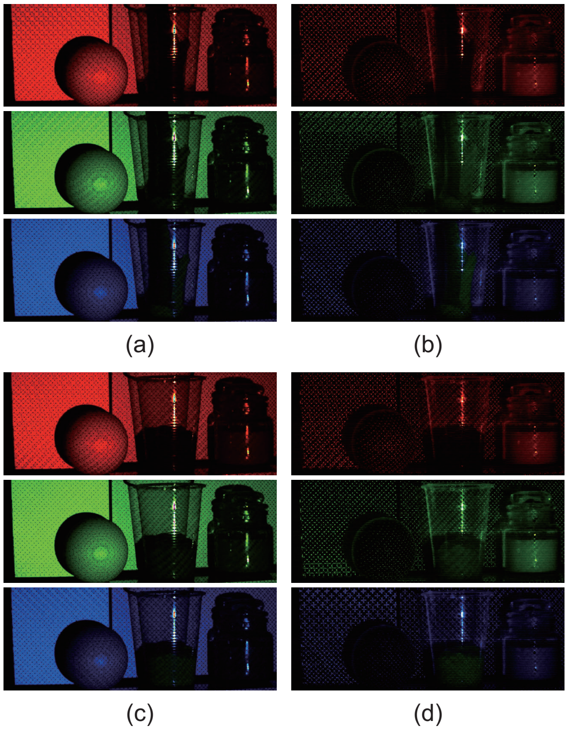


Figure 6. The result for the first scene: (a) the direct and (b) the global components of a certain frame of the result image sequence and (c)(d) those of another frame.

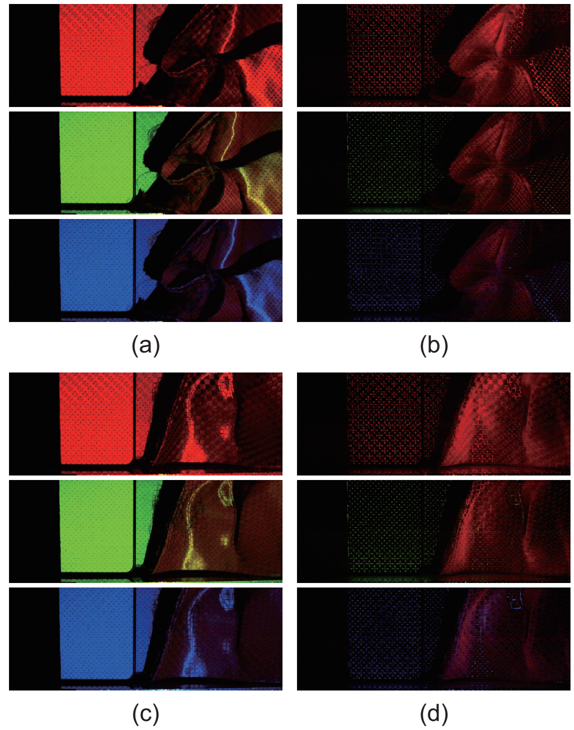


Figure 8. The result for the second scene: (a) the direct and (b) the global components of a certain frame of the result image sequence and (c)(d) those of another frame.

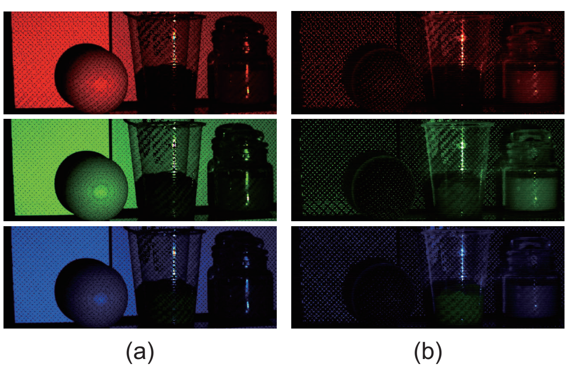


Figure 7. The result for the first scene with fixed correspondence: (a) the direct and (b) the global components of the same frame as Figure 6 (c)(d).

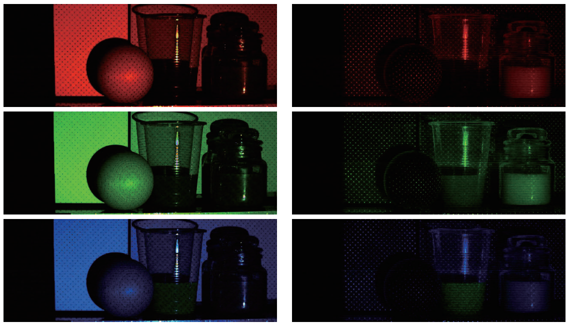
incident light at a certain wavelength, and then emits light at longer wavelengths than the incident one [2, 18]. One of the advantages of the multispectral direct-global separation is that it can capture wavelength-dependent phenomena such as fluorescent and translucent material.

Unfortunately, however, some artifacts are still visible mainly near the boundaries between the "white" and "black" blocks of the checkered projection pattern. The main reason would be the limited spatial resolution of the high-speed camera: 640×240. Another possible reason is that the projector has a shallow depth of field. For the above reasons, those boundaries are blurred, and then the pixel intensities deviates from eq.(3) or eq.(4) near the boundaries.

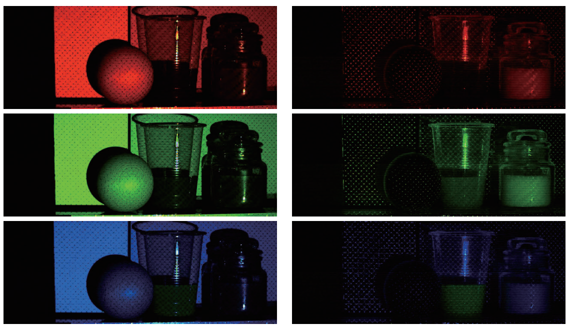
We show the result of our proposed method for the second scene in Figure 8. The target object is a cloth (fluorescent satin). Similar to the result for the first scene, we can observe fluorescence; the cloth appears reddish under B and G illumination colors. In addition, the interreflection among wrinkled surfaces is observed in the global components.

Projector-camera correspondence: Figure 7 shows the result when we assume a static scene. Specifically, we did not conduct our auto-calibration of projector-camera correspondence, but fixed the correspondence to that of the initial frame. When comparing the same frame of the result image sequence, *i.e.* comparing Figure 6 (c)(d) with Figure 7 (a)(b), we can see that some artifacts are visible near the upper half of the plastic cup in the result assuming a static scene. Since the slime is there in the initial frame, those artifacts are considered to be caused by object motion. Thus, we can confirm the effectiveness of our proposed method, which conducts dynamical auto-calibration of projector-camera correspondence.

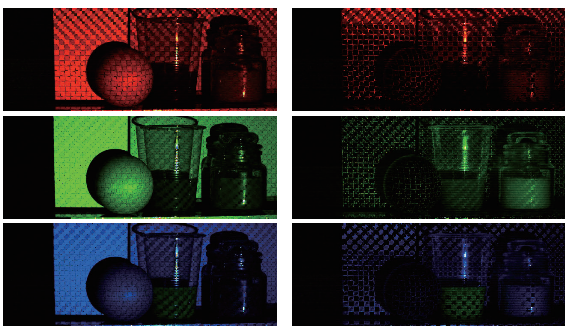
Projection pattern: Figure 9 shows the results of the direct-global separation, when we change the two pixel in-



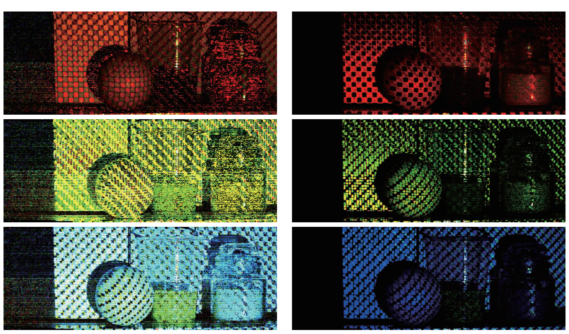
(a)



(b)



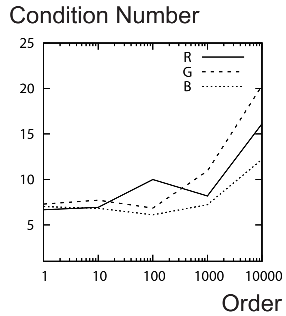
(c)



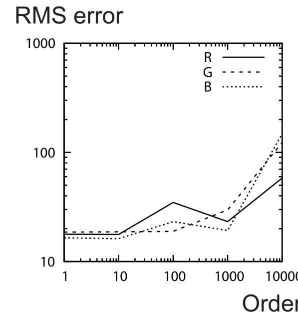
(d)

Figure 9. The direct (left) and the global (right) components: (a) the ground truth and the results using (b) the best, (c) the 100-th best, and (d) the 10000-th best projection patterns.

tensities of the checkered projection pattern. Specifically, we tested the best, the 100-th best, and the 10000-th best pairs of pixel intensities from ${}_{256}\mathrm{C}_2 = 32,640$ candidates. For fair comparison, we use a static scene, and consider the result when we use 4 black-and-white checkered projection patterns in a similar manner to the original direct-global separation method [11] as the ground truth. We can see qualitatively that the best and the 100-th best pairs work well, but the result using the 10000-th best pair is significantly degraded.



(a)



(b)

Figure 10. The numerical analysis: (a) the condition number and (b) the RMS error for each primary color vs. the order of the pair.

Figure 10 shows the numerical analysis: (a) the condition number and (b) the RMS error for each primary color vs. the order of the pair. We can see that the RMS error is correlated with the condition number. Thus, we can confirm the effectiveness of our proposed method, which optimizes a projection pattern on the basis of noise propagation analysis in terms of condition number.

5. Applications

We demonstrate that our proposed method is effective for image-based material editing and multispectral relighting of dynamic scenes where wavelength-dependent phenomena are observed. Please see our supplementary material for the result image sequences.

Image-based material editing: Figure 11 (a) shows the original images of a dynamic scene under white illumination. We can change the material perception of the scene by editing (b)(c) the ratio of the direct and global components and (d)(e) the color of fluorescence.

Multispectral relighting: Figure 12 shows the result of the multispectral relighting for (a) the direct and (b) the global components. Our proposed method enables us to change illumination color for each component by editing the weights of R, G, B images. The multispectral relighting for the direct and global components can be combined with image-based material editing.

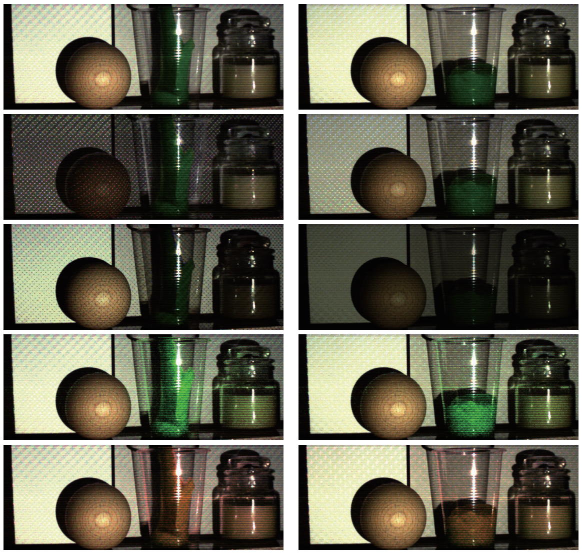


Figure 11. Application to image-based material editing: (a) the original images under white illumination, (b)(c) the ratio of the direct and global components and (d)(e) the color of fluorescence are edited.

Figure 12. Application to multispectral relighting: (a) the direct and (b) the global components.

6. Conclusion and Future Work

We proposed a fast, robust, and easy-to-implement method for separating direct and global components of a dynamic scene per illumination color. Specifically, our proposed method exploits the rapidly-varying illumination conditions due to both the color switch and the temporal dithering of a DLP projector. We conducted a number of experiments and showed that our method, in particular our auto-calibration of projector-camera correspondence and optimization of projection pattern work well. Furthermore, we demonstrated that our method is effective for applications such as image-based material editing and multispectral relighting of dynamic scenes where wavelength-dependent phenomena are observed. Our future study includes designing the color filters of the color wheel in a DLP projector, *i.e.* optimizing the number and SPDs of the primary colors for specific computer vision applications.

Acknowledgments

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