Acquiring 4D Light Fields of Self-Luminous Light Sources Using Programmable Filter

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Abstract. Self-luminous light sources in the real world often have nonnegligible sizes and radiate light inhomogeneously. Acquiring the model of such a light source is highly important for accurate image synthesis and understanding. In this paper, we propose a method for measuring 4D light fields of self-luminous extended light sources by using a liquid crystal (LC) panel, *i.e.* a programmable filter and a diffuse-reflection board. The proposed method recovers the 4D light field from the images of the board illuminated by the light radiated from a light source and passing through the LC panel. We make use of the feature that the transmittance of the LC panel can be controlled both spatially and temporally. The proposed method enables us to utilize multiplexed sensing, and therefore is able to acquire 4D light fields more efficiently and densely than the straightforward method. We implemented the prototype setup, and confirmed through a number of experiments that the proposed method is effective for modeling self-luminous extended light sources in the real world.

Keywords: self-luminous light source, extended light source, 4D light field, programmable filter, multiplexed sensing

1 Introduction

The appearance of an object depends not only on the geometric and photometric properties of the object but also on light sources illuminating the object. Therefore, acquiring the models of self-luminous light sources is highly important in the fields of computer graphics and computer vision, in particular for photorealistic image synthesis and accurate image-based modeling.

Conventionally, in the field of computer vision, ideal light sources such as directional light sources (point light sources at infinity) and isotropic point light sources are mostly assumed for photometric image analysis. Unfortunately, however, this is not the case; an object of interest is illuminated by nearby light sources, and more importantly, self-luminous light sources in the real world often have nonnegligible sizes, *i.e.* they are considered to be extended light sources and radiate light inhomogeneously. This means that the illumination distribution seen from a point on an object surface varies over the surface. Therefore, in order to analyze the shading observed on an object surface under real-world

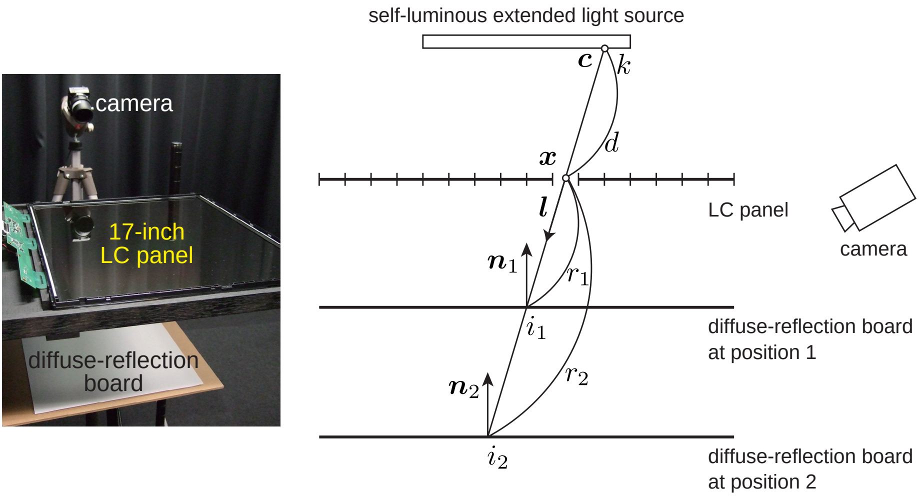

Fig. 1. Our proposed setup consisting of an LC panel and a diffuse-reflection board (left) and the sketch of its cross section (right).

extended light sources, we need to acquire the radiant intensity distributions of the light sources.

The difficulty in acquiring the radiant intensity distribution of an extended light source, which is described by a 4D light field [1], is that we need to measure a wide range of the light field. Note that consumer light field cameras are not suitable for such a purpose because their measurement ranges are limited. To cope with this problem, Goesele *et al.* [4] propose a setup consisting of a static optical filter and a diffuse-reflection board, and demonstrate the effectiveness of the setup for modeling extended light sources.

In this paper, we propose a method for acquiring the radiant intensity distribution of a self-luminous extended light source in the real world by using an LC panel, *i.e.* a programmable filter and a diffuse-reflection board as shown in Fig. 1. The key idea of the proposed method is to make use of the feature that the transmittance of the LC panel can be controlled both spatially and temporally. Specifically, the proposed method changes the transmittance patterns of the LC panel dynamically, and recovers the 4D light field from the images of the board illuminated by the light radiated from a light source and passing through the LC panel. In particular, the proposed method utilizes multiplexed sensing [11, 10, 15], which is a well-known technique for increasing signal-to-noise ratio (SNR) without increasing measurement time, and acquires 4D light fields more efficiently and densely than the straightforward method.

We implemented the prototype setup, and confirmed through a number of experiments that the proposed method can increase the SNR of the acquired images from which the 4D light field of a self-luminous extended light source is computed. In other words, the proposed method can acquire the models of self-luminous light sources in the real world more efficiently and densely than the straightforward method. The main contribution of this paper is to demonstrate that the proposed method using a programmable filter is effective for modeling self-luminous extended light sources in the real world.

The rest of this paper is organized as follows. We briefly summarize related work in Section 2. A method for acquiring 4D light fields of self-luminous extended light sources by using a programmable filter and a diffuse-reflection board is proposed in Section 3. We report the experimental results in Section 4 and present concluding remarks in Section 5.

2 Related Work

Existing techniques can be classified into 3 categories; (i) techniques for acquiring 2D radiant intensity distributions of self-luminous point light sources, (ii) techniques for acquiring 4D light fields of self-luminous extended light sources, and (iii) techniques for acquiring 4D light fields of general scenes. In this section, we briefly explain the existing techniques in each category, and then describe the relationship between those techniques and our proposed method.

2D radiant intensity distributions of self-luminous point light sources

Since the size of a point light source is negligible, the radiant intensity distribution of a self-luminous point light source is described by a 2D function, *i.e.* a function with respect to the direction seen from the center of the point light source. Verbeck and Greenberg [14] propose a basic method for measuring the 2D radiant intensity distributions of anisotropic point light sources by using a goniophotometer. Their method can directly sample the radiant intensity distribution of a light source by moving a sensor around the light source. However, their method requires a large amount of measurement time because it samples the radiant intensity distribution only at a single direction at a time.

To cope with this problem, image-based techniques, which can sample the radiant intensity distribution at a large number of directions simultaneously, are proposed. Rykowski and Kostal [9] propose an efficient method for measuring 2D radiant intensity distributions of LEDs by using the imaging sphere. They make use of the combination of a hemispherical chamber with diffuse coating and a hemispherical mirror, and capture the radiant intensity distribution with 2π steradian field of view at a time. Tan and Ng [12] use a diffuse translucent sheet and a flatbed scanner, and Moreno and Sun [5] use a diffuse translucent screen and a camera for efficiently capturing the 2D radiant intensity distributions of LEDs.

It is demonstrated that the above methods are useful for modeling real-world point light sources, in particular for inspecting LEDs. Unfortunately, however, we cannot use them for acquiring the 4D light fields of self-luminous extended light sources because they assume point light sources, *i.e.* light sources with negligible sizes.

4D light fields of self-luminous extended light sources

As mentioned in the introduction, the radiant intensity distributions of self-luminous extended light sources are described by 4D light fields. In a similar manner to Verbeck and Greenberg [14], Ashdown [3] proposes a basic method for measuring the 4D light field of a self-luminous light source by using a goniophotometer. However, his method requires a huge amount of measurement time because it samples the 4D distribution only at a single point in the 4D space at a time.

To cope with this problem, image-based techniques are proposed also for measuring 4D light fields. Goesele *et al.* [4] propose a method for measuring 4D light fields of self-luminous light sources by using an optical filter and a diffuse-reflection board. Their method recovers the 4D light field from the images of the board illuminated by the light radiated from an extended light source and passing through the optical filter. Although their method is suitable for measuring a wide range of a 4D light field and works well with an optimally-designed optical filter, it is not easy to acquire a 4D light field efficiently and densely because the optical filter is static and one has to slide the position of the light source (or the optical filter) manually during the measurement.

Aoto *et al.* [2] propose a method for recovering the 4D light field of a self-luminous light source from the images of a diffuse-reflection board moving in front of the light source. Their method is unique in the sense that it does not require any static or dynamic filters but use only a diffuse-reflection board. However, it would be difficult to stably recover the high-frequency components of the 4D light field from the images of the diffuse-reflection board because diffuse reflectance behaves like a low-pass filter [8].

4D light fields of general scenes

Other than the above techniques specialized for measuring the 4D light fields of self-luminous extended light sources, there are a number of techniques for acquiring 4D light fields of general scenes. Since it is impossible to cover all the existing techniques due to limited space, we briefly mention the advantages and limitations of some of representative approaches when they are used for measuring the 4D light fields of self-luminous extended light sources.

One approach to general 4D light field acquisition is to use a spherical mirror array [13] and a camera array [16]. Those methods have the advantage that they can measure the wide range of the 4D light field of a self-luminous extended light source. However, they are not suited for densely measuring the 4D light field because it is not easy to place spherical mirrors and cameras densely.

Another approach to general 4D light field acquisition is to use a single camera with a micro-lens array [6] and a coded aperture [7]. Those methods have the advantage that they can measure the 4D light field of a self-luminous extended light source densely. However, they are not suited for measuring the wide range of the 4D light field because their measurement ranges are limited. Note that the objective of our study is not to acquire the incoming intensity distribution to a small area in a scene but to acquire the outgoing intensity distribution from an extended light source. In general, light field cameras are suited for the former purpose but are not suited for the latter purpose.

3 Proposed Method

3.1 Light Source Model

Fig. 1 shows the cross section of our proposed setup which consists of a pair of an LC panel and a diffuse-reflection board. Actually, we place the light source close to the LC panel as much as possible so that we can acquire a wider range of the light field. Our proposed method acquires the description of the light passing through a point $\boldsymbol{x}$ on the LC panel toward a direction $\boldsymbol{l}$ by using the images of the diffuse-reflection board illuminated by the transmitted light. For the reason described below, we move the diffuse-reflection board and observe the reflection of the transmitted light on the board twice at the positions 1 and 2. Note that we assume that a light source radiates unpolarized light since the transmittance of an LC panel depends on polarization state[3].

We assume that a self-luminous extended light source is approximately represented by a set of anisotropic point light sources, and therefore the light passing through $\boldsymbol{x}$ toward $\boldsymbol{l}$ comes from an unknown anisotropic point light source $\boldsymbol{c}$. We denote the surface normal and distance of the board at the first position by $\boldsymbol{n}_1$ and r_1, and those at the second position by $\boldsymbol{n}_2$ and r_2. We assume that the geometry of the setup is calibrated in advance, *i.e.* we assume that those surface normals and distances are known. On the other hand, there are two unknowns; one is the distance d between $\boldsymbol{x}$ and the point light source $\boldsymbol{c}$, and the other is the radiant intensity k of the light source toward the direction $\boldsymbol{l}$. Our proposed method estimates those two parameters for each $(\boldsymbol{x}, \boldsymbol{l})$ by using two radiances observed on the diffuse-reflection board at the positions 1 and 2.

When the diffuse-reflection board is placed at the first position, the radiance i_1 of the reflected light is given by[4]

$$i_1 = k\frac{(-\boldsymbol{l})^\top \boldsymbol{n}_1}{(d + r_1)^2}, \tag{1}$$

assuming the Lambertian model and the attenuation according to the inverse-square law[5]. Similarly, when the board is placed at the second position, the radiance i_2 is given by

$$i_2 = k\frac{(-\boldsymbol{l})^\top \boldsymbol{n}_2}{(d + r_2)^2}. \tag{2}$$

Taking the ratio of eq.(1) and eq.(2), we can derive

$$\frac{(d + r_1)^2}{(d + r_2)^2} = \frac{i_2}{i_1}\frac{(-\boldsymbol{l})^\top \boldsymbol{n}_1}{(-\boldsymbol{l})^\top \boldsymbol{n}_2} \equiv \alpha. \tag{3}$$

[3] One could use a depolarizing filter in front of the LC panel.

[4] In general, the transmittance of an LC panel depends on the direction of incident light. Since we used an LC display with a wide viewing angle of 165° in our experiments, we do not take the angle-dependency into consideration.

[5] This description is more complicated than that of the 4D light field because we take the distance from an anisotropic point light source into consideration.

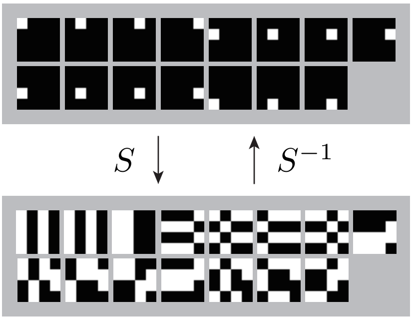

Fig. 2. The filters for the straightforward measurement (top) and the multiplexed measurement (bottom). Here, $n = 15$ for display purpose.

Thus, we can estimate one of the unknowns d as

$$d = \frac{\sqrt{\alpha} r_2 - r_1}{1 - \sqrt{\alpha}}. \tag{4}$$

Substituting eq.(4) into eq.(1) and/or eq.(2), we can estimate the other unknown k.

3.2 Straightforward Measurement

The straightforward method for measuring the light field of a self-luminous extended light source is to capture the images of the diffuse-reflection board at the first and second positions by using a set of *single filters* shown in the top of Fig. 2. Specifically, we divide an area of interest of the LC panel into n square patches, and then set the transmittance of a single patch to 1 and those of the other patches to 0 at a time in turn. The advantage of using a programmable filter, *i.e.* an LC panel in our case, is that we can control the transmittance both spatially and temporally without direct manual manipulation.

Unfortunately, however, such a straightforward measurement has limitations. In order to acquire light fields more densely, we need to make the size of each patch smaller. Since the transmittance of only a single patch is 1 in the straightforward measurement, the smaller the size of each patch is, the smaller the amount of light passing through the LC panel and reflected on the diffuse-reflection board is. Therefore, if we make the size of each patch smaller while keeping the measurement time constant, the SNRs of the captured images decrease and then the accuracy of the recovered light field is also degraded. On the other hand, if we make the size of each patch smaller while keeping the SNRs of the captured images constant, we need a longer exposure time for each image and then we need longer total measurement time. Hence, the straightforward measurement has a tradeoff between its accuracy and efficiency.

3.3 Multiplexed Measurement

To cope with the limitations of the straightforward measurement, our proposed method makes more use of the feature that the transmittance of the LC panel can be controlled both spatially and temporally. Our method utilizes multiplexed sensing [11, 10, 15], which is a well-known technique for increasing SNR without increasing measurement time, and acquires 4D light fields more efficiently and densely than the straightforward method.

Specifically, we use the *multiplexed filters* in which the transmittances of about half of the patches are 1 and those of the other patches are 0 as shown in the bottom of Fig. 2, and capture the images of the diffuse-reflection board illuminated by the transmitted light. We can obtain those n multiplexed filters by applying the so-called S-matrix, which is constructed on the basis of the Hadamard matrix of order $(n + 1)$, for n individual filters. In an opposite manner, we can obtain the single filters by applying the inverse matrix S^{-1} to the multiplexed filters. Therefore, by applying S^{-1} to the captured images of the diffuse-reflection board under the multiplexed filters, we can obtain the decoded images under the single filters. It is known that S^{-1} can be computed analytically: $S^{-1} = 2(2S^\top - 1_n)/(n+1)$, where 1_n is an $n \times n$ matrix whose all elements are 1. See Sloane *et al.* [11] for more detail.

It is known that the ratio of the SNR of multiplexed sensing $\mathrm{SNR}_{\mathrm{multi}}$ and that of single sensing $\mathrm{SNR}_{\mathrm{single}}$ is at most

$$\frac{\mathrm{SNR}_{\mathrm{multi}}}{\mathrm{SNR}_{\mathrm{single}}} \simeq \frac{\sqrt{n}}{2}, \tag{5}$$

when n, *i.e.* the number of the patches in our case, is large enough. Therefore, the proposed method based on multiplexed sensing can acquire light fields more efficiently and densely than the straightforward method while keeping the SNR constant.

4 Experiments

4.1 Multiplexed Sensing

To demonstrate the effectiveness of multiplexed sensing, we compared the images of the diffuse-reflection board captured and decoded by multiplexed sensing with those captured by single sensing. We used a fluorescent light located nearby the LC panel and set the number of patches n to 63. Because a small amount of light passes through the LC panel even though the transmittance is set to 0, we captured an image when all the transmittances are set to 0 and then subtracted this image from all the images captured under the single and multiplexed filters.

Fig. 3 shows the example images of the diffuse-reflection board under a certain single filter taken with a fixed exposure time. We consider the average of 1000 images taken under the same condition as the ground truth (left). We can see that the image captured by single sensing (middle) is grained due to noise. On

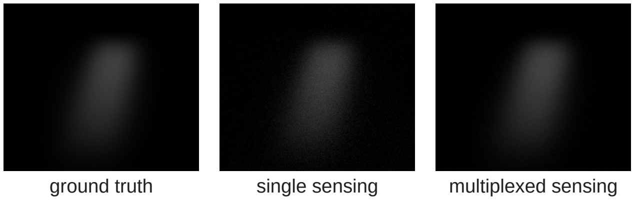

Fig. 3. The example images of the diffuse-reflection board under a single filter; the ground truth computed by averaging, the captured image by single sensing, and the captured and decoded image by multiplexed sensing from left to right. Pixel values are scaled for display purpose.

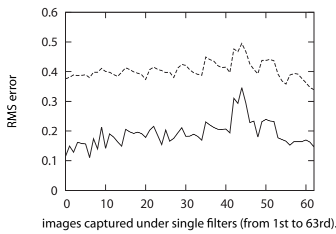

Fig. 4. The RMS errors of the images of the diffuse-reflection board under the single filters; captured by the straightforward measurement (dotted line) and captured and decoded by the multiplexed measurement (solid line).

the other hand, we can see that the image captured and decoded by multiplexed sensing is similar to the ground truth. This result qualitatively demonstrates that our proposed method based on multiplexed sensing works better than the straightforward method based on single sensing.

In addition, we conducted quantitative evaluation. Fig. 4 shows the RMS errors of the images of the diffuse-reflection board under all the single filters. We can see that the RMS errors of the captured and decoded images by multiplexed sensing (solid line) are always smaller than those of captured images by single sensing (dotted line) although the gain of multiplexed sensing, *i.e.* $\mathrm{SNR}_{\mathrm{multi}}/\mathrm{SNR}_{\mathrm{single}} \simeq 0.40/0.19 \simeq 2.1$ is smaller than the theoretical upper limit $\sqrt{n}/2 \simeq 4.0$. This result quantitatively demonstrates that the proposed method based on multiplexed sensing works better than the straightforward method based on single sensing.

4.2 Image Reconstruction

To demonstrate the effectiveness of the proposed method, we acquired the 4D light fields of three light sources and used them for image reconstruction. In this experiment, as described in Section 3, we acquired the light fields from the images of the diffuse-reflection board at the positions 1 and 2 by using the straightforward method based on single sensing and the proposed method based

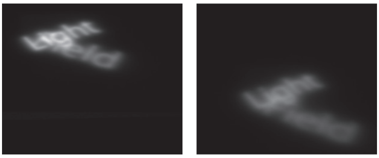

Fig. 5. The images of the diffuse-reflection board placed at the positions 1 (left) and 2 (right) for measurement under two projectors.

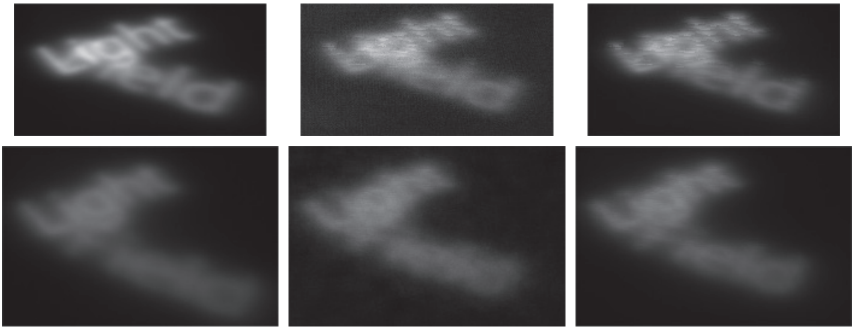

Fig. 6. The reconstruction results on the two projectors. The closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom); the ground truth image (left) and the reconstructed images by using single sensing (middle) and multiplexed sensing (right).

on multiplexed sensing. Then, we reconstructed the images of the board at two positions different from those for measurement, say positions 3 and 4, when the transmittances of all the patches are set to 1 by using the acquired light fields. Specifically, the intensity of each pixel in the reconstructed image is computed by assuming that the corresponding surface point is illuminated by n anisotropic point light sources whose intensities and distances are estimated as described in Section 3.1.

The first light source is two projectors. Fig. 5 shows the images of the diffuse-reflection board placed at the positions 1 (left) and 2 (right) for measurement. The transmittances of all the patches are set to 1 for display purpose. We can see that the characters of "Light" radiated from one projector cross the characters of "Field" radiated from another projector.

Fig. 6 shows the closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom); the ground truth images and the reconstructed images by using single sensing and multiplexed sensing from left to right. Here, the number of patches n is 255. We can see that both the straightforward method and the proposed method can capture how the characters radiated from the two projectors cross according to the distance from the projectors. Furthermore, we

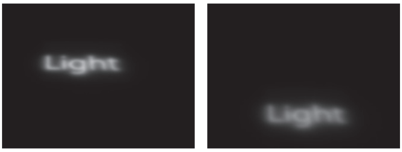

Fig. 7. The images of the diffuse-reflection board placed at the positions 1 (left) and 2 (right) for measurement under a single projector.

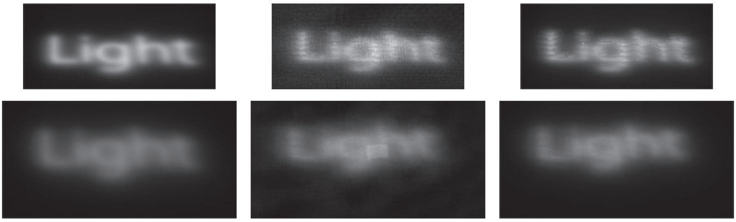

Fig. 8. The reconstruction results on the single projector. The closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom); the ground truth image (left) and the reconstructed images by using single sensing (middle) and multiplexed sensing (right).

can see that the images reconstructed by using the proposed method based on multiplexed sensing are less noisy than the images reconstructed by using the straightforward method based on single sensing. Although some artifacts due to the discretization (the number of patches $n = 255$ is not necessarily large enough) and errors in geometric calibration are still visible, this result demonstrates that the proposed method works better than the straightforward method.

The second light source is a single projector. Fig. 7 shows the images of the diffuse-reflection board placed at the positions 1 (left) and 2 (right) for measurement. We can see that the characters of "Light" radiated from the projector is in focus and out of focus depending on the distance from the projector.

Fig. 8 shows the closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom); the ground truth images and the reconstructed images by using single sensing and multiplexed sensing from left to right. Here, the number of patches n is 255. We can see that both the straightforward method and the proposed method can capture how the characters radiated from the projector blur according to the distance from the projector. Similar to the above, we can see that the images reconstructed by using the proposed method are less noisy than the images reconstructed by using the straightforward method.

The third light source is an electric torch which consists of three LEDs. Fig. 9 shows the images of the diffuse-reflection board placed at the positions 1 (left)

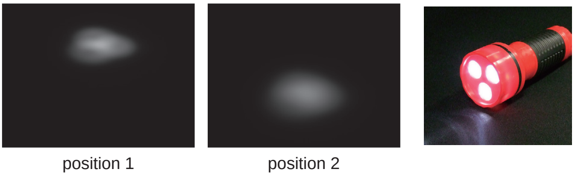

Fig. 9. The images of the diffuse-reflection board placed at the positions 1 (left) and 2 (right) for measurement under an electric torch.

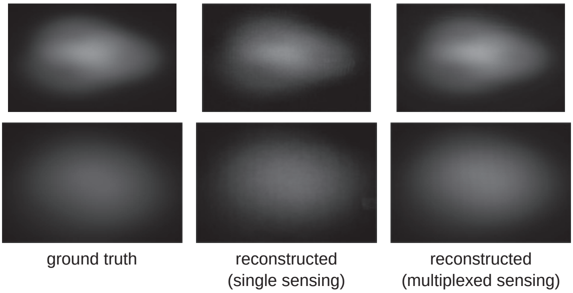

Fig. 10. The reconstruction results on the electric torch. The closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom); the ground truth image (left) and the reconstructed images by using single sensing (middle) and multiplexed sensing (right).

and 2 (right) for measurement. We can see that the lights radiated from the three LEDs cross each other depending on the distance from the torch.

Fig. 10 shows the closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom); the ground truth images and the reconstructed images by using single sensing and multiplexed sensing from left to right. Here, the number of patches n is 255. We can see that both the straightforward method and the proposed method can capture how the lights radiated from the three LEDs cross each other according to the distance from the torch. Similar to the above, we can see that the images reconstructed by using the proposed method are less noisy than the images reconstructed by using the straightforward method.

5 Conclusions and Future Work

In this paper, we proposed a method for measuring 4D light fields of self-luminous extended light sources by using an LC panel, *i.e.* a programmable filter and a diffuse-reflection board. Our proposed method recovers the 4D light field from the images of the board illuminated by the light radiated from an extended light source and passing through the LC panel. Our method makes use of the feature that the transmittance of the LC panel can be controlled both spatially and temporally, and recovers 4D light fields efficiently and densely on the basis of multiplexed sensing. We implemented the prototype setup, and confirmed through a number of experiments that the proposed method works better than the straightforward measurement.

One direction of future study is to use more sophisticated filters, *e.g.* filters for adaptive sampling and compressive sensing. Another direction of future study is the applications of the acquired light fields to computer vision problems such as image-based modeling.

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