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PAPER

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

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SUMMARY 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 an approach to measuring 4D light fields of self-luminous extended light sources by using a liquid crystal (LC) panel, *i.e.* a programmable optical filter and a diffuse-reflection board. The proposed approach 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 approach enables multiplexed sensing and adaptive 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 our approach is effective for modeling self-luminous extended light sources in the real world.

key words: *4D light field, extended light source, programmable filter, multiplexed sensing, adaptive sensing*

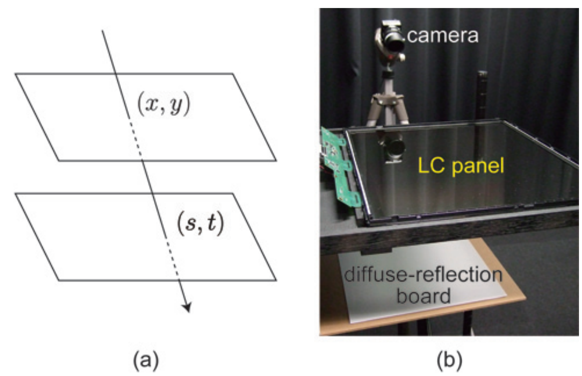

Fig. 1 (a) One of the representations of a 4D light field, and (b) our proposed setup consisting of an LC panel and a diffuse-reflection board.

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, most often ideal light sources such as directional light sources (point light sources at infinity) and isotropic point light sources are assumed for photometric image analysis. Unfortunately, however, this is not the case; an object of interest is often 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 extended light sources, we need to acquire the radiant intensity distributions of the light sources.

The radiant intensity distribution of an extended light source is described by a 4D light field [3] which is represented by the amount of light passing through the pair of points (x, y) and (s, t) on two planes in general position as shown in Fig. 1 (a). The difficulty in acquiring the radiant intensity distribution of an extended light source 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 of their limited entrance pupil. 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 an efficient approach to acquiring the radiant intensity distribution of a self-luminous extended light source by using an LC panel, *i.e.* a *programmable* optical filter and a diffuse-reflection board as shown in Fig. 1 (b). The key idea of the proposed approach is to make use of the feature that the transmittance of the LC panel can be controlled both spatially and temporally. Specifically, the approach changes the transmittance patterns of the LC panel dynamically, and recovers the 4D light field of a self -luminous extended light source from the images of the board illuminated by the light radiated from the light source and passing through the LC panel.

In the preliminary version of this paper [6], we propose a method based on multiplexed sensing [11], [12], [16], which is a well-known technique for increasing signal-to-noise ratio (SNR) without increasing measurement time, for

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acquiring 4D light fields more efficiently than the straightforward method. The proposed method divides an area of interest of the LC panel into small patches with the same size, *i.e.* measures the 4D light field of an extended light source with uniform spatial resolution. Unfortunately, however, the measurement with uniform spatial resolution is not suited for efficiently acquiring the 4D light field; the high-frequency components of the 4D light field are often lost, or the number of patches and measurement time increase in order to acquire those high-frequency components.

Accordingly, we further make use of the feature of the programmable filter, and propose a method for acquiring the 4D light field of a self-luminous extended light source with non-uniform spatial resolution. Specifically, the proposed method measures the 4D light field by using a small number of patches with large size at first, and then iteratively divides important patches into smaller ones and measures the 4D light field adaptively by using them. That is, the proposed method adaptively and non-uniformly increases the spatial resolution according to the radiant intensity distribution of a light source of interest.

We implemented the prototype setup, and confirmed through a number of experiments that our multiplexed method can acquire the 4D light field of a self-luminous extended light source more efficiently than the straightforward method. In addition, we confirmed that our adaptive method can densely acquire the 4D light field by using a smaller number of patches, *i.e.* in a shorter measurement time than our multiplexed method. The main contribution of this paper is to demonstrate that our proposed approach 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 Sect. 2. An approach to acquiring 4D light fields of self-luminous extended light sources by using a programmable filter and a diffuse-reflection board is proposed in Sect. 3. We report the experimental results in Sect. 4 and present concluding remarks in Sect. 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 approach.

Acquisition of 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 [15] 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 [10] 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 [13] 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.

Acquisition of 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 [15], Ashdown [2] proposes a basic method for measuring the 4D light field of a self-luminous extended 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 the 4D light field of a self-luminous extended light source by using an optical filter and a diffuse-reflection board as illustrated in Fig. 2 (a). Their method recovers the 4D light field from the images of the board illuminated by the light radiated from the light source and passing through the optical filter. Although their

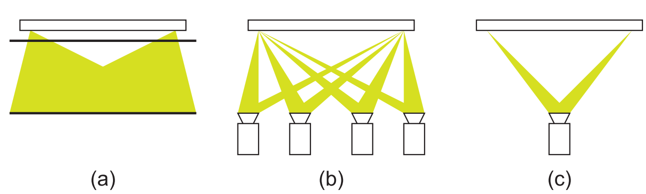


Fig. 2 The rays radiated at two points on the surface of a self-luminous extended light source are captured by each setup: (a) an optical filter and a diffuse reflection board, (b) a camera array, and (c) a light field camera.

method is suitable for measuring the 4D light field in a wide range and works well with the optimally-designed optical filter, it is not easy to acquire the 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.* [1] propose a method for recovering the 4D light field of a self-luminous extended 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 uses 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 [9].

Acquisition of 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 [14] and a camera array [17]. Those methods have the advantage that they can measure the wide range of the 4D light field of an extended light source as illustrated in Fig. 2 (b). 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 light field camera with a micro-lens array [7] and a coded aperture [8]. Those methods have the advantage that they can measure the 4D light field of a self-luminous extended light source easily. However, they are not suited for measuring the wide range of the 4D light field because of their limited entrance pupil as illustrated in Fig. 2 (c). 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 Approach

3.1 Light Source Model

Figure 3 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 a light source of interest as close as possible to the LC panel so that we can acquire the 4D light field of the light source in a wider range. Our proposed method acquires the description of the light passing through a point $\boldsymbol{x}$ on the LC panel toward a direction $\boldsymbol{l}$

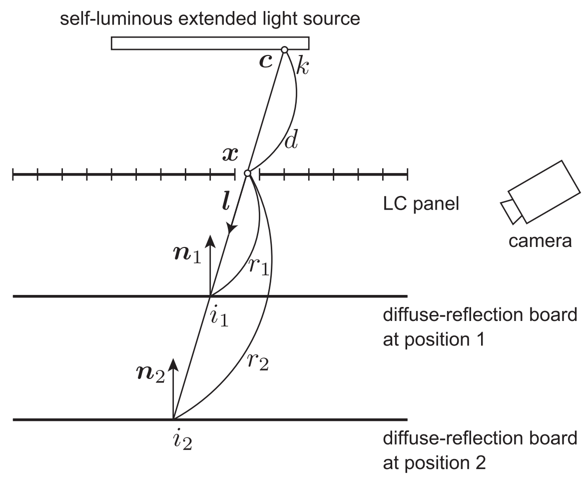


Fig. 3 The cross section of our proposed setup. Two positions are used in order to solve for two unknowns: the distance d and the radiant intensity k of a light source.

by using the images of the diffuse-reflection board illuminated by the transmitted light. In order to solve for two unknowns as 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[†].

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[††]

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

assuming the Lambertian model and the attenuation according to the inverse-square law[†††]. Similarly, when the board

[†]When a light source radiates polarized light, one could use a depolarizing filter in front of the LC panel.

[††]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.

[†††]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.

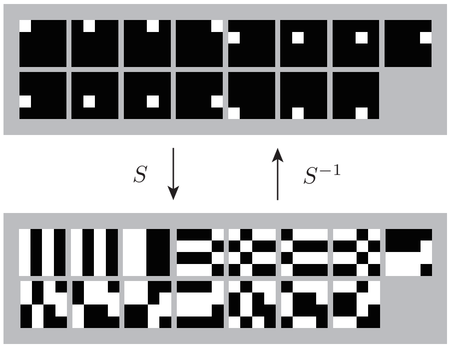


Fig. 4 The filters for the straightforward method (top) and the multiplexed method (bottom). Here, $n = 15$ for display purpose.

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

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

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 Method

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. 4. 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 method has limitations. In order to acquire 4D 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 method, 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 method has a tradeoff between its accuracy and efficiency.

3.3 Multiplexed Method

To cope with the limitations of the straightforward method, we propose a multiplexed method that 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], [12], [16], 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. 4, 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.* [12] for more detail.

The ratio between 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 4D light fields more efficiently and densely than the straightforward method while keeping the SNR constant.

3.4 Adaptive Method

Both the straightforward method and multiplexed method divide an area of interest of the LC panel into small patches with the same size, *i.e.* measure the 4D light field of a self-luminous extended light source with uniform spatial resolution. Unfortunately, however, extended light sources radiate light inhomogeneously, and therefore both the amount of light and the angular distribution of light passing through each patch are not uniform across the LC panel. Therefore, the measurement with uniform spatial resolution is not suited for efficiently acquiring the 4D light field; the high-frequency components of the 4D light field are often lost, or the number of patches and measurement time increase in order to acquire those high-frequency components.

Accordingly, we propose an adaptive method for acquiring the 4D light field of an extended light source with non-uniform spatial resolution. Specifically, the proposed method measures the 4D light field by adaptively dividing some important patches into smaller ones as follows.

1. Setting the initial number of patches to n_0 and conducting the multiplexed measurement.
2. Selecting the most important m patches and dividing each of them into 4 small patches. Thus, the number of patches is increased by $3m(= 4m - m)$.
3. Conducting the multiplexed measurement for the newly-divided $4m$ patches. Here, the number of required images is $3m^{\dagger}$.
4. Repeating 2 and 3 while the total number of patches is less than the predetermined number n.

We define the importance of a patch on the basis of the image of the diffuse-reflection board when only the transmittance of the patch is 1. More specifically, we compute the discrete Fourier transform of the image and define the importance as

$$\sum_{u,v} |F(u, v)|^2 \sqrt{u^2 + v^2}. \tag{6}$$

Here, u and v are the spatial frequencies, and $|F(u, v)|^2$ is the power spectral density of the image. That is, the importance is the weighted average of the power spectral density with the weight $\sqrt{u^2 + v^2}$ for emphasizing high-frequency components. Therefore, the brighter the image is, and/or the more high-frequency components the image has, the more important the corresponding patch is.

3.5 Comparison between Multiplexed and Adaptive Methods

Then, we compare our multiplexed method and adaptive method, and discuss their advantages and disadvantages when the total number of patches is n. First, since the number of required images is equal to the number of patches, the both methods require the same measurement time if the exposure time for capturing each image is the same. Second, as to the computational cost, we compare the cost for demultiplexing, that is the most time consuming computation in the both methods. In our multiplexed method, the cost is $O(n^2)$ since the product between a $n \times n$ matrix and n-dimensional vector is computed. In our adaptive method, we iteratively divide important patches and conduct multiplexed measurement $(n - n_0)/(3m)$ times, and therefore the demultiplexing cost is $O(n_0^2 + (3m)^2 \times (n - n_0)/(3m))$. Assuming that $n \gg n_0$ and $n_0 \simeq m$, the computational cost is $O(nm)$. Since $n \gg m$, the computational cost of the adaptive method is smaller than that of the multiplexed method. Finally, the gains of the SNRs of the multiplexed method and adaptive method are about $\sqrt{n}/2$ and $\sqrt{3m}/2$ respectively from Eq. (5). Therefore, the multiplexed method is better than the adaptive method in terms of SNRs. If the SNR of the adaptive method is not sufficient, we can conduct the multiplexed measurement with the adaptively divided filter although additional time is required.

†The amount of light passing through a single parent patch is equal to the amount of light passing through the corresponding 4 child patches.

4. Experiments

In our setup, we used an LC panel of LCD-AD172SE from I-O DATA whose resolution and DPI are 1280×1024 and 96 respectively. The images of the diffuse-reflection board were captured by using CMLN-13S2C-CS from Point Grey with 1296×964 resolution.

4.1 Effects of Multiplexed Method

To confirm 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 the image from all the images captured under the single and multiplexed filters.

Figure 5 shows the example images of the diffuse-reflection board under a certain single filter taken with a fixed exposure time. Here, the single filter is on the x-y plane and the diffuse-reflection board is on the s-t plane in Fig. 1 (a). Therefore, those images show how the light passing through the single filter on one plane from various directions propagate to various positions on another plane. We consider the average of 1000 images taken under the same condition as the ground truth (a). We can see that the image captured by single sensing (b) is grained due to noise. On the other hand, we can see that the image captured and decoded by multiplexed sensing (c) is similar to the ground truth. This result qualitatively shows that multiplexed sensing works better than single sensing.

In addition, we conducted quantitative evaluation. Figure 6 shows the RMS errors of the images of the diffuse-reflection board under all the single filters. We can see that

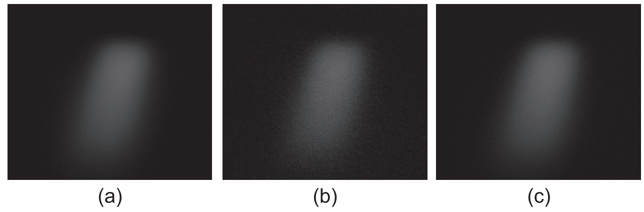


Fig. 5 The example images of the diffuse-reflection board under a single filter: (a) the ground truth computed by averaging, (b) the captured image by single sensing, and (c) the captured and decoded image by multiplexed sensing. Pixel values are scaled for display purpose.

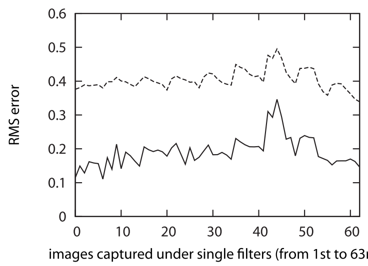


Fig. 6 The RMS errors of the images of the diffuse-reflection board under the single filters: captured by the single sensing (dotted line) and captured and decoded by the multiplexed sensing (solid line).

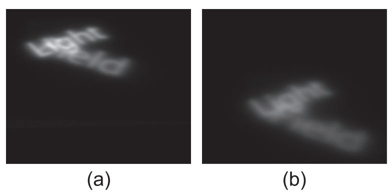


Fig. 7 The images of the diffuse-reflection board placed at (a) the position 1 and (b) the position 2 for measurement under two projectors.

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 shows that multiplexed sensing works better than single sensing.

Next, to demonstrate the effectiveness of our multiplexed method, we acquired the 4D light fields of two different light sources and used them for image reconstruction. As described in Sect. 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 and the multiplexed method. 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 Sect. 3.1. In this experiment, we set the number of patches n to 255.

The first light source is two projectors: NP-L51WJD from NEC with 1280×800 resolution. Figure 7 shows the images of the diffuse-reflection board placed at (a) the position 1 and (b) the position 2 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.

Figure 8 shows the closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth images and the reconstructed images by using (b) the straightforward method and (c) the multiplexed method. We can see that both the straightforward method and multiplexed method can capture how the characters radiated from the two projectors cross according to the distance from the projectors. Furthermore, we can see that the images reconstructed by using the multiplexed method are less noisy than the images reconstructed by the straightforward method. 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.

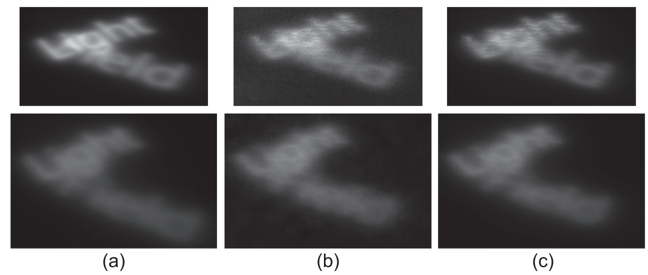


Fig. 8 The reconstruction results on the two projectors. The closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth image and the reconstructed images by using (b) the straightforward method and (c) the multiplexed method.

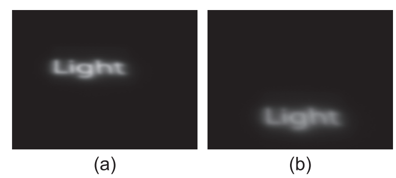


Fig. 9 The images of the diffuse-reflection board placed at (a) the position 1 and (b) the position 2 for measurement under a single projector.

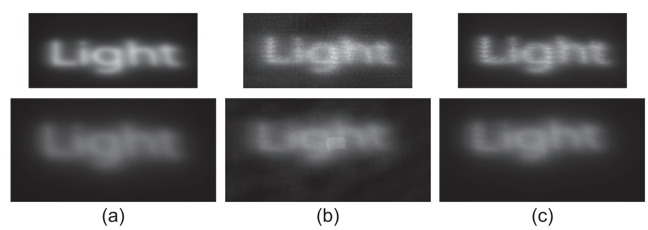
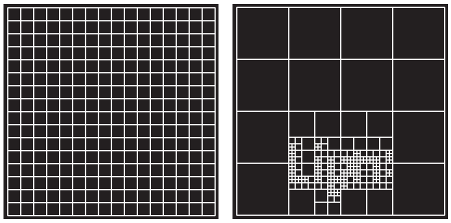


Fig. 10 The reconstruction results on the single projector. The closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth image and the reconstructed images by using (b) the straightforward method and (c) the multiplexed method.

The second light source is a single projector. Figure 9 shows the images of the diffuse-reflection board placed at (a) the position 1 and (b) the position 2 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 due to a shallow depth of field.

Figure 10 shows the closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth images and the reconstructed images by using (b) the straightforward method and (c) the multiplexed method. We can see that both the straightforward method



(a) (b)

Fig. 11 The filters used for acquiring the 4D light field of a projector by using (a) the multiplexed method and (b) the adaptive method.

(a) (b) (c)

Fig. 12 The reconstruction results on the projector. The closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth image and the reconstructed images by using (b) the multiplexed method and (c) the adaptive method. Note that the projector position and the character size are different from Fig. 10.

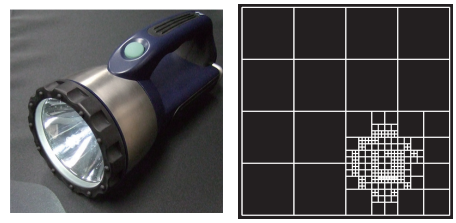
and multiplexed method can capture how the characters radiated from the projector blur according to the distance from the projector. This result shows that acquiring light fields is effective even for a single projector, which is often treated as a light source with negligible size. Similar to the above, we can see that the images reconstructed by using the multiplexed method are less noisy than the images reconstructed by using the straightforward method.

4.2 Effects of Adaptive Measurement

To demonstrate the effectiveness of our adaptive method, we acquired the 4D light fields of two different light sources and used them for image reconstruction in a similar manner to Sect. 4.1. In this experiment, we set $n = 255$, $n_0 = 15$, and $m = 4$.

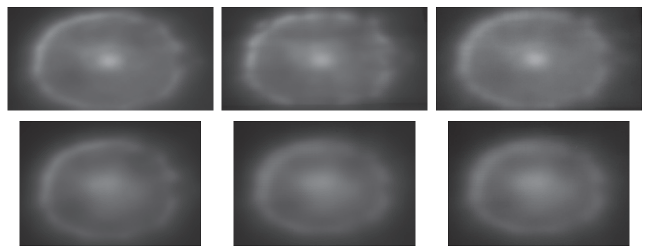
The first light source is a single projector. Figure 11 shows the filters used for acquiring the 4D light field of the projector by using (a) the multiplexed method and (b) the adaptive method. We can see that the filter for the adaptive method is divided according to the characters of “Light” radiated from the projector as we expected. Figure 12 shows the closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth images and the reconstructed images by using (b) the multiplexed method and (c) the adaptive method. We can see that our adaptive method works well, whereas some artifacts due to uniform spatial resolution on the LC panel are visible in the reconstructed images by using the multiplexed method, in particular in the top of (b).

The second light source is a large electric torch. Figure 13 shows (a) the image of the large electric torch and (b) the adaptive filter for acquiring the 4D light field of the torch. We can see that the filter for the adaptive method is divided almost symmetrically with respect to the center of the rays radiated from the torch. Figure 14 shows the closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth images and the reconstructed images by using (b) the multiplexed method and (c) the adaptive method. Similar to the above, we can see that artifacts due to uniform spatial resolution on the LC panel are visible in the reconstructed images by using the multiplexed method.



(a) (b)

Fig. 13 (a) The image of the large electric torch and (b) the adaptive filter for acquiring the 4D light field of the torch.



(a) (b) (c)

Fig. 14 The reconstruction results on the large electric torch. The closeup images of the diffuse-reflection board at the positions 3 (top) and 4 (bottom): (a) the ground truth image and the reconstructed images by using (b) the multiplexed method and (c) the adaptive method.

5. Conclusion and Future Work

In this paper, we proposed an approach to measuring the 4D light field of a self-luminous extended light source by using an LC panel, *i.e.* a programmable filter and a diffuse-reflection board. The approach 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 proposed methods make use of the feature that the transmittance of the LC panel can be controlled both spatially and temporally, and recover 4D light fields efficiently and densely on the basis of multiplexed sensing and adaptive sensing. We implemented the prototype setup, and confirmed through a number of experiments that the proposed approach is effective for modeling self-luminous extended light sources in the real world.

The future work of this study includes the applications of the acquired light fields to computer graphics problems such as photorealistic image synthesis and computer vision problems such as image-based modeling.

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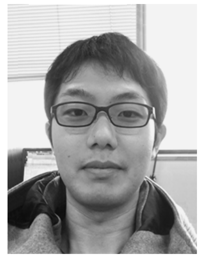

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