Plenoptik kamera ile yüksek dinamik aralıklı görüntüleme
High dynamic range imaging using a plenoptic camera

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***Özetçe* —Işık alan ya da plenoptik görüntüleme; yeniden odaklama, perspektif değiştirme, ve derinlik kestirimi gibi çekim sonrası kabiliyetlerinden dolayı ilgi çeken bir araştırma alanı olarak ortaya çıkmaktadır. Yakın zamanda ortaya çıkan mikrolens dizisi temelli plenoptik kameralar ışık alan kaydını pratik bir hale getirmiştir. Bu makalede, bu tarz bir plenoptik kameranın lensinde yaptığımız bir modifikasyonla kamerayı yüksek dinamik aralıklı görüntü kaydedebilen bir kamera haline getirmeyi öneriyoruz. Yaptığımız modifikasyon sayesinde, vinyetleme olarak bilinen, görüntünün kenarlarına doğru olan ışık miktarındaki azalma daha da arttırılmış ve sahnedeki dinamik aralığın farklı kısımları farklı ışık alan perspektif görüntülerinde kaydedilmiştir. Bu görüntüler, daha sonra fotometrik eşleştirme ve optik akış vektörlerinden faydalanılarak birleştirilip yüksek dinamik aralıklı görüntü oluşturulmuştur.**

Anahtar Kelimeler—Yüksek dinamik aralıklı görüntüleme, ışık alan görüntüleme, plenoptik kameralar

***Abstract*—Light field (or plenoptic) imaging has become an attractive research field due to its post-capture capabilities, including refocusing, perspective change and depth estimation. Micro-lens array based cameras that recently emerged have made the light field acquisition process a practical task. In this paper, we propose to convert such a plenoptic camera into a high-dynamic range camera through a minor optical modification. The optical modification is an optical mask placed in front of the main lens to increases the vignetting effect, which darkening towards the borders of the image plane due to loss of light. As a result, different parts of the dynamic range are captured with different sub-aperture images of the light field. These sub-aperture images are then fused through photometric registration and optical flow vectors to produce a high-dynamic range image.**

Keywords—High dynamic range imaging, light field imaging, plenoptic cameras

I. INTRODUCTION

Light field (or plenoptic) imaging refers to capturing light rays from different directions separately, unlike the traditional imaging systems, where the light rays from different directions are accumulated, losing the directional light information. The theoretical and practical aspects of light field imaging have been developed over the years since the early works of Lippman [1] and Gershun [2].

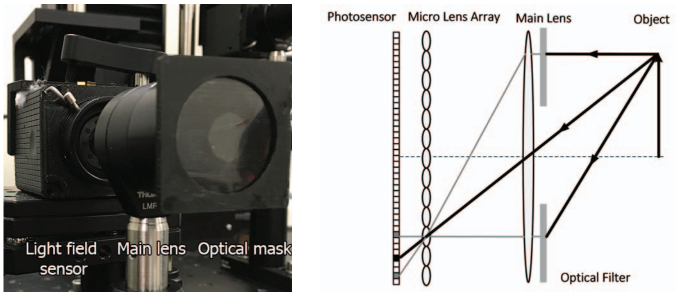

Figure 1: (Left) Optical setup. (Right) Schematic of the optical setup.

In light field imaging, a scene is represented as a four dimensional function, with two dimensions contain the spatial information of the scene while the other two contain the directional information [3], [4]. This directional information enables a variety of new applications in computer vision and image processing. The features of light field imaging include post-capture refocusing, synthetically varying aperture size, 3D rendering and depth estimation.

Light field acquisition can be done in several ways, such as camera arrays [5], coded masks [6], lens arrays [7] and microlens arrays [8], [9]. Micro-lens array (MLA) based light field cameras, including the commercial products of Lytro [10] and Raytrix [11], use micro-lenses in front of the image sensor to capture different sub-aperture images in a single shot. Being portable and cost-effective, MLA based light field cameras are becoming the popular approach for capturing light field.

While light field imaging is an emerging field, another computational photography field, specifically, high dynamic range imaging, has been of great interest over the last two decades. The main reason is that the dynamic range of an image sensor is typically less than the dynamic range of the scene; and this limits the performance in machine vision applications and the expected image quality in digital photography. Through capturing and processing multiple images with different exposure values, high dynamic range imaging methods aim to exceed the limited dynamic range [12]. The downside of such an approach is the requirement to capture multiple images, which introduces additional complexities when the scene and the camera are not fixed.

In this paper, we convert an MLA based light field camera

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into a high dynamic range camera. Our idea is to amplify the vignetting effect and capture different parts of the dynamic range with different sub-aperture images of a light field sensor. Our optical setup consists of a light field sensor, an achromatic doublet lens, and an optical mask, as shown in Figure 1. In addition to extending the dynamic range, we preserve the light field capabilities, meaning that we produce a high dynamic range light field at the end.

II. RELATED WORK

The most common way to overcome the dynamic range limitation of image sensors is the multi-capture approach, where multiple images with different exposure values are captured and combined to generate a high dynamic range (HDR) image. While this approach works well for static scenes, for dynamic scenes, it is necessary to compensate for the movement of objects, which would result in ghost-like artifacts in the final image if not taken care of [12].

Alternative to the multi-capture approach, multiple cameras, each with a different exposure value, can be used to capture different parts of the dynamic range simultaneously [13]. With a camera array, it is still necessary to compensate for the different viewpoints of cameras when generating the HDR image. Another downside of camera arrays is the size of the system, making it impractical to use. Micro-lens array based light field cameras can be considered as a compact version of the camera arrays. Through the use of a MLA, multiple viewpoints within the objective lens are obtained. Since the baseline between the sub-aperture images obtained from a MLA array based light field camera is very small, the occlusion problem is not as prominent as in the case of actual camera arrays. In [14], a focused plenoptic camera was used to capture high dynamic range images. An optical mask with the shape of a checkerboard pattern, where each square of the pattern allows different amount of light to pass, is placed in front of the objective lens. In that way, each sub-aperture image has a different spatially uniform exposure value.

While our approach is similar to that of [14], yet there are some major differences. We use a plenoptic sensor, where the micro-lens array is focused at infinity [8], unlike the focused plenoptic camera where the micro-lens array is focused on an intermediate image plane of the main objective lens. In our design, the optical mask is used to amplify the vignetting effect. It is not necessary to match the sub-aperture images with the optical mask pattern; with a calibration process, space-varying exposure values for each sub-aperture image is stored and used in the HDR creation. That is, the exposure value of each pixel is estimated individually as opposed to uniform exposure for the entire image.

III. OPTICAL SETUP AND LIGHT FIELD PRE-PROCESSING

The optical setup, as shown in Figure 1, consists of a light field sensor, a single objective lens, and an optical mask. For the light field sensor, we used the light field sensor of a dismantled first generation Lytro light field camera. For the objective lens a 60mm doublet is used. And for the optical mask, we printed a circular mask on a transparency. The circular mask can be designed to control the vignetting amount. The sub-aperture images formed by the rays passing through the outer regions of the main lens are damped and have lower intensities. The opacity of the outer portion of the mask is used to adjust the amount of vignetting, that is, the exposure values of the sub-aperture images. In Figure 2, the effect of optical mask can be seen on the decoded light field.

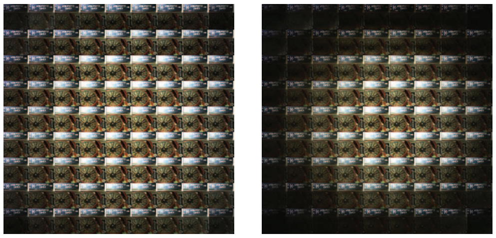

Figure 2: The effect of optical filter on captured light fields. (Left) Without the optical mask. (Right) With the optical mask.

The raw light field captured by the Lytro light field sensor should be decoded to extract the sub-aperture images [15], [16], [17]. Since the camera is dismantled and the objective lens is changed, the white images that come with the manufacturer to calibrate and decode the sub-exposure images cannot be used. We captured a set of white images with the new optical setup and used a Matlab toolbox [17] to decode the light field sub-aperture images. As a result, a regular grid of 9x9 sub-apertures images, each with a spatial resolution of 380x380 pixels, are obtained from a single capture.

IV. HIGH DYNAMIC RANGE IMAGING

High dynamic range imaging with the proposed optical setup requires registration of the sub-aperture images, followed by irradiance estimation.

A. Spatial registration of light field sub-aperture images

To generate an artifact-free HDR image, the light field sub-aperture images should be spatially registered. It is possible to exploit the regular sampling of the light field sub-aperture images, and avoid doing pairwise optical flow estimation between sub-aperture images as suggested in [18]. We estimate the optical flow between the top-most and bottom-most sub-aperture images on the middle column of the sub-aperture images and the optical flow between the left-most and right-most sub-aperture images on the middle row of the sub-aperture images using the approach given in [19], and interpolate these optical flow fields to estimate all optical flow vectors among the sub-aperture images.

B. Irradiance estimation

Pixel-by-pixel exposure values of the light field sub-aperture images need to be estimated for accurate HDR image creation. We utilize the white images captured during calibration to estimate the relative exposure values of each pixel. Assuming a linear camera response function in the un-saturated portion of the sensor response, the intensity value $Z_k(x,y)$ at a pixel location (x,y) in the kth sub-aperture image can be written as

$$Z_k(x,y) = E(x,y)T_k(x,y), \tag{1}$$

where $E(x,y)$ is the irradiance and $T_k(x,y)$ is the exposure time.

Figure 3: (Left) High exposure image. (Middle) Low exposure image. (Right) HDR image.

When the image of a white uniform scene is taken, the measured intensity $Z_{k,white}(x,y)$ should give the relative exposure time of the pixels in the images. That is, we can set $T_k(x,y)$ to $Z_{k,white}(x,y)$. As a result, the irradiance can be estimated as

$$E(x,y) = \frac{Z_k(x,y)}{Z_{k,white}(x,y)}, \tag{2}$$

using the kth sub-aperture image. We can estimate the irradiance from each sub-aperture images separately; however, the estimates that come from properly exposed pixels would be more reliable than the ones coming from over-exposed or under-exposed images. Thus, a weighted sum of the estimates is taken to get the final irradiance:

$$E(x,y) = \frac{1}{N}\sum_k \left(w\left(Z_k(x,y)\right) \frac{Z_k(x,y)}{Z_{k,white}(x,y)} \right), \tag{3}$$

where $w(\cdot)$ is a triangular weight function, giving more weight to pixels that come from mid-tones [20], and N normalizes the weights.

V. EXPERIMENTAL RESULTS

In this section, several experimental results are presented to demonstrate the dynamic range extension. In Figure 3, we show two sub-aperture images from the light field given in Figure 2 with the proposed optical setup with optical mask. One image is the middle sub-aperture, corresponding to the highest possible exposure value; the other image is a low-exposure sub-aperture image. The resulting HDR image is also shown in the figure, clearly demonstrating the extension of the dynamic range.

In Figure 4 and Figure 5, we compare the HDR images (and their histograms) without the optical mask and with the optical mask, whose light fields are given in Figure 2. It is seen that with the optical mask, lower exposure values are achieved, enabling to capture more of the dynamic range without saturation.

In addition to creating HDR image, we preserve the light field capabilities. Using the estimated optical flow and the HDR image, we warp the HDR image onto each sub-aperture image to create an HDR light field. In Figure 6, the captured light field and the generated HDR light field are shown. Sample high-exposure, low-exposure, and HDR sub-aperture images are shown in Figure 7. In Figure 8 and Figure 9, we show that we can perform post-capture digital refocusing without introducing any artifacts using the shift and sum technique [5] on the HDR light field.

Figure 4: (Left) HDR image without optical mask. (Right) HDR image with optical mask.

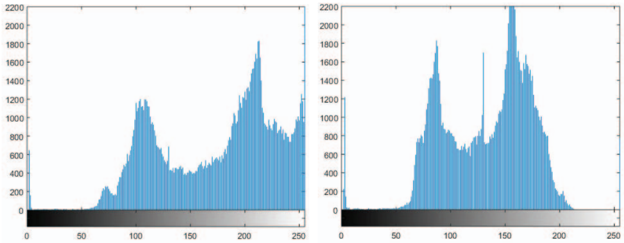

Figure 5: Comparison between the histograms of the HDR images. (Left) Without optical mask. (Right) With optical mask.

VI. CONCLUSIONS

In this paper, we demonstrated an idea to convert a light field camera into a single-shot HDR camera. We presented an optical setup, which includes a light field sensor, an objective lens, and an optical mask, which amplifies vignetting in order to capture different parts of the dynamic range with different sub-aperture images. While generating an HDR image, we preserve the light field; we demonstrated refocusing with the

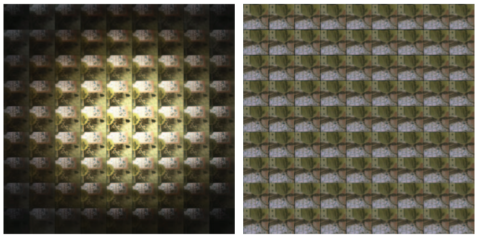

Figure 6: (Left) Captured light field. (Right) HDR light field.

Figure 7: (Left) High exposure image. (Middle) Low exposure image. (Right) HDR image.

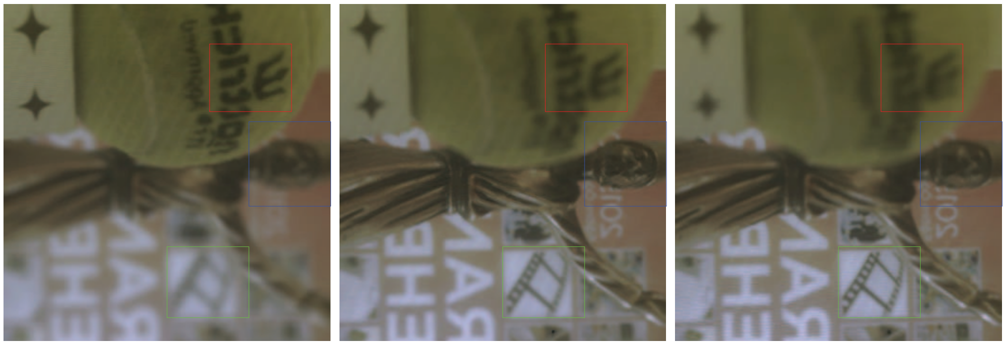

Figure 8: Post-capture digital refocusing. (Left) Close-depth refocus. (Middle) Mid-depth refocus. (Right) Far-depth refocus.

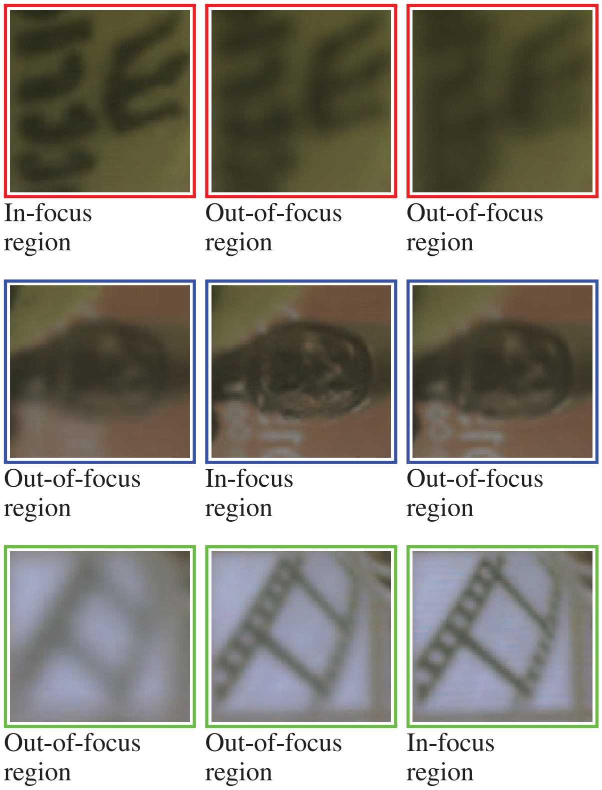

Figure 9: Post-capture digital refocusing. Zoomed-in regions from Figure 8 are shown. (Left column) Close-depth refocus. (Middle column) Mid-depth refocus. (Right column) Far-depth refocus.

created HDR light field. Since the baseline between the sub-aperture images is small, the occlusion issue did not result in any significant artifacts in HDR creation. In case of visible artifacts due to occlusion, it is possible to utilize de-ghosting algorithms developed for multi-capture HDR methods, which is left as a future work.

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