Hibrid sensörlü yüksek çözünürlüklü
ışık alan görüntüleme
Hybrid-sensor high-resolution light field imaging

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***Özetçe* —Işık alan kameraları, yeniden odaklama, diyafram kontrolü ve 3 boyutlu modelleme gibi çekim sonrası ayar kabiliyetlerinden dolayı, giderek daha çok ilgi çekmekte olan bir araştırma konusu olarak ortaya çıkmaktadır. Tek çekimli, tek sensörlü ışık alan kameraları uzamsal ve açısal çözünürlük arasındaki temel değiş-tokuşu dengelemeye çalışırlar. Bu makalede, en az optik eleman, standart bir sensör ve mikrolens dizili ışık alan sensörü kullanarak yüksek uzamsal çözünürlüklü ışık alanı üreten bir kamera öneriyoruz. Tek bir lensin kullanılması ve çakışan görüntü düzlemlerinin kullanılması; çok lensli sistemlerdeki objelerin birbirlerini kapatması gibi güçlükleri ortadan kaldırmaktadır. Gerçekleştirdiğimiz deneylerde, önerilen hibrid sensörlü ışık alan kamerasıyla uzamsal çözünürlüğün yanı sıra derinlik kestiriminin de iyileştirildiği gösterilmektedir.**

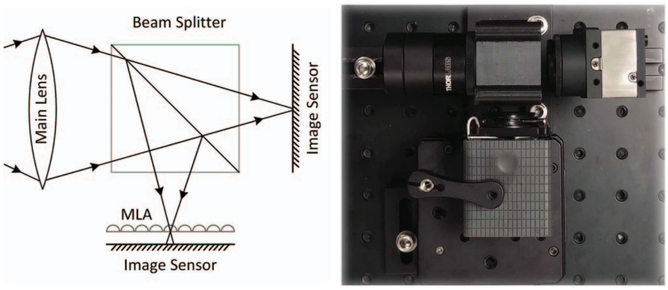
Anahtar Kelimeler—Işık alan görüntüleme, çözünürlük arttırma, hibrid sensörlü kamera,

***Abstract*—Light field imaging is an emerging research field due to the new capabilities it brings, including post-capture refocusing, aperture control, and 3D modeling. Single-shot single-sensor light field cameras try to balance the fundamental trade-off between spatial and angular resolution. The spatial resolution achieved with such cameras is typically far from being satisfactory, limiting the extensive adoption of light field cameras. In this paper, we present a hybrid-sensor light field camera that uses minimal optical components, a regular sensor and a micro-lens array based light field sensor to produce high-spatial-resolution light field. The use of a single lens and matching image planes prevent complexities, such as occlusions, that multi-lens systems suffer from. In our experiments, we demonstrate that the proposed hybrid-sensor camera leads to improved depth estimation in addition to increase in spatial resolution.**

Keywords—Light field imaging, resolution enhancement, hybrid-sensor camera,

I. INTRODUCTION

Unlike conventional cameras, light field cameras store information from multiple viewpoints through capturing light amount coming from different directions separately. Having multiple viewpoints enables new post-capture capabilities, such as digital refocusing, adjusting aperture size and shape, depth estimation and 3D model construction. There are two popular ways of capturing light field images. One is to use an array of cameras [1] and the other is to use a micro-lens array based single-sensor camera [2].



(a) (b)

Figure 1: (a) Proposed optical design; (b) Top view of the hardware setup based on the optical design.

Micro-lens array (MLA) based light field cameras have high potential for use in machine vision and digital photography applications, because they are economic, have small form factor, and have the ability to capture light field information in a single shot. The biggest issue with the MLA based light field cameras is the low-resolution due to the trade-off between spatial and angular resolution. In order to capture angular information, spatial resolution has to be sacrificed. For example, the first generation Lytro light field camera [2], incorporating an 11 megapixel sensor, has a spatial resolution of only 380x380=0.14 megapixels while having an angular resolution of 9x9. Such a spatial resolution is very small in today's standards. As a result, spatial resolution enhancement of an MLA based light field camera has become a crucial problem in light field imaging.

This paper presents a hybrid-sensor light field imaging system, which has a regular sensor and an MLA based light field sensor. The high-resolution image captured with the regular sensor is used to increase the spatial resolution of light field images, while preserving the light field capabilities.

II. PRIOR WORK

One approach to enhance the spatial resolution of MLA based light field cameras is to apply super-resolution restoration on the light-field sub-aperture images [3], [4]. The performance of such a restoration based approach is limited by accuracy of the imaging model and the image prior used. Another disadvantage of the restoration based approach is

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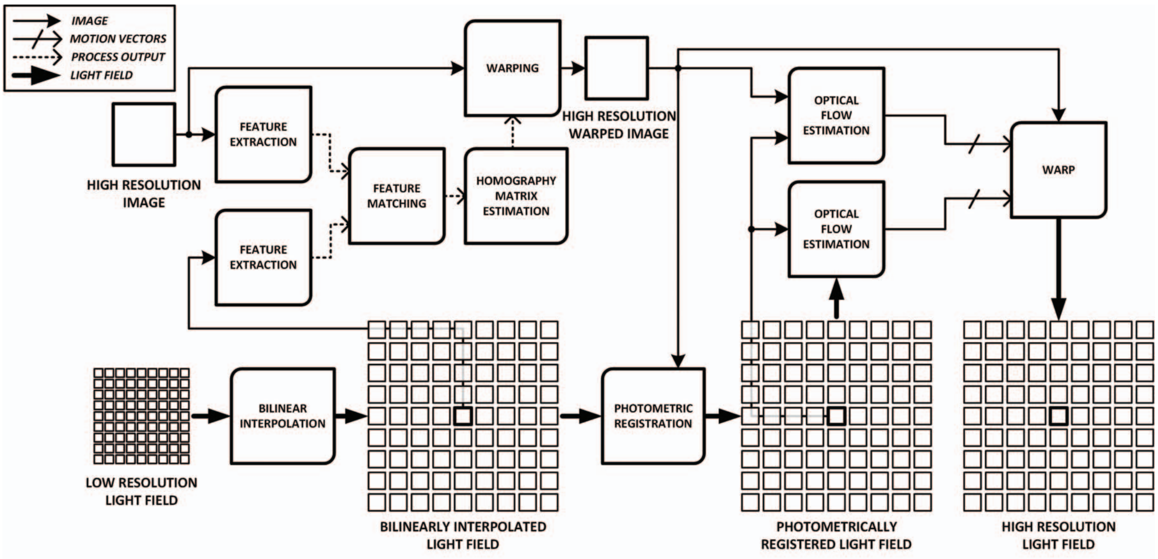


Figure 2: Illustration of the proposed light field resolution enhancement algorithm.

the typical high computational complexity. Alternative to the restoration based approach, a two-camera system is proposed in [5], which includes a regular camera and a light field camera. The spatial resolution of the image captured with the regular camera is transferred to the sub-aperture images captured with the light field camera. In this approach, the spatial resolution of the light field can be increased to that of the regular camera. While the light field and regular camera positions are arbitrary in [5], they are placed as a stereo system in [6], which enables faster processing through pre-calibration. Such a hybrid stereo system also allows extended and more accurate depth estimation capability due to larger baseline [6]. With two-camera systems, the main problem is occlusion due to different viewpoints of the cameras. The problem can be alleviated by using a beam-splitter before the cameras to have the same viewpoints [7], [8], [9]. One challenge that multi-lens systems should address is the need to register and compensate for optical distortions when non-identical objective lenses are used.

The optical system presented in this paper, utilizes a single lens which prevents potential problems such as occlusion, radial distortion etc., that multi-lens systems may have. The use of a single lens also enables more compact camera design.

III. OPTICAL DESIGN AND LIGHT FIELD CAPTURE

Our hybrid-sensor light field imaging system consists of a regular sensor, a light field sensor, a 50:50 beam-splitter and an objective lens, as shown in Figure 1. Since the sensors are adjusted to have the same viewpoint, the occlusion problem is minimized; and the common objective lens avoids any issues that would be a result of mis-matching objective lenses.

The light field sensor is obtained by dismantling a first generation Lytro camera. The regular sensor is a 1.6 megapixel CMOS image sensor. A 60mm achromatic lens doublet is used as the objective lens. The objective lens aperture is adjusted to match the micro-lens pitch to focal length ratio of the light field sensor to avoid any overlap between the micro-lens images while maximally utilizing the sensor [10]. There is an additional aperture along the optical path of the regular sensor, which is used to achieve large depth of focus, resulting in sharp images in the working range of the light field portion of the imaging system.

To decode light field images, we used a Matlab toolbox [11] developed for the Lytro camera. The decoding process requires white images to calibrate the sensor, which includes detection of the micro-lens centers on the sensor and transforming light field sub-aperture images from a hexagonal grid to a square grid. Since the Lytro camera is dismantled, the white images provided by the manufacturer cannot be utilized. Therefore, we captured white images with the setup, and followed the calibration procedure given in [11].

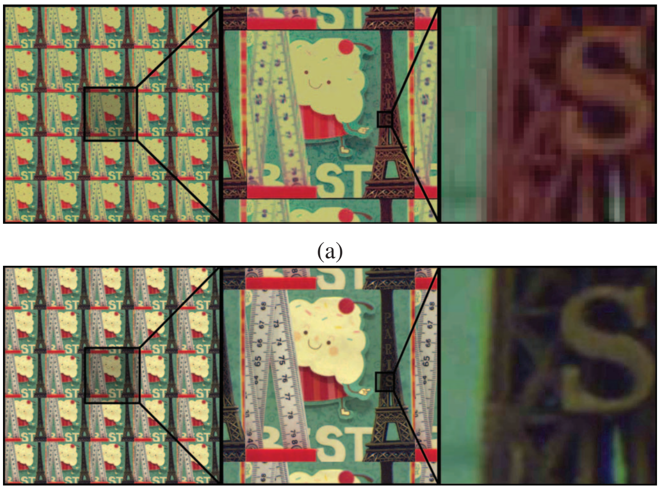
IV. LIGHT FIELD RESOLUTION ENHANCEMENT

The proposed light field resolution enhancement algorithm is illustrated in Figure 2. The low-resolution light field sub-aperture images captured by the light field sensor is first interpolated to match the size of the high-resolution image captured by the regular sensor. The portion of the high-resolution image that is outside the field of view of the sub-aperture images is cropped to produce a 1280x1280 image. Although we manually adjust the viewpoints and the image planes during optical setup and calibration, a homographic correction improves the accuracy and helps with the spatial registration process to come. We extract and match the SURF features [12] in the regular sensor image and the middle sub-aperture image of the light field. To eliminate the outliers, we used the RANSAC technique while estimating the homography. The regular sensor image is then warped using the estimated homography.

To enhance the spatial resolution of each sub-aperture image, it is necessary to warp the high-resolution image onto each of the sub-aperture images and then fuse them. The fusion of different resolution images has been studied extensively in the literature, especially in the domain of pansharpening. In [6], it is shown that it also possible to simply replace the low-resolution sub-aperture image with the warped high-resolution image because both images are from the same spectral range, unlike in the case of the pansharpening problem. We followed

(a) (b)

Figure 3: Photometric registration of light field images and regular sensor image. (a) Middle sub-aperture light field image before photometric registration; (b) Middle sub-aperture light field image after photometric registration.



(a)

(b)

Figure 4: Spatial resolution enhancement of light field. (a) Low-resolution bilinearly interpolated light field captured by the light field sensor; (b) Spatially enhanced light field as a result of the proposed algorithm.

this idea, first photometrically registering the images, then estimating the optical flow among sub-aperture images as well as between the middle sub-aperture image the high-resolution image, and finally warping the high-resolution image onto each sub-aperture light field image to form the high-resolution light field. The photometric registration and optical flow estimation steps follow the algorithm presented in [13].

A result of the photometric mapping is shown in Figure 3. A comparison of the low-resolution light field and the high-resolution light field achieved is shown in Figure 4. The spatial resolution of the original light field is 380 x 380 pixels. As a result of the resolution enhancement, it becomes1280x1280.

V. EXPERIMENTAL RESULTS

In this section, we provide a set of results to demonstrate the improvement in spatial resolution as well as depth map estimation. Although our goal was to improve the spatial resolution, it turns out that increase in spatial resolution also improves depth estimation performance.

An important capability of light field imaging is the ability to digitally refocus. Refocusing can be done easily using the *shift-and-sum* technique [14]. In Figure 5, the original low-resolution light field and the resolution-enhanced light field are refocused to close-depth, mid-depth, and far-depth objects in the scene. Different regions from in-focus and out-of-focus parts of the scene are zoomed in. The improvement in the spatial resolution in both in-focus and out-of-focus regions are clearly seen in these figures.

A side product of spatial resolution enhancement is increase in depth estimation accuracy. One approach to estimate depth in light field images to use epipolar plane images (EPI) [15]. In Figure 6, it is seen that high-resolution light field results in more defined and accurate features, which eventually improve the depth estimation performance. The disparity map generated through the EPI is shown in Figure 7 for both light fields. The disparity map (which is used to generate depth map) for the high-resolution light field is far more accurate than the disparity map of the original low-resolution light field.

VI. CONCLUSIONS

In this paper, a hybrid sensor light field imaging system, that includes a regular and a light field sensor, is presented. We proposed an algorithm to create high-resolution light field with the images captured by the system. The spatial resolution achieved is 1280x1280 pixels, which is approximately three times higher than the original light field in each direction. The resolution enhancement factor depends on the resolution of the regular sensor used; that is, the proposed setup and the algorithm can be used with higher resolution sensors to achieve better results. We believe the proposed hybrid sensor approach is an effective and economic way to address the spatial resolution issue of micro-lens array based light field cameras.

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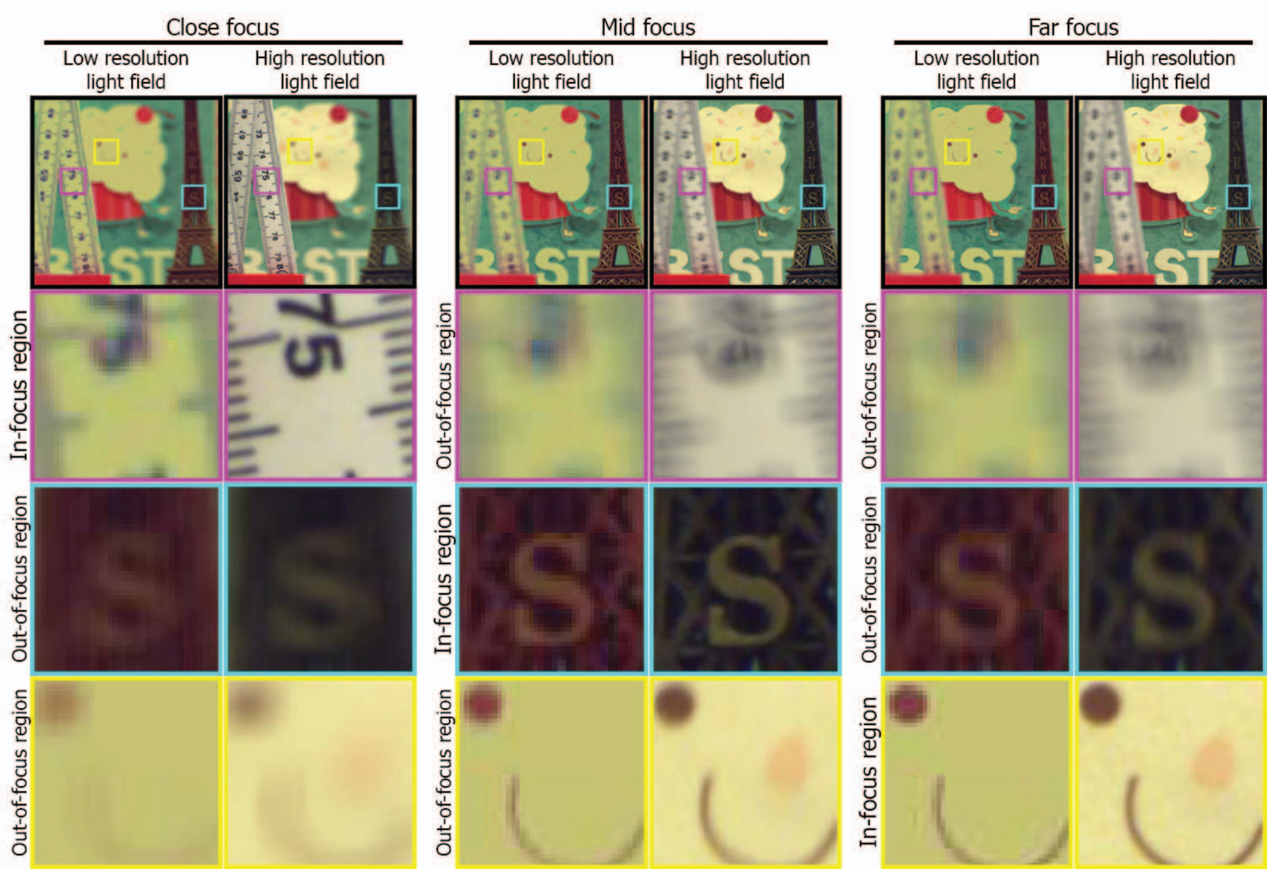

Figure 5: Spatial resolution comparison between original and spatially enhanced light fields for digital refocusing. Using the shift-and-sum technique, light fields are focused at three different depths for both low-resolution and high-resolution light fields.

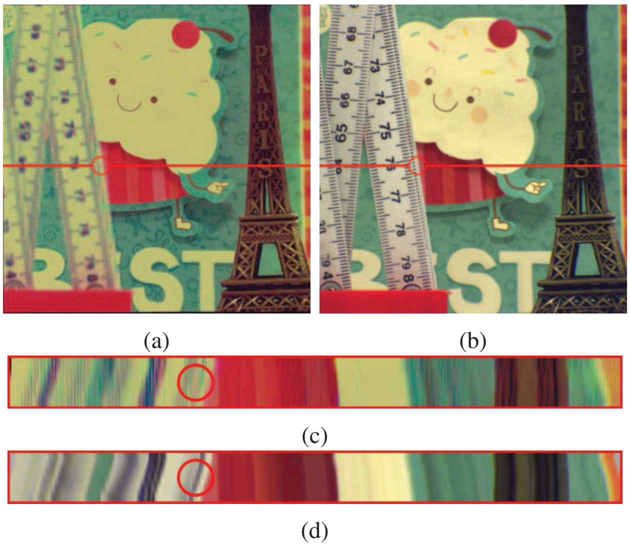

Figure 6: Improvement in epipolar plane image (EPI) due to spatial resolution enhancement. (a) Low-resolution light field sub-aperture image; (b) High-resolution light field sub-aperture image; (c) EPI for the low-resolution light field; (d) EPI for the high-resolution light field.

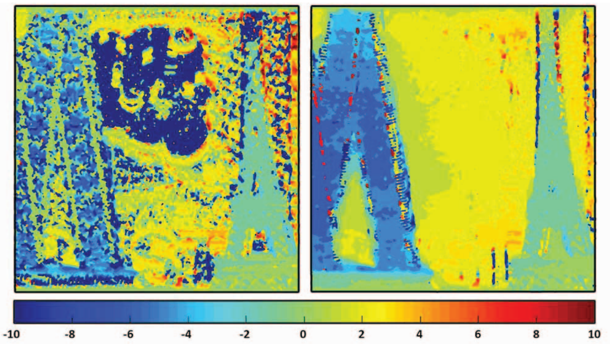

Figure 7: Disparity map comparison. Left: Disparity map for the original light field. Right: Disparity map for the spatially enhanced light field.

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