Light Field Super Resolution Through Controlled Micro-Shifts of Light Field Sensor

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Abstract—Light field cameras presents new capabilities, such as post-capture refocusing and aperture control, through capturing directional and spatial distribution of light rays in space. Among different light field camera implementations, micro-lens array based light field cameras is a cost-effective and compact approach to capture light field. One drawback of the micro-lens array based light field cameras is low spatial resolution due to the fact that a single sensor is shared to capture both spatial and angular information. To address the low spatial resolution issue, we present a light field imaging approach that captures and fuses multiple light fields to improve the spatial resolution. For each capture, the light field sensor is shifted in fractional micro-lens steps by means of an XY stage for optimal performance.

Index Terms—Light field, super-resolution, micro-scanning.

I. INTRODUCTION

In light field imaging, the spatial and directional distribution of light rays in space is recorded. This enables new capabilities, including post-capture refocusing, post-capture aperture size and shape control, post-capture viewpoint change, depth estimation, 3D modeling and rendering. The first implementation of a light field imaging system is presented by Lippmann [1], who proposed to use an array of lenslets in front of a film to capture light field, and used the term “integral photography” for the idea. The term “light field” was coined by Gershun [2], who formulated the distribution of light in space. The idea of light field did not get much attention until 1990s. In 1991, Adelson et al. [3] conceptualized light field as the entire visual information, including spectral and temporal information of light in addition to 3D position and angular distribution of light rays in space. In 1996, Levoy et al. [4] and Gortler et al. [5] independently formulated light field as a four-dimensional function at a time instant, assuming lossless medium and one spectral component. Since then, light field imaging has become popular, resulting in new applications and theoretical developments.

There are different ways of capturing light field, including camera arrays [4], micro-lens arrays [7], coded mask [9], lens array [10], gantry-mounted camera [11], and kaleidoscope-like optics [12]. Among these different approaches, micro-lens array (MLA) based light field cameras provide a cost-effective and compact approach to capture light field. There are commercial light field cameras based on the MLA approach [13], [14]. The main problem with MLA based light field cameras is low spatial resolution due to the fact that a single image sensor is shared to capture both spatial and directional information. For instance, the first generation Lytro camera incorporates a sensor of 11 megapixels but has an effective spatial resolution of about 0.1 megapixels, as each micro-lens produces a single pixel of a light field perspective image [15].

One possible approach to address the low spatial resolution issue of MLA based light field cameras is to apply a super-resolution restoration method to light field perspective images. Multi-frame super-resolution methods require the input images to provide pixel samples at proper spatial sampling locations. For example, to double the resolution of an image in both horizontal and vertical directions, there should be exactly four input images with half pixel shifts in horizontal, vertical, and diagonal directions. Typically, however, it is necessary to have much more than the minimum possible number of input images since the ideal shifts are not guaranteed. The number of input images, along with the need to estimate the shift amounts, add to the computational cost of multi-frame super-resolution methods.

By controlling the sensor shifts, and designing them for the proper sampling locations, it is possible to achieve the needed resolution enhancement performance with the minimum number of input images. The idea of shifting the sensor in sub-pixel units and composing a higher resolution image from the input images is known as “micro-scanning” [16].

In this paper, we demonstrate the use of the micro-scanning idea for light field spatial resolution enhancement. While micro-scanning is well known, this paper is the first application of this idea to light field imaging. The shift amounts are designed for a specific light field sensor (first generation Lytro sensor) considering the arrangement and dimensions of the micro-lenses. We show both qualitatively and quantitatively that, with the application of micro-scanning, the spatial resolution of Lytro light field sensor can be improved significantly.

In Section II we survey the literature related to spatial resolution enhancement of light field cameras and discuss the micro-scanning technique. In Section III we give an overview of our approach to improve the spatial resolution of light field images. The camera prototype is explained in Section IV. The details of our resolution enhancement algorithm is given in Section V. We provide experimental results in Section VI. And finally, we conclude our paper in Section VII.

II. RELATED WORK

A. Light field spatial resolution enhancement

There are a number of software based methods proposed to improve the spatial resolution light field perspective images, including frequency domain interpolation [17], Bayesian super-resolution restoration with texture priors [18], Gaussian
mixture modeling of high-resolution patches [19], dictionary learning [20], variational estimation [21], and deep convolutional neural network [22]. These methods can be applied to both classical light field cameras [23], where the objective lens forms the image on the MLA, as well as the “focused” light field cameras [8], where micro-lenses and objective lens together form the image on the sensor. There are also methods specifically designed to improve the spatial resolution of focused light field cameras [24].

Hybrid systems that include a light field camera and a conventional camera have also been proposed to improve the spatial resolution light fields. In [25], high-resolution patches from the conventional camera are used to improve the spatial resolution light field perspective images. A dictionary learning method is presented in [26]. In [27], optical flow based registration is used for efficient resolution enhancement. When the light field camera and the conventional camera do not have the same optical axis, the cameras have different viewpoints, resulting in occluded regions; and the above-mentioned methods should tackle this issue. In [28] and [29], beamsplitters are used in front of the cameras to have the same optical axis and prevent the occlusion issue. In [30], the objective lens is common and the beamsplitter is placed in front of the sensors to avoid any issues (such as different optical distortions) due to mismatching objective lenses.

B. Micro-scanning

In super-resolution image restoration, multiple input images are fused to increase the spatial resolution. There should be movement among the input images (due to the camera movement or movement of the objects in the scene) to have diversity of pixel sampling locations. Instead of capturing large number of images and hoping to have proper movement among these images to cover the pixel sampling space, one can induce the movement on the sensor directly and record the necessary samples with the minimum possible image captures. For example, an image sensor can be moved by half a pixel in horizontal, vertical and diagonal directions to produce four different images, which are later composited to form an image with four times the original resolution. This micro-scanning idea [16] has been used in digital photography, scanning and microscopy applications. The micro-scanning idea was recently used in [31] to obtain high-resolution video. One drawback of the micro-scanning technique is that the scene needs to be static during the capture of multiple images in order to avoid any registration process. Using piezo-electric actuators synchronized with fast image sensors, the dynamic scene issue can be alleviated. However, even when there are moving objects in the scene, the technique can be applied through incorporating a registration step into the restoration process, which would take care of the moving regions while ensuring there is the required movement in the static regions.

III. ENHANCING SPATIAL RESOLUTION THROUGH MICRO-SHIFTED LIGHT FIELD SENSOR

The spatial resolution of an MLA based light field camera is determined by the number of micro-lenses in the micro-lens array [15]. For example, in the first-generation Lytro camera, there are about 0.1 million micro-lenses packed in a hexagonal grid in front of a sensor. There is about a 9x9 pixel region behind each micro-lens, resulting in 9x9 perspective images (i.e., angular resolution). The decoding process includes conversion (interpolation) from the hexagonal grid to a square grid to form perspective images [15]. In order to increase the spatial resolution, the micro-lens size could be reduced, increasing the sampling density of the micro-lens array. With denser packing of micro-lenses, the main lens aperture should also be reduced to avoid overlaps of the light rays on the sensors; as a result, the angular resolution is reduced.

In the proposed imaging system, the light rays are recorded at a finer spatial distribution by applying micro-shifts to the light field (LF) sensor. The idea is illustrated in Figure 1 where two light fields are captured with a vertical shift of half the size of the micro-lens. The combination of these two light field captures will result in a light field with twice the spatial resolution of the light field sensor. Effectively, we are increasing the micro-lens sampling density without reducing the micro-lens size, thus preserving the angular resolution.

IV. CAMERA PROTOTYPE

We dismantled a first generation Lytro camera and removed the objective lens. The sensor part is placed on an XY stage, consisting of two motorized translation stages from ThorLabs [82]. A 60mm objective lens and an optical diaphragm are placed in front of the light field sensor. The optical diaphragm is adjusted to match the f-numbers of the objective lens and the micro-lenses. The micro-shifts are applied on the sensor part by the XY stage controlled through the software provided by ThorLabs. The prototype camera is shown in Figure 2.

The arrangement and dimensions of micro-lenses on the sensor are shown in Figure 3. The distance between the centers of two adjacent micro-lens is 14 \( \mu \text{m} \); the vertical distance between adjacent two rows of the micro-lens array is 12.12 \( \mu \text{m} \). The sensor on which the MLA is attached has a size of...
Fig. 2. Micro-scanning light field camera prototype. (Top-left) Graphical illustration. The light field sensor is shifted by a translation stage. (Bottom-left) Side view of the optical setup. Note that the lens and the sensor are not joint. (Right) Optical setup showing the translation stages.

Fig. 3. Micro-lens arrangement and dimensions of a first generation Lytro light field sensor.

3,280 x 3,280 pixels. There are about 0.1 million micro-lenses. Using the decoding process described in [15], we extract 7x7 perspective images, each with size 378x328 pixels, from each light field capture.

We designed the micro-shifts to increase the spatial resolution four times in horizontal direction and four times in vertical direction. We capture 16 light fields; the shift amounts for each capture are listed in Table I. The shifts amounts are multiples of the micro-lens spacings divided by four, the resolution enhancement factor along a direction; that is, the shift amounts are multiples of 14/4=3.5\(\mu\)m and 12.12/4=3.03\(\mu\)m, in horizontal and vertical directions, respectively. The resulting grid is shown in Figure 4(e). For later comparison and analysis of resolution enhancement, additional subsets of light field captures are generated by picking one, two, four and eight light fields from the original 16 captures. All the light field capture sets are shown in Figure 4.

V. RECONSTRUCTING HIGH RESOLUTION LIGHT FIELD

A. Micro-lens grid calibration

Each micro-lens forms an image of the main lens on the sensor; and the center of the main lens image does not necessary match the center of the corresponding micro-lens [15]. For the proper decoding of the light field, the center locations for each micro-lens region should be determined. Since we dismantled the original Lytro camera, we cannot rely on the optical centers provided by the manufacturer to decode the light field. We followed the procedure described in [15] to determine the center locations for each micro-lens region, which involves taking the picture of a white scene and determining the brightest point behind each micro-lens region. The calibration process also involves transformation from the hexagonal grid to a square grid, for which we again used [15].

B. Light field registration

While the micro-shifts are designed for optimal positioning, the translation stages may not have perfect accuracy. Thus, we did apply a registration step to improve accuracy of the light field positions. For a pair of light fields, we estimate the shifts between each corresponding perspective images (for example, between the center perspective image of the first light field and the center perspective image of the second light field) using phase correlation. Since the shift between each corresponding should be equal, we average all the estimated shifts to have a robust estimate of the shift between two light fields. The process is repeated for all light field captures.

C. Interpolation onto a high resolution grid

After determining the shift amounts, the recorded samples are interpolated to a finer resolution regularly spaced grid. The interpolation is done using a Delaunay triangulation based method [33]. Figure 5 provides illustrations of the interpolation process for a perspective image. When there are more light fields available, we would have more densely distributed samples available, resulting in a better estimate of the missing pixel values.

VI. EXPERIMENTAL RESULTS

Through the process capturing and fusing multiple (16) light fields, each with spatial resolution of 378x328 pixels and angular resolution of 7x7 perspectives, we obtain a light field of 16 times the original spatial resolution (1512x312) and the same angular resolution. Figure 6(a) shows an input light field, and Figure 6(b) shows the resulting light field.

| Capture | \(T_u(\mu m)\) | \(T_v(\mu m)\) | Capture | \(T_u(\mu m)\) | \(T_v(\mu m)\) |
|---------|---------------|---------------|---------|---------------|---------------|
| 1       | 0.00          | 0.00          | 9       | 3.50          | -18.18        |
| 2       | 0.00          | -3.03         | 10      | 3.50          | -15.15        |
| 3       | 0.00          | -6.06         | 11      | 3.50          | -12.12        |
| 4       | 0.00          | -9.09         | 12      | 3.50          | -9.09         |
| 5       | 0.00          | -12.12        | 13      | 3.50          | -6.06         |
| 6       | 0.00          | -15.15        | 14      | 3.50          | -3.03         |
| 7       | 0.00          | -18.18        | 15      | 3.50          | 0.00          |
| 8       | 0.00          | -21.21        | 16      | 3.50          | 0.00          |

TABLE I

Translation amounts in horizontal \((T_u)\) and vertical \((T_v)\) directions for 16 light field captures. (Refer to Figure 4(e) for a graphical illustration.)
A. Effect of increasing the number of light fields

During the experiment, 16 light fields are captured with the controlled shifts of light field sensor as described in Table I. To investigate the effect of the number of light fields, five different subsets of captured light fields are picked as illustrated in Figure 4. For each case, a high resolution light field (with 1512x312 spatial resolution) is obtained using the interpolation method described in the previous section. In Figure 7, we provide a visual comparison of the resulting perspective images. As expected, when we use all 16 light fields, we achieve the best visual performance.

To quantify the resolution enhancement, we used a region from the test chart, shown in Figure 8 to determine the highest spatial frequency. The region consists of horizontal bars with increasing spatial frequency (cycles per mm). In each case, we profiled the bars, and marked the location beyond which the bars become indistinguishable; the highest spatial frequencies are plotted in Figure 9.

B. Comparison with base techniques

In Figure 10, we compare post-capture refocusing of light fields obtained by our imaging system along with the techniques presented in [15] and [20], which incorporates a learning based super-resolution method. Our light field is obtained by merging 16 light field captures. The shift-and-sum technique [23] is used to focus at close, middle, and far depths. We show focused regions produced by each method. Apparently, the proposed method produces the best visual results.

In addition, we obtained the maximum spatial frequencies achieved by [15] and [20] for the same test chart shown in Figure 8. The spatial frequency for [20] was near 50 cycles/mm and for [15] it was around 55 cycles/mm, whereas for resulting light field with 16 captures for interpolation the spatial frequency was around 132 cycles/mm.

C. Computation time

The implementation is done with MATLAB, running on a PC with Intel Core i5-4570 processor clocked at 3.20 GHz with 12 GB RAM. The computation times for different number of input light fields (per perspective) are shown in Figure 11.

VII. Conclusions

In this paper, we presented a micro-scanning based light field spatial resolution enhancement method. The shift amounts are determined for a specific light field sensor according to the arrangement and size of micro-lenses. The method incorporates a shift estimation step to improve the accuracy of the micro-shifts. With a translation stage of high accuracy, the registration step could be eliminated.

The method assumes that the scene is static. This is indeed the main assumption of all micro-scanning based resolution enhancement applications. One possible extension of micro-scanning techniques to applications with dynamic scenes is to incorporate an optical flow estimation step into the process. We did not investigate this idea as it is outside the scope of this paper.

Finally, we should note that software-based light field super-resolution methods are complimentary to the micro-scanning based idea presented here. That is, it is possible to apply a software based super-resolution method to the light field obtained by micro-scanning to further increase the light field spatial resolution.
Fig. 7. Visual comparison of light field middle perspective images for various number of light field captures used for enhancement.

Fig. 8. The effect of the number of light field captures used on spatial resolution enhancement.

Fig. 9. Highest spatial resolution achieved versus the number of light field captures used in light field formation.

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Fig. 10. Visual comparison of post-capture refocusing for three different depths. Light fields include bicubically interpolated single light field capture, light field obtained by Dansereau et al. [15], light field obtained by Cho et al. [20], and light field obtained by our method merging 16 input light fields.

Fig. 11. Time required to generate single high resolution light field perspective versus the number of input light fields.

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