Superresolution with Plenoptic 2.0 Cameras

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Abstract: We demonstrate working superresolution with Plenoptic 2.0 camera without need for traditional image registration in software. This paper describes our method, based only on the camera geometry and microlens parameters.

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1. Introduction

The Plenoptic camera, a digital realization of Lippmann's integral photography [5], was introduced in 1992 [1] as an approach to solve computer vision problems. An improved version, the Plenoptic 2.0 camera, has been independently introduced in [8, 3, 6]. The Plenoptic 2.0 camera also follows ideas originating from Lippmann [5]. In one realization, the camera has microlenses placed at distance b from the sensor, so that they are focused at the image plane of the main camera lens, at a distance a in front of them (see Figure 1). In this configuration, a, b, and the focal length f satisfy the lens equation and construct a relay system with the main camera lens.

Capturing data with plenoptic cameras makes possible greater processing capabilities and solves many of the problems faced by photographers using conventional digital cameras. Rendering refocused images and 3D views are just two such capabilities. Unfortunately, Plenoptic 1.0 cameras render images at very low resolution. For example, images rendered from Ng's camera data have a final resolution of 300×300 pixels [7].

Superresolution is a widely used technique.Superresolution is based on extracting subpixel information from multiple images of a given scene to produce a higher-resolution image. For images captured by arrays of separate cameras, superresolution is directly applicable. Superresolution with lightfield cameras has been described in [2].

In this paper we show that the Plenoptic 2.0 camera can be interpreted as an array of cameras that are focused on the photographed object through the relay optics. Based on this interpretation, we develop superresolution techniques for rendering high resolution images from the captured data. The geometry of the microlens array makes it possible to apply superresolution without traditional registration in software.

2. Super Resolution for Plenoptic 2.0

2.1. Super Resolution Model

The super-resolution problem is to recover a high-resolution source from multiple low-resolution observations. In the plenoptic camera those observations are captured by an array of microcameras. Each of the microcamera pixels samples a version of the outside world scene, blurred through a kernel H due to the camera optics and considering the finite pixel size. If we also add the noise term, we come to the typical analysis of superresolution, now applied to the focused plenoptic camera:

$$i = Hx + n. \tag{1}$$

Here, i represents the collected low-resolution observed images, H is the blur matrix, n is a noise term, and x is the high-resolution image that we wish to recover.

Recovering x can be cast as a minimization problem:

$$\min_x \left\{ \|Hx - i\|_2^2 + \alpha R(x) \right\}, \tag{2}$$

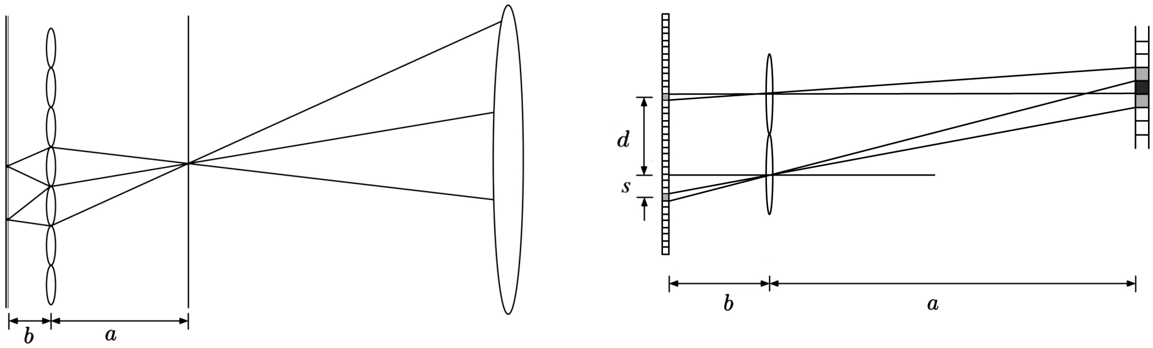

Fig. 1. Left: Plenoptic 2.0 camera as a relay system. Right: Low resolution acquisition of the high-resolution image generated by the main camera lens.

where $R(f)$ is a regularization term whose choice depends on the application and desired solution characteristics. Formulating and solving this problem efficiently in different application areas is an active area of research.

Key to the success of any superresolution approach is that there be nonintegral (subpixel) shifts between different aliased observations of the high-resolution images. In the general case, estimating these shifts (and, consequently, forming H) is also part of the superresolution problem. In the case of our Plenoptic 2.0 superresolution, the problem is simplified as we have an array of cameras spaced with predetermined micron precision.

2.2. *Plenoptic 2.0 Camera Design for Super Resolution*

From Figure 1 (right) we see that $a = db/s$. In general, the distance d between microlens centers is not an integer number of pixels. Let the next integer larger than d be $\Delta = d + x$, and let $s = x + t$. Since we know the pixel size and d with great precision, we know x. Then, t is the translation from the integer pixel location to the image of the observed point, and it needs to have a nonintegral value for the purpose of superresolution.

Note that there are multiple regions in the scene (multiple values of a and b) for which t will have a nonintegral value. For instance, we can take t to be 0.5 pixels, but we could also take it to be 1.5, or 2.5, or, in general, 0.5 + n for $n = 0, 1, 2, 3, \ldots$. After super resolving, these provide the same $2\times$ increase in the resolution.

The general case is $t = k + n$, where k is a fraction less than 1. Different types of interleaving for superresolution are used with different k. With these notations our general equation can be written as

$$a = \frac{db}{s} = \frac{db}{x + k + n}. \tag{3}$$

In the Plenoptic 2.0 camera optical infinity is imaged at the largest distance a from the microlenses. It has the greatest reduction in size (which is simply a/b for each microcamera). That is, it has the lowest spatial resolution under plenoptic 2.0 rendering. At the same time, it creates the most images in different microcameras. The low resolution and the availability of many images means that this region of the scene is the most important to use with superresolution.

Infinity is also the depth that can be handled with the highest precision for superresolution since it is fixed, i.e., always mapped to the focal plane of the main camera lens. In our camera we place it at one of the superresolved planes of the microlenses. Subpixel correspondence is therefore established and exactly known in advance. Thus our method works directly, with registration provided by camera geometry and not computed from the imagery. This makes our registration much more precise and reliable.

3. Specific Design Example

3.1. *Camera*

We are working with a medium format camera, using an 80-mm lens and a 39-megapixel digital back from Phase One. The lens is mounted on the camera with a 13-mm extension tube, which provides the needed spacing a.

The microlens array is custom made by Leister Axetris. We have designed it to work with the sensor without removing the cover glass. For that purpose, the microlenses have focal length of 1.5 mm and the array is placed directly on the cover glass of the sensor. We have also crafted a way to provide variable additional spacing of up to 0.2 mm, which in our experience proved to be extremely important for fine tuning the microlens focus. The pitch of the microlenses is 500 μm with a precision better than 1 μm. This precision makes subpixel registration possible. The sensor pixels are 6.8 μm. Thus, $d = 73.5294$ pixels, $\Delta = 74$ pixels, and $x = 0.4706$ pixels. The value of $b \approx 1.6$ mm was estimated with precision 0.1 mm from known sensor parameters and independently from the microlens images at different F/numbers. From this we compute $db \approx 120mm$. Note that a and b are measured in millimeters while everything else is measured in pixels.

3.2. Superresolution

For this paper we super resolve a plenoptic 2.0 image to increase resolution three times in each direction. We need $t = 1/3 + n$, where $n = 0, 1, 2, 3, \ldots$ and $a = db/(x + 1/3 + n)$. With the parameters of our camera above, we have approximately $a \approx 120/(0.8 + n)$ measured in millimeters. To solve equation (1) in our case, we use the following approach.

1. Create a high-resolution observed image i by interleaving pixels from adjacent microlens images. For the experiments shown here, we use a 3×3 resolution increase, so each microlens image interleaves pixels from its eight nearest neighbors.

2. Solve equation (1) with an appropriate computational method. For the results shown here, we used the approach described in [4], with Gaussian and sparse priors. The kernel used for deconvolution was obtained by imaging a point light source (pinhole).

3.3. Working Range

To estimate the range of depths in the real world at which our super resolution works, consider that we place the image of infinity at distance $13.6mm$ from the microlenses, corresponding to $n = 8$. The next closer plane good for 3×3 super resolution would be at $12.2mm$, and between them there is a plane where super resolution would fail. Our data must be super resolvable at least within half of that, i.e. $0.5mm$ (from $13.1mm$ to $13.6mm$). Consider the lens equation for the main camera lens $(A - F)(B - F) = F^2$, where $F = 80mm$ is the focal length of the main lens, A is the distance to the object, and B is the distance to the image. Our estimate above that $B - F = 0.5mm$ leads to a distance $A = 12.8m$. Anything that is located at more than $13m$ from the camera is well superresolved. This has been confirmed by our experiment.

4. Conclusion

One factor that has limited the adoption of plenoptic cameras has been the relatively low resolution. With the Plenoptic 2.0 camera, and with the application of super-resolution techniques, one can achieve great increase of the attainable spatial resolution. Based on a 39 megapixel sensor we achieve 4 megapixel final image. With a slightly modified geometry one can increase the range of depth that are superresolvable without registration. This all enables rendered images of sizes acceptable to modern photographers, making lightfield photography practical.

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