# New Results on the Plenoptic 2.0 Camera

*(Invited Paper)*

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***Abstract*—The Plenoptic camera, a digital realization of Lippmann's "Integral Photography" ideas, was introduced in 1992 by Adelson as an approach to solve computer vision problems. Recently, an improved version called Plenoptic 2.0 camera has been independently proposed by Ng, Fife, Lumsdaine, and others. The important part about it is the much higher spatial resolution. In this paper I will describe the two different focusing modes of this new camera, image rendering for it, as well as methods for capture extended modes at high resolution, including HDR, multispectral color, polarization, superresolution, and others. These are applicable only to Plenoptic 2.0 camera, which fact makes it unique. A live demo of the camera will be shown.**

## I. Introduction

The Plenoptic camera, a digital realization of Lippmann's integral photography [7], was introduced in 1992 [1] as an approach to solve computer vision problems. We will refer to it as the Plenoptic 1.0 camera. An improved version, the Plenoptic 2.0 camera, has been independently introduced in [12], [5], [8], and others. The Plenoptic cameras are generally known with photographic effects like capturing 3D, and refocussing after the fact.

Plenoptic 1.0 cameras produce final rendered image with very low resolution, one pixel per microlens [11]. The main idea leading to the Plenoptic 2.0 approach is very simple: The reason for the low resolution of Plenoptic 1.0 is that it is not properly focused. While its main lens creates a focused image of the scene, the microlenses are not focused on that image. See Figure 1. With a defocused system, we are getting poor resolution.

It is clear that with appropriately focused plenoptic camera and a new rendering algorithm we could produce a final image utilizing multiple pixels per microlens, thus significantly increasing resolution.

In one configuration, the 2.0 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 2). In the other configuration (not shown here), the main lens image is formed at a distance $a$ behind the microlenses, which are capturing and re-imaging it to the sensor as a virtual image. Again the sensor is placed a distance $b$ behind the microlenses. The first configuration resembles Keplerian telescope, the second configuration resembles Galilean telescope with multiple eyepieces. In both configurations, $a, b$, and the focal length $f$ satisfy the lens equation and construct a relay system with the main camera lens.

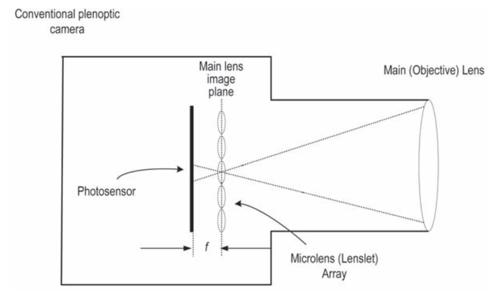


Fig. 1. Plenoptic 1.0 camera

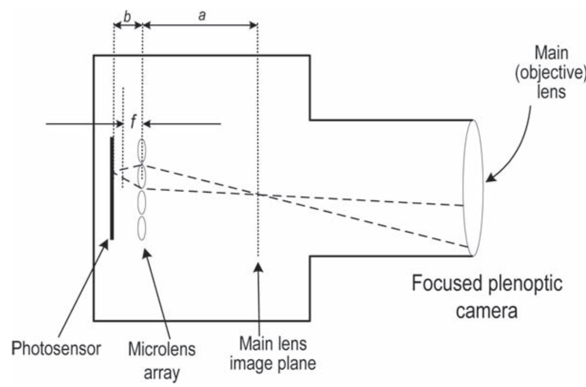


Fig. 2. Plenoptic 2.0 camera

The Plenoptic 2.0 approach decouples resolution from number of microlenses, and makes radianmce sampling more flexible. The photographer is free to vary resolution while taking the picture: The spatial resolution in Plenoptic 2.0 is $b/a$ of the sensor resolution, and can be varied by moving the microlens array relative to the sensor.

Capturing data with plenoptic cameras makes possible greater processing capabilities. It solves many of the problems faced by photographers using conventional digital cameras. Rendering refocused images and 3D views are just two such capabilities, but there are many others, including HDR and multi-spectral imaging, superresolution, and much more. This paper discusses some of those new methods, emphasizing the ideas and leaving out some of the technical details.

## II. Plenoptic 2.0 HDR

### *A. Traditional HDR Capture*

Commercially available image sensors typically record energy in the range of 75 dB and offer 12 bits or less of useful image data per color channel. At the same time, natural scenes can show variation in radiance of 120 dB and more.

The most common method for High Dynamic Range (HDR) image capture is the *multiple exposure technique* [3], which uses multiple images of the same scene, each taken with different exposure. If the scene is static, these images can be merged into a single HDR image. Obviously, this method doesn't work for dynamic scenes.

Other approaches to HDR capture are based on appropriate electronics and include multiple reading of the pixels, or different size/type of pixels (see for example [13], [10]), and others. These approaches capture one single frame and can be used to photograph moving scenes.

With the widely used multiple exposure technique, the same scene is photographed multiple times, at different exposures/apertures, with the goal of capturing dark as well as bright areas at the right levels, in different frames. Since digital sensors are essentially linear, the result is a set of images captured at different slopes in the conversion of radiant energy into pixel value. Next, these pixel values are merged into one single floating point image with extended dynamic range. Often the above is combined with tone mapping or other HDR compression techniques designed to produce low range output image while preserving contrast and image details for the purpose of display (see [3], [4] and references therein).

### *B. Plenoptic 2.0 Camera Design for HDR capture*

To obtain HDR image of a moving scene using the multiple exposures technique, we need to take all images be *at the same time*. This capability is provided optically by the Plenoptic 2.0 camera. See Figure 3.

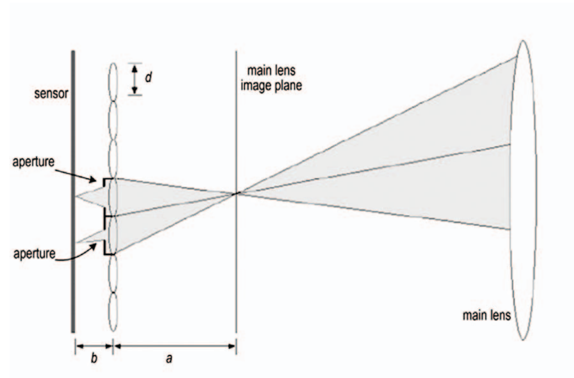


Fig. 3. Plenoptic 2.0 camera for HDR capture. Two microlens apertures are shown.

Each microlens re-images part of the main lens image to the sensor. It creates its own image of part of the scene, as seen through the main lens aperture. Each microlens works as a microcamera and its aperture determines the image exposure based on its F-number, or based on the filter placed in front of it. Different microlenses are provided with different neutral density filters or, alternatively, different apertures, that limit the amount of light through the microlenses. By carefully adjusting the values of $a$ and $b$, we can select different reductions in size. We choose $a/b > 1$, so every point in the main lens focal plane is captured at least in one microimage (typically, in two or more microimages).

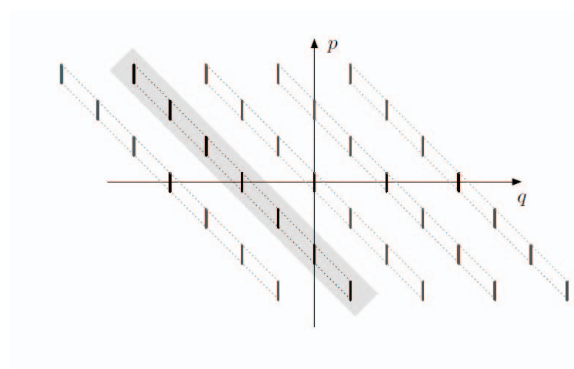


Fig. 4. Plenoptic 2.0 sampling in phase space.

In Figure 4 (taken directly from [9]) we see the phase space diagram of the above sampling of the main lens image that takes place in a Plenoptic 2.0

camera. Each microlens implements a microcamera that samples from a plane a distance $a$ in front of it, along a tilted line in $q, p$. The final rendered image is created by simply projecting onto the $q$ axis.

One microlens is covered with gray, assuming different aperture or filter on it. It is clear that each pixel with location $q$ in the final image can be derived from different microlenses. The filtered microlens would provide different pixel value than that from a neighboring unfiltered microlens. That's equivalent to capturing two images at the same time, at different exposures.

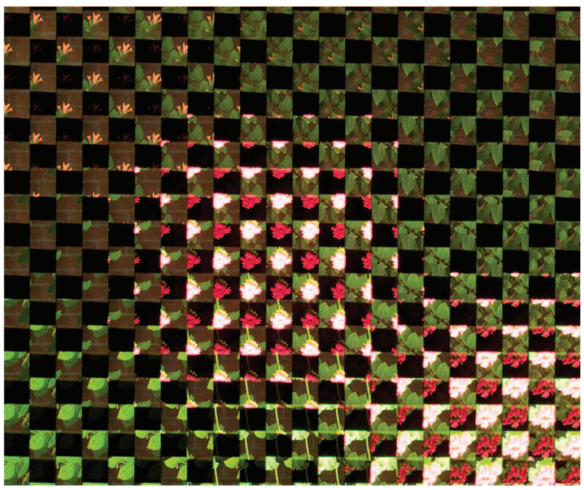

Fig. 5. Raw image from Plenoptic 2.0 HDR camera.

In Figure 5 we see a crop from the array of microimages created by the microlenses. Since aperture diameters are alternating, we observe respectively bright and dark microimages, each with the shape of the main lens aperture (square in our case). Figures 6 and 7 show two images rendered from the raw data based on filtered and unfiltered microlenses.

Similar images can be also captured by filiters at the main camera lens aperture. This is easy to see if we imagine Figure 3 with different filters at the main lens, covering the samr sections of rays that would go to the curresponding microlenses.

The microimages captured with any of these methods with the thousands of microcameras are reduced in size by a factor of $a/b$ relative to the focal plane image. This resolution is much higher than similar results with the Plenoptic 1.0 camera.

Plenoptic capture of HDR is unique in several ways. It is one of the few approaches that can give us HDR of dynamic scenes. Being optical, it is additional to any other method and can be combined with it. But also there is one more important point to make. Compared to [13], [10], our method is an improvement with respect to blooming. In other words, methods that have interleaved bright and dark "assorted" pixels cannot avoid spill of electrons from an overexposed pisels to the neighfours. Our method avoids that by simply using a different sense of neighforhood – in the angilar, not in spatial domain. If some pixels under one microlens are overexposed, corresponding pixels in the neighboring filtered microlens would not ne overexposed and would not be influenced electronically.

Fig. 6. Bright rendered image from Plenoptic 2.0 HDR camera.

Fig. 7. Dark rendered image from Plenoptic 2.0 HDR camera.

### C. Multi-spectral Color and Polaization

These are no different from HDR capture. We just need to place the appropriate filters at the microlens apertures or at the main lens aperture and then render multiple filtered versions of the image,all captured at the same time.

Figure 8 shows our main lens apertures with added filters for HDR, color and polarization.

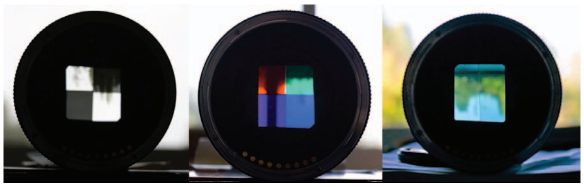

Fig. 8. Main lens with filters at the aperture.

Figures 9 and 10 show the Adobe San Jose building captured at two different polarizations with a single snapshot. The lens Figure 8 (right) is used with two polarization filters, capturing orthogonal polarizations. Notice the sky is darker in one of the images, and some of the reflections from the glass windows are different due to eliminating rays with certain polarization.

Fig. 9. Linear polarization filter has been used.

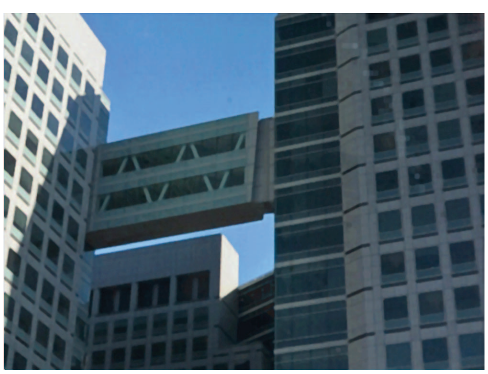

Fig. 10. Linear polarization filter orthogonal to that in Figure 9 has been used.

A lot can be achieved with multispectral color. All these topics need to be addressed in the future.

## III. Plenoptic 2.0 Superresolution

Other flexible imaging modes can be achieved with the Plenoptic 2.0 camera even without any filtering. Actually, creating novel views and stereo is already one such mode. Considering again Figure 4, pixels in different microlenses do not have to be exactly on top of each other. Since they have certain size in space, they implement kernels with which radiance is sampled in phase space. Capturing identical images with subpixel shift is a familiar approach to superresolution, and conceptually it is exactly the same setting as the one discussed here.

Superresolution with plenoptic cameras has been anticipated for a long time. But it has become practical only based on the Plenoptic 2.0 approach. Lightfield superresolution has been discussed in [2], [6].

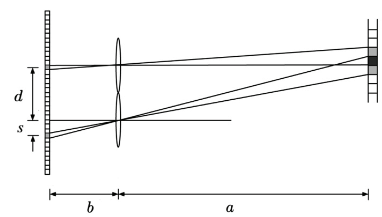


Fig. 11. Two microlens images and pixel overlap for superresolution.

In this paper we show the intuition of how the Plenoptic 2.0 camera can be used for superresolution. Considering Figure 11, we see that pixels from different microlens images can have overlaping sampling areas in the main lens image. Overlapping pixels is the setting for superresolution.

The advantage we have with Plenoptic 2.0 is we don't need to compute correspondence. All the data is available in the camera parameters, like pixel size and distance between microlenses. Those are known with great precision.

Figure 12 shows a crop from our raw plenoptic 2.0 image. Figure 13 is zoom in into the green rectangle.

Figure 14 is image with each pixel coming ftom one individual microlens, and Figure 15 is superresolved image.

## IV. Conclusion

In this paper I have demonstrated some of the new capabilities of the Plenoptic camera. These

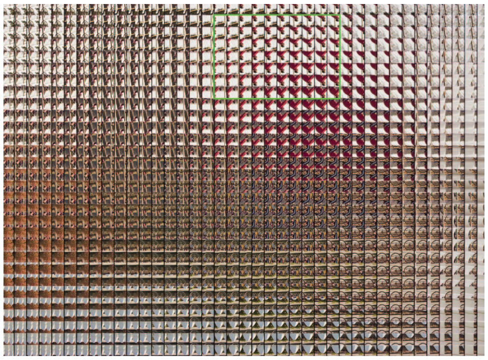

Fig. 12. Raw captured image (crop).

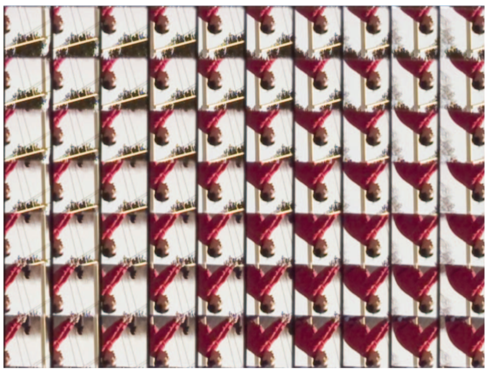

Fig. 13. Raw captured image zoom in.

Fig. 14. Normal 2.0 rendering.

and many others are based on the 2.0 approach viewing the camera as a relay system equivalent to an array of telescopes. All these new functionalities are possible because of the unique multiplexing power of the camera capturing many images in one.

Fig. 15. Superresolved image.

## References


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