Lensless Light-field Imaging with Fresnel Zone Aperture

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Abstract Attractive revolutions of imaging technologies, such as Light Field Camera and Lensless Camera, are expected to innovate various imaging applications. We propose another technology to realize a lensless light-field imaging method. The device consists of an image sensor and a Fresnel zone aperture (FZA) slightly separated in a few millimeter spacing. Synthesized shadows of it with the incident light are detected and generate moiré fringes interfering with another virtual FZA in a computer. Images are reconstructed by FFT of the fringes. Re-focusing is available by changing the size of the virtual FZA. We experimentally confirmed feasibility of the method by using a prototype which can reconstruct image at over 30 fps.

Keywords: lensless, light-field, Fresnel zone, moiré, computational photography

1. Introduction

The history of the camera could be almost summarized as that of the lenses. Nowadays, however, they have been the last obstacle for further miniaturization and lower cost. On the other hand, one of the greatest breakthroughs of the cameras in the last century, changing from silver halide films to digital image sensors, is recently causing new emerging technologies so called Computational Photography. Lensless cameras [1] are one of them and must be the ultimate slimming down technology to remove the last obstacle. Another is Light field cameras [2] which are able to obtain the light field which contains not only intensities but also directions of the incident rays, which results in re-focusing function.

We believe these kinds of technologies are beneficial for the world of “Internet-of-Things” (IoT) in the near future as key sensing devices mounted in various things.

We propose in this paper the new lensless camera which has re-focusing function. The conventional lensless cameras seem to need large amount of computational power to get final images of the sensing objects from the coded direct images. Image computation in our camera is basically simple Fast Fourier Transformation (FFT), which is fast enough to get conventional video rate movie. The conventional light field camera needs several tens millimeter’s length lens, which is removed in our proposed camera. These effects could be realized by processing moiré images generated by Fresnel zone apertures (FZA). We successfully confirmed the basic principle, experimentally.

2. Lensless light-field imaging method

Figure 1 shows a schematic diagram of lensless light-field imaging system which consists of a FZA, an image sensor, and a signal processor.

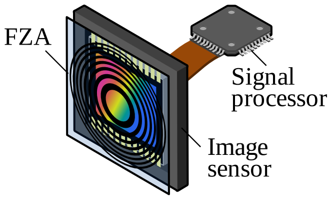

Fig. 1. Schematic diagram of lensless light-field imaging system.

The FZA is made of a transparent modulation film which can be manufactured by using low cost way, e.g. printing. The intensity transmittance of FZA pattern is defined by

$$I(x) = \frac{1}{2}(1 + cos\beta x^2), \tag{1}$$

in an analogy of light interference fringe between a parallel light wave and a spherical light wave, where x is a radius of the center of the image sensor, and β is a coefficient to define the pitch of the pattern. In addition, for simplicity, we discuss the formulas in a one-dimensional field.

Figure 2 shows the side view of the optical unit consists of the FZA and the image sensor, which are placed in a slight distance from each other. When taking a picture with this system, an incident parallel light from a light source of an object in an infinite distance irradiates the FZA in Fig. 3(a). Then, the slant incident light makes a shifted shadow of FZA pattern on the image sensor, as shown in Fig. 3(b).

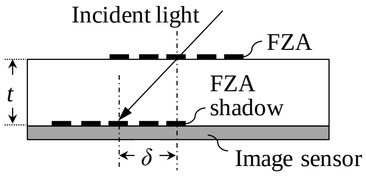

Fig. 2. Side view of schematic diagram of lensless optical unit.

The FZA shadow can be given by

$$I(x + \delta) = \frac{1}{2}(1 + cos\beta(x + \delta)^2), \tag{2}$$

where δ is a shift distance between the FZA and the shadow. Next, in the signal processor, the interference between the captured shadow with the image sensor and a virtual FZA in the processor makes moiré fringes, as shown in Fig. 3(c). The fringes can be described as following

$$\begin{aligned} I(x)I(x + \delta) = \frac{1}{8}\,&[2 + 4cos\beta(x^2 + \delta x)cos\delta\beta x \\ &+ cos2\beta(x^2 + \delta x) + cos2\delta\beta x]. \end{aligned} \tag{3}$$

In this Eq. (3), $cos2\delta\beta x$ is a signal term in this system, and it depends on the incident angle of the lights. Figure 3(d) shows a 2D-Fourier transform of the signal term, and the result indicates the reconstructed image of the light source. It is also obvious in a following equation.

$$\mathcal{F}[cos2\delta\beta x] = \delta\left(u + \frac{\delta\beta}{\pi}\right) + \delta\left(u - \frac{\delta\beta}{\pi}\right), \tag{4}$$

where u is a frequency value.

In this sequence, the crucial point is that an incident angle corresponds to the spatial frequency of the moiré fringes. Eventually, this lensless imaging method can reconstruct the original object image by using 2D Fast Fourier Transform (FFT) which is known as a low-computing-power calculation.

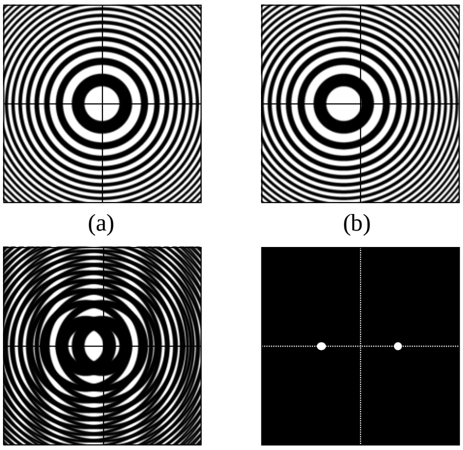
(a) (b)
(c) (d)

Fig. 3. (a) Example of FZA pattern, (b) shifted shadow FZA by slant incident light, (c) moiré fringes by interference between FZA and the shadow, and (d) Fourier transform of the fringes.

Figure 4 shows the side view of the optical unit in the case of a light source placed at a finite distance from the FZA. The light source generates a larger shadow FZA than the infinite-distance light source shown in Fig. 2.

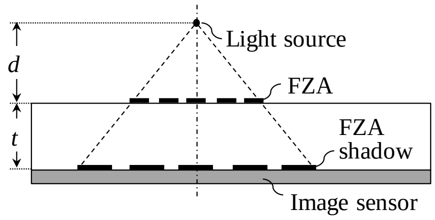

Fig. 4. Side view of schematic diagram of lensless optical unit in the case of finite light source.

The magnification rate α of the enlarged shadow FZA comparing to the original FZA is given by

$$\alpha = \frac{d+t}{d}. \tag{5}$$

As the result, interference between the shadow and the original virtual FZA makes a distorted moiré fringes as shown in Fig. 5(a). Then, the reconstructed image by the 2D-FFT of the fringes indicates a de-focused light source, as shown in Fig. 5(b).

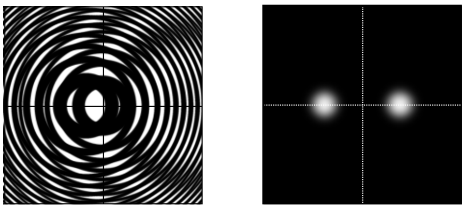
(a) (b)

Fig. 5. (a) Distorted moiré fringes by interference between FZA and the shadow, and (b) Fourier transform of the fringes.

However, we can easily re-focus on the finite-distance light source by adjusting the pitch of the virtual FZA after capturing the sensor image. The virtual FZA adjusted the coefficient with Eq. (6) is available to reconstruct without distortion. Eventually, this method also works as a light-field camera.

$$\beta' = \frac{\beta}{\alpha^2}, \tag{6}$$

3. Experimental results

To confirm feasibility of the lensless light-field imaging method using the FZA, an experimental setup was established to evaluate it. Figure 6 shows a picture of the prototype. The image sensor has 2048×2048 pixels and 11×11 mm^2 size; a distance between the FZA and the image sensor is 2 mm.

Moreover, we made a signal processing unit for reconstruction. The unit has ability to calculate 2D-FFT and noise reduction of the moiré fringes at over 30 fps.

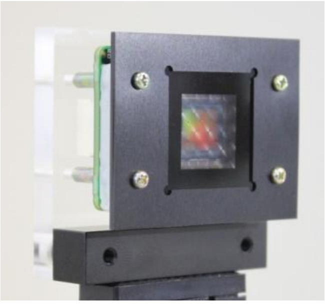

Fig. 6. Prototype of lensless light-field imaging camera.

Figure 7 shows the reconstructed images of real objects by using the prototype. In this experiment, the objects are “lena” as a standard test image and a check pattern, whose size are about 400 mm and 20 mm respectively. The objects are displayed on 300 mm distance and 10 mm distance from the surface of the FZA. The focal position of each image was adjusted by changing β of the FZA, after capturing the sensor images.

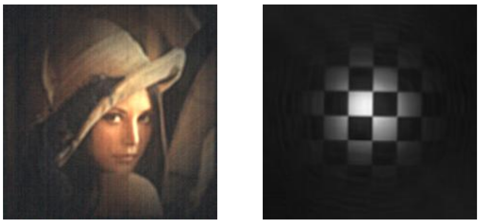
(a) (b)

Fig. 7. Experimental results (a) standard test image “lena” displayed on 300 mm distance and (b) check pattern displayed on 10 mm distance.

As the results, we experimentally confirmed feasibility of the method as the lensless and light-field cameras.

4. Conclusion

We proposed the lensless light-field imaging method which can reconstruct with the 2D-FFT. The simple reconstruction way enables real-time processing; moreover the method enables advanced features of the light-field camera such as re-focusing. In addition, we established the prototype and obtained the reconstructed image of the real object at real-time.

Consequently, feasibility of the lensless light-field imaging method was confirmed experimentally. As a future work, we will study to improve the quality of the reconstructed image.

References

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[2] R. Ng., M. Bredif, G. Duval, M. Horowitz and P. Hanrahan, Stanford Tech. Rep., CTSR 2005-02, (2005).