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Wave Optics Simulations of a Focused Plenoptic System

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Abstract: A wave optics numerical simulation of focused Plenoptic systems using Fresnel propagation is presented. This shows the dependence on the lenslet array parameters of the real optical resolution of this system at the diffraction limit.

OCIS codes: (110.1758) Computational imaging; (070.7345) Wave propagation; (110.6880) Three dimensional image acquisition

1. Introduction

The main purpose of this study is to evaluate the optical performance of a focused Plenoptic imaging system (Plenoptic 2.0) under a wave optics approach for applications such as eye imaging [1]. The Light Field is defined as a four dimensional function, also known as Plenoptic function, representing radiance along rays as a function of position and direction in space [2]. The presence of two additional coordinates enables the acquisition of directional information. Most of the literature studies Plenoptic systems using geometrical optics, which is not suitable to understand the behavior of the system close to its diffraction limit. Recently a wave optics study of Plenoptic system has been done by Oh *et al.* [3].
In this work a full numerical simulation platform that takes into account Fresnel propagation of light has been developed in MATLAB. Results regarding the diffraction limit of a simple Plenoptic 2.0 system and the effect of lenslet configurations will be shown.

2. Numerical Simulations

Numerical simulation of light propagating in a Light Field Imaging system has been performed using a wave optics approach. Propagation of light has been simulated using the Angular Spectrum of Plane Waves approximation, where an optical field is seen as a superposition of plane waves, angular spectrum A, and the propagation is seen as a linear, dispersive, spatial filter with a defined bandwidth that depends on the propagation distance, defined by a transfer function H, as shown in equation 1 [4].

$$A(f_x, f_y, z) = A(f_x, f_y, 0)H(f_x, f_y) \quad (1)$$

Band Limited Angular spectrum method proposed by Matsushima *et al*. [5] has been used to overcome the aliasing that arises from digital sampling of the transfer function.
The main lens and micro lenses present in the Plenoptic 2.0 system were simulated with a pupil $L(x,y)$ with an appropriate quadratic phase factor as shown in equation 4, where x and y are spatial coordinates at the pupil plane and k is the wave number, $P(x,y)$ is unity inside the pupil and zero elsewhere [4].

$$L(x, y) = P(x, y)e^{j\frac{k}{2f}(x^2+y^2)} \quad (2)$$

Similar resolution considerations to those made for the angular spectrum propagation can be made regarding the quadratic phase factor of the lens which leads to aliasing due to under sampling of the phase. Applying the same method used for the transfer function, for a lens of focal length f, and diameter D, the minimum digital resolution N to avoid aliasing is:

$$N \geq \frac{2kD^2}{f} \quad (3)$$

In the simulations performed, the object field consists of a sinusoidal grating. This propagates a distance $2f$, where f is the focal length of the main lens, passes through it, and propagates by another $2f$. In a Plenoptic 2.0 system each micro lens ensures that the sensor plane is conjugate to the image plane of the main lens and hence images a small region of the image plane onto the sensor [5]. Therefore we propagate the image plane further by a distance a to the micro lens array, and then by a distance b from micro lens array to sensor, where a and b satisfy the lens equation.

Final images are then rendered from raw sensor data according to Georgiev *et al*. [7]. All the simulations were run with incoherent light of wavelength λ=500nm.

3. Results

The results presented are from a system consisting of a main lens of focal length 0.419 m and diameter 0.007 m, and a micro lens array formed by micro lenses with focal length 0.04 m and diameter of 500 μm. Propagation distances before and after the main lens are 0.838 m (2f system) while both *a* and *b* change in order to have a magnification M between image plane of main lens and the sensor of M=0.25 (*a*=0.2m and *b*=0.05m) and M=0.5 (*a*=0.12m and *b*=0.06m). Both the main lens and the lenslet array have a similar f-number. This is close to the condition of f-number matching as prescribed by Georgiev *et al*. [6]. Therefore the cutoff frequency of the main lens [4], is 16,672 cycles/m (cpm) and that of the lenslet is 20,006 cpm when M=0.25 and 16,672 cpm when M=0.5. The frequency of the sinusoidal field is 5,000 cpm. The images obtained are shown in figure 1.

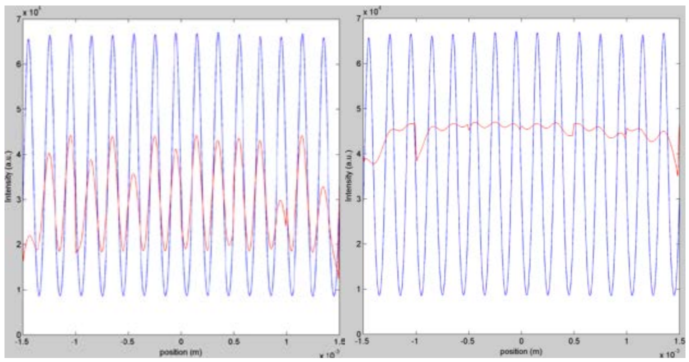

Figure 1: Cross section intensity profile of the image of the main lens (blue) and the rendered Plenoptic image (red) rescaled to match the main lens image for comparison. Left: M=0.5. Right: M= 0.25.

The results in figure 1 show that the magnification provided by the lenslets affects the optical resolution. This is because a spatial frequency ν at the image plane of the main lens becomes a spatial frequency ν/M. So when M=0.5 the image on the sensor has a spatial frequency of 10,000 cpm, that is below the cutoff frequency of the lenslets, letting the information pass, with a significantly reduced modulation. When M=0.25 the image on the sensor has a spatial frequency of 20,000 cpm, which is exactly the cutoff frequency of the lenslets. So the information is lost.

4. Conclusions and future works

This paper presents wave optics numerical simulations of focused Plenoptic systems showing the real optical resolution of these systems. The results presented show that for an optimal focused Plenoptic system, in which the f-number of the main lens and lenslet array is matched [6], resolution is limited by the lenslet and is dependents on the magnification between the main lens image plane and the sensor plane. The trade-off between directional and spatial resolution must therefore also include considerations of diffraction effects. Further studies will use this simulation platform to investigate Plenoptic modalities in which the full optical resolution could be recovered.

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