High-speed Light Field Image Formation Analysis Using Wavefield Modeling with Flexible Sampling

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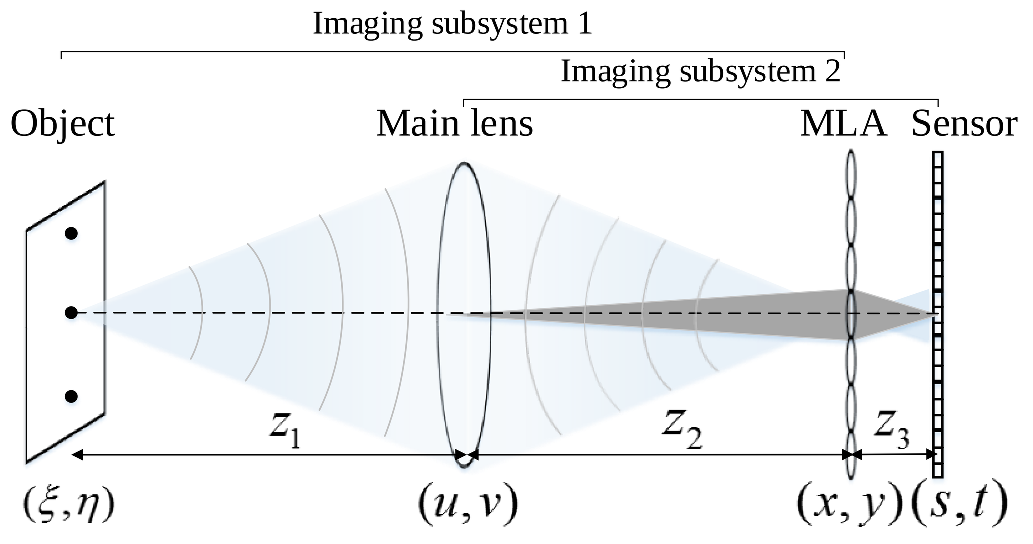
1. Abstract

In order to understand the image formation inside plenoptic systems, a wave-optic-based model is proposed in this paper that uses the Fresnel diffraction equation to propagate the whole object field into the plenoptic systems. The proposed model is much flexible at sampling on propagation planes by utilizing the method of multiple partial propagations. In order to verify the effectiveness of the proposed model, numerical simulations are conducted by comparing with existing wave optic model under different optical configurations of plenoptic cameras. Results demonstrate that the proposed model can describe the light field image formation properly. In addition, the time for image formation has been reduced by a factor of 19.22 using the proposed model.

2. Incoherent Image Formation Model



Schematic layout of a plenoptic camera 1.0 system

The distances among the optical component planes satisfy the Gaussian equation, which are given by

$$\frac{1}{z_1}+\frac{1}{z_2}=\frac{1}{F_{main}}$$

$$\frac{1}{z_2}+\frac{1}{z_3}=\frac{1}{f_{MLA}}$$

2.1. Traditional wave optic model

Wave analysis is performed in [11]. In the formulas, paraxial approximation is exploited and lenses are assumed to be thin and aberration-free. According to [11], the intensity at the sensor plane is given by:

$$I_1(s,t)=\iint d\xi' d\eta' I_0\left(\frac{\xi'}{M_1},\frac{\eta'}{M_1}\right)\left|\frac{e^{ikz_1}e^{ikz_2}e^{ikz_3}}{i\lambda z_3 M_1}\exp\left[\frac{ik}{2z_3}\left(s^2+t^2\right)\right]\right.$$
$$\times\sum_m\sum_n \exp\left\{-\frac{ik}{2f_{micro}}\left[(md_1)^2+(nd_1)^2\right]\right\}$$
$$\times\iint dxdy P(x-md_1,y-nd_1)\exp\left[\frac{ik}{2}\left(\frac{1}{z_2}+\frac{1}{z_3}-\frac{1}{f_{micro}}\right)\left(x^2+y^2\right)\right]$$
$$\left.\times\exp\left\{-ik\left[x\left(\frac{s}{z_3}-\frac{md_1}{f_{micro}}\right)+y\left(\frac{t}{z_3}-\frac{nd_1}{f_{micro}}\right)\right]\right\}h_1'(x-\xi',y-\eta')\right|^2$$

$h_1'(x,y)$ is defined as the Fourier transform of

$$P_1(u\lambda z_2,v\lambda z_2)\times\exp\left\{\frac{ik}{2}\left(\frac{1}{z_1}+\frac{1}{z_2}-\frac{1}{F_{main}}\right)\left[(u\lambda z_2)^2+(v\lambda z_2)^2\right]\right\}$$

However, this kind of image formation is **time-consuming** since the impulse responses needs to be obtained point-by-point to satisfy incoherent imaging.

2.2. Proposed wave optic model

Considering the time cost, we proposed a wave optic model that propagates the whole object field to the sensor plane simultaneously. In order to decrease the coherence during propagation, the proposed model applies random transmittance screens to the object field.

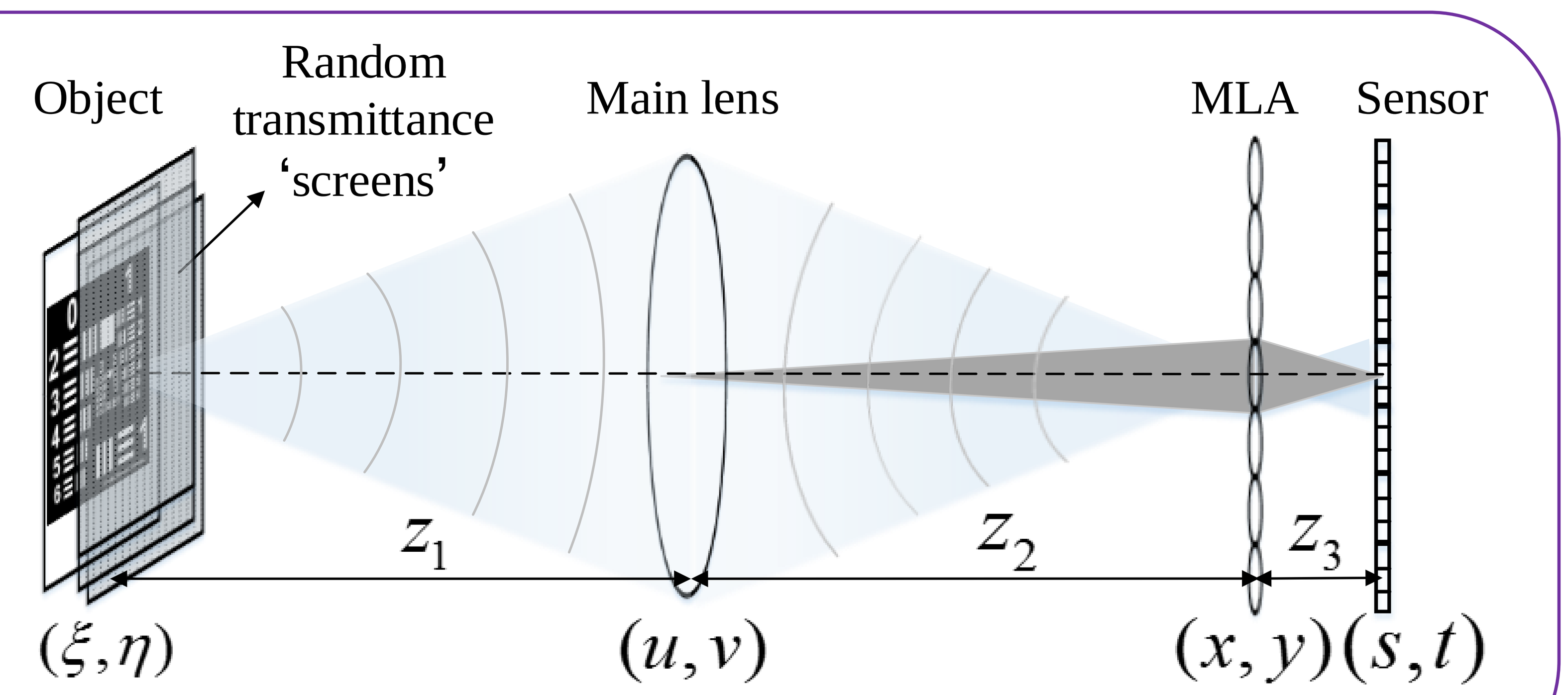


Illustration of the proposed wave optic propagation model

The object field is now modeled as

$$U(\xi,\eta)=U_o(\xi,\eta).*\exp\left[i*2\pi*rand(\text{Num})\right]$$

The object field is propagated into the plenoptic system utilizing Fresnel propagation equation and the process is repeated N_1 times with different realizations of phase. The intensities are averaged to produce the final incoherent result.

$$U(u,v)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{e^{ikz_1}}{i\lambda z_1}U(\xi,\eta)\exp\left\{\frac{ik}{2z_1}\left[(\xi-u)^2+(\eta-v)^2\right]\right\}d\xi d\eta$$

$$U'(u,v)=U(u,v)P_1(u,v)\exp\left[-\frac{ik}{2F_{main}}(u^2+v^2)\right]$$

$$U(x,y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{e^{ikz_2}}{i\lambda z_2}U'(u,v)\exp\left\{\frac{ik}{2z_2}\left[(u-x)^2+(v-y)^2\right]\right\}dudv$$

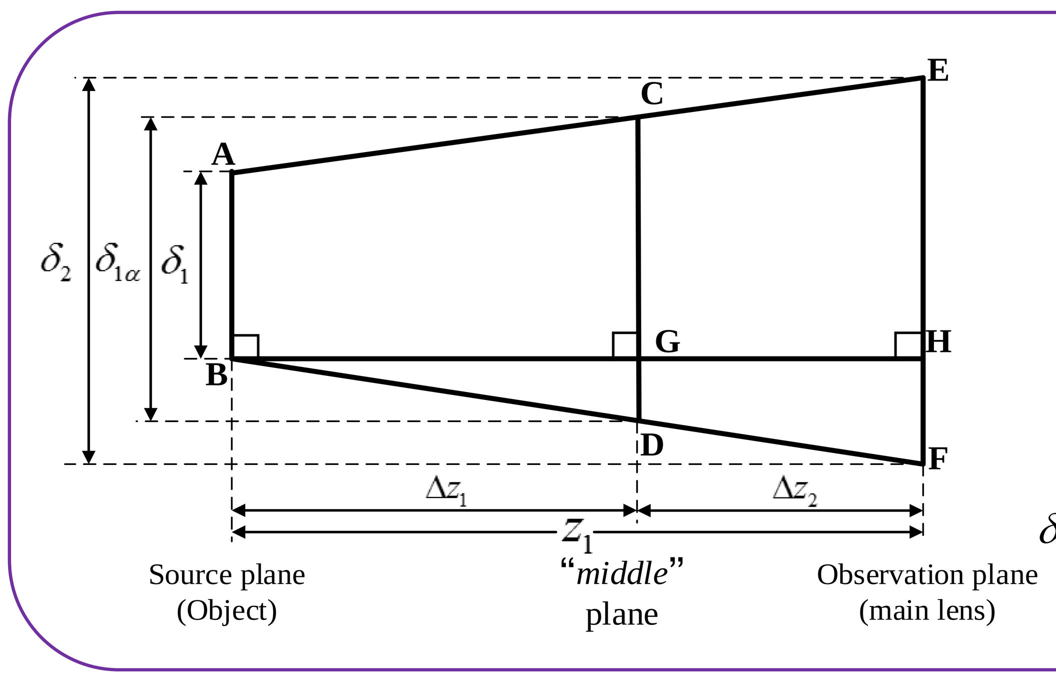
$$U'(x,y)=U(x,y)\sum_{m\in M}\sum_{n\in N}P(x-md_1,y-nd_1)\exp\left\{-\frac{ik}{2f_{MLA}}\left[(x-md_1)^2+(y-nd_1)^2\right]\right\}$$

$$U(s,t)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{e^{ikz_3}}{i\lambda z_3}U'(x,y)\exp\left\{\frac{ik}{2z_3}\left[(x-s)^2+(y-t)^2\right]\right\}dxdy$$

$$I_1(s,t)=\left|U(s,t)\right|^2 \qquad I(s,t)=\frac{1}{N_1}\sum_{j=1}^{N_1}I_j(s,t)$$

2.3. Relaxed sampling with partial propagations

For the sake of having more flexibility in selecting the grids on the observation plane, the proposed model adopts the method of **multiple partial propagation** provided by Schmidt [16] that introduces "middle" planes between the source plane and the observation plane.



$$\frac{\delta_{1\alpha}-\delta_1}{2\Delta z_1}=\frac{\delta_2-\delta_1}{2z_1}=\frac{\delta_2-\delta_{1\alpha}}{2\Delta z_2}$$

$$\alpha=\Delta z_1/z_1 \qquad \beta=\Delta z_2/\Delta z_1$$

$$\delta_{1\alpha}=(1-\alpha)\delta_1+\alpha\delta_2$$

$$\delta_{1\alpha}=\frac{\lambda\Delta z_1}{\text{Num}\delta_1}$$

$$\delta_2=\frac{\lambda\Delta z_2}{\text{Num}\delta_{1\alpha}}=\frac{\lambda\Delta z_2}{\text{Num}\left(\frac{\lambda\Delta z_1}{\text{Num}\delta_1}\right)}=\beta\delta_1$$

$$\mathbf{r}_1=\xi\mathbf{i}+\eta\mathbf{j} \qquad \mathbf{r}_2=u\mathbf{i}+v\mathbf{j}$$

$$\left|\mathbf{r}_2-\mathbf{r}_1\right|^2=r_2^{\,2}-2\mathbf{r}_2\bullet\mathbf{r}_1+r_1^{\,2}$$
$$=(r_2^{\,2}+\frac{r_2^{\,2}}{\beta}-\frac{r_2^{\,2}}{\beta})-2\mathbf{r}_2\bullet\mathbf{r}_1+(r_1^{\,2}+\beta r_1^{\,2}-\beta r_1^{\,2})$$
$$=\beta\left[(\frac{r_2}{\beta})^2-2(\frac{\mathbf{r}_2}{\beta})\bullet\mathbf{r}_1+r_1^{\,2}\right]+(1-\frac{1}{\beta})r_2^{\,2}+(1-\beta)r_1^{\,2}$$
$$=\beta\left|\frac{\mathbf{r}_2}{\beta}-\mathbf{r}_1\right|^2-(\frac{1-\beta}{\beta})r_2^{\,2}+(1-\beta)r_1^{\,2}$$

$$U(\mathbf{r}_2)=\frac{e^{ikz_1}}{i\lambda z_1}\int_{-\infty}^{\infty}U(\mathbf{r}_1)\exp\left[\frac{ik}{2z_1}\left|\mathbf{r}_2-\mathbf{r}_1\right|^2\right]d\mathbf{r}_1$$

$$U(\mathbf{r}_2)=\frac{e^{ikz_1}e^{-\frac{ik}{2z_1}\left(\frac{1-\beta}{\beta}\right)r_2^{\,2}}}{i\lambda z_1}\int_{-\infty}^{\infty}\beta U'(\mathbf{r}_1)\exp\left[\frac{ik\beta}{2z_1}\left|\frac{\mathbf{r}_2}{\beta}-\mathbf{r}_1\right|^2\right]d\mathbf{r}_1$$

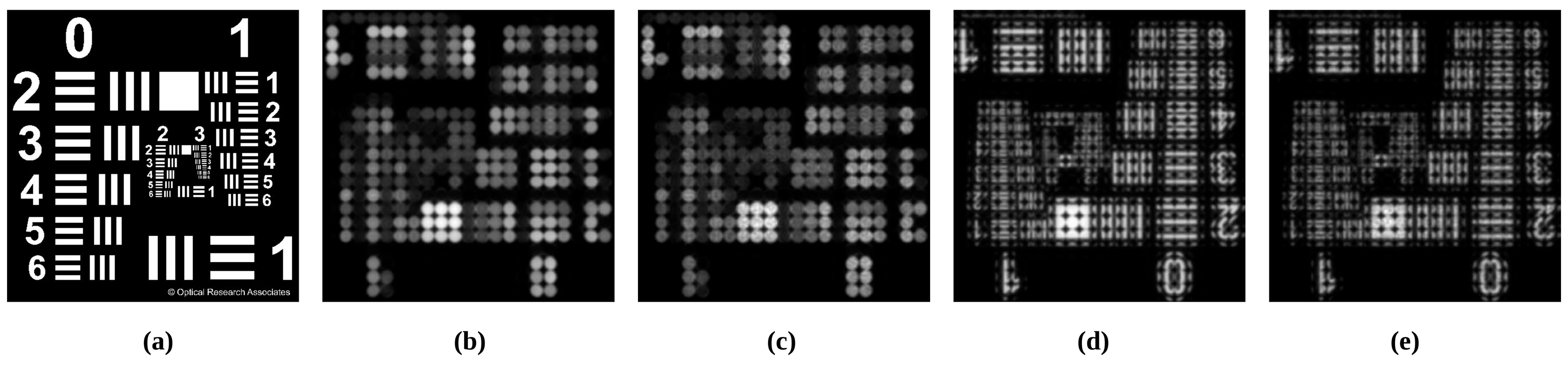
$$\mathbf{r}_2'=\mathbf{r}_2/\beta, \quad z_1'=z_1/\beta$$

$$U(\beta\mathbf{r}_2')=\frac{e^{ik\beta z_1'}e^{-\frac{ik}{2z_1'}(1-\beta)r_2'^2}}{i\lambda z_1'}\int_{-\infty}^{\infty}U'(\mathbf{r}_1)\exp\left[\frac{ik}{2z_1'}\left|\mathbf{r}_2'-\mathbf{r}_1\right|^2\right]d\mathbf{r}_1$$

The scaling parameter is determined by the location of the "*middle*" plane, it is adjustable as the location changes. This leads to the flexibility of grid spacing on the observation plane.

3. Experimental results

3.1. Simulation results



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

Simulation results for a 23×23 array of lenslets. (b) and (d) are the in-focus and close-to-focus cropped plenoptic sensor data obtained by using the wave optic model in [11]; (c) and (e) are the corresponding results obtained by using the proposed model. The SSIMs are 0.9295 and 0.9158, respectively.

3.2. Performance comparison

Cases	b	c	d	e
Simulation time (s)	352682.1	**18101.4**	373896.1	**19882.7**
Ratio ([11] vs Proposed)	b/c=19.48		d/e=18.81	

[11] S.A. Shroff and K. Berkner, "Image formation analysis and high resolution image reconstruction for plenoptic imaging systems," Applied Optics, 52(10), pp. D22–D31, Apr. 2013.
[16] J.D. Schmidt, Numerical simulation of optical wave propagation with examples in MATLAB, SPIE Press, 2010.