Near-Invariant Blur for Depth and 2D Motion via Time-Varying Light Field Analysis

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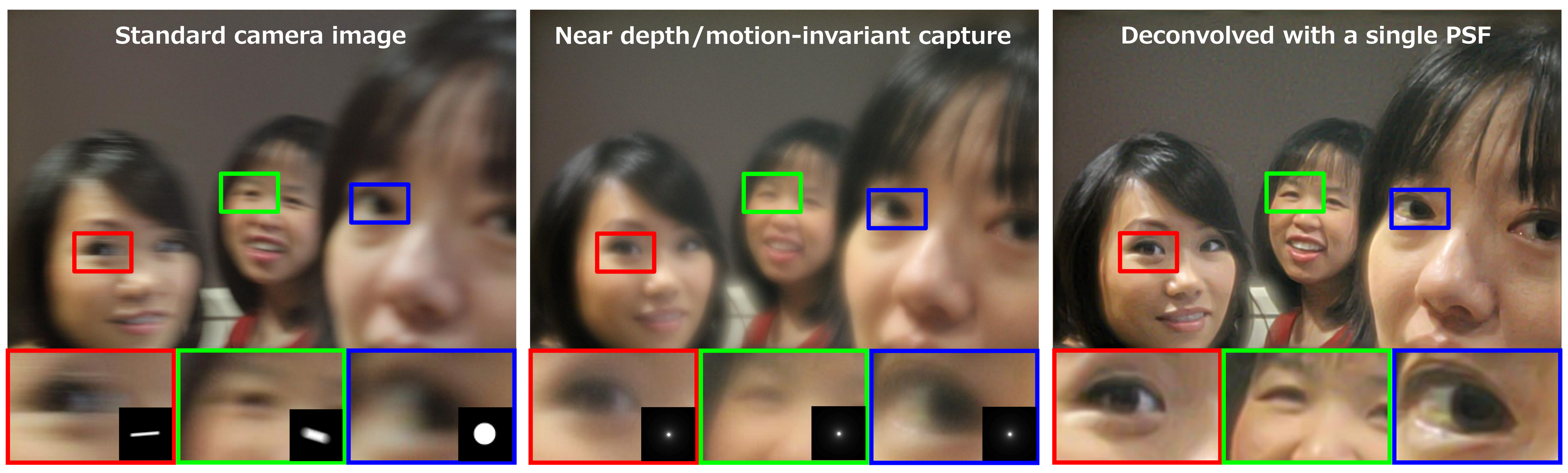
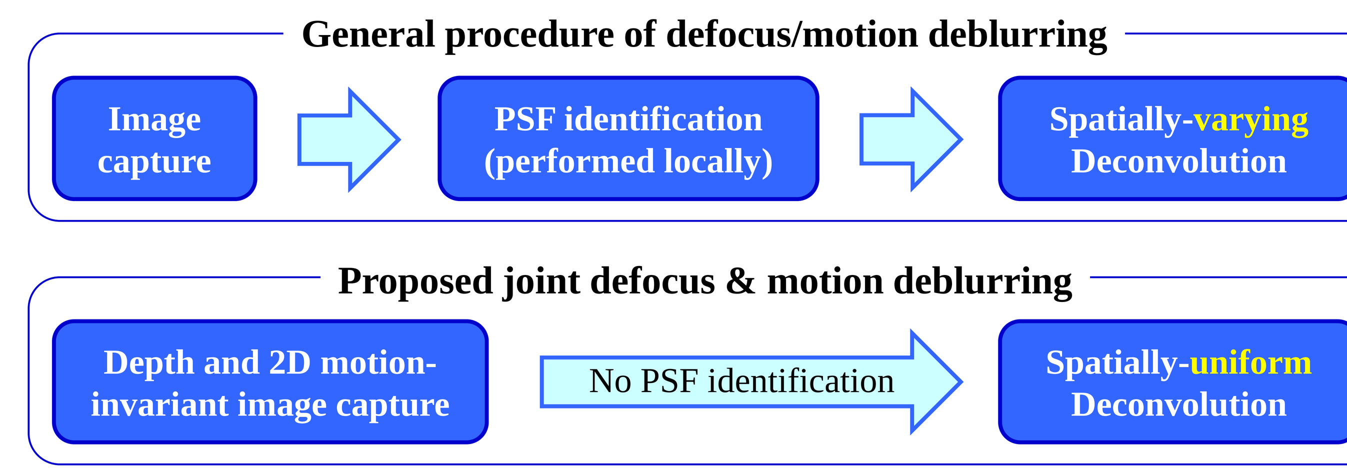
Overview





Contributions

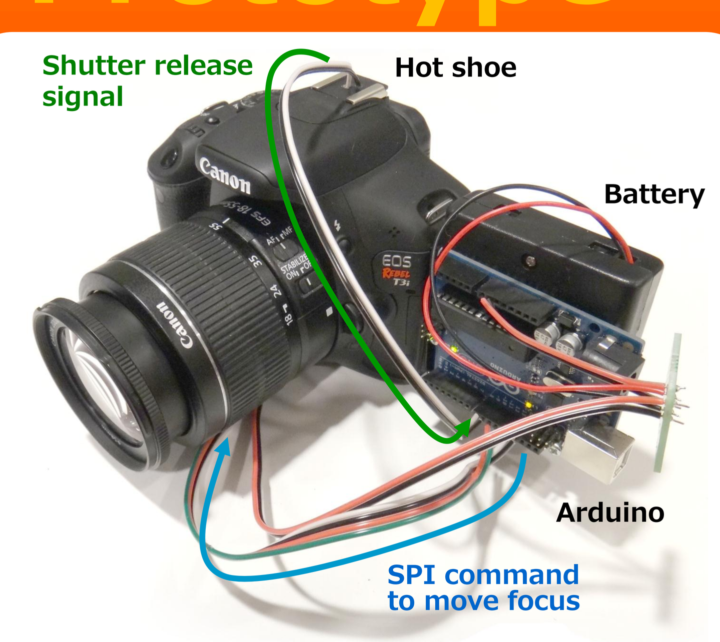
- Proof of near-optimality of focus sweep in depth and 2D motion invariance and in high-frequency preservation
- Comparison of all the existing computational cameras for deblurring via 5D (4D light field + 1D time) analysis
- Prototype camera demonstration

Related Work

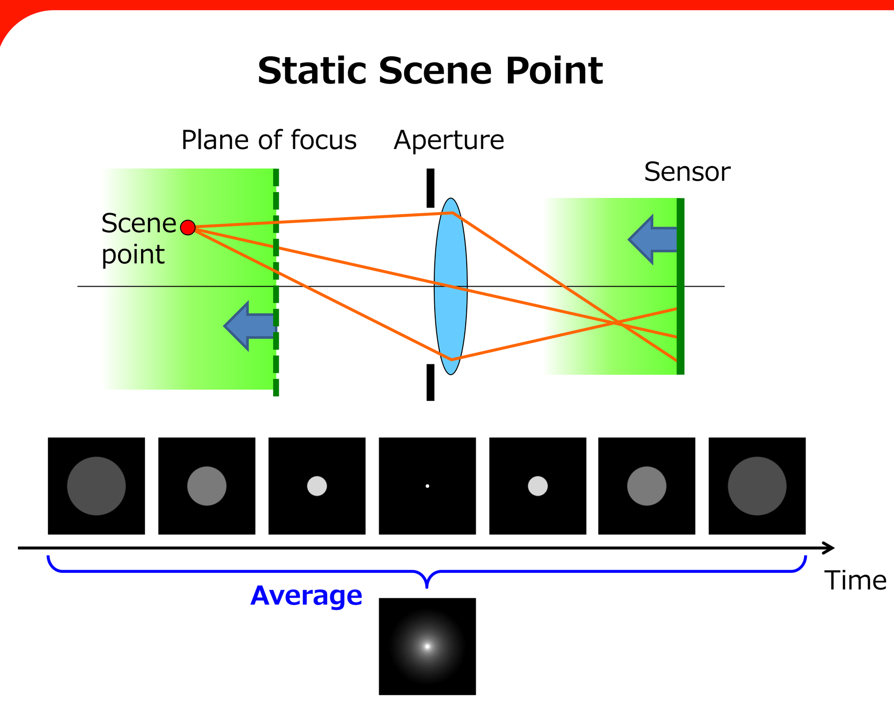
	Defocus deblurring	Motion deblurring
High frequency preservation (requires blur estimation)	**Coded aperture** [Levin et al. 2007; Veeraraghavan et al. 2007] **Lattice-focal lens** [Levin et al. 2009]	**Coded exposure** [Raskar et al. 2006] **Orthogonal parabolic exposures** [Cho et al. 2010] **Circular sensor motion** [Bando et al. 2011]
Invariant capture (no need for blur estimation)	**Wavefront coding** [Dowski and Cathey 1995] **Focus sweep** [Hausler 1972; Nagahara et al. 2008] **Diffusion coding** [Cossairt et al. 2010] **Spectral focus sweep** [Cossairt and Nayar 2010]	**Motion-invariant photography** (for 1D motion) [Levin et al. 2008]

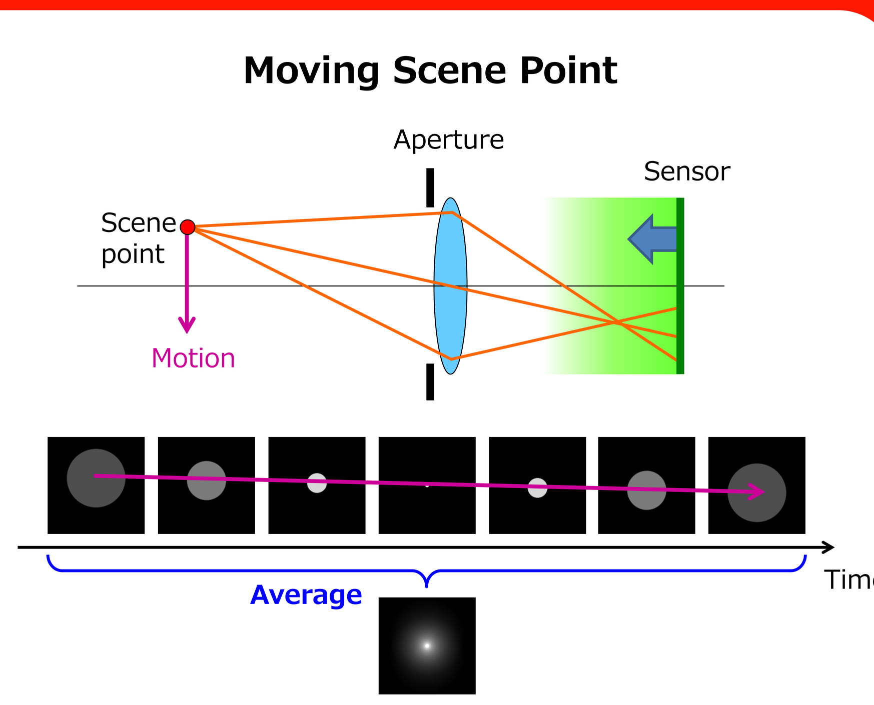
We prove its near depth and 2D motion invariance

Prototype

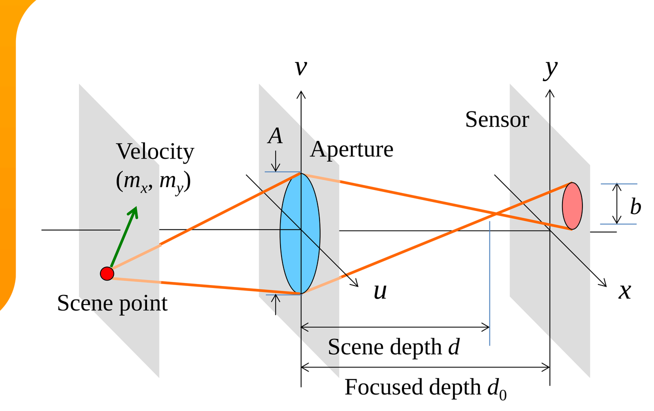


How It Works





Analysis



$\mathbf{f_x} = (f_x, f_y)$	Spatial frequency
t	Time
$s = (d - d_0)/d$	Scene depth
A	Diameter of circular aperture
A'	Size of square aperture $\sqrt{\pi}A/2$
T	Exposure time
S	Depth range
M	Motion range
Ω	Maximum spatial frequency
γ_j	Pseudo-random code
$\varepsilon A', \varepsilon T$	Sub-aperture/exposure size
(u_j, v_j)	Sub-aperture location
t_j	Sub-exposure time instance
Δs	Depth step
a	Parabolic integration coef.
r	Circular motion radius
w	Focus sweep speed

(a) Defocus deblurring.

Camera design	4D kernel $k_a(\mathbf{x}, \mathbf{u})$ Integration surface	Integration window	Squared MTF $\lvert\hat{\phi}_s(\mathbf{f_x})\rvert^2 = \lvert\hat{k}_a(\mathbf{f_x}, -s\mathbf{f_x})\rvert^2$	High freq. preserv. $\min_s \lvert\hat{\phi}_s(\mathbf{f_x})\rvert^2$	MTF invariance $\min_s \lvert\hat{\phi}_s\rvert^2 / \max_s \lvert\hat{\phi}_s\rvert^2$
Upper bound	–	–	–	$\frac{2A^3}{3S\lvert\mathbf{f_x}\rvert}$	1
Standard lens	$\delta(\mathbf{x} - s_0\mathbf{u})$	$R(\lvert\mathbf{u}\rvert/A)$	$\frac{\pi^2 A^4}{16}\mathrm{jinc}^2(\pi A s\lvert\mathbf{f_x}\rvert)$	0	0
Narrow aperture	$\delta(\mathbf{x} - s_0\mathbf{u})$	$R(S\Omega\lvert\mathbf{u}\rvert)$	$\frac{\pi^2}{16S^4\Omega^4}\mathrm{jinc}^2(\frac{\pi}{S\Omega}s\lvert\mathbf{f_x}\rvert)$	$\frac{\pi^2}{16S^4\Omega^4}\mathrm{jinc}^2(\frac{\pi}{2\Omega}\lvert\mathbf{f_x}\rvert)$	$\mathrm{jinc}^2(\frac{\pi}{2\Omega}\lvert\mathbf{f_x}\rvert)$
Coded aperture	$\sum_j\{\delta(\mathbf{x} - s_0\mathbf{u})$	$\gamma_j R(\frac{u-u_j}{\varepsilon A'})R(\frac{v-v_j}{\varepsilon A'})\}$	$\frac{A'^2}{2S^2\Omega^2}\mathrm{sinc}^2(\frac{\pi}{S\Omega}sf_x) \cdot\mathrm{sinc}^2(\frac{\pi}{S\Omega}sf_y)$	$\frac{A'^2}{2S^2\Omega^2}\mathrm{sinc}^2(\frac{\pi}{2\Omega}f_x) \cdot\mathrm{sinc}^2(\frac{\pi}{2\Omega}f_y)$	$\mathrm{sinc}^2(\frac{\pi}{2\Omega}f_x)\cdot\mathrm{sinc}^2(\frac{\pi}{2\Omega}f_y)$
Lattice-focal lens	$\sum_j\{\delta(\mathbf{x} - s_j\mathbf{u})$	$R(\frac{u-u_j}{\varepsilon A'})R(\frac{v-v_j}{\varepsilon A'})\}$	$\frac{A'^{8/3}}{(S\Omega)^{4/3}}\sum_j \mathrm{sinc}^2(\frac{\pi(s-j\Delta s)}{\Delta s\Omega}f_x) \cdot\mathrm{sinc}^2(\frac{\pi(s-j\Delta s)}{\Delta s\Omega}f_y)$	$\lvert\hat{\phi}_{\Delta s/2}(\mathbf{f_x})\rvert^2$	$\lvert\hat{\phi}_{\Delta s/2}(\mathbf{f_x})\rvert^2/\lvert\hat{\phi}_0(\mathbf{f_x})\rvert^2$
Wavefront coding	$\delta(\mathbf{x} - (au^2, av^2))$	$R(u/A')R(v/A')$	$\frac{A'^2}{S^2\lvert f_x\rvert\lvert f_y\rvert}$	$\frac{A'^2}{S^2\lvert f_x\rvert\lvert f_y\rvert}$	1
Static focus sweep	$\frac{1}{S}\int_{-S/2}^{+S/2}\{\delta(\mathbf{x} - s_0\mathbf{u})$	$R(\lvert\mathbf{u}\rvert/A)\}ds_0$	$\frac{A^2}{S^2\lvert\mathbf{f_x}\rvert^2}$	$\frac{A^2}{S^2\lvert\mathbf{f_x}\rvert^2}$	1

(b) Motion deblurring.

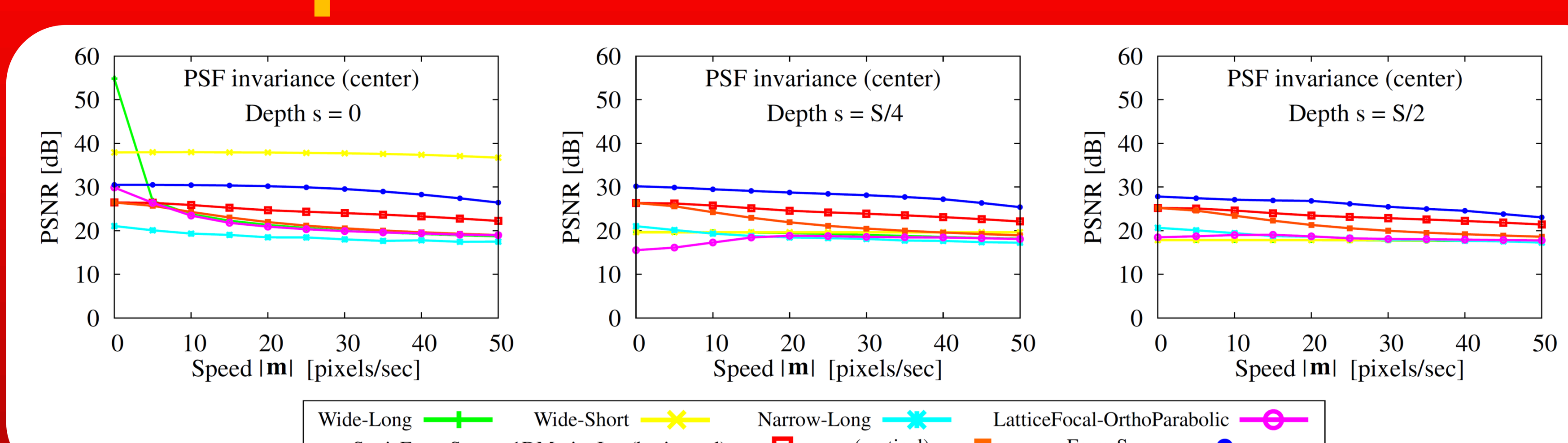
Camera design	3D kernel $k_e(\mathbf{x}, t)$ Integration surface	Integration window	Squared MTF $\lvert\hat{\phi}_\mathbf{m}(\mathbf{f_x})\rvert^2 = \lvert\hat{k}_e(\mathbf{f_x}, -\mathbf{m}\cdot\mathbf{f_x})\rvert^2$	High freq. preserv. $\min_\mathbf{m} \lvert\hat{\phi}_\mathbf{m}(\mathbf{f_x})\rvert^2$	MTF invariance $\min \lvert\hat{\phi}_\mathbf{m}\rvert^2 / \max \lvert\hat{\phi}_\mathbf{m}\rvert^2$
Upper bound	–	–	–	$\frac{T}{M\lvert\mathbf{f_x}\rvert}$	1
Static/follow-shot	$\delta(\mathbf{x} - \mathbf{m}_0 t)$	$R(t/T)$	$T^2\mathrm{sinc}^2(\pi T(\mathbf{m} - \mathbf{m}_0)\cdot\mathbf{f_x})$	0	0
Short exposure	$\delta(\mathbf{x})$	$R(M\Omega t)$	$\frac{1}{M^2\Omega^2}\mathrm{sinc}^2(\frac{\pi}{M\Omega}\mathbf{m}\cdot\mathbf{f_x})$	$\frac{1}{M^2\Omega^2}\mathrm{sinc}^2(\frac{\pi}{2\Omega}\lvert\mathbf{f_x}\rvert)$	$\mathrm{sinc}^2(\frac{\pi}{2\Omega}\lvert\mathbf{f_x}\rvert)$
Coded exposure	$\sum_j\{\delta(\mathbf{x})$	$\gamma_j R(\frac{t-t_j}{\varepsilon T})\}$	$\frac{T}{2M\Omega}\mathrm{sinc}^2(\frac{\pi}{M\Omega}\mathbf{m}\cdot\mathbf{f_x})$	$\frac{T}{2M\Omega}\mathrm{sinc}^2(\frac{\pi}{2\Omega}\lvert\mathbf{f_x}\rvert)$	$\mathrm{sinc}^2(\frac{\pi}{2\Omega}\lvert\mathbf{f_x}\rvert)$
1D motion-invariant	$\delta(\mathbf{x} - (at^2, 0))$	$R(t/T)$	$\frac{T}{M\lvert f_x\rvert}R(\frac{\mathbf{m}\cdot\mathbf{f_x}}{M\lvert f_x\rvert})$	$\frac{T}{M\lvert f_x\rvert}$ $(f_y = 0)$ 0 $(f_y \neq 0)$	1 $(f_y = 0)$ 0 $(f_y \neq 0)$
Circular motion	$\delta(\mathbf{x} - \mathbf{r}(t))$ with $\mathbf{r}(t) = (r\cos(2\pi t/T), r\sin(2\pi t/T))$	$R(t/T)$	$T^2 J_n^2(\frac{MT}{2}\lvert\mathbf{f_x}\rvert)$ with $n = T\mathbf{m}\cdot\mathbf{f_x}$	0	0
Orthogonal parabolic exposures	$\delta(\mathbf{x} - (at^2, 0))$ $\delta(\mathbf{x} - (0, at^2))$	$R(2t/T)$ (1st shot) $R(2t/T)$ (2nd shot)	$\frac{T}{2\sqrt{2}M\lvert f_x\rvert}R(\frac{\mathbf{m}\cdot\mathbf{f_x}}{\sqrt{2}M\lvert f_x\rvert})$ $\frac{T}{2\sqrt{2}M\lvert f_y\rvert}R(\frac{\mathbf{m}\cdot\mathbf{f_x}}{\sqrt{2}M\lvert f_y\rvert})$	$\frac{T}{2\sqrt{2}M\lvert f_x\rvert}R(\frac{f_y}{2\lvert f_x\rvert})$ $\frac{T}{2\sqrt{2}M\lvert f_y\rvert}R(\frac{f_x}{2\lvert f_y\rvert})$	1 $(\lvert f_y\rvert \leq \lvert f_x\rvert)$, 0 (o/w) 1 $(\lvert f_x\rvert \leq \lvert f_y\rvert)$, 0 (o/w)

(c) Joint defocus and motion deblurring.

Camera design	5D kernel $k(\mathbf{x}, \mathbf{u}, t)$ Integration surface	Integration window	Squared MTF $\lvert\hat{\phi}_{s,\mathbf{m}}(\mathbf{f_x})\rvert^2 = \lvert\hat{k}(\mathbf{f_x}, -s\mathbf{f_x}, -\mathbf{m}\cdot\mathbf{f_x})\rvert^2$	High freq. preserv. $\min_{s,\mathbf{m}} \lvert\hat{\phi}_{s,\mathbf{m}}(\mathbf{f_x})\rvert^2$	MTF invariance $\min \lvert\hat{\phi}_{s,\mathbf{m}}\rvert^2 / \max \lvert\hat{\phi}_{s,\mathbf{m}}\rvert^2$
Upper bound	–	–	–	$\frac{2A^3T}{3SM\lvert\mathbf{f_x}\rvert^2}$	1
Combination of existing designs	$k_a(\mathbf{x}, \mathbf{u}) * k_e(\mathbf{x}, t)$		$\lvert\hat{\phi}_s(\mathbf{f_x})\rvert^2 \cdot \lvert\hat{\phi}_\mathbf{m}(\mathbf{f_x})\rvert^2$	$\min_s \lvert\hat{\phi}_s\rvert^2 \cdot \min_\mathbf{m} \lvert\hat{\phi}_\mathbf{m}\rvert^2$	$(\min \lvert\hat{\phi}_s\rvert^2 / \max \lvert\hat{\phi}_s\rvert^2) \cdot (\min \lvert\hat{\phi}_\mathbf{m}\rvert^2 / \max \lvert\hat{\phi}_\mathbf{m}\rvert^2)$
Focus sweep	$\delta(\mathbf{x} - wt\mathbf{u})$	$R(\lvert\mathbf{u}\rvert/A)R(t/T)$	$\frac{A^3T}{\sqrt{3}SM\lvert\mathbf{f_x}\rvert^2}\left(1 - \frac{4\lvert\mathbf{m}\cdot\mathbf{f_x}\rvert^2}{3M^2\lvert\mathbf{f_x}\rvert^2}\right)$	$\boxed{\frac{2A^3T}{3\sqrt{3}SM\lvert\mathbf{f_x}\rvert^2}}$	$\boxed{\frac{2}{3}}$

- 58% of the upper bound in high-frequency preservation
- 67% of the upper bound in depth and 2D motion invariance

Comparison



Result