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V-SENSE

A Spatio-Angular Filter for High Quality Sparse Light Field Refocusing

CLIM Workshop on Computational Imaging with Novel Image Modalities 2021
INRIA Rennes – 29/09/2021

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Outline

- **Introduction**
- **Two-parallel plane light field Circle of Confusion**
- **Proposed filter for sparse light field refocusing**
- **Experiments and results**
- **Conclusion**

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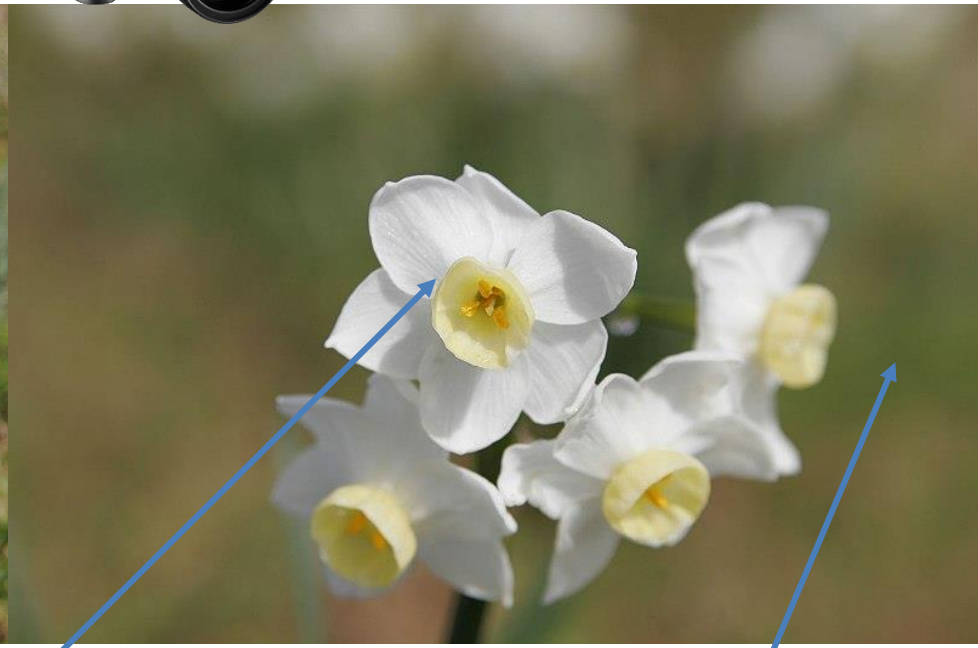
Defocus blur

Attribution: en.wikipedia.org/wiki/Aperture
Fir0002/Flagstaffotos



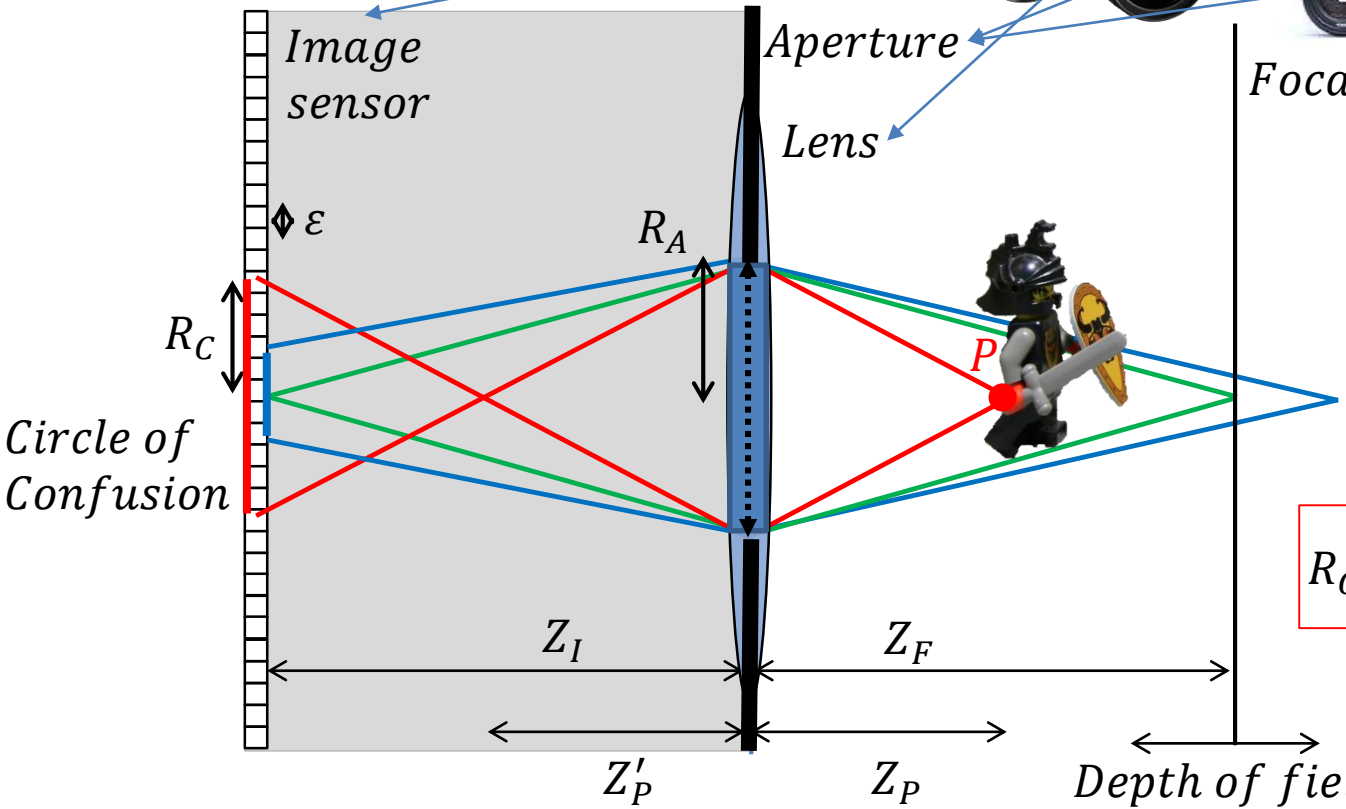
Mild defocus blur

In focus

Strong defocus blur

Defocus blur

Thin lens model

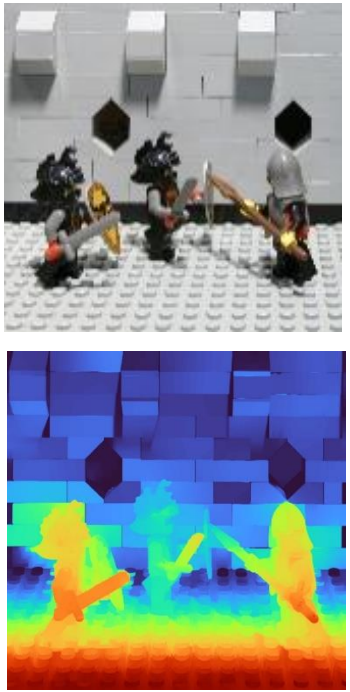


Thin lens model:

$$\frac{1}{Z_P} + \frac{1}{Z_P'} = \frac{1}{f}$$

$$R_C = R_A \frac{f}{|Z_F - f|} \frac{|Z_F - Z_P|}{Z_P}$$

Synthetic aperture / depth-of-field rendering



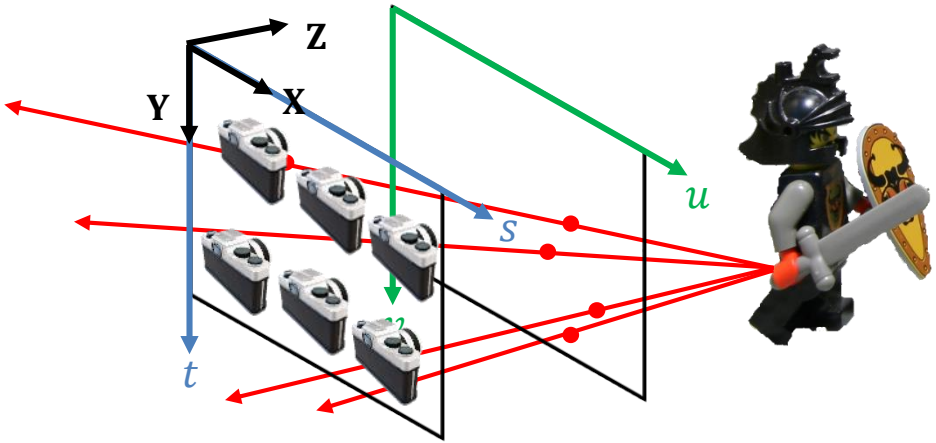
Potmesil, Michael, and Indranil Chakravarty. "A lens and aperture camera model for synthetic image generation." *ACM SIGGRAPH Computer Graphics* 15.3 (1981): 297-305.

Lee, Sungkil, Gerard Jounghyun Kim, and Seungmoon Choi. "Real-time depth-of-field rendering using anisotropically filtered mipmap interpolation." *IEEE Transactions on Visualization and Computer Graphics* 15.3 (2009): 453-464.

Wadhwa, Neal, et al. "Synthetic depth-of-field with a single-camera mobile phone." *ACM Transactions on Graphics (ToG)* 37.4 (2018): 1-13.

Light field imaging

2 parallel planes parameterization

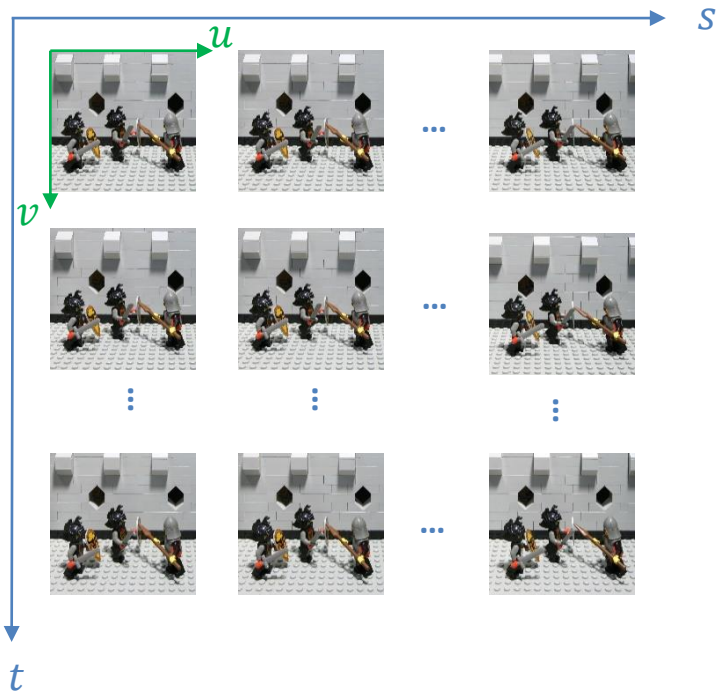


the camera plane

Angular dimensions

the sensor / image plane

Spatial dimensions

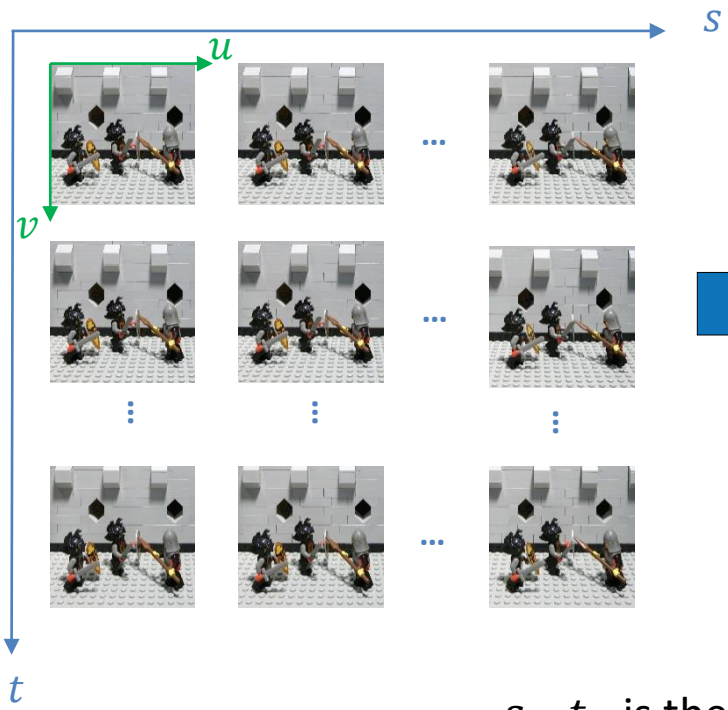


The light field $L = L(s, t, u, v)$

Light field applications

Refocusing: shift-and-sum algorithm

Shift each light field image to a target disparity, i.e. where object corresponding to that disparity value are aligned

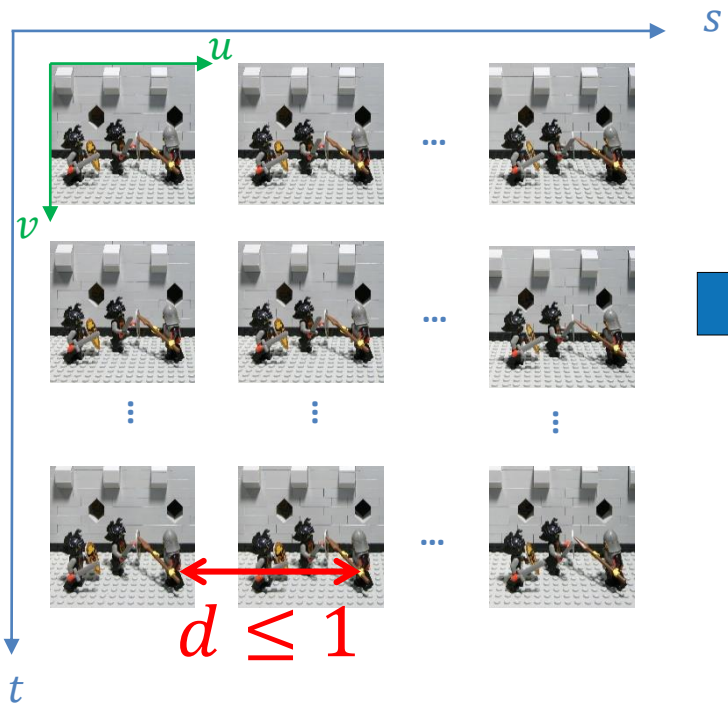


$$I_R = \sum_{s,t} L(s, t, u + (s - s_R)d_R, v + (t - t_R)d_R)$$

s_R, t_R is the position of the refocus image, d_R is the refocus disparity

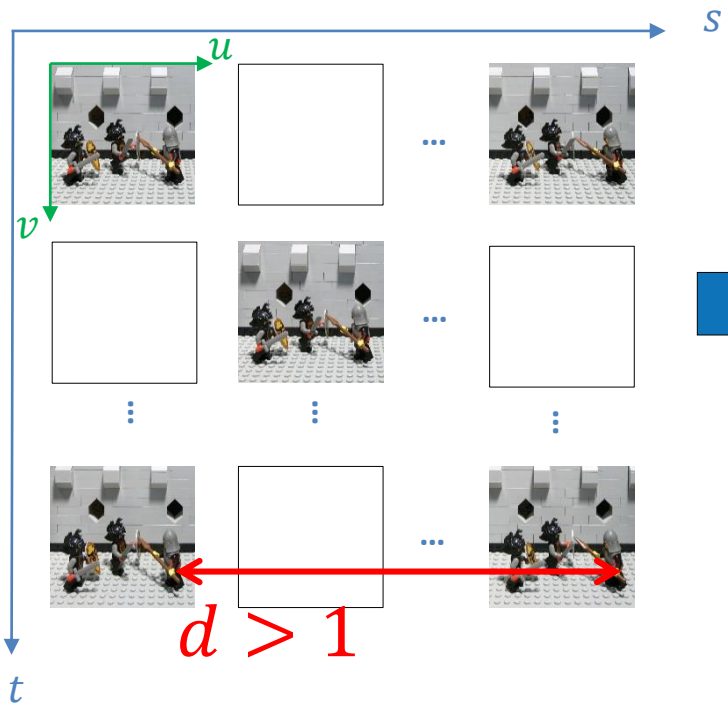
Light field applications

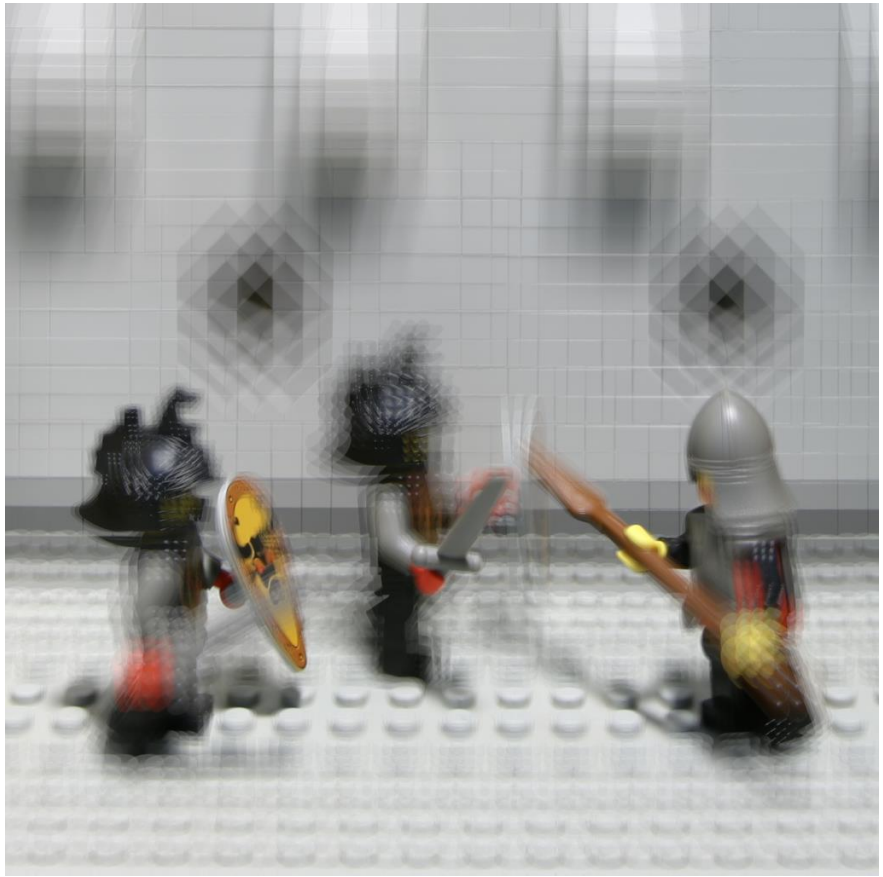
Dense light field refocusing



Light field applications

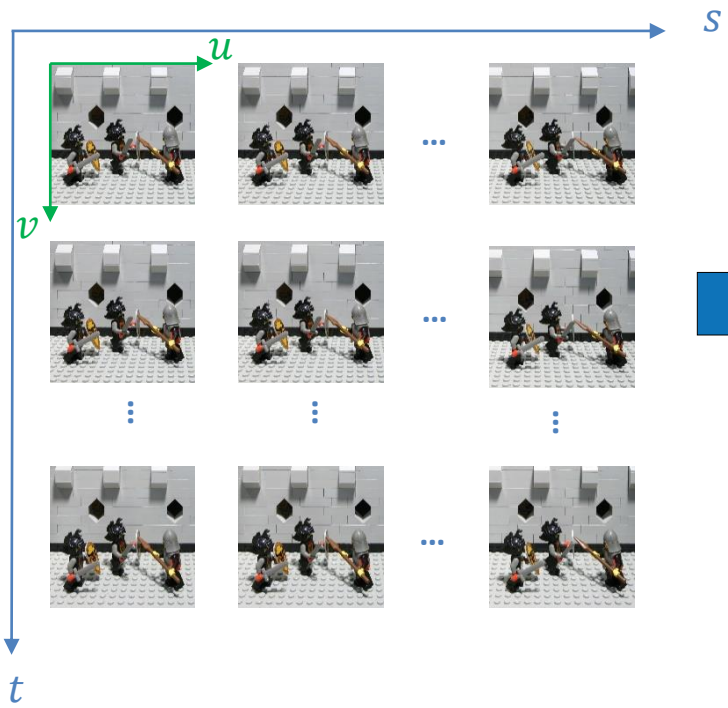
Sparse light field refocusing

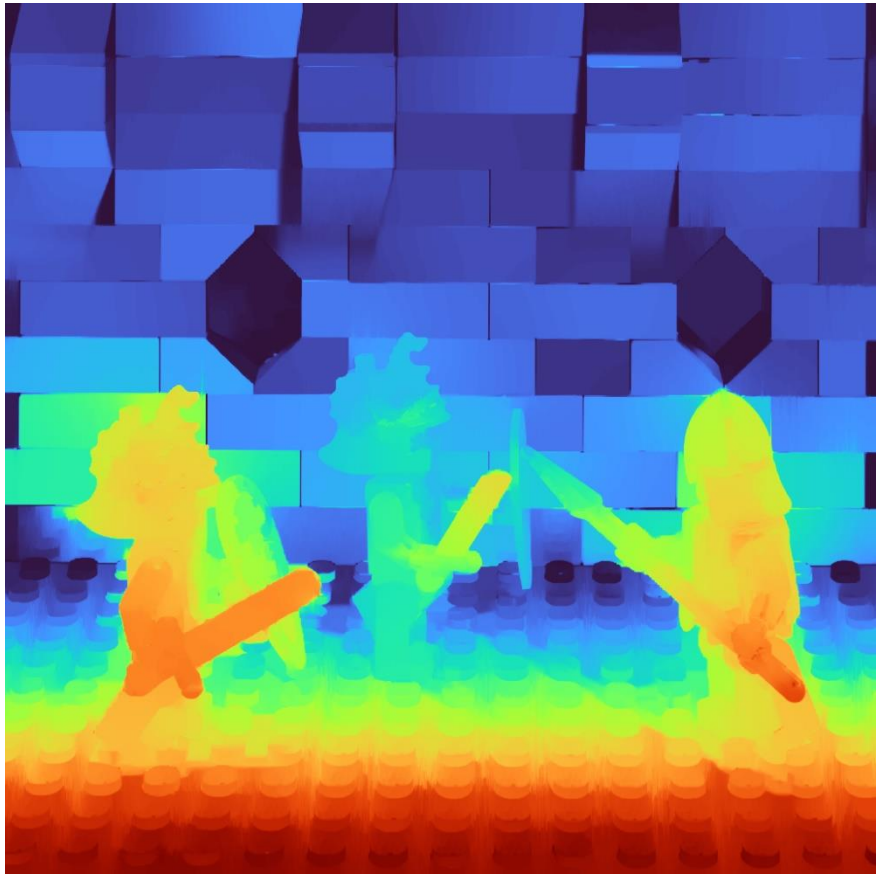




Light field applications

Disparity estimation





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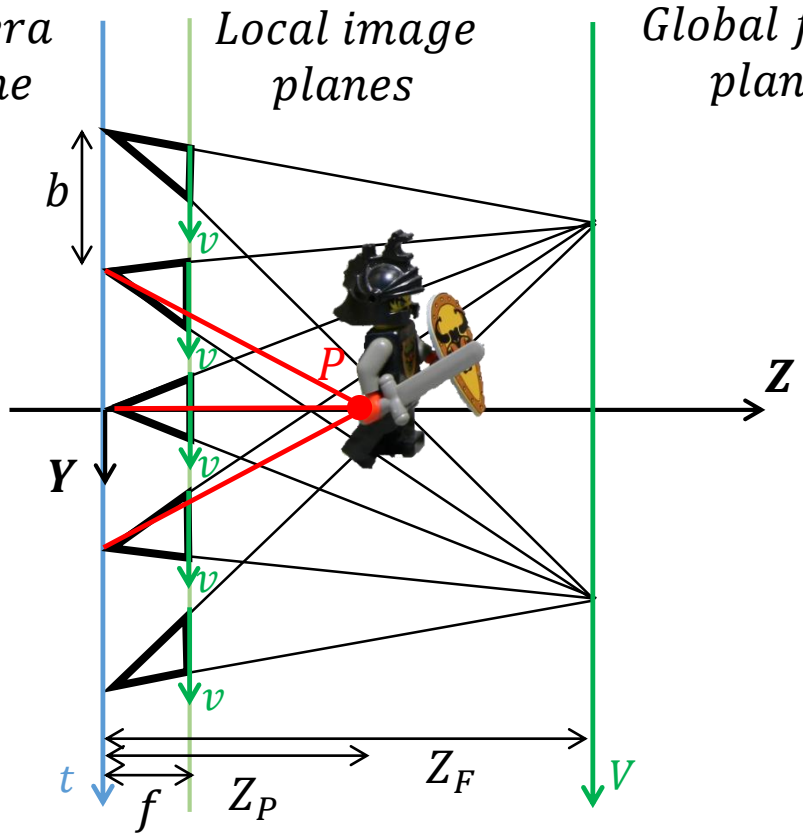
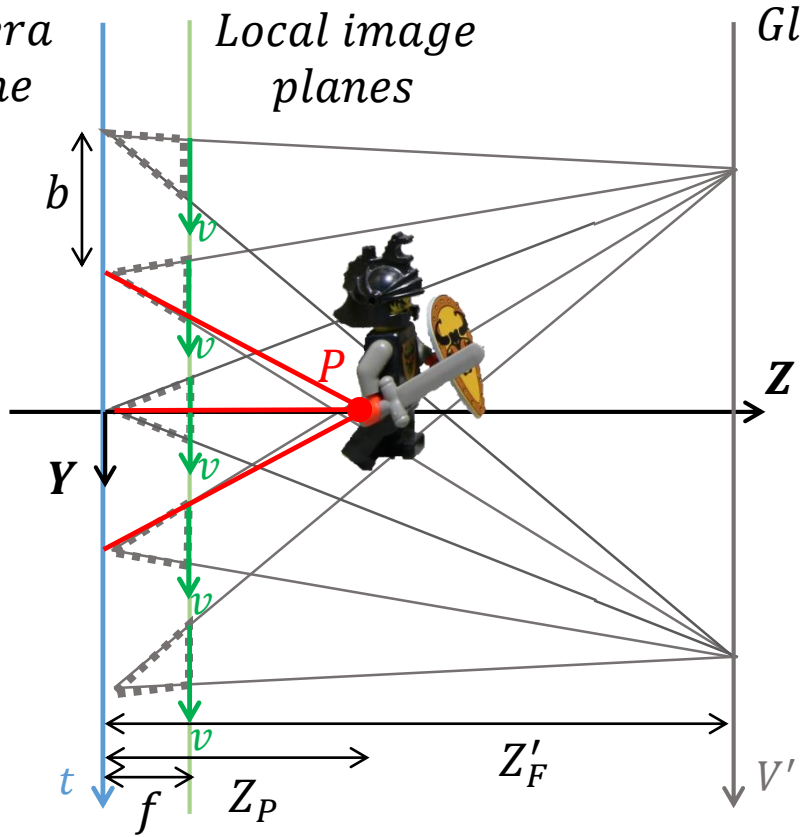
Global and local image plane parameterization



$$u = \frac{U}{Z_F} \quad v = \frac{V}{Z_F} \quad (1)$$

$$Z_P = \frac{b f_{px}}{d_P + d f_{px}/Z_F} \quad (2)$$

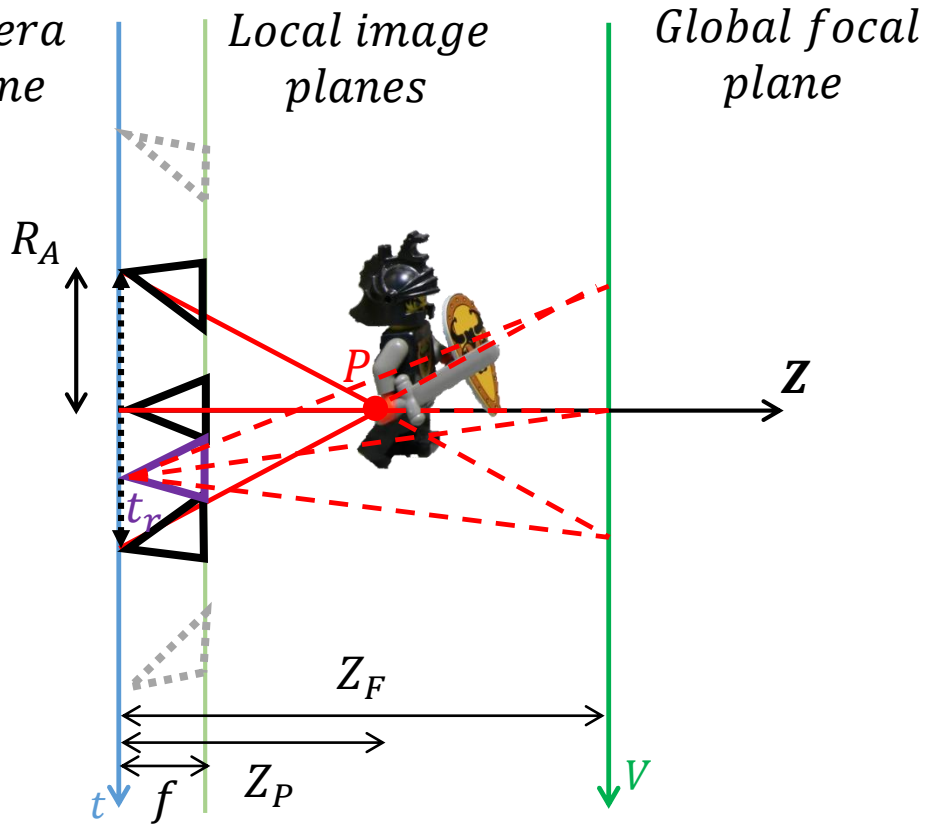
Global and local image plane parameterization



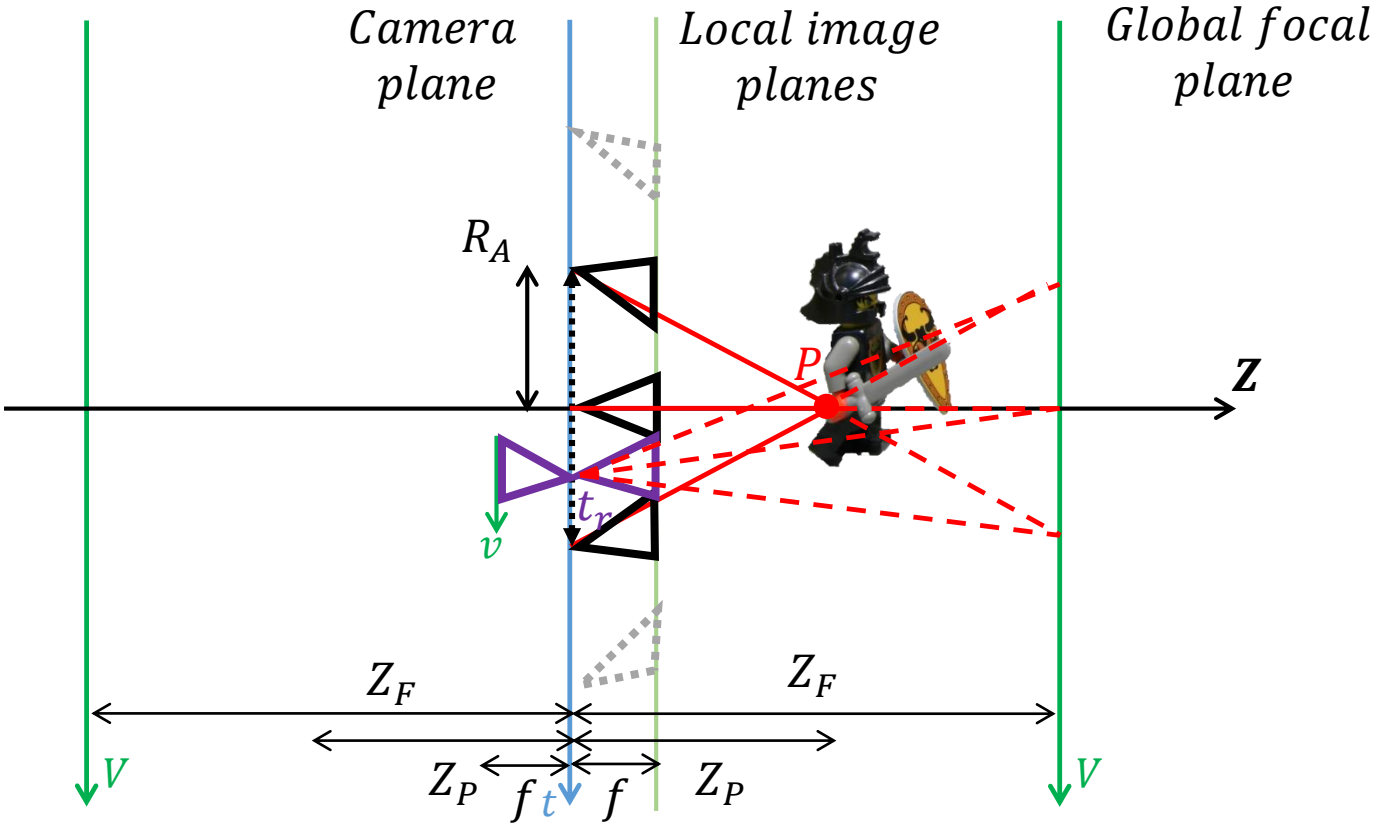
$$u = \frac{U}{Z_F} \quad v = \frac{V}{Z_F} \quad (1)$$

$$Z_P = \frac{b f_{px}}{d_P + d f_{px}/Z_F} \quad (2)$$

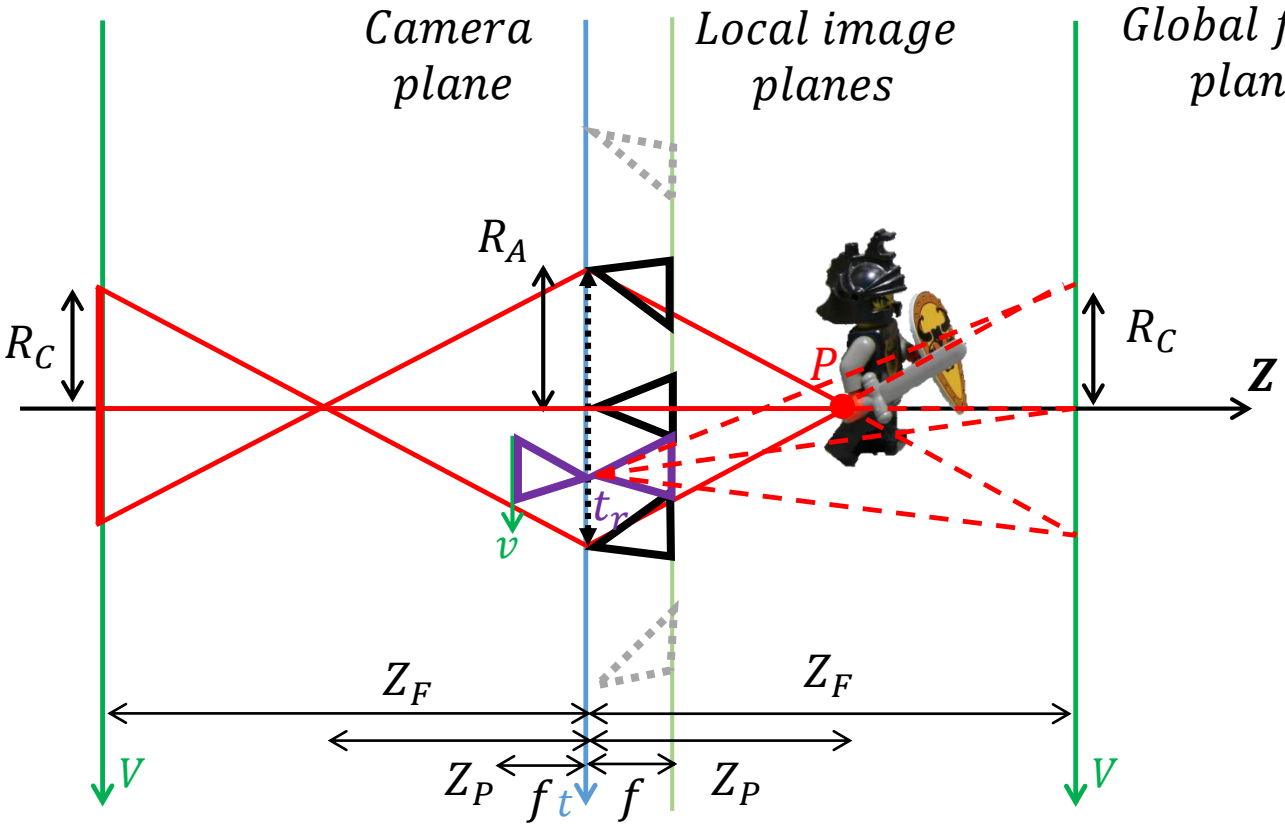
Light field circle of confusion



Light field circle of confusion

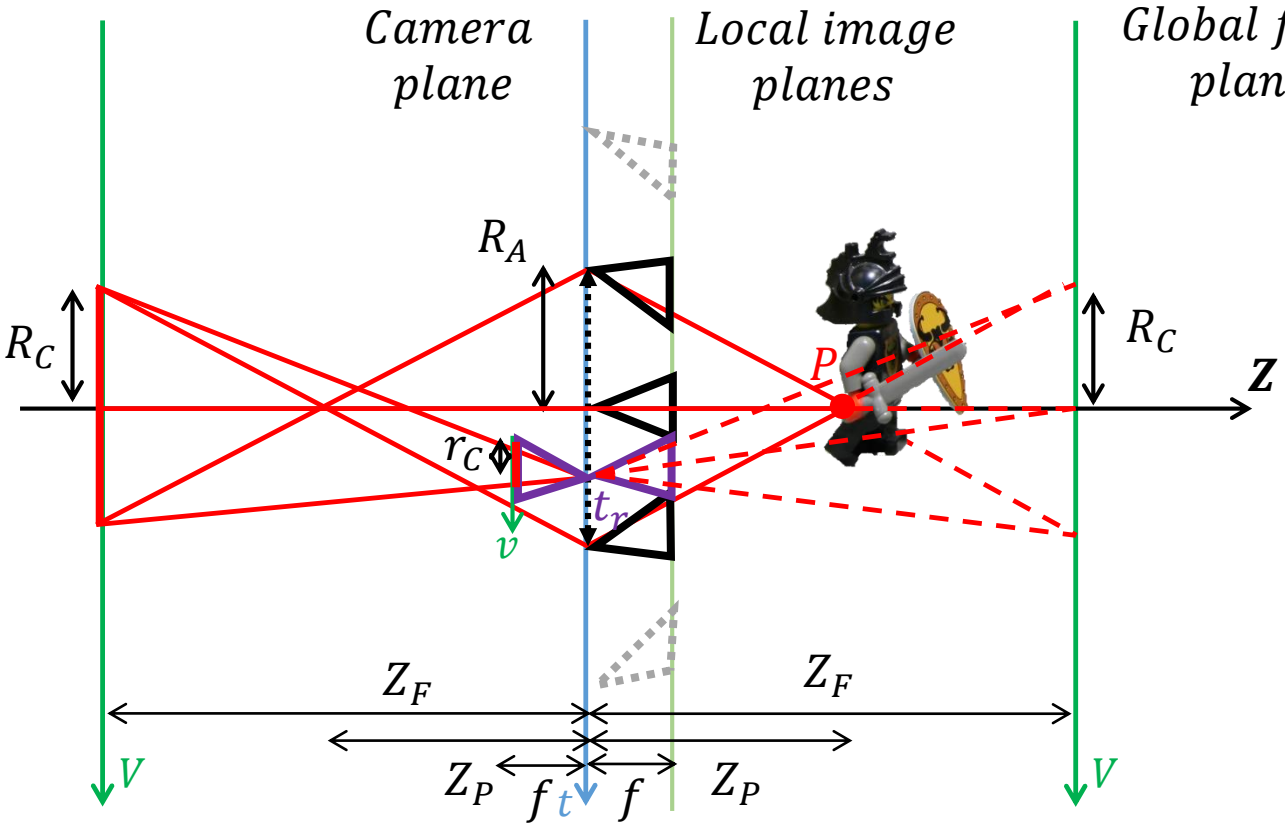


Light field circle of confusion



$$R_C = R_A \frac{|Z_F - Z_P|}{Z_P} \quad (3)$$

Light field circle of confusion



$$R_C = R_A \frac{|Z_F - Z_P|}{Z_P} \quad (3)$$

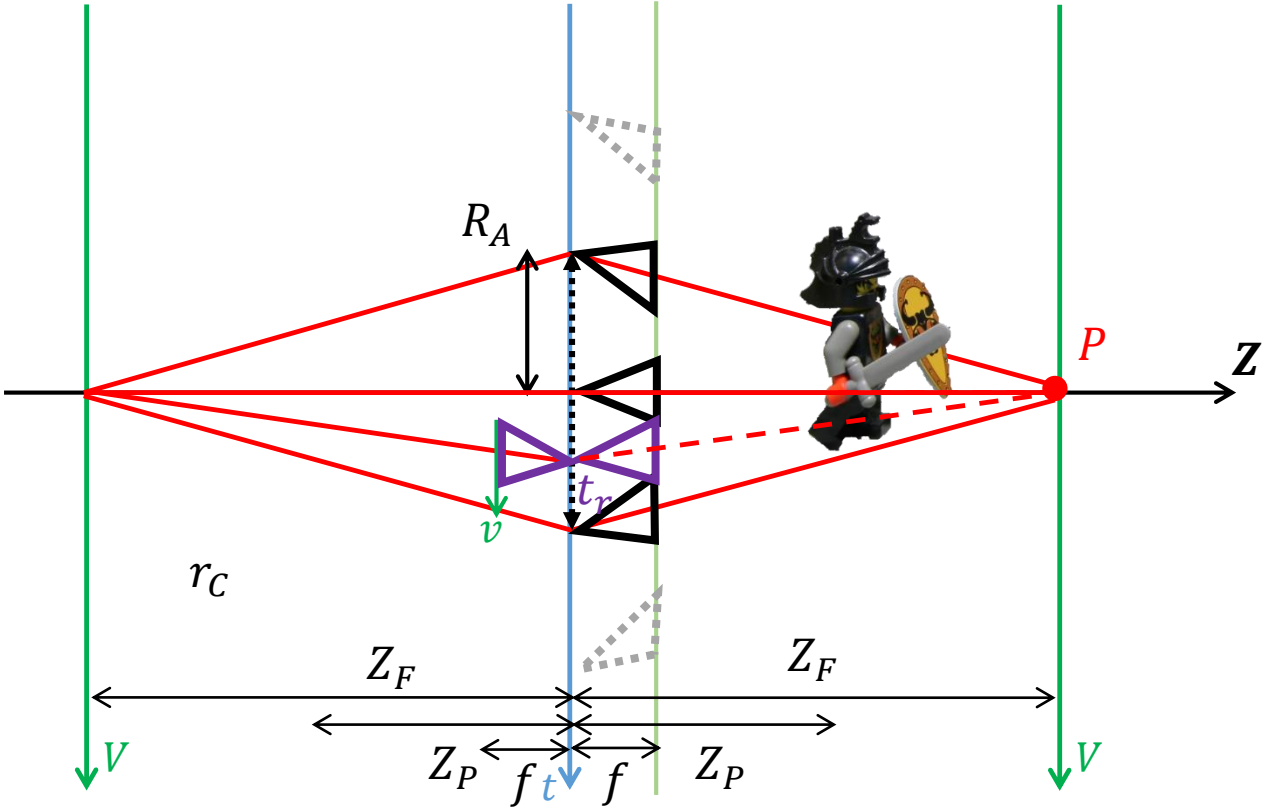
$$r_C = \frac{R_A |Z_F - Z_P|}{Z_P} \frac{f}{Z_F} \quad (4)$$

$$\rho_C = \rho_A |d_P - d_F| \quad (5)$$

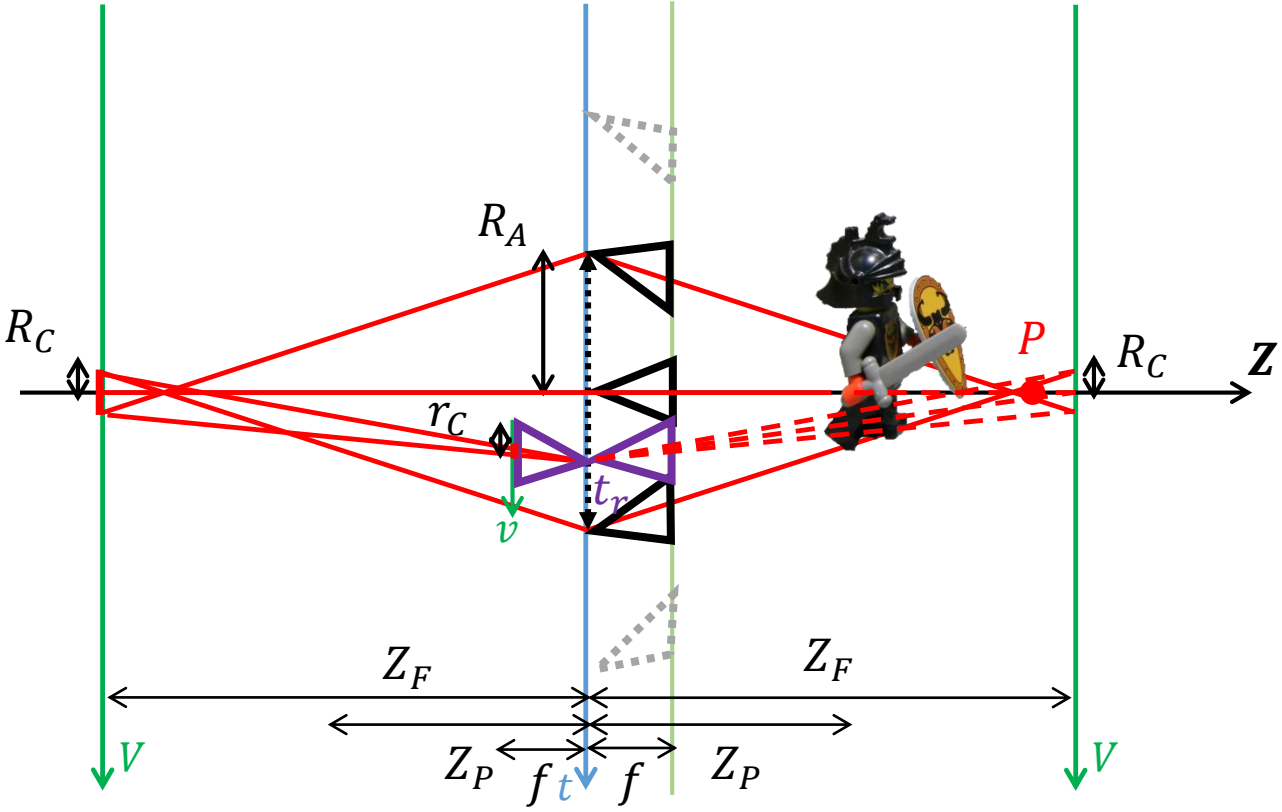
Light field circle of confusion

In focus

$$|d_P - d_F| = 0$$



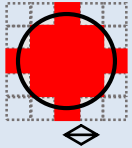
Light field circle of confusion



In focus

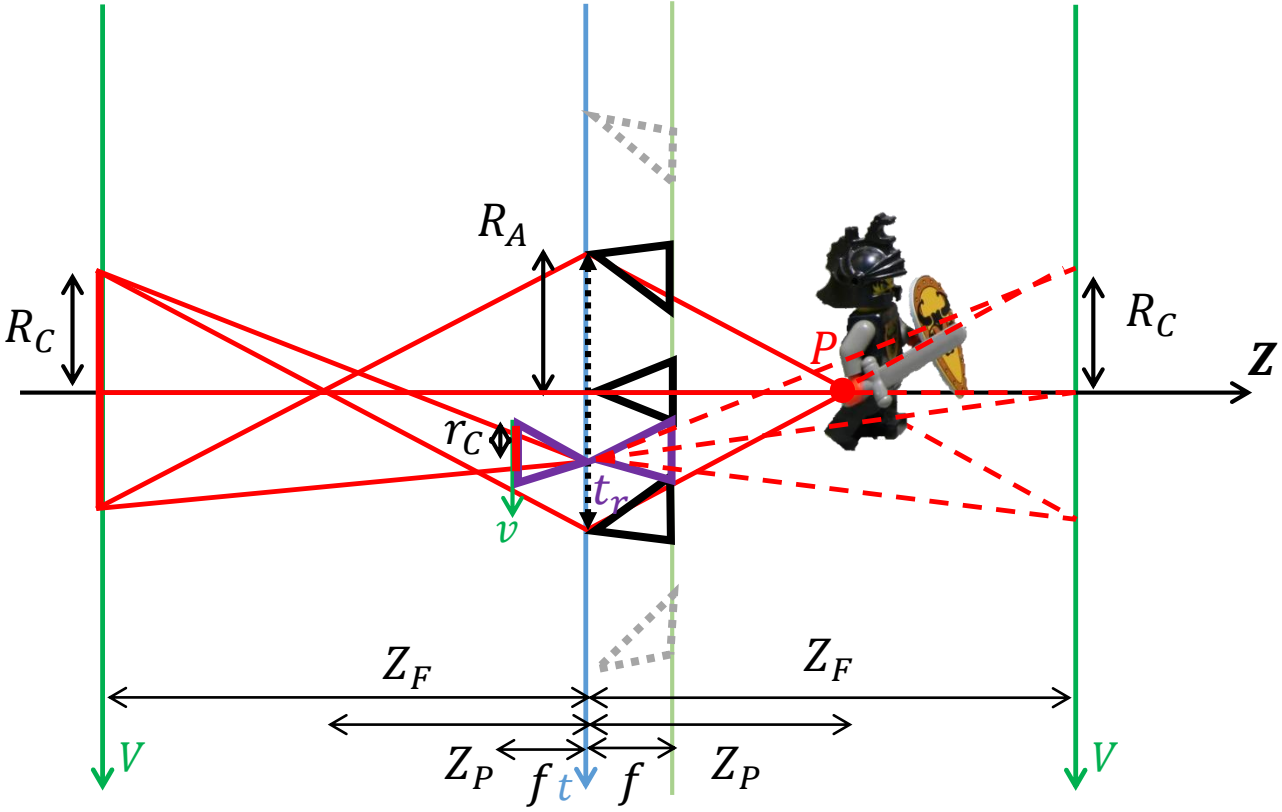
$$|d_P - d_F| = 0$$

Defocus blur



$$|d_P - d_F| \leq 1$$

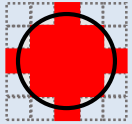
Light field circle of confusion



In focus

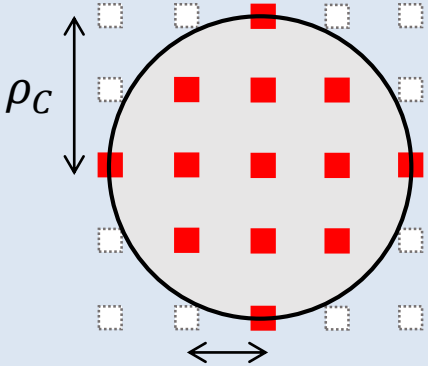
$|d_P - d_F| = 0$

Defocus blur



$|d_P - d_F| \leq 1$

Aliased defocus blur



$|d_P - d_F| > 1$

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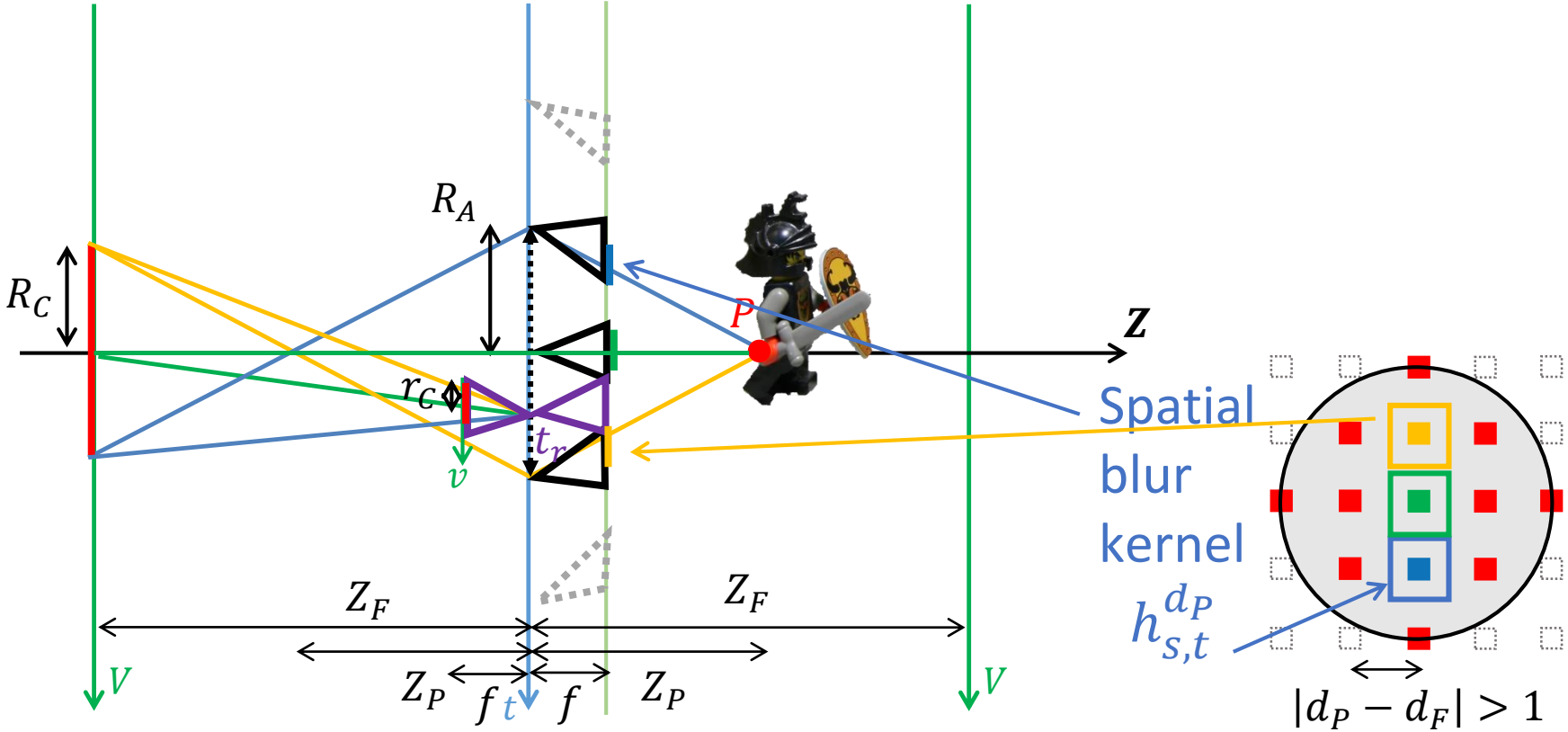
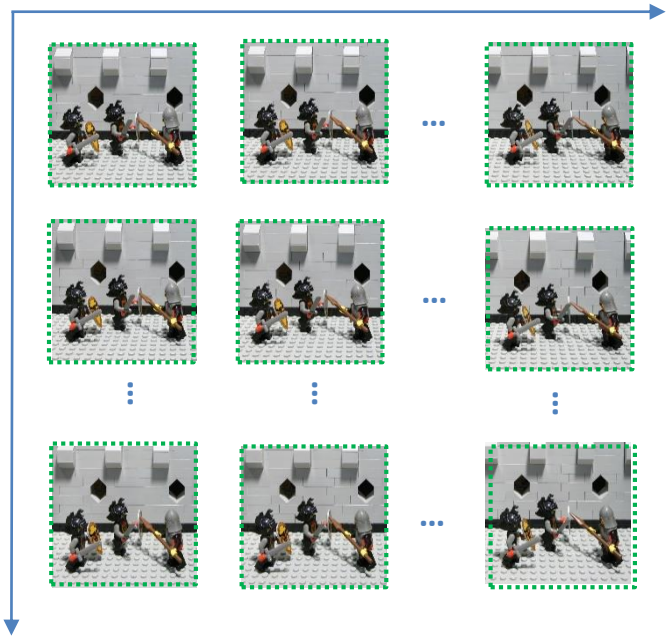
Proposed filter for sparse light field refocusing



Proposed filter for sparse light field refocusing

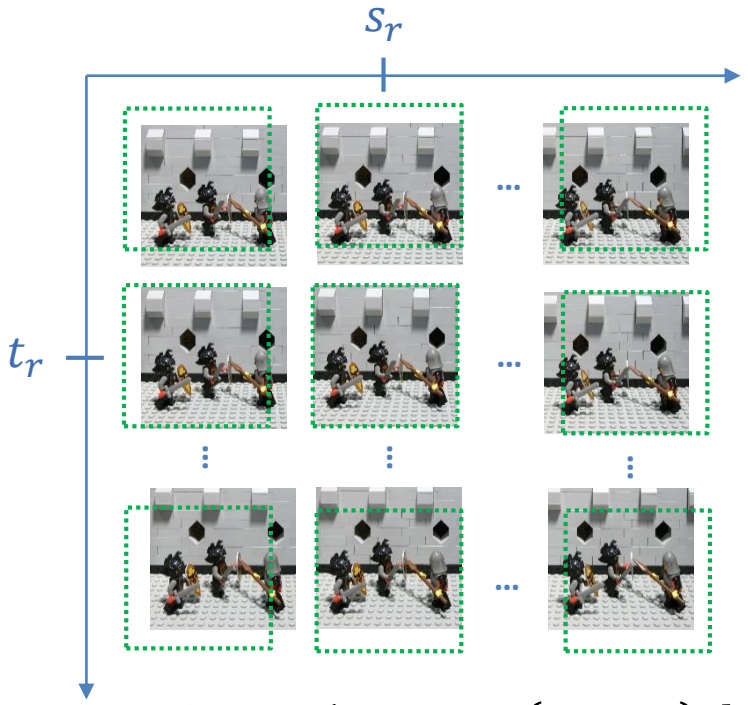
1 – Shift



Original light field $L(s,t,u,v)$

Proposed filter for sparse light field refocusing

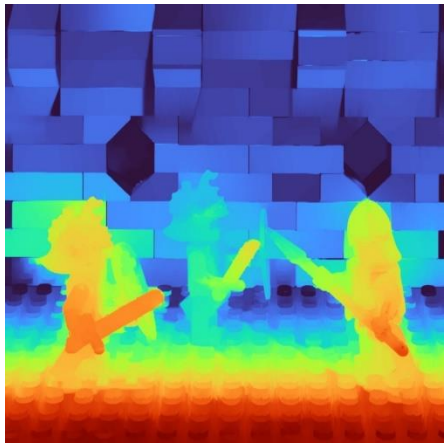
1 – Shift



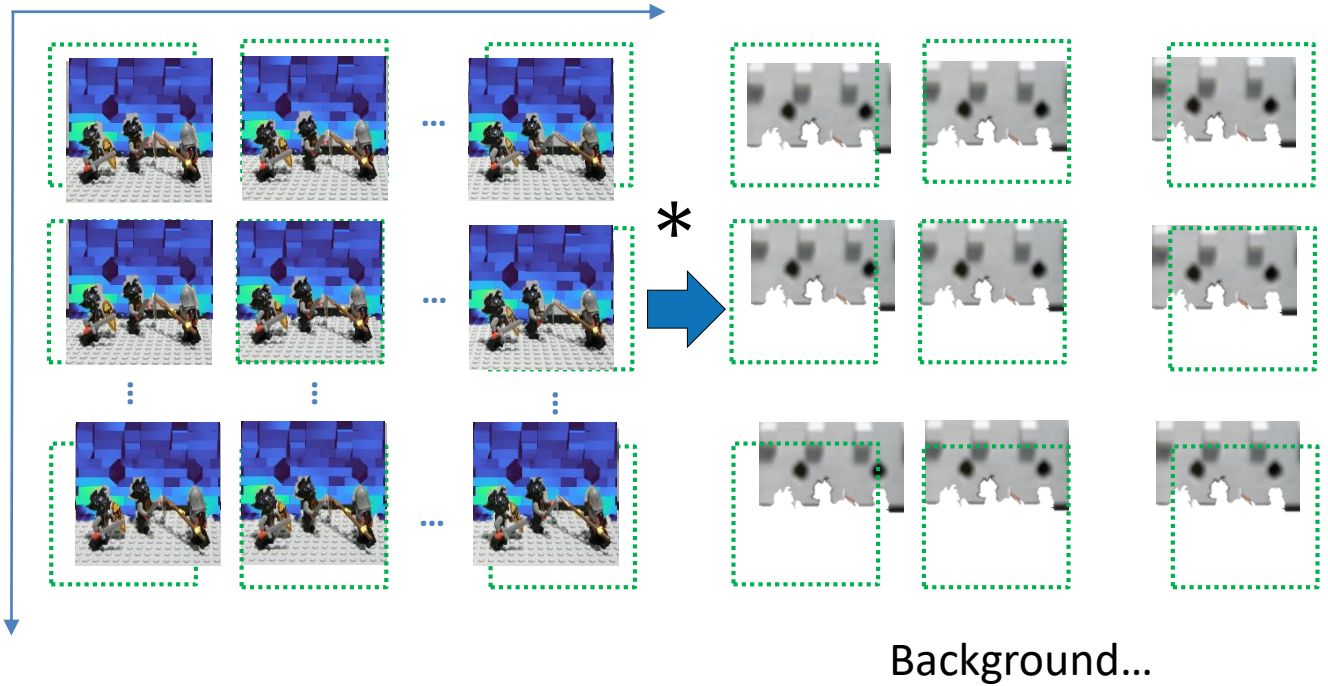
Shifted light field $L(s, t, u + (s - s_r)d_F, v + (t - t_r)d_F)$

Proposed filter for sparse light field refocusing

2 – Disparity-based blurring

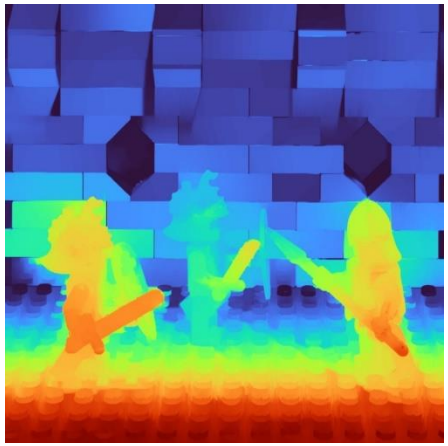


Disparity map

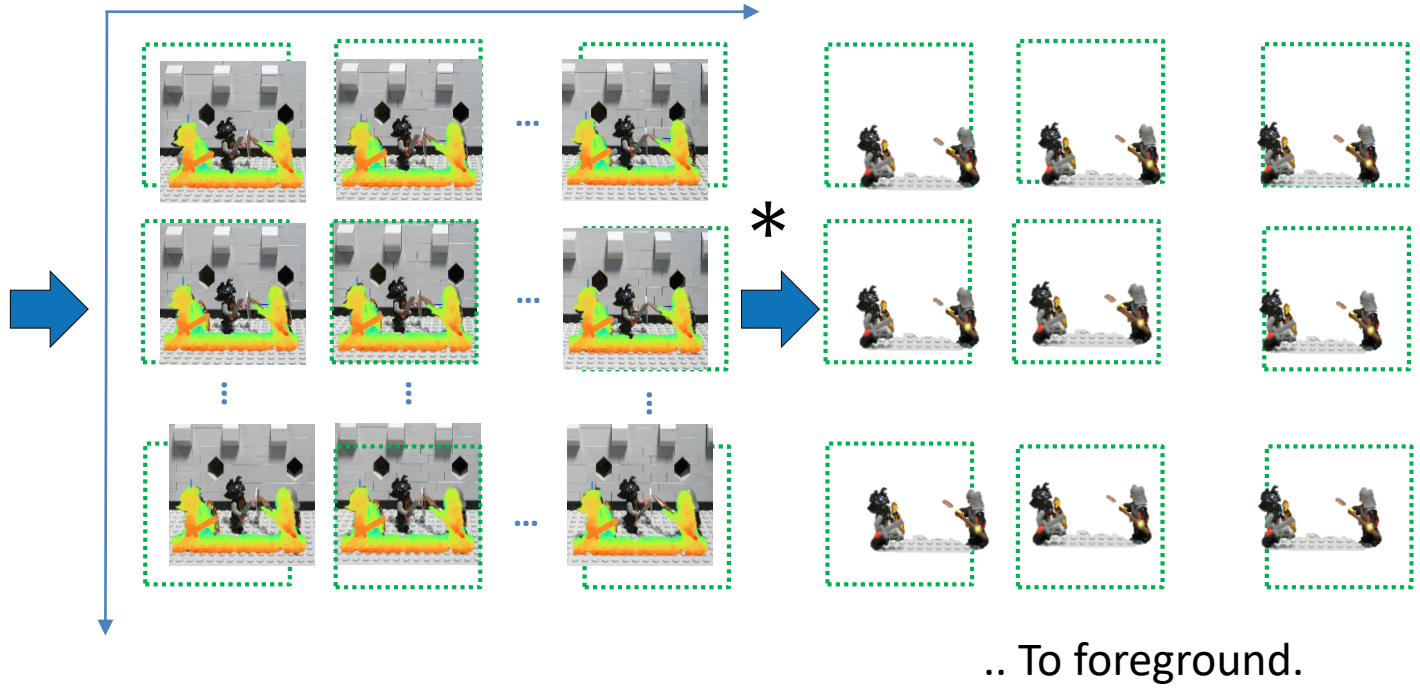


Proposed filter for sparse light field refocusing

2 – Disparity-based blurring



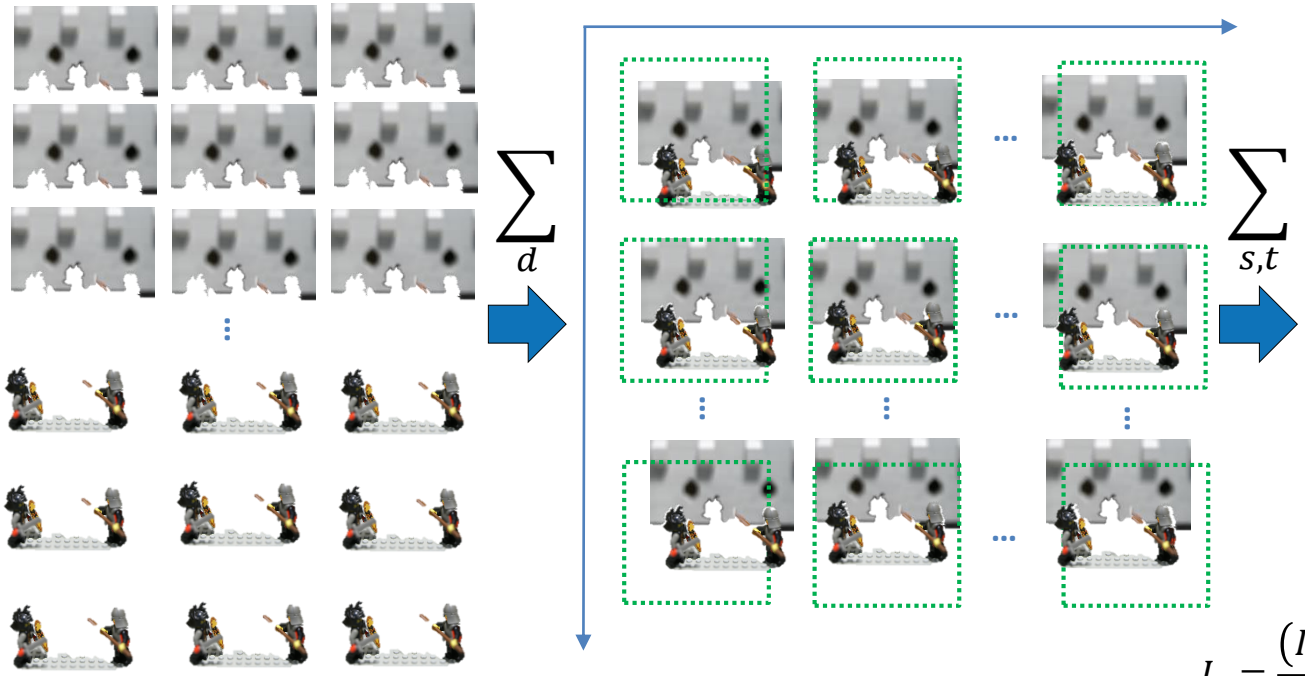
Disparity map

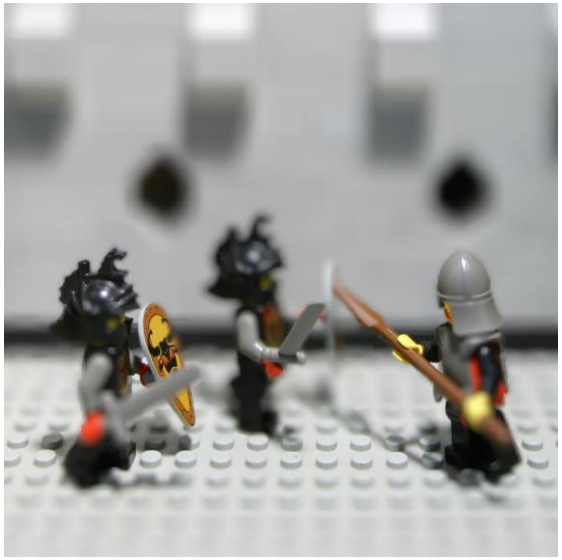


.. To foreground.

Proposed filter for sparse light field refocusing

3 – Sum





$$I_r = \frac{\left(I_b^n(1-\alpha_F) + I_{i_r,j_r}\alpha_F\right)(1-\alpha_f) + I_f^n\alpha_f}{\left(I_b^d(1-\alpha_F)+1\right)(1-\alpha_f) + I_f^d\alpha_f}$$

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Objective evaluation

Experimental protocol

- **Datasets**
  - HCI benchmark
  - Stanford Gantry
- **Simulate sparsity by subsampling light fields**
  - $\alpha_s = 2, 3, 4$
- **Disparity estimation**
  - Optical flow based method [1]
- **Comparisons with existing work**
  - Shift-and-sum (SAS) [2]
  - Fourier Disparity Layer (FDL) [3]
  - Selective light field refocusing (SLFR) [4]
  - Single image depth-based bokeh rendering (SIBR) [5]

[1] Y. Chen, M. Alain, and A. Smolic, "Fast and accurate optical flow based depth map estimation from light fields," in Proc. IMVIP, 2017.
[2] V. Vaish, B.Wilburn, N. Joshi, and M. Levoy, "Using plane + parallax for calibrating dense camera arrays," in Proc. IEEE CVPR, 2004.
[3] M. Le Pendu, C. Guillemot, and A. Smolic, "A fourier disparity layer representation for light fields," IEEE TIP, 2019.
[4] S. Lee, G. J. Kim, and S. Choi, "Real-time depth-of-field rendering using anisotropically filtered mipmap interpolation," IEEE Trans. on Visualization and Computer Graphics, 2009.
[5] Y. Wang, J. Yang, Y. Guo, C. Xiao, and W. An, "Selective light field refocusing for camera arrays using bokeh rendering and superresolution," IEEE Signal Processing Letters, 2018.

Objective evaluation

Average scores for the HCI dataset.

Method	PSNR / SSIM $\alpha_s = 2$	$\alpha_s = 3$
SAS	**47.23 / 0.997**	36.14 / 0.971
FDL	40.12 / 0.977	33.81 / 0.940
SLFR - GT	x	36.14 / 0.985
SIBR - GT	36.85 / 0.984	34.08 / 0.973
Ours - GT	*42.64 / 0.995*	**39.84 / 0.991**
Ours w/ MS - GT	41.85 / 0.994	*37.93 / 0.988*
SLFR	x	35.03 / 0.975
SIBR	34.80 / 0.974	33.92 / 0.970
Ours	39.39 / 0.987	37.68 / 0.983
Ours w/ MS	39.06 / 0.986	36.76 / 0.983

GT indicate the use of the ground truth disparity maps.

Average scores for the Stanford dataset.

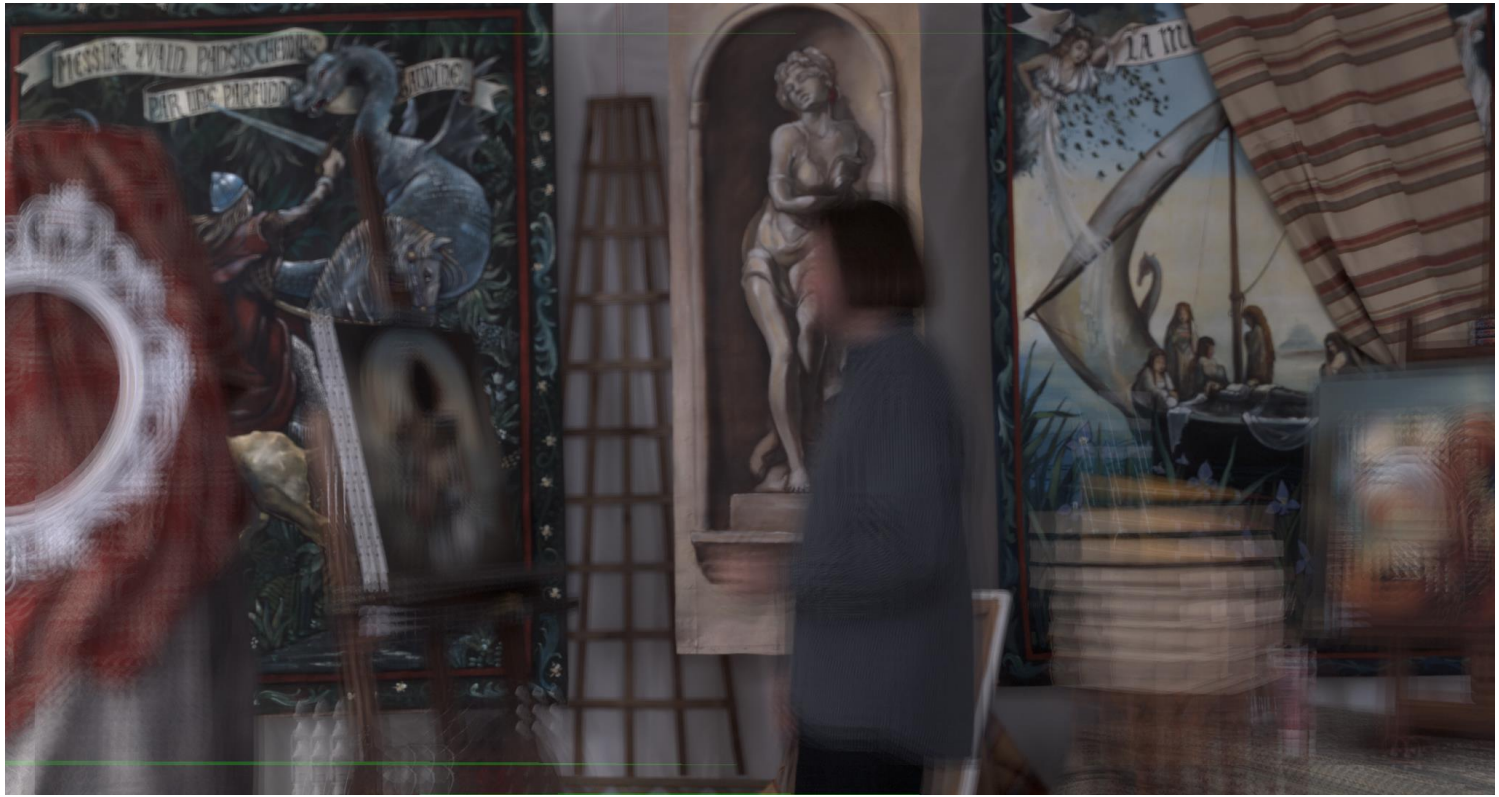
Method	PSNR / SSIM $\alpha_s = 2$	$\alpha_s = 3$	$\alpha_s = 4$
SAS	**42.68 / 0.988**	*36.13* / 0.954	28.85 / 0.893
FDL	*42.40* /0.986	35.86 / 0.950	28.66 / 0.881
SLFR	x	x	29.36 / 0.931
SIBR	31.64 / 0.964	31.48 / 0.963	29.38 / 0.951
Ours	39.59 / *0.987*	**38.18 / 0.982**	**32.97 / 0.964**
Ours w/ MS	39.31 / 0.986	35.01 / *0.977*	*31.20 / 0.961*

Processing time in seconds.

Method	HCI $\alpha_s = 2$	$\alpha_s = 3$	Stanford $\alpha_s = 2$	$\alpha_s = 3$	$\alpha_s = 4$
SAS	0.08	0.05	0.80	0.34	0.20
FDL	0.01	0.01	0.03	0.02	0.02
SLFR	x	10.79	x	x	65.35
SIBR	0.46	0.31	5.66	3.74	3.22
Ours	0.53	0.79	17.33	17.72	22.15
Ours w/ MS	0.36	0.21	3.99	1.58	0.85

Subjective evaluation

Shift-and-sum ~0.5s



Subjective evaluation

FDL ~0.1s

Subjective evaluation

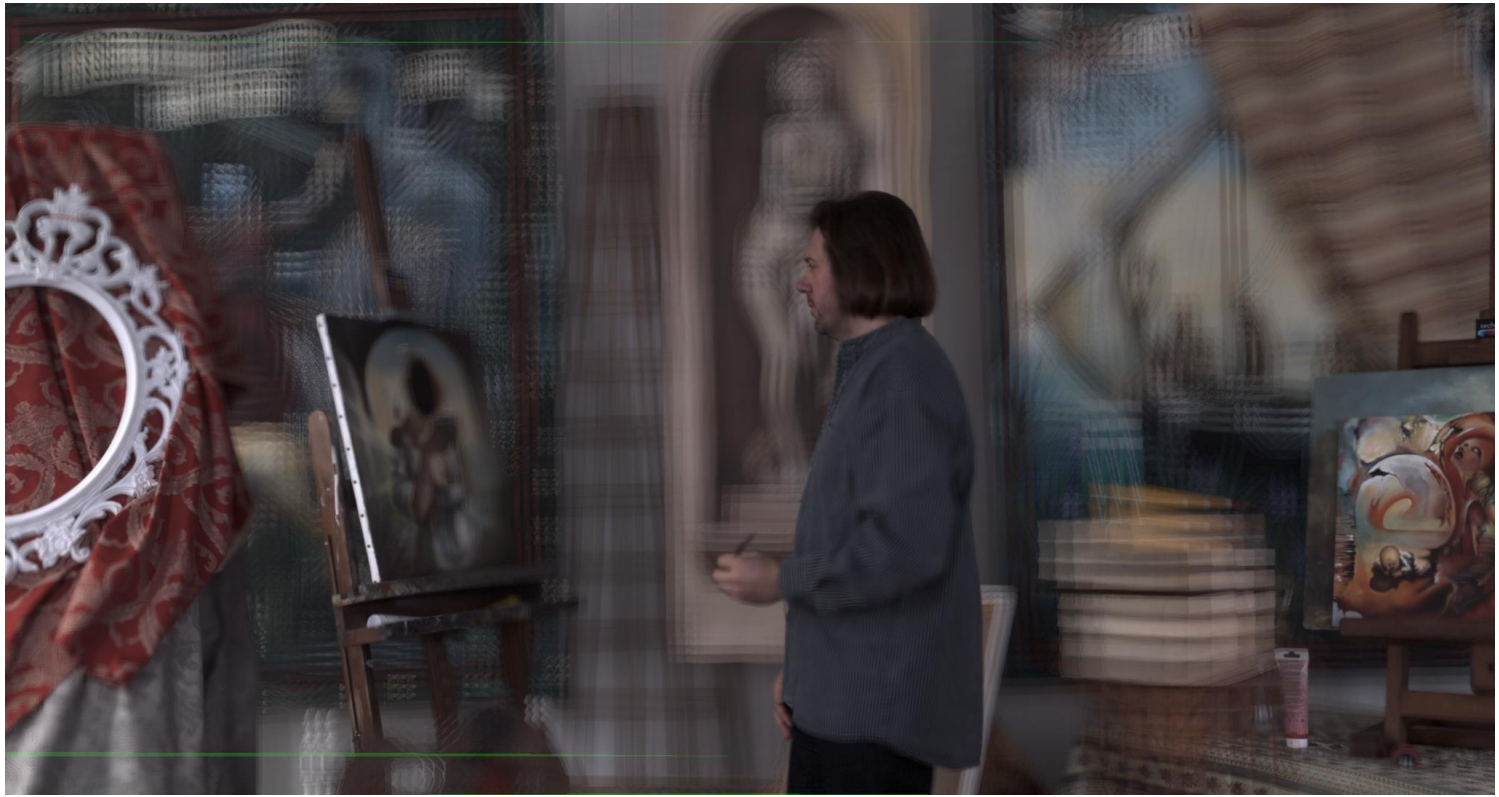
SLFR ~100s

Subjective evaluation

Ours ~1.5s

Subjective evaluation

Shift-and-sum ~0.5s



Subjective evaluation

FDL ~0.1s

Subjective evaluation

SLFR ~100s

Subjective evaluation

Ours ~1.5s

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Conclusion

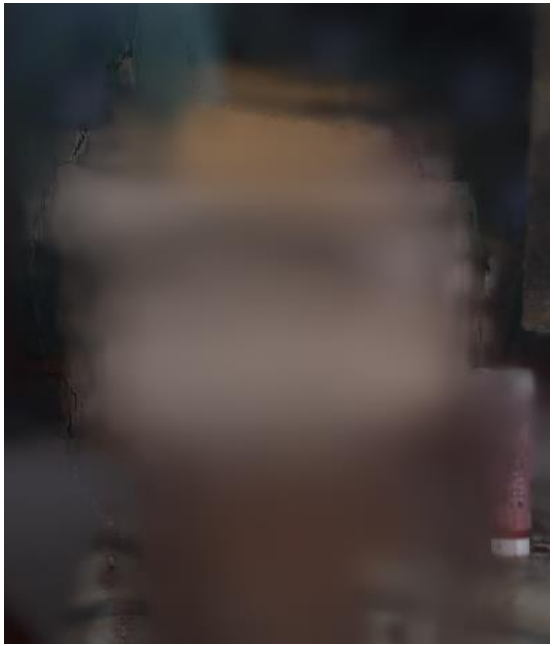
Summary

- A novel spatio-angular filter for sparse light field refocusing is introduced, based on the in-depth analysis of the circle of confusion for two-parallel plane parameterization
- Experiments demonstrate improved performance compared to existing refocusing methods in terms of PSNR and SSIM

Conclusion

Limitations

- Depends on the quality of the disparity map



Conclusion

Future work

- Address limitations, e.g. using more advanced alpha matting
- Test for more applications such as simulating small aperture radius
- Use more recent metrics in evaluation (LPIPS)

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V-SENSE

Many Thanks!

- alainm@tcd.ie
- https://v-sense.scss.tcd.ie/research/light-field-imaging/
- https://v-sense.scss.tcd.ie/research/light-fields/a-spatio-angular-filter-for-high-quality-sparse-light-field-refocusing/
- https://github.com/V-Sense/