Computational Cameras and Displays
IEEE CVPR 2016 Workshop

SAMSUNG

Color coded aperture

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Skolkovo Institute of Science and Technology

The Goal

Input

3D scene

Lens modification

Conventional lens

?

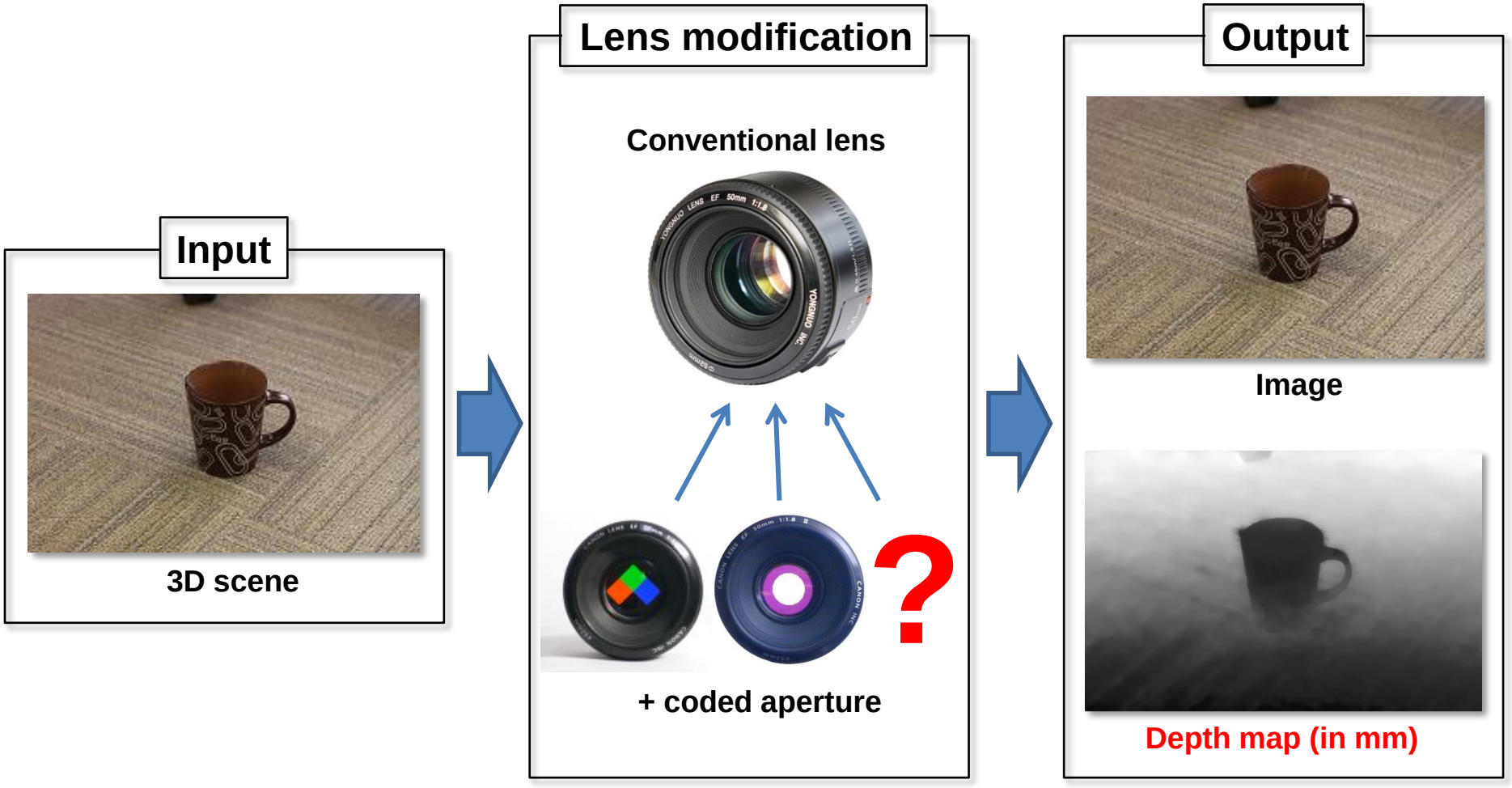
+ coded aperture

Output

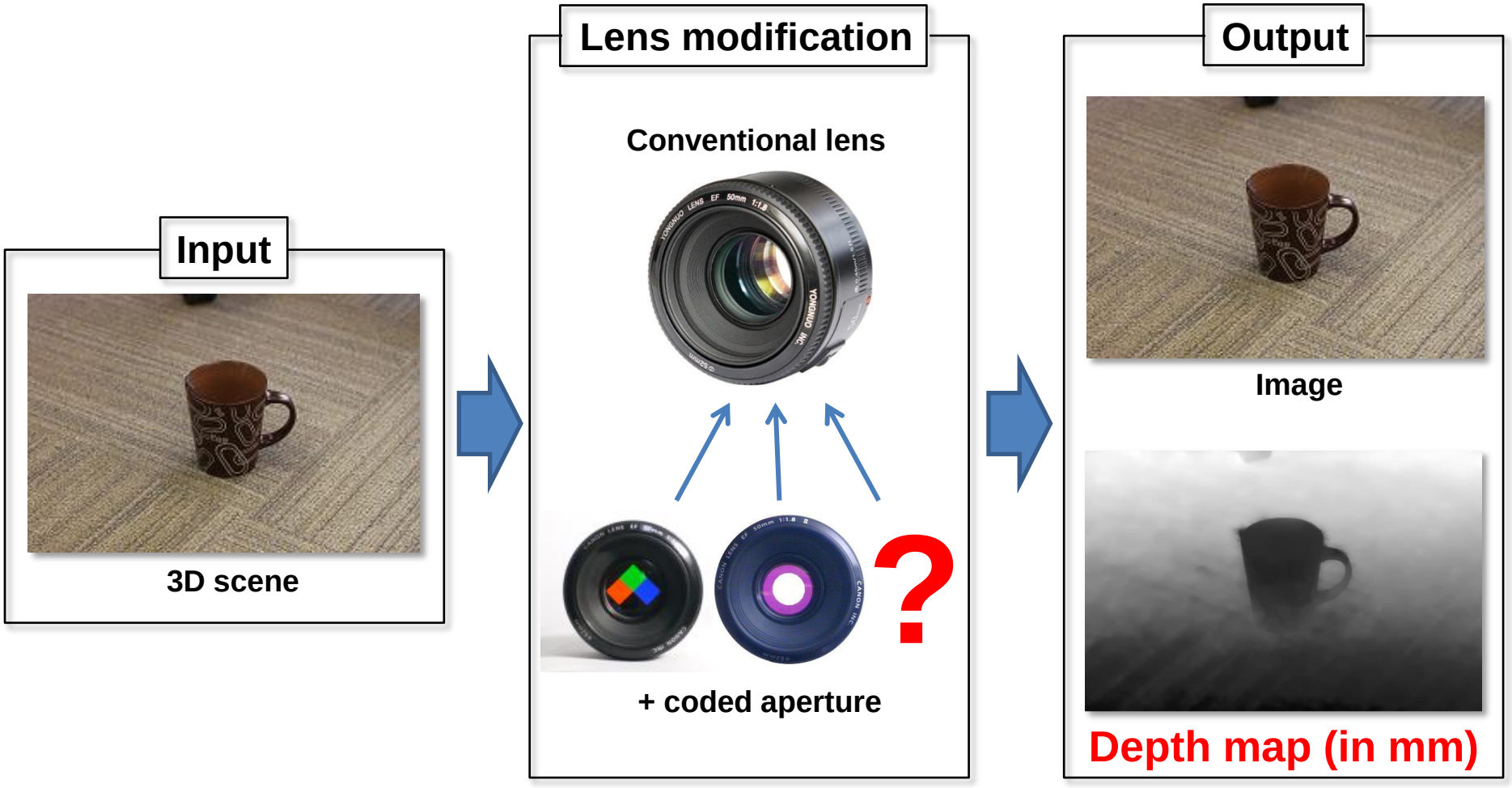
Image

Depth map (in mm)

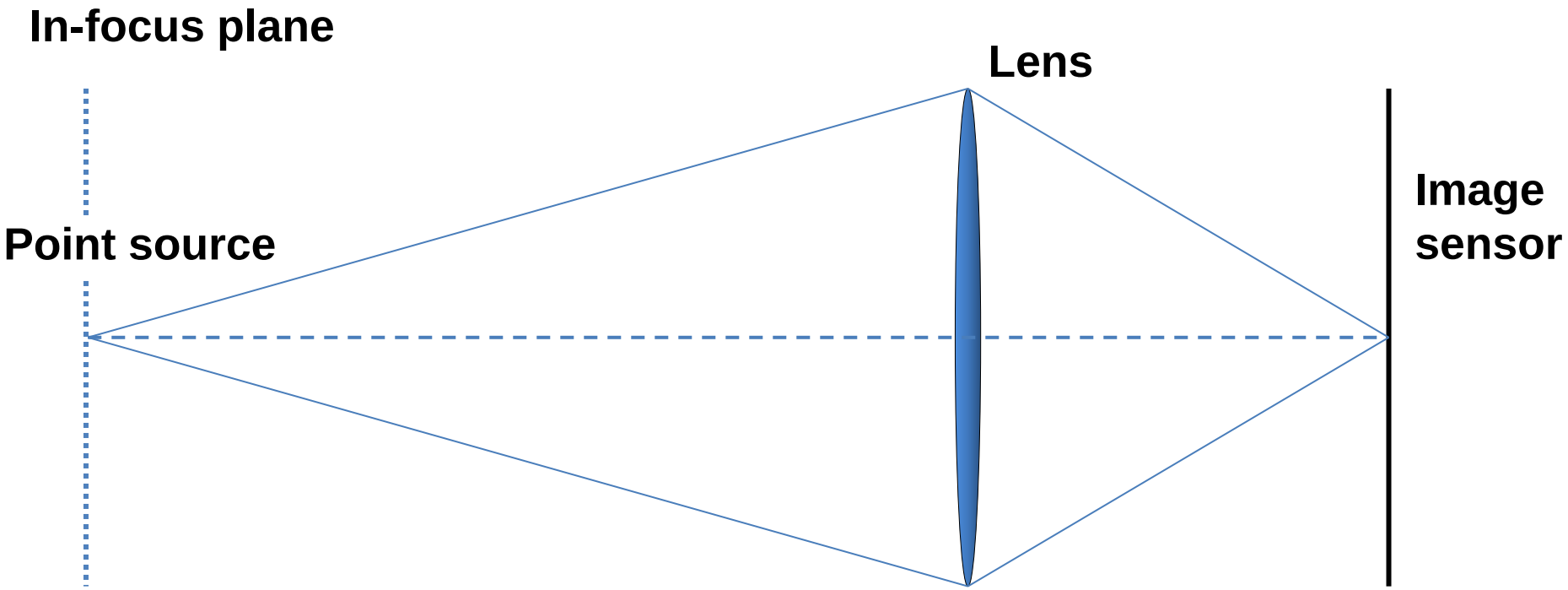
The Goal



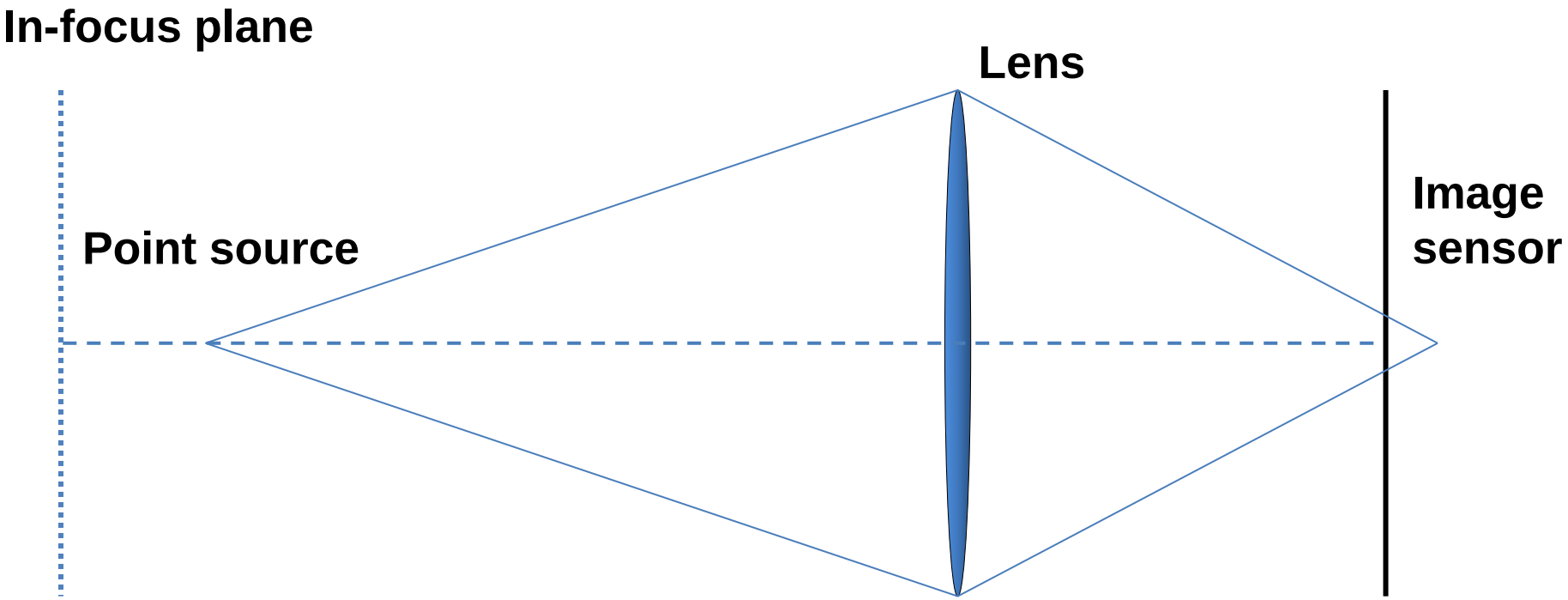
The Goal



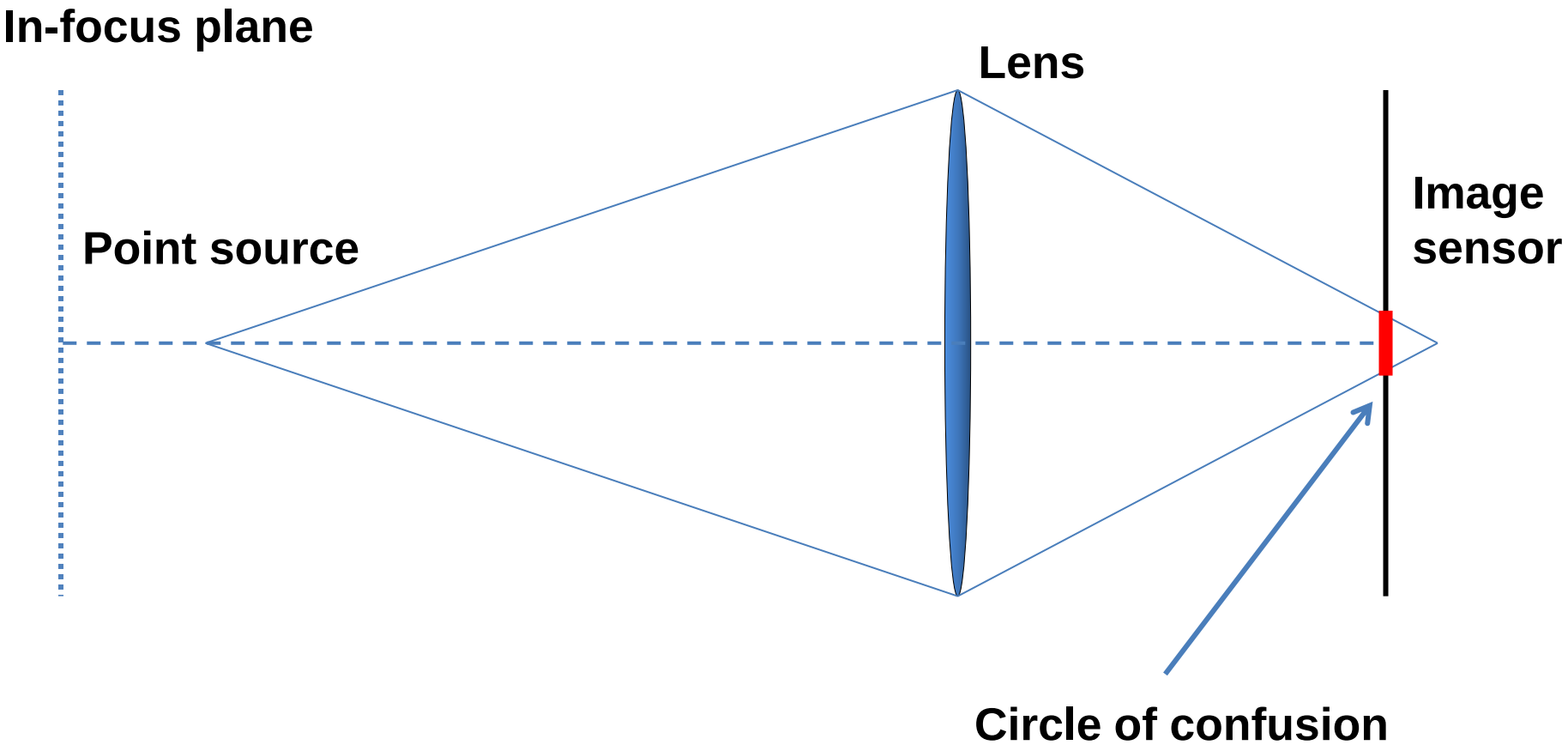
Open aperture image formation



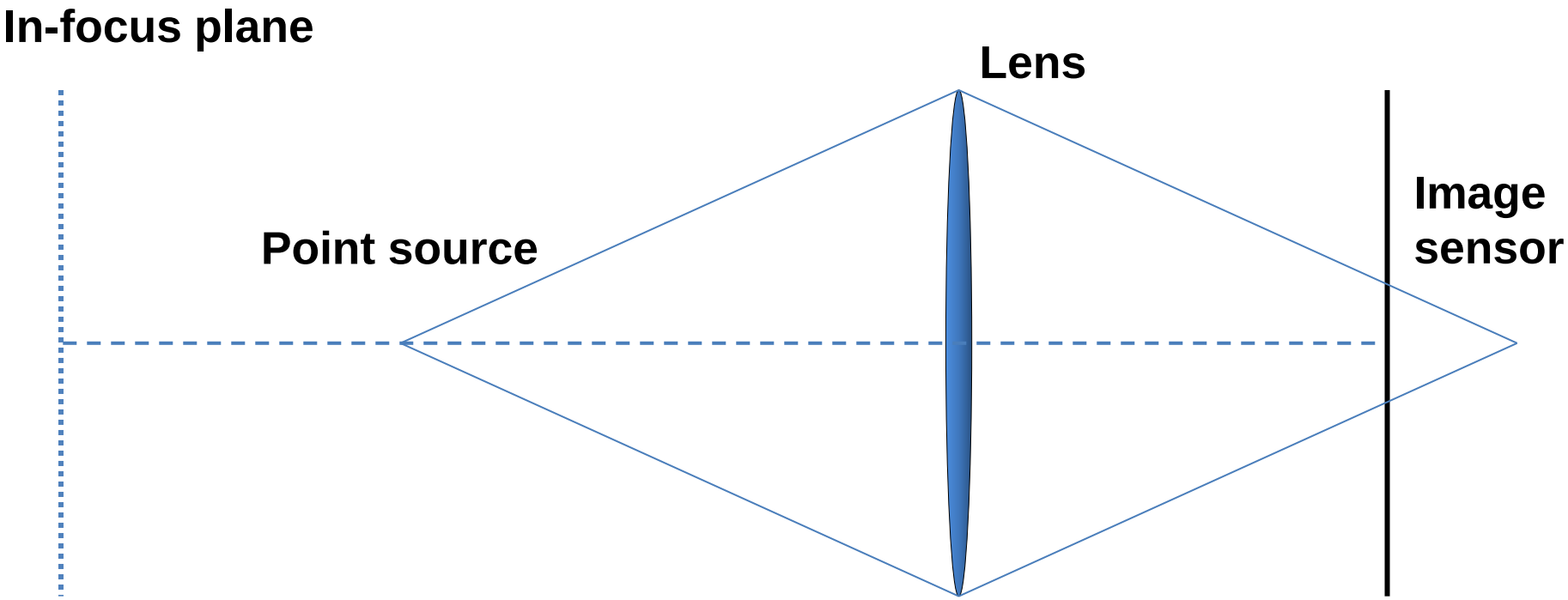
Open aperture image formation



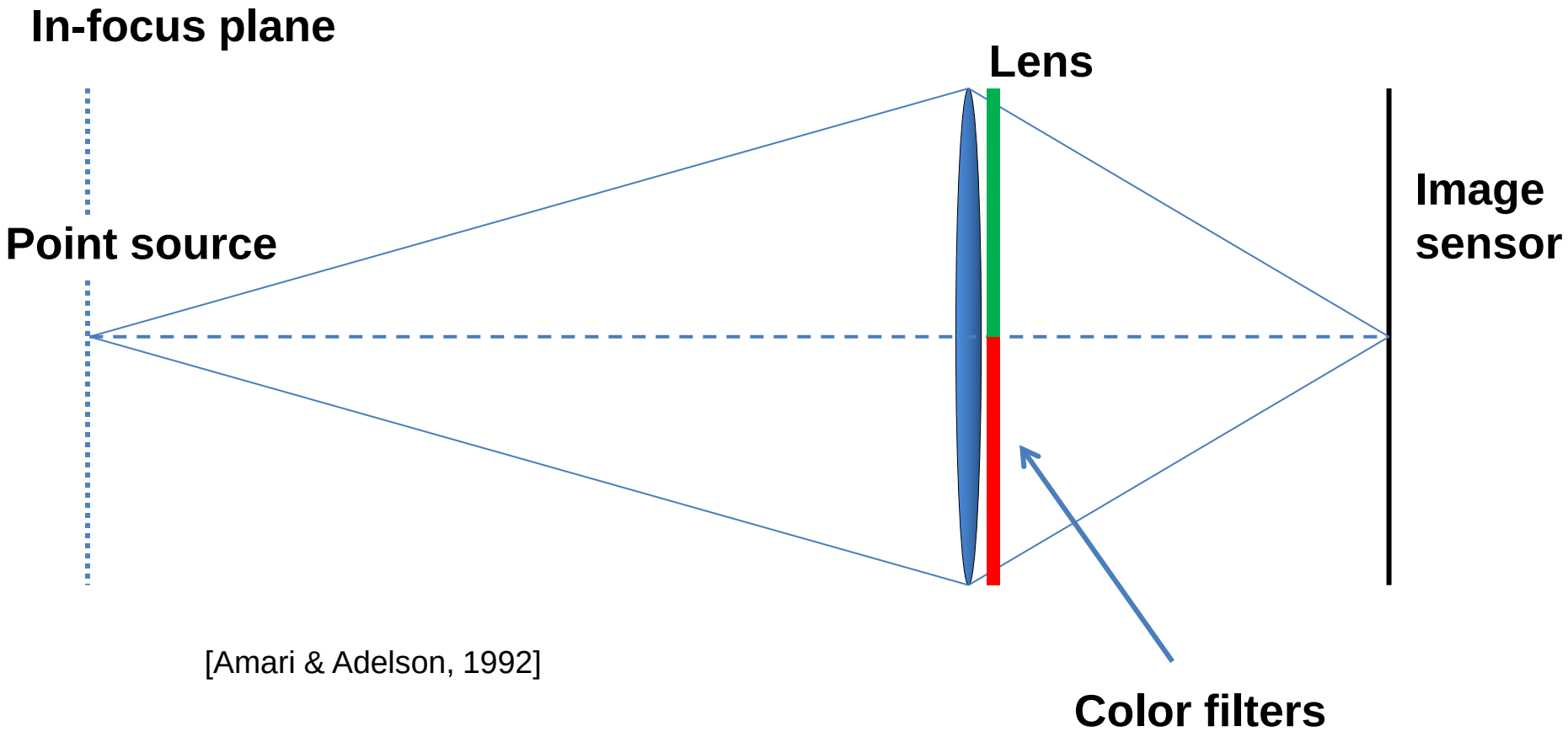
Open aperture image formation



Open aperture image formation

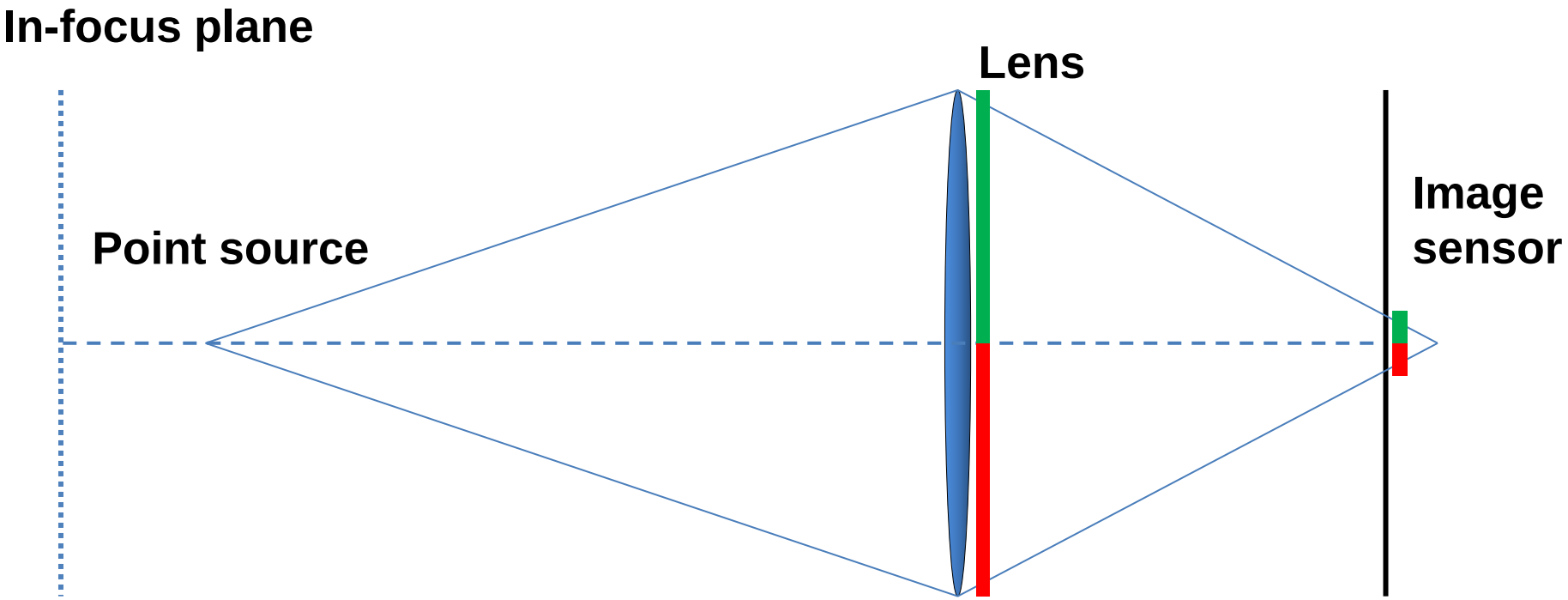


Displaced apertures with color filters



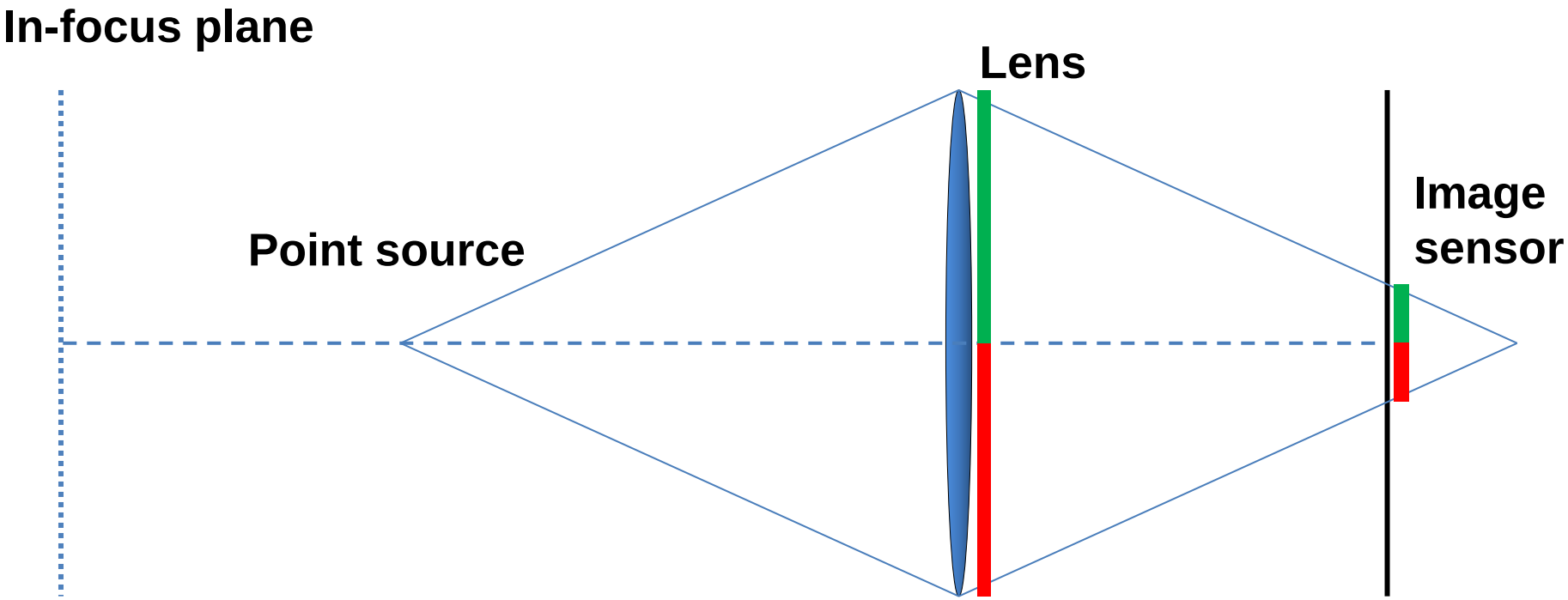
[Amari & Adelson, 1992]

Displaced apertures with color filters



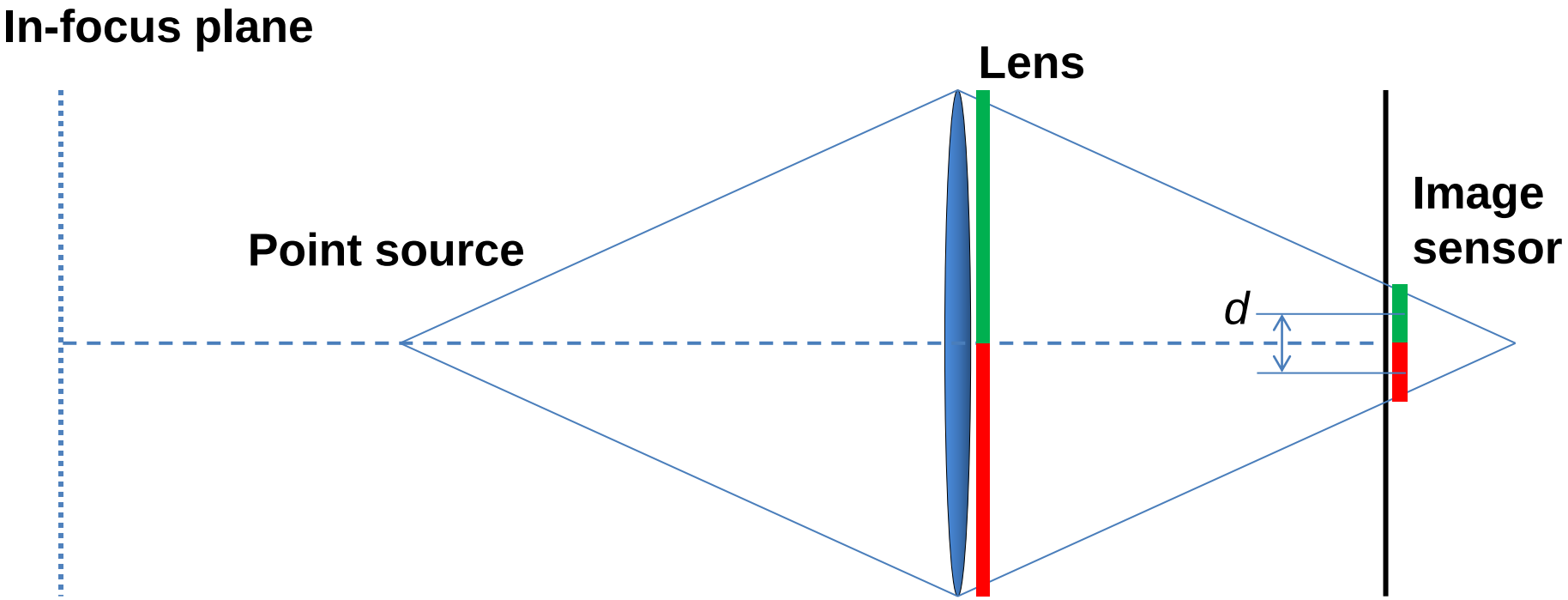
[Amari & Adelson, 1992]

Displaced apertures with color filters



[Amari & Adelson, 1992]

Displaced apertures with color filters



[Amari & Adelson, 1992]

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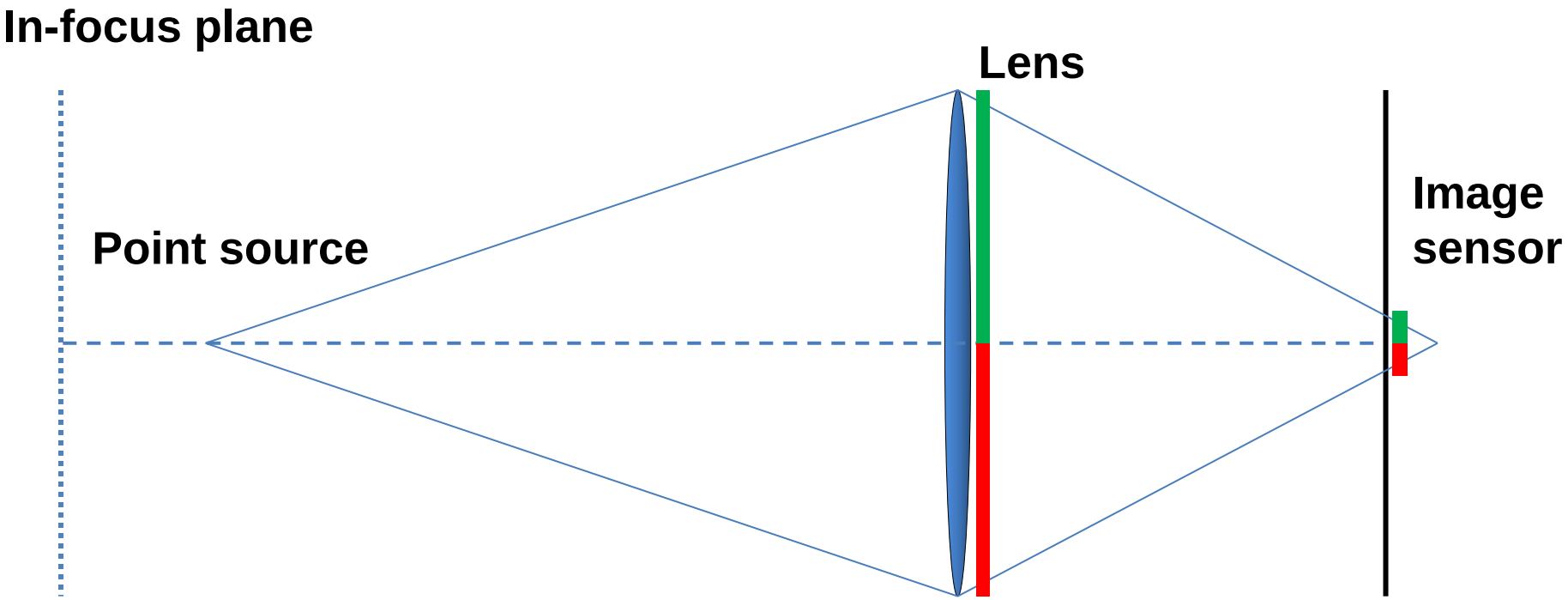

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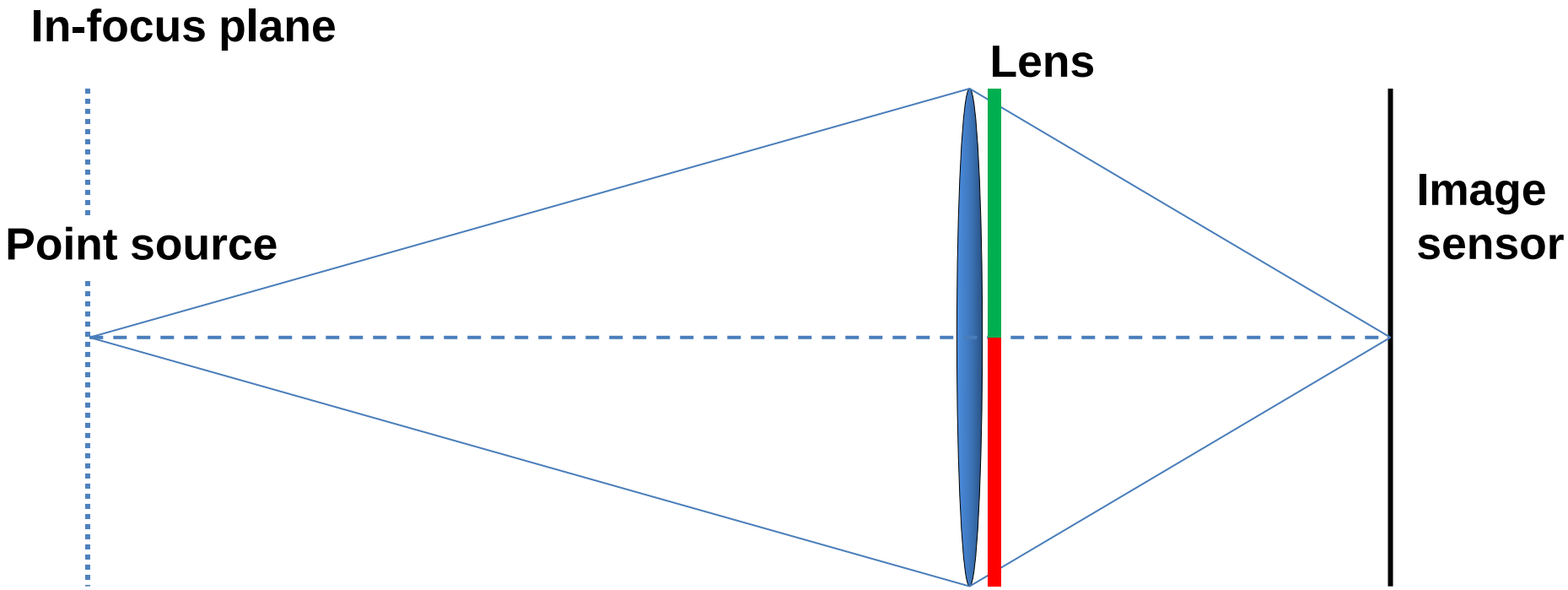
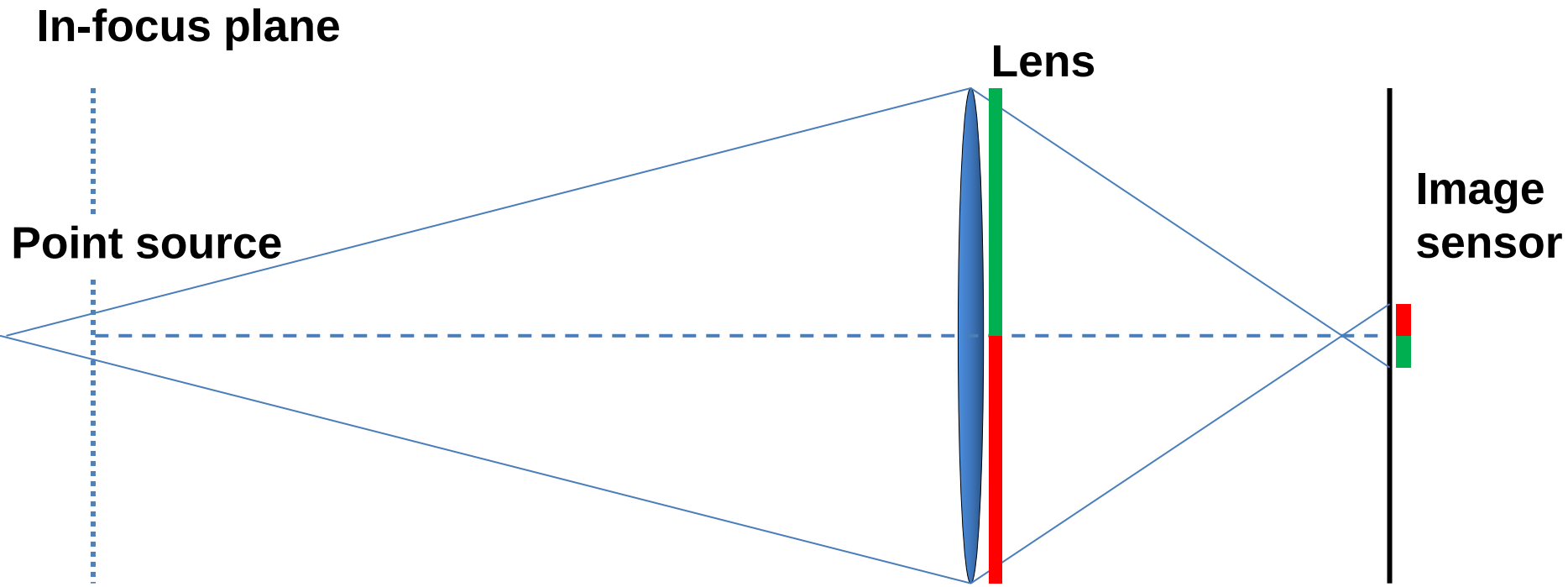


[Amari & Adelson, 1992]

Displaced apertures with color filters

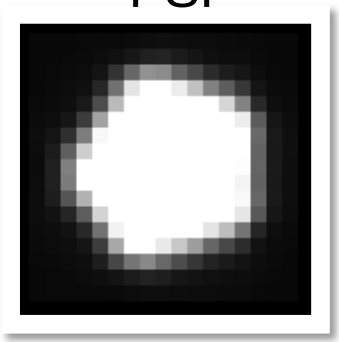


[Amari & Adelson, 1992]

Displaced apertures with color filters

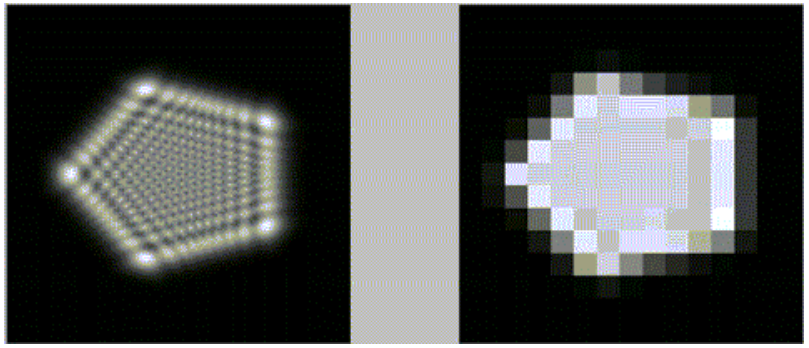
Open aperture

PSF



[A. Levin et al., 2007]

PSF simulation for open aperture



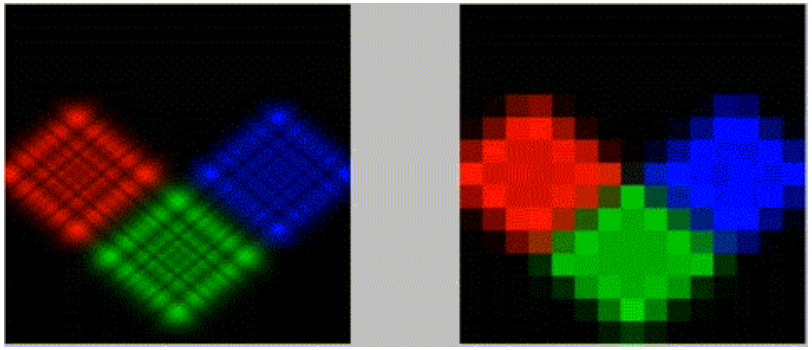
Incident light On photo-array

Color coded aperture

PSF

[Y. Bando et al., 2008]

PSF simulation for coded aperture



Incident light On photo-array

Captured Image

[Y. Bando et al., 2008]

Red Channel

[Y. Bando et al., 2008]

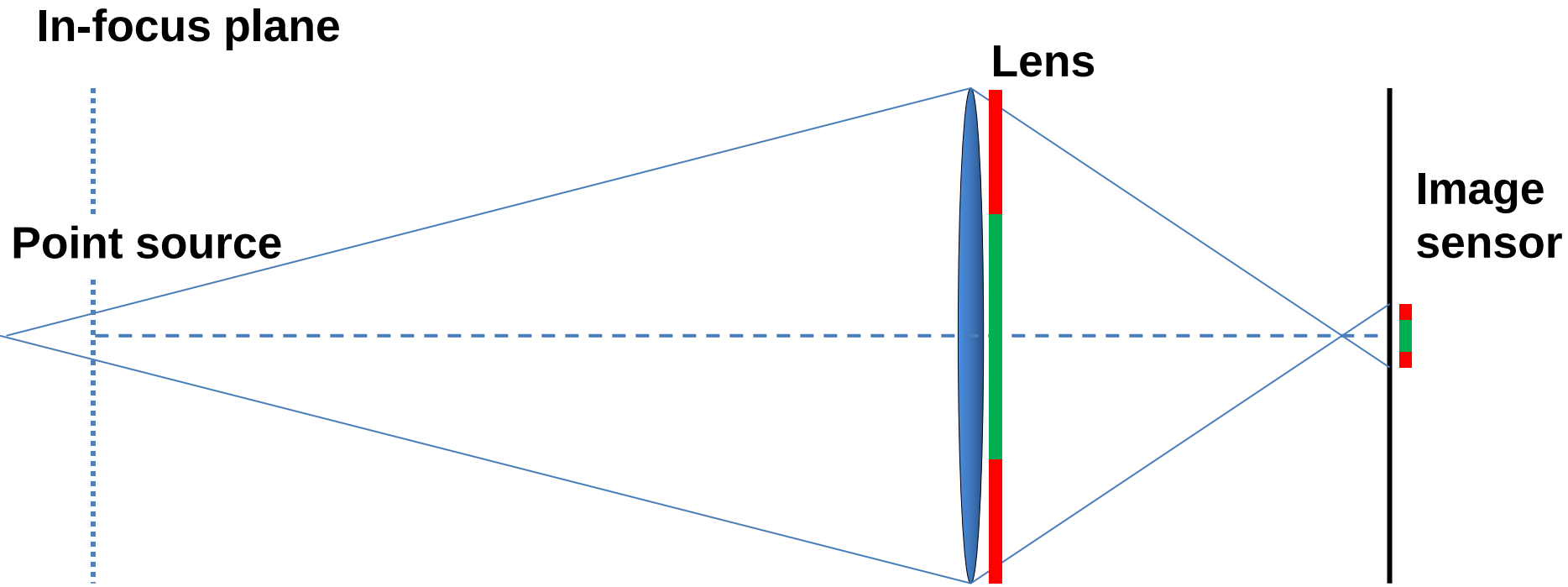
Green Channel

[Y. Bando et al., 2008]

Blue Channel

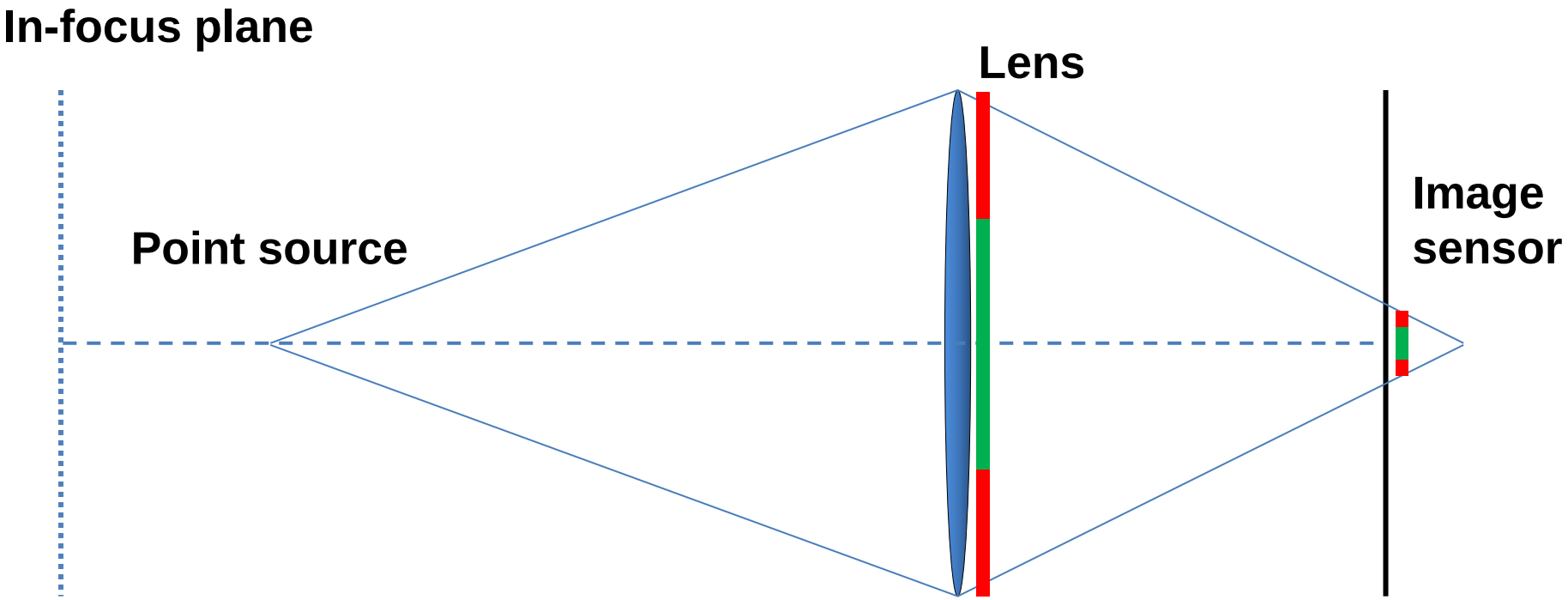
[Y. Bando et al., 2008]

Dual aperture with color filters



[Chakrabarti & Zickler, 2012]

Dual aperture with color filters

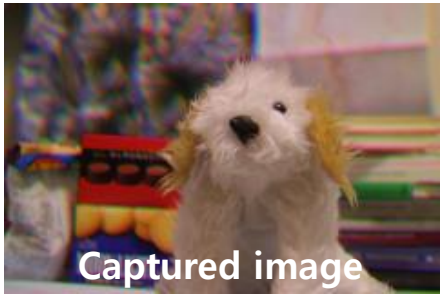


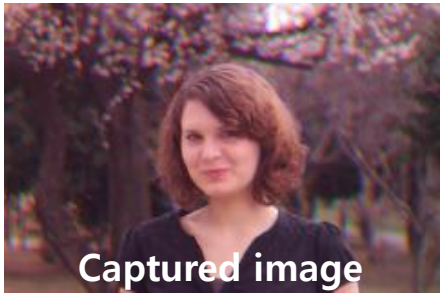
[Chakrabarti & Zickler, 2012]

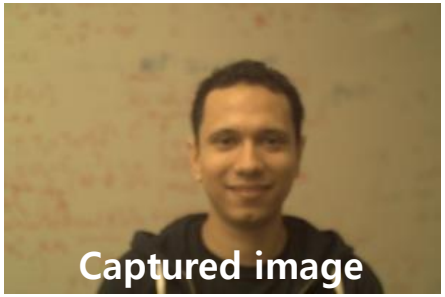
Prior-art approaches

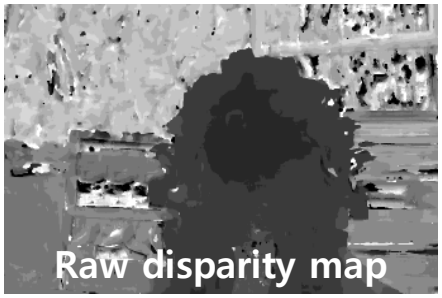
[Bando et al. 2008]

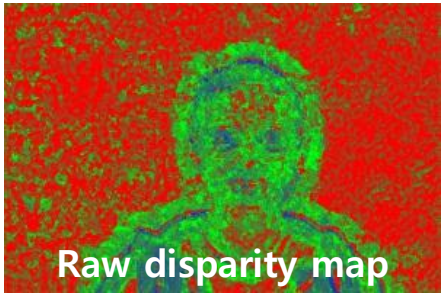
[Chakrabarti & Zickler, 2012]









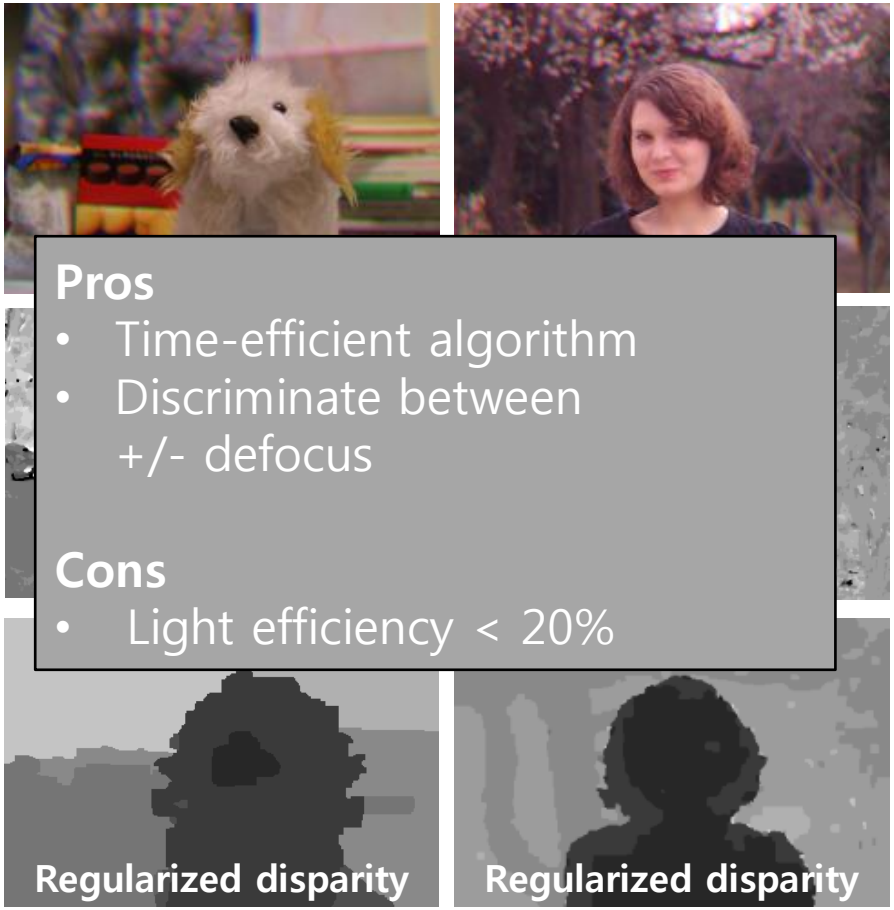


N/A

Raw disparity map

Prior-art approaches

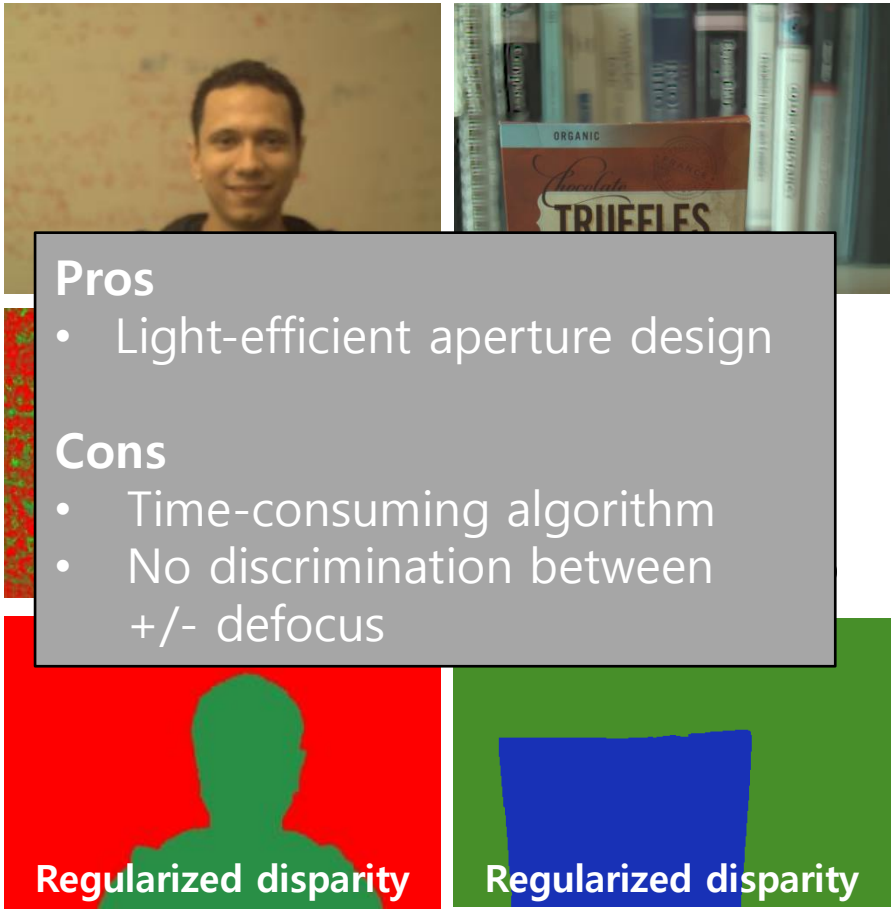
[Bando et al. 2008]



Pros
- Time-efficient algorithm
- Discriminate between +/- defocus

Cons
- Light efficiency < 20%

[Chakrabarti & Zickler, 2012]



Pros
- Light-efficient aperture design

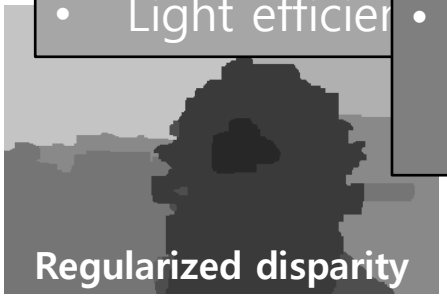
Cons
- Time-consuming algorithm
- No discrimination between +/- defocus

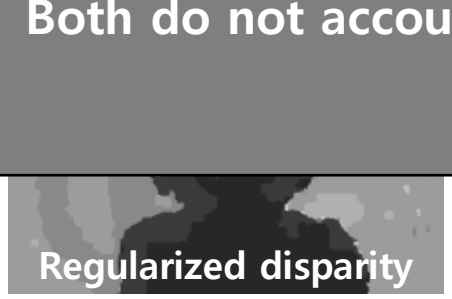
Prior-art approaches

[Bando et al. 2008]

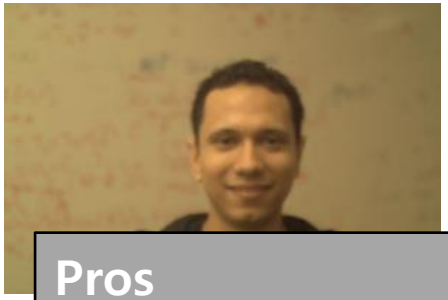
Pros
- Time-efficient algorithm
- Discriminate +/- defocus

Cons
- Light efficien



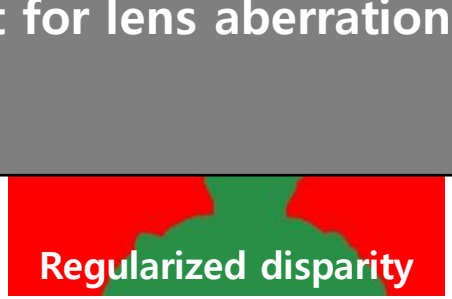


[Chakrabarti & Zickler, 2012]



Pros
- Light-efficient aperture design

algorithm
n between



- **Both approaches provide disparity map only and no depth map**
- **Both do not account for lens aberrations**

Challenges

- **Time performance**

  real-time implementation feasibility

- **Light efficiency**

  compact prototype feasibility (e.g. smartphone)

- **Disparity to depth conversion**

  3D scene reconstruction feasibility

Challenges

- **Time performance**

  real-time implementation feasibility

We opt for:
- color channel shift approach [Amari & Adelson, 1992]
- algorithm optimizations proposed in [Panchenko et al., 2016]

- **Light efficiency**

  compact prototype feasibility (e.g. smartphone)

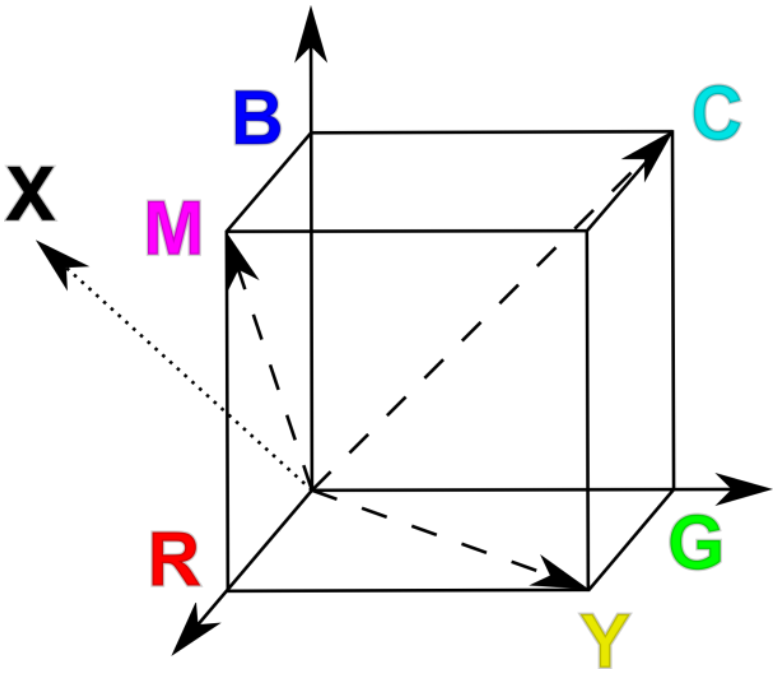
We propose:
- Novel color coded aperture designs

- **Disparity to depth conversion**

  3D scene reconstruction feasibility

We propose:
- Disparity to depth conversion formula and sensor calibration procedure

Color space change

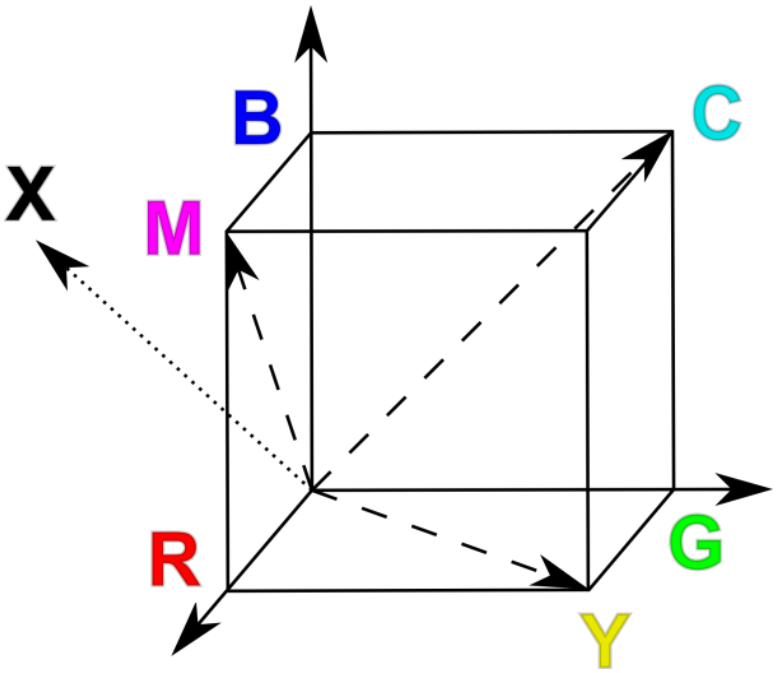


R + G = Y

R + B = M

G + B = C

Color space change



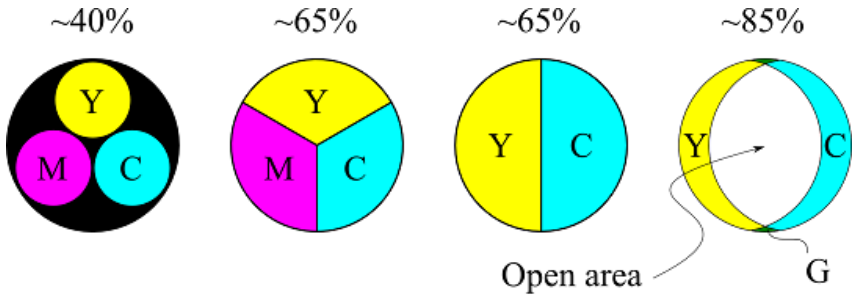
R + G = Y

R + B = M

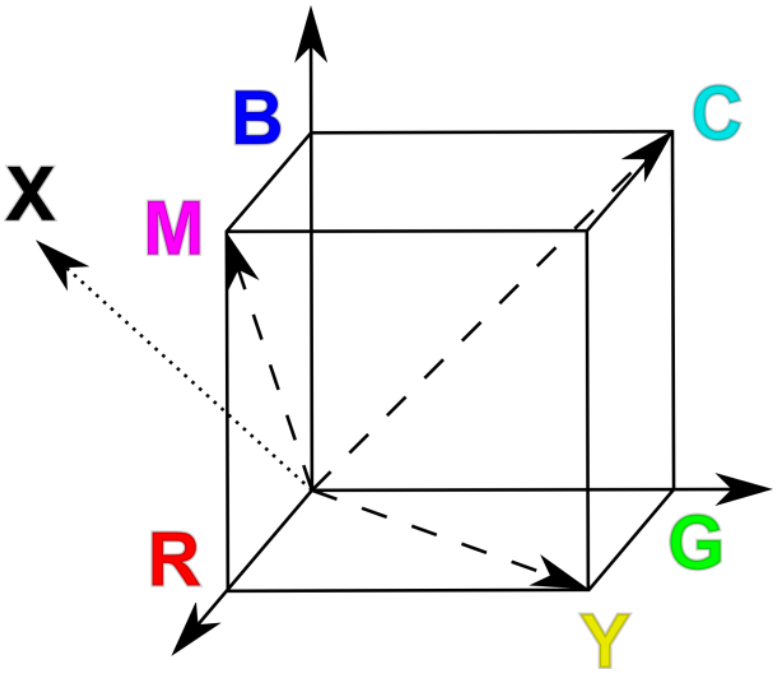
G + B = C

$$\mathbf{w}_{CYX}^{i,j} = \mathbf{M}^{-1}\mathbf{w}_{RGB}^{i,j}$$

[Amari & Adelson, 1992]



Color space change



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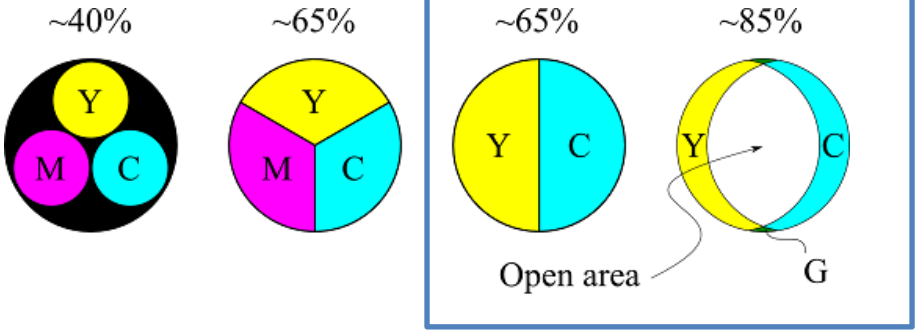
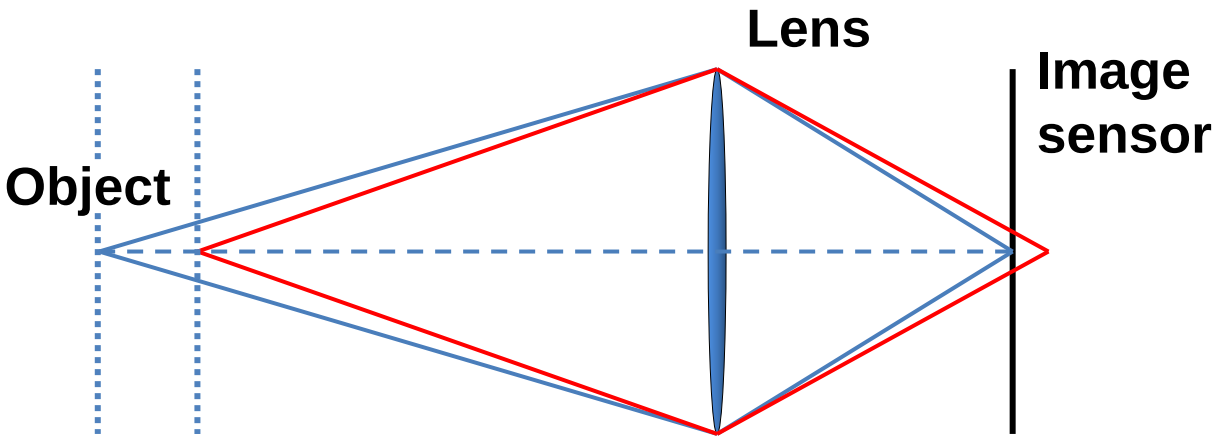


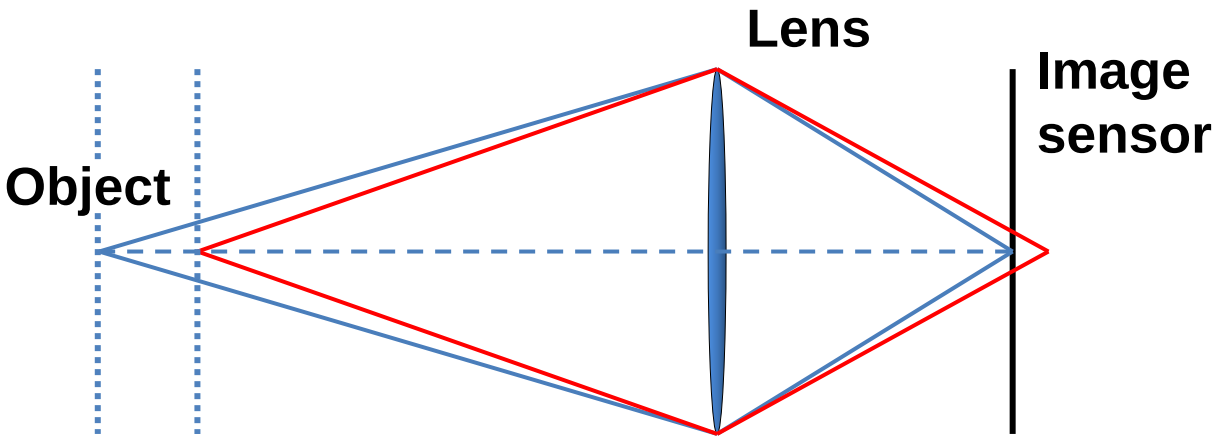
CYX

Calibration



Canon 50mm f/1.8

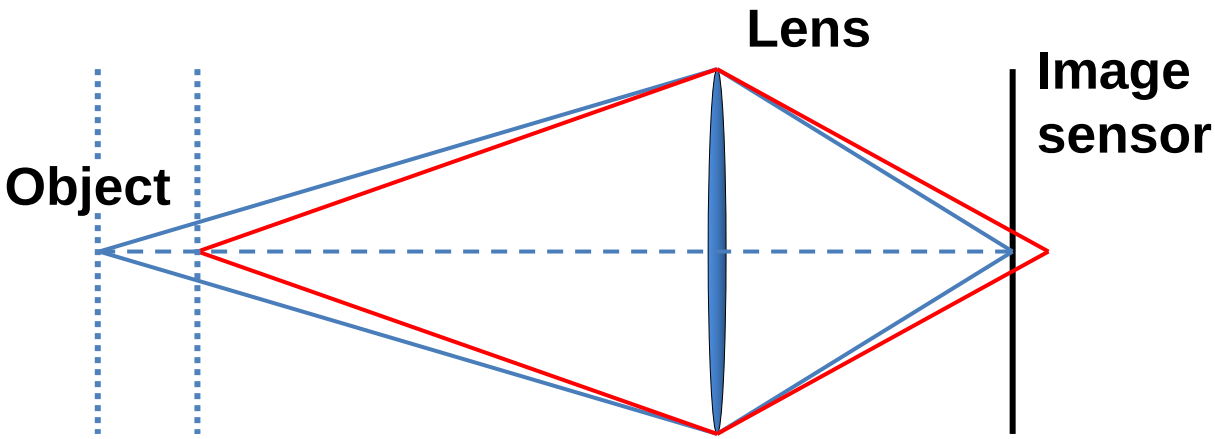
Calibration

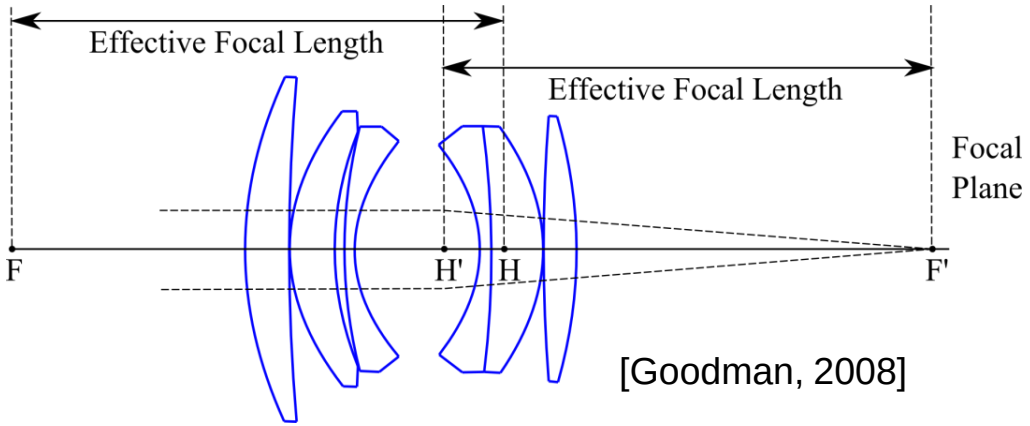


Canon 50mm f/1.8

51.6mm

Calibration





[Goodman, 2008]

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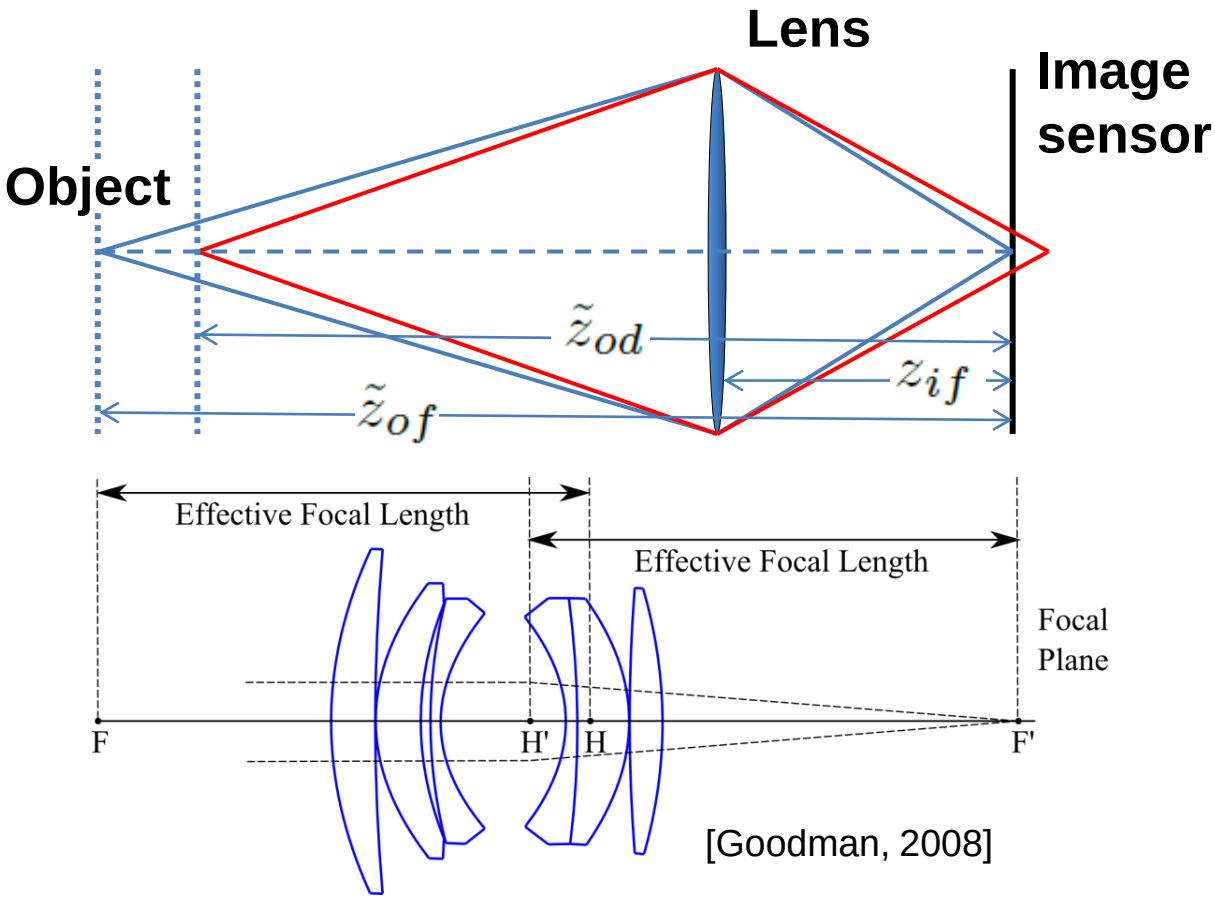

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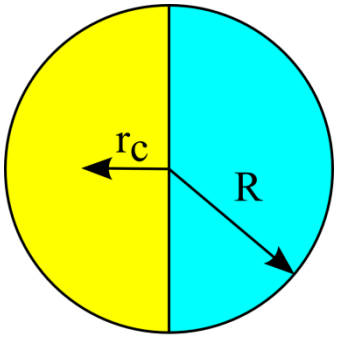
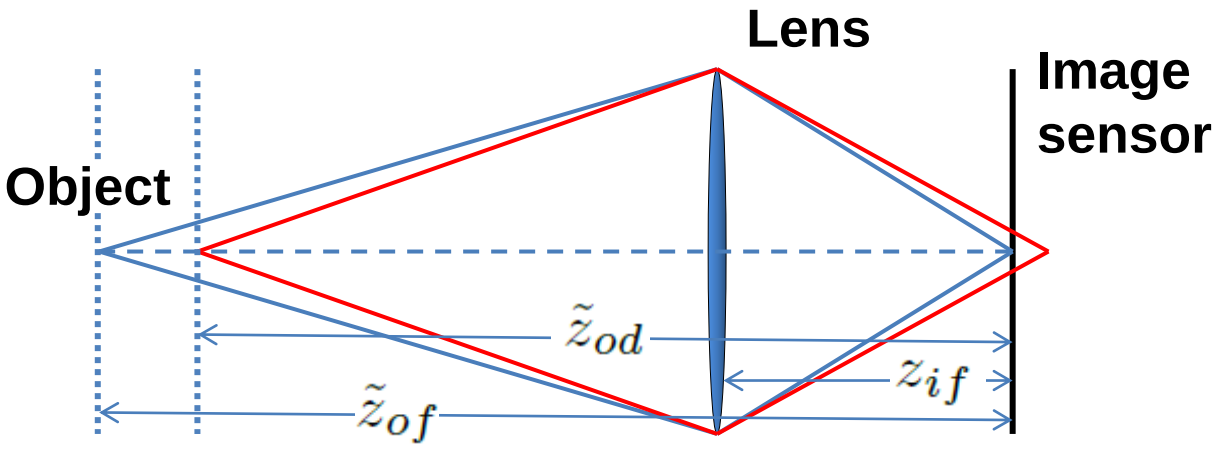
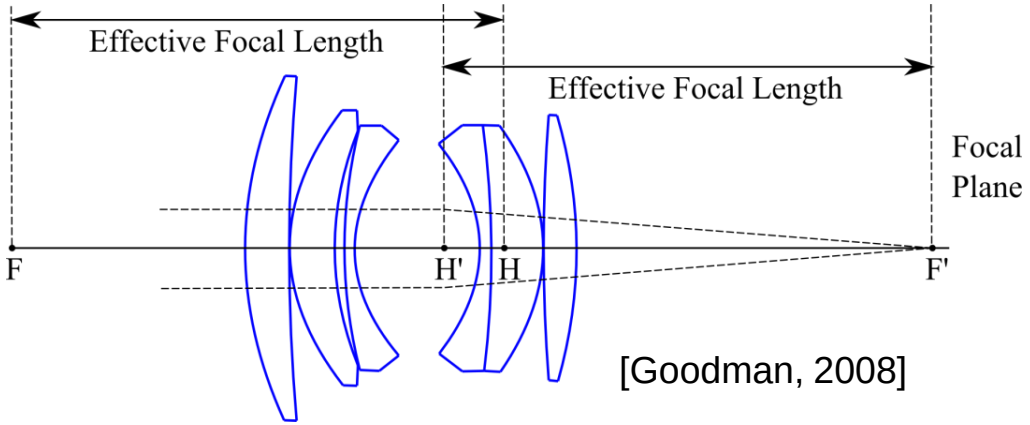


Aperture geometry

$$\tilde{z}_{od} = \frac{bf\tilde{z}_{of} - 2\mu d\delta(\tilde{z}_{of} - \delta - f)}{bf - 2\mu d(\tilde{z}_{of} - \delta - f)}$$

Calibration





[Goodman, 2008]

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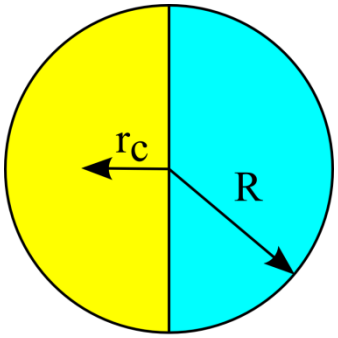


Aperture geometry

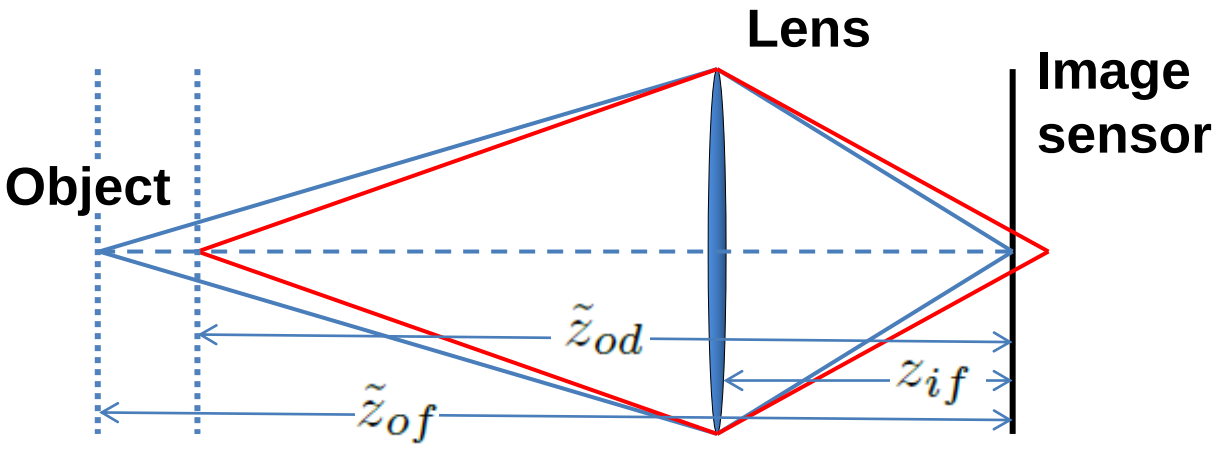
$$\tilde{z}_{od} = \frac{bf\tilde{z}_{of} - 2\mu d\delta(\tilde{z}_{of} - \delta - f)}{bf - 2\mu d(\tilde{z}_{of} - \delta - f)}$$

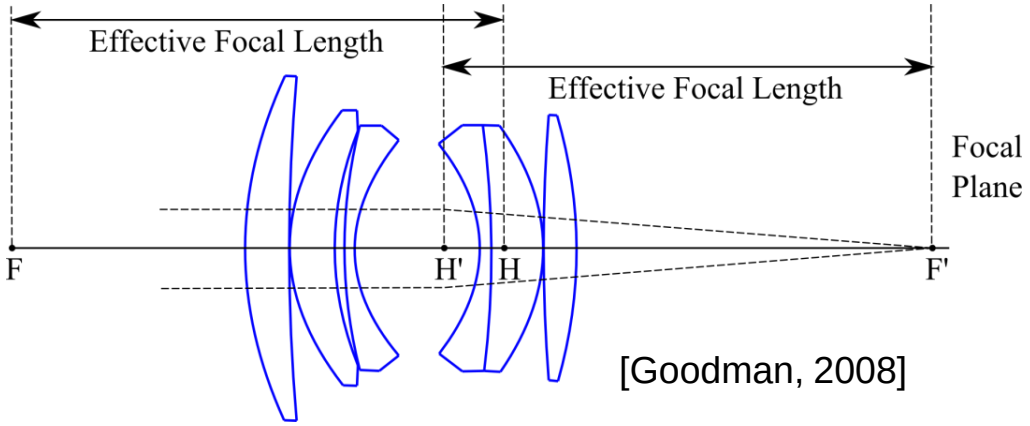
$\tilde{z}_{of}$ - Distance to the in-focus plane

$b = 2r_c$ - baseline

$\delta = z_{if} + HH'$

Calibration





[Goodman, 2008]

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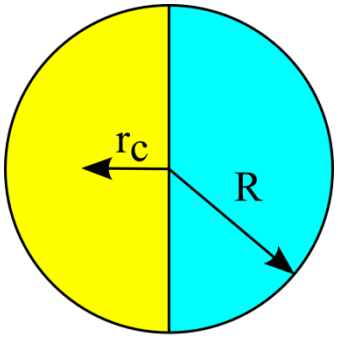

Aperture geometry

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$\tilde{z}_{of}$ - Distance to the in-focus plane

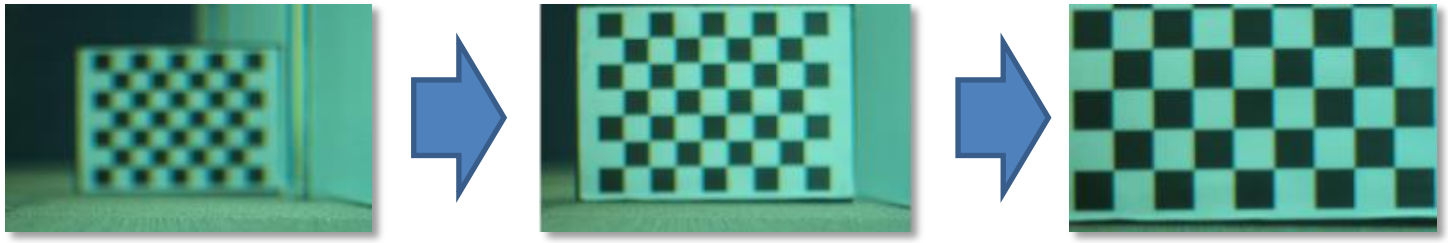
$b = 2r_c$ - baseline

$\delta = z_{if} + HH'$

Conventional calibration using pinhole camera model [Zhang, 1998]

Calibration: procedure

1. Capture 31 images with chessboard pattern moving along the optical axis between 1 and 4 meters measured from camera sensor (10cm step).

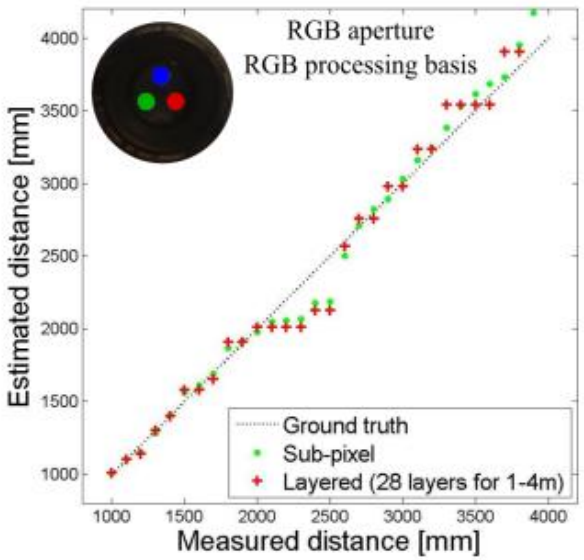


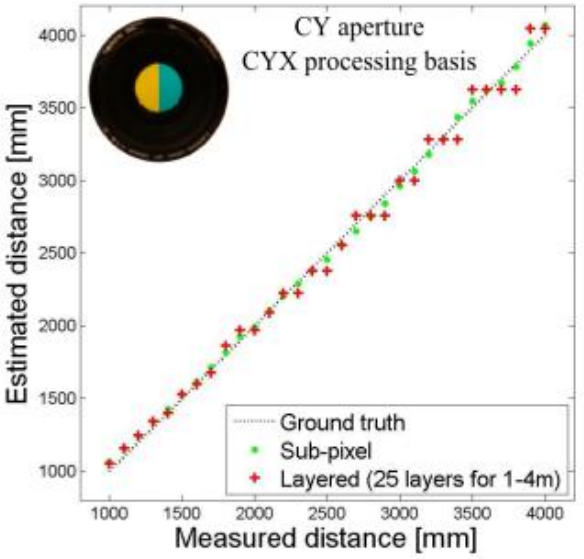
2. Extract 31 corresponding disparity values (in the central pixel).

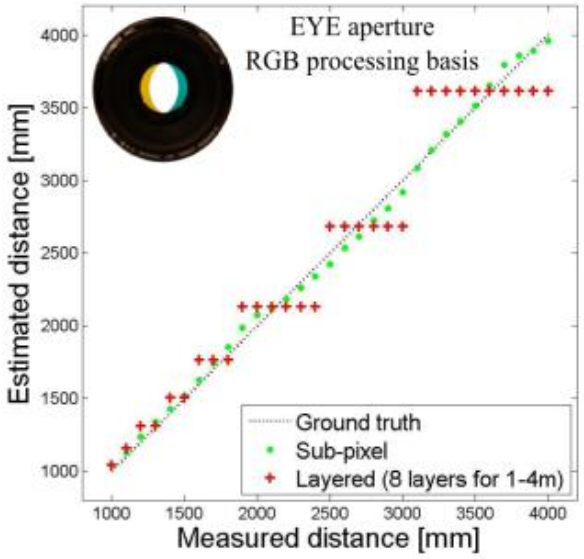
At this point we have **a set of disparity values** and a set of corresponding **ground truth depth values**.

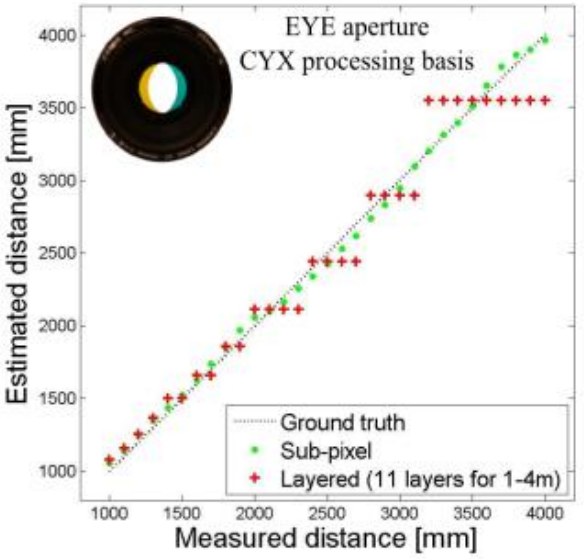
3. Fit the complex lens model to the data (optimization w.r.t. $\tilde{z}_{of}$, b, HH')

Calibration: results









Calibration: should be done in each pixel

2 reasons:

Petzval field curvature: $\tilde{z}_{of} \neq const$

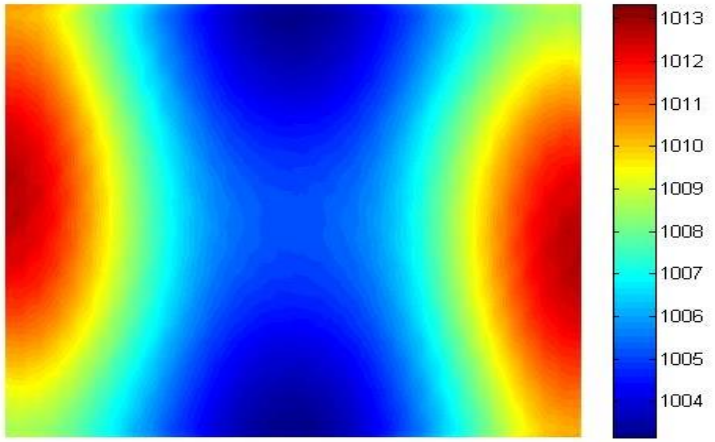
and

PSF nonuniformity: $b \neq const$

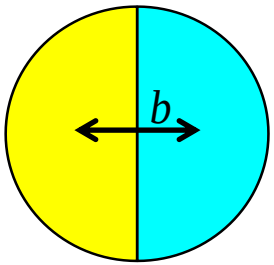
$$\tilde{z}_{od}(i,j) = \frac{b(i,j) f \tilde{z}_{of}(i,j) - 2\mu d\delta(\tilde{z}_{of}(i,j) - \delta - f)}{b(i,j) f - 2\mu d(\tilde{z}_{of}(i,j) - \delta - f)}.$$

We have to perform calibration for each pixel independently

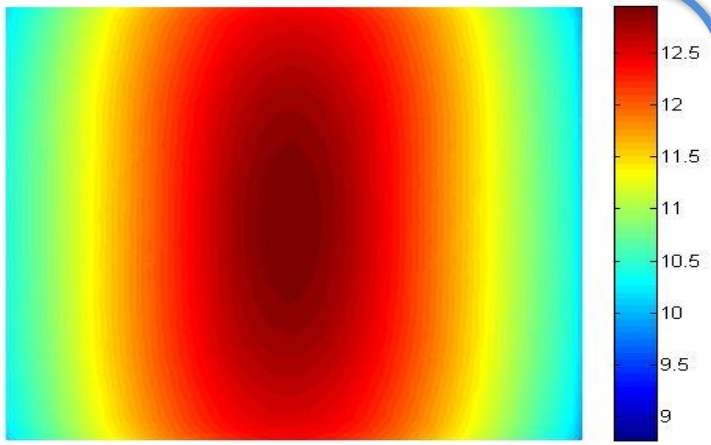
Calibration



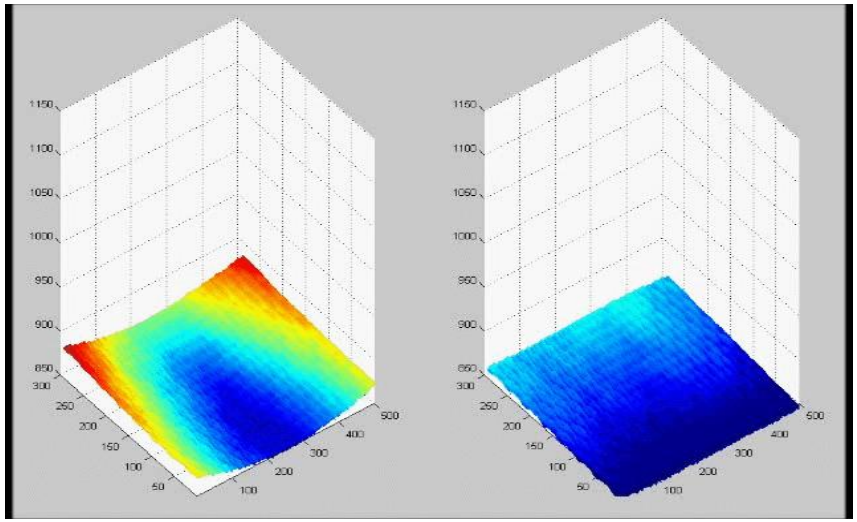
Distance to the focused plane, mm



Coded aperture

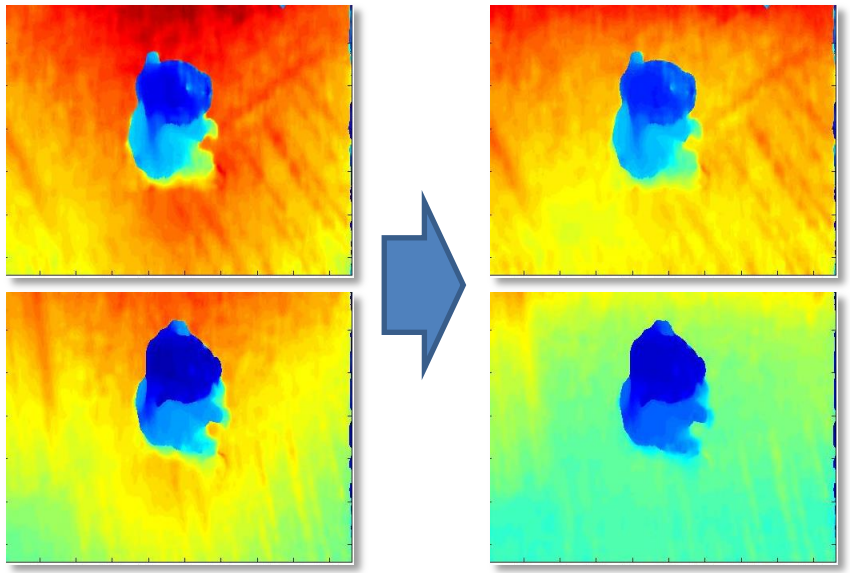


SCA baseline b, mm



Distorted depth for planar surface

Undistorted depth for planar surface



Distorted depth

Undistorted depth

DSLR based prototype

Captured image

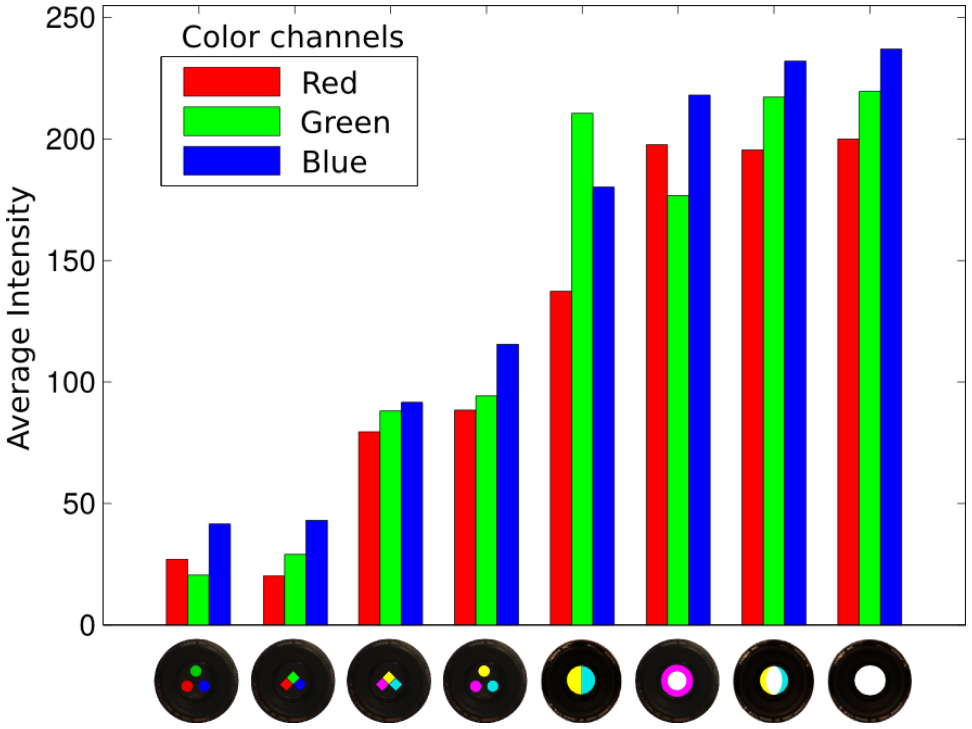
Depth map

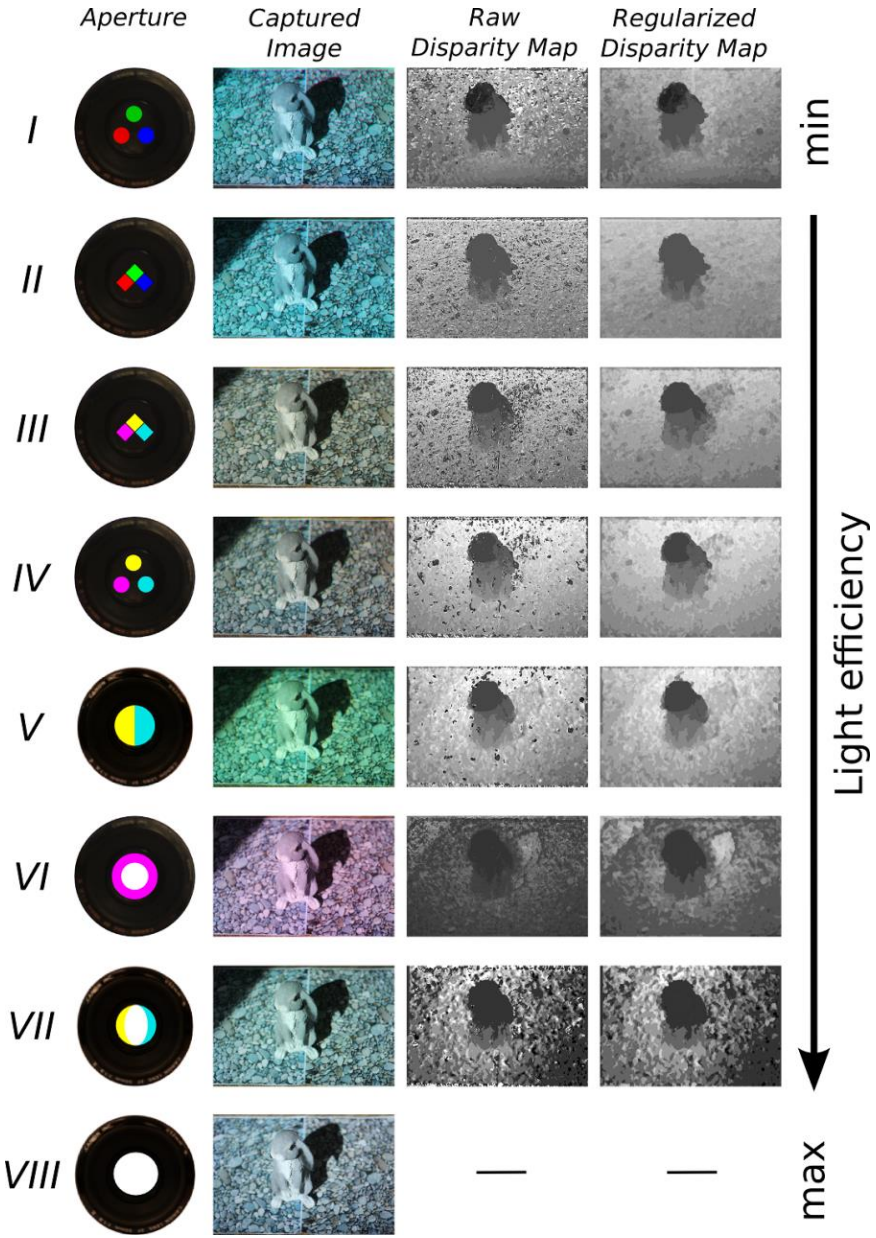
DSLR based prototype: comparison with prior-art

Light efficiency VS depth accuracy

Trade-of should be found
taking into account its application

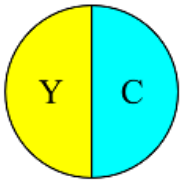
Light efficiency





Smartphone based prototype

HW:
Samsung Note 3 LTE (N9005), OpenCL

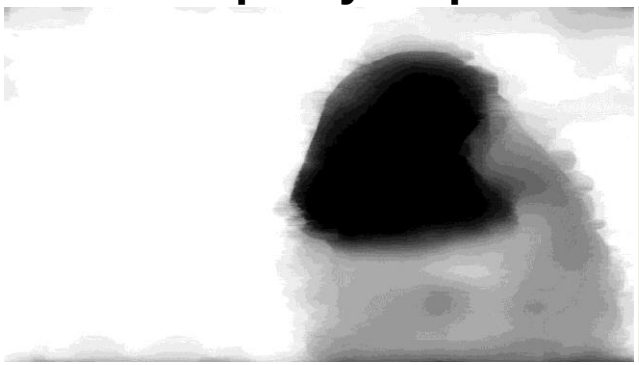


Time performance:
5 seconds for HD image

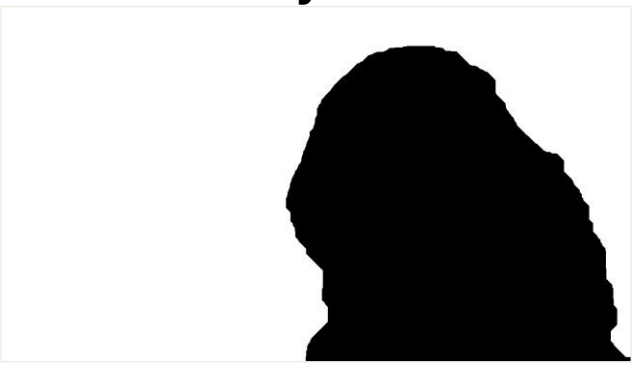
Depth-dependent image effects

Image

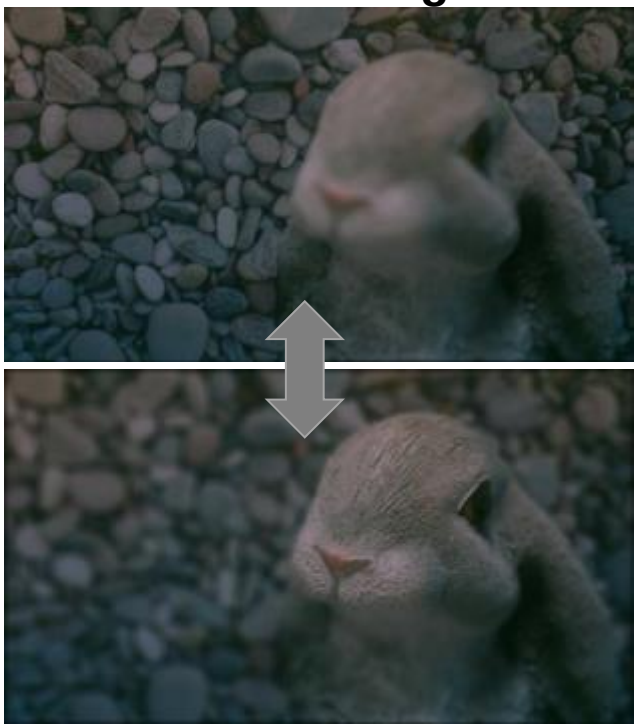
Disparity map



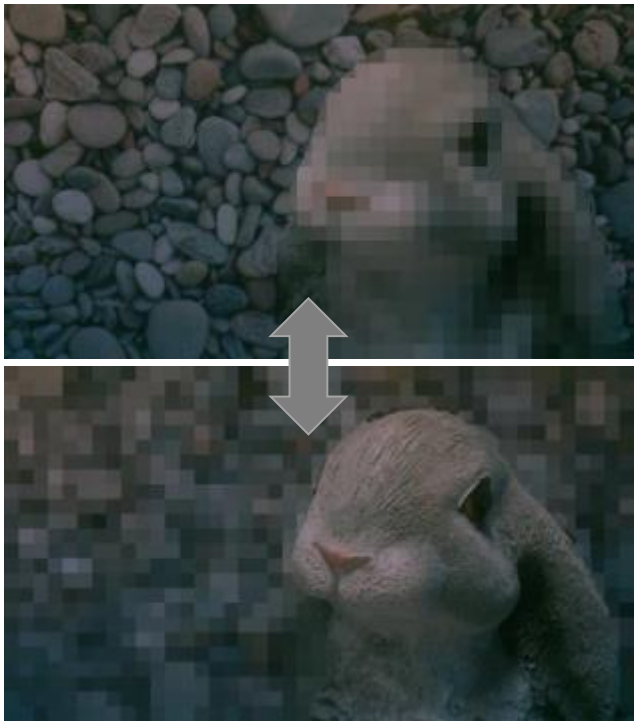
Binary mask



Refocusing



Pixelization

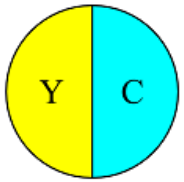


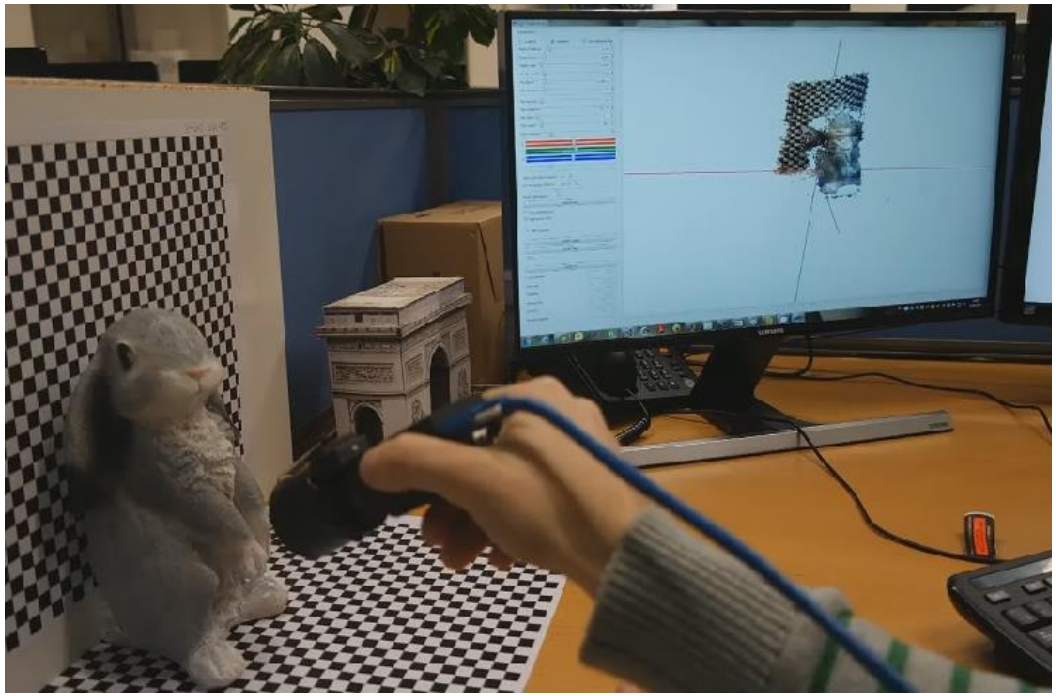
Colorization

PointGrey camera prototype

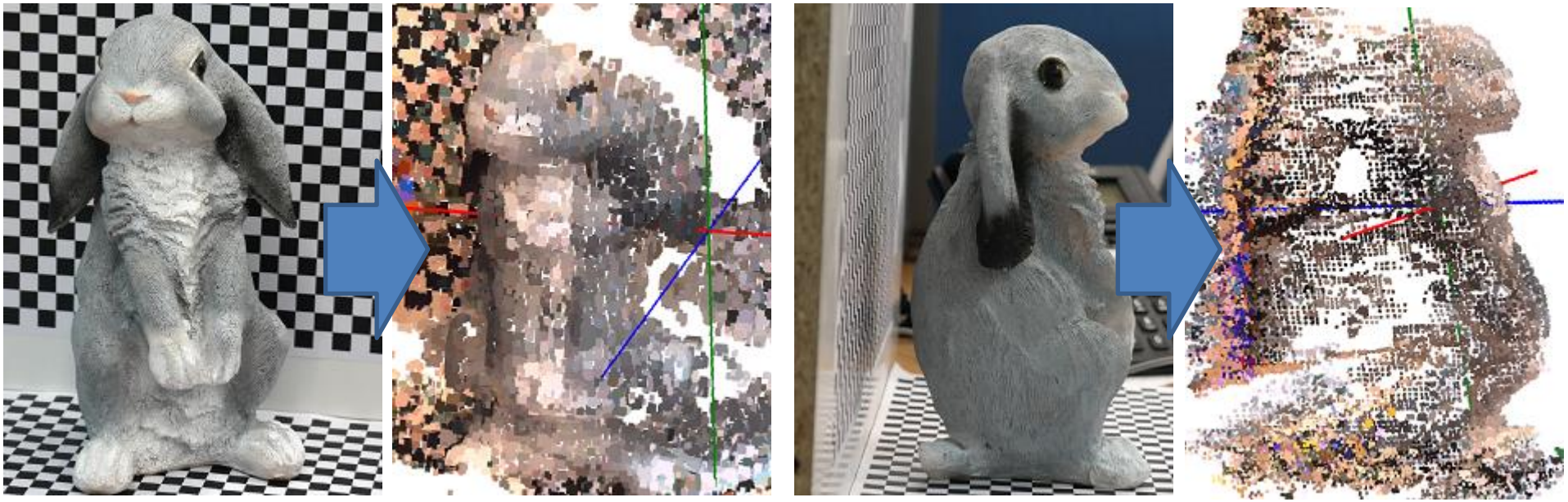
HW:
PC GPU (Nvidia GeForce 780 Ti) using OpenCL
PointGrey Grasshopper 3 camera
Fujinon DV3.4x3.8SA-1 lens

Time performance:
Depth: 53 fps for HD image
3D: 45 fps (KinFu)
All: 15 fps



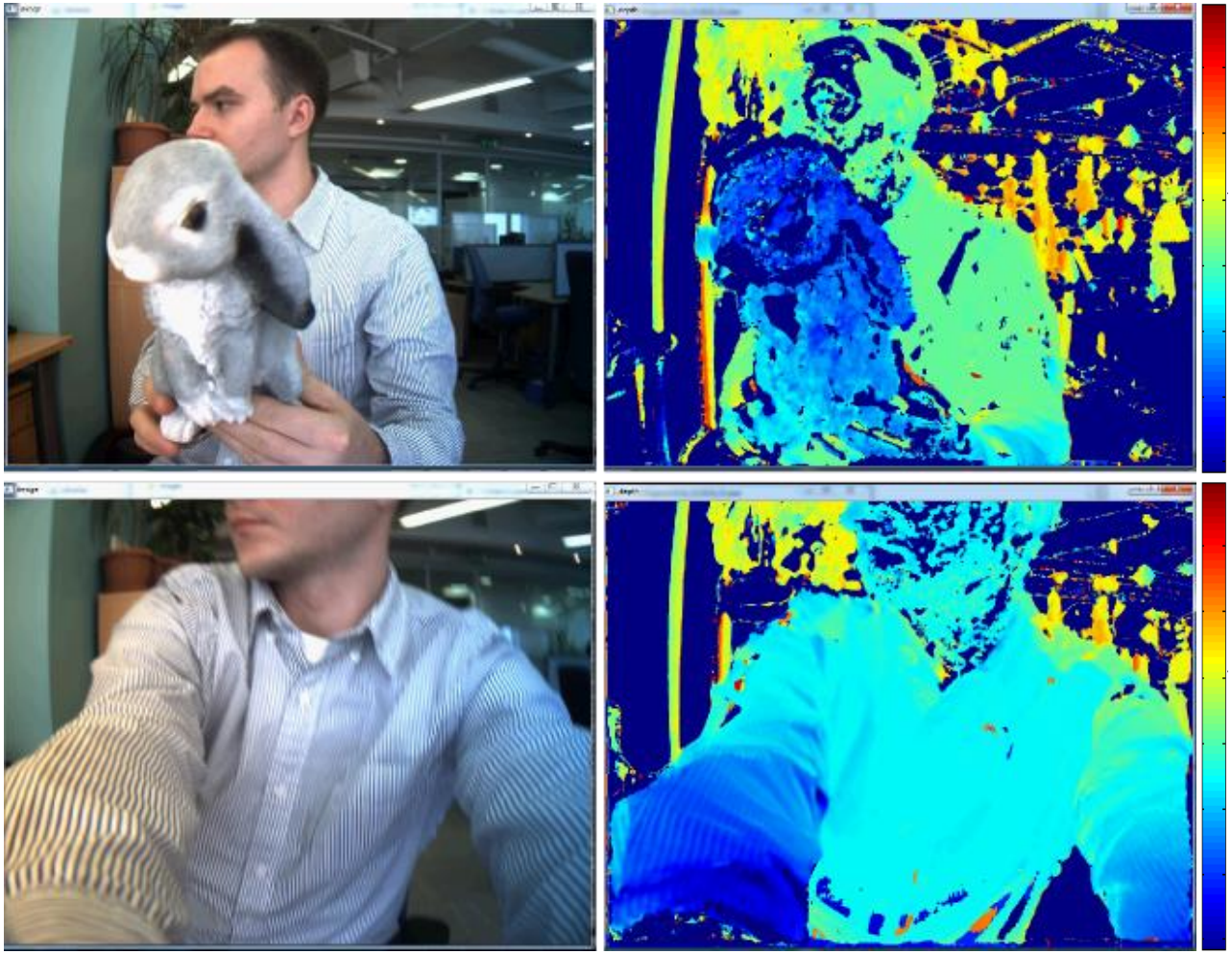


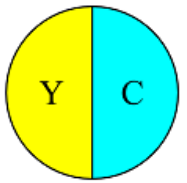
PointGrey camera prototype: close range



Webcamera prototype: dynamic scene

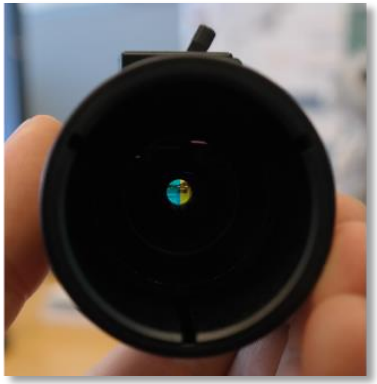
- Static or dynamic camera
- Static or dynamic scene
- Real-time processing

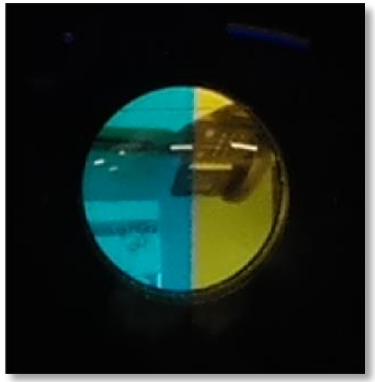


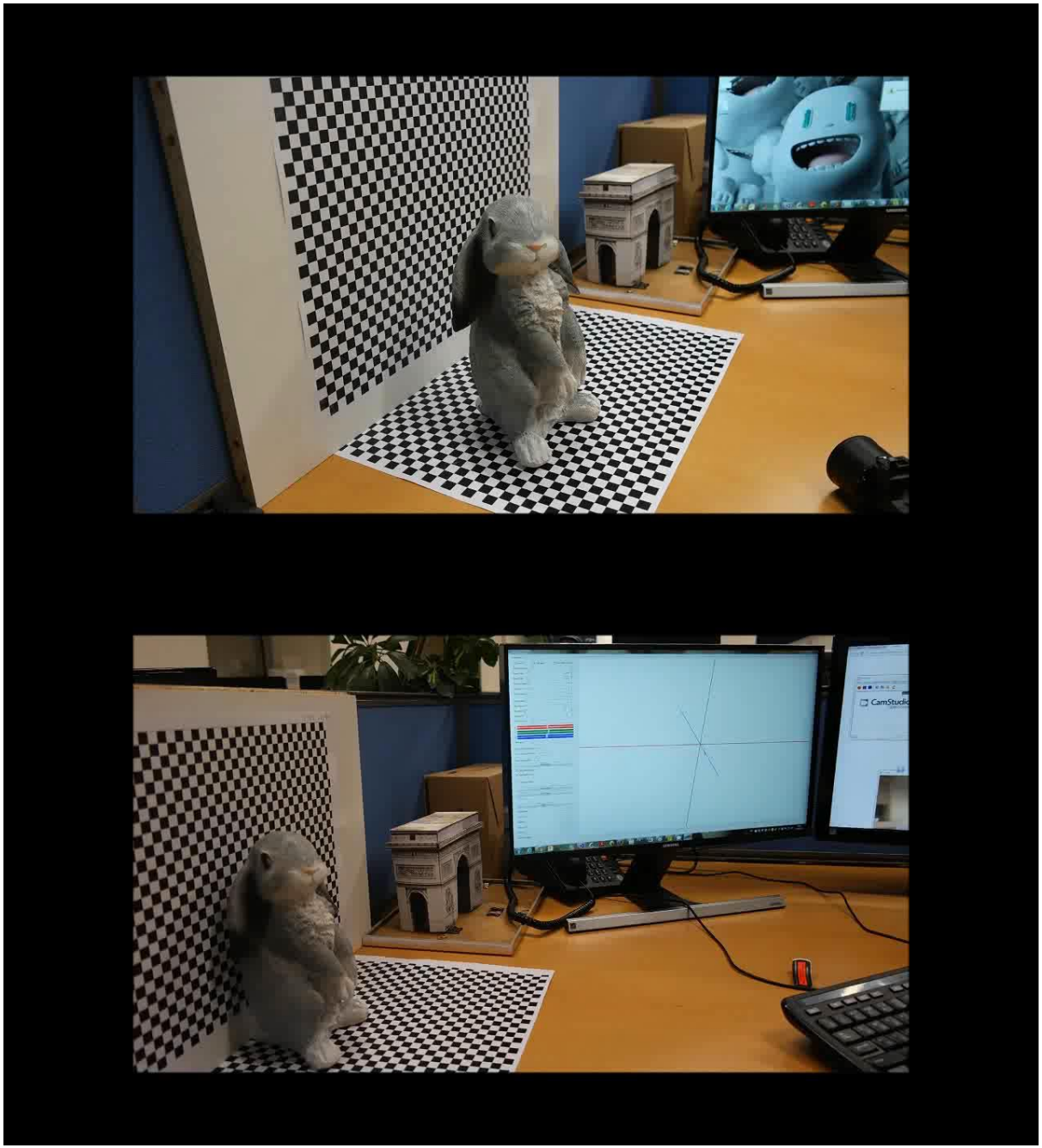


Microsoft LifeCam Studio

Demo





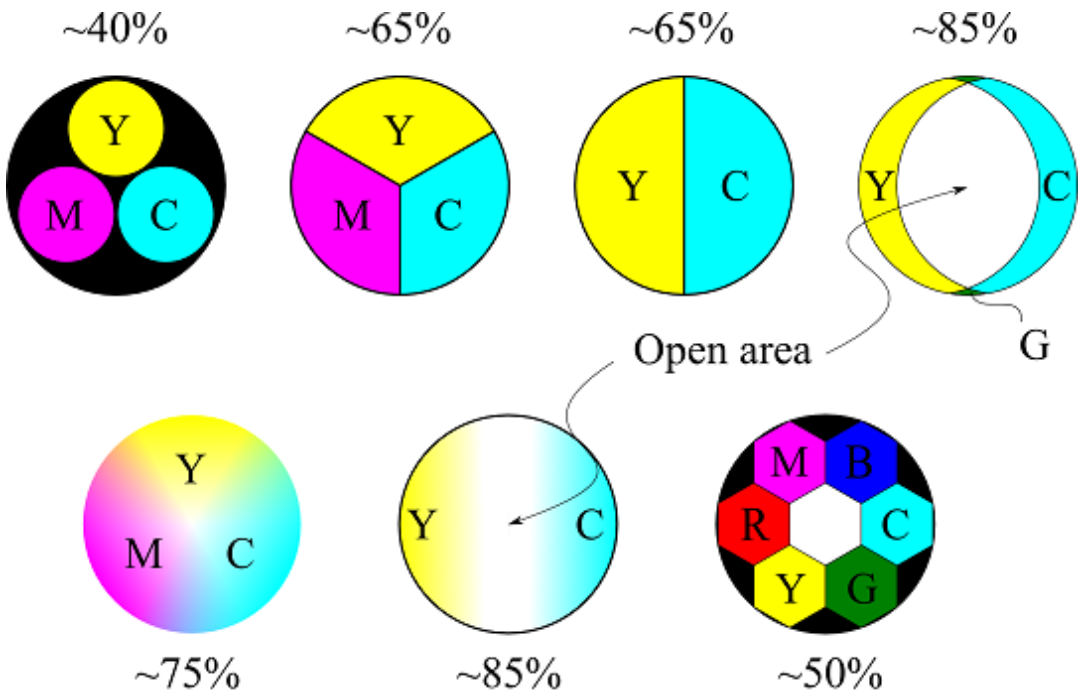


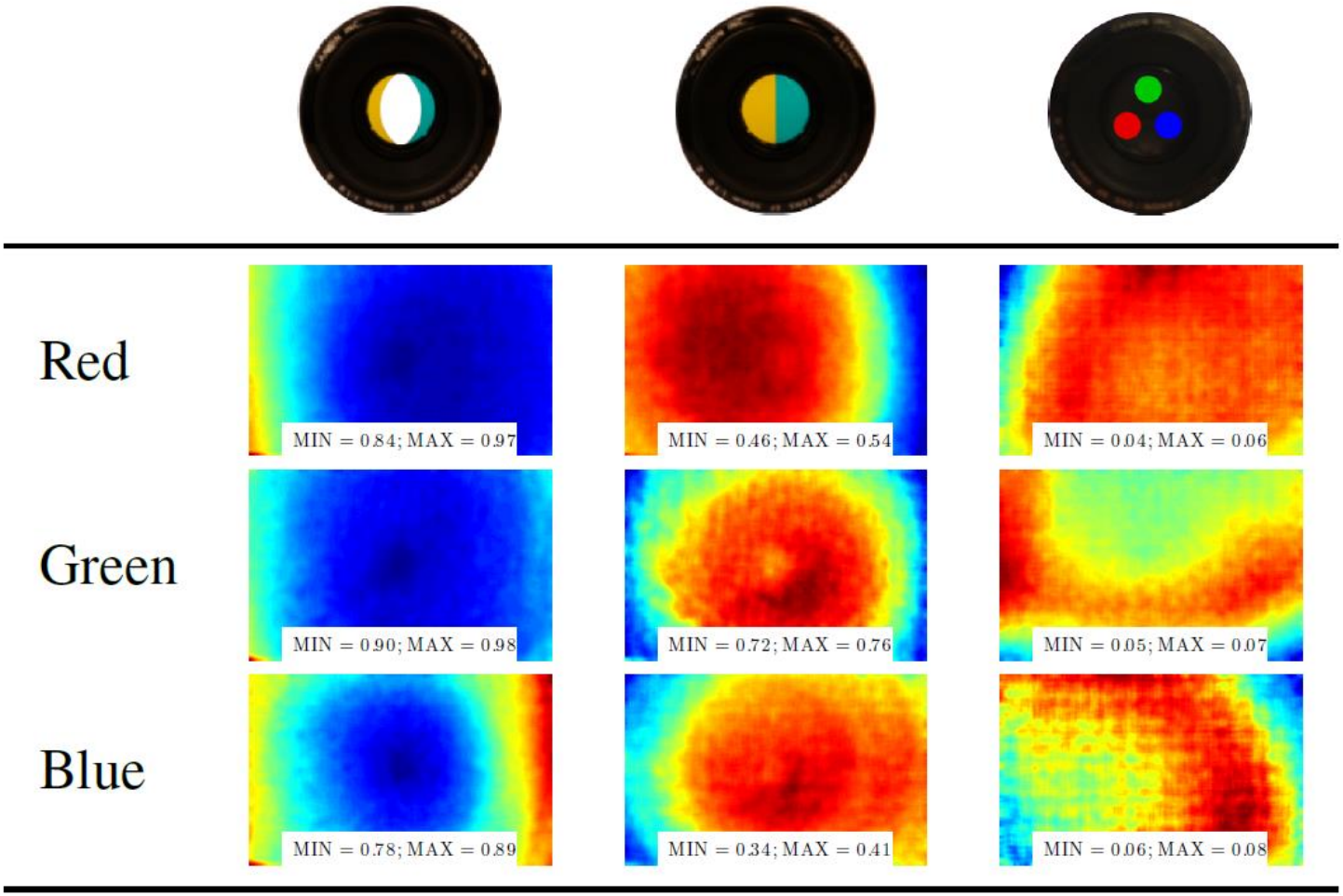
Conclusion

- Novel light-efficient color coded aperture designs were proposed
- Color coded aperture approach provides accurate depth maps (depends on equivalent baseline of the system and scene texture)
- Real-time 3D reconstruction is possible using color coded aperture
- Color coded aperture could be used in tiny smartphone cameras

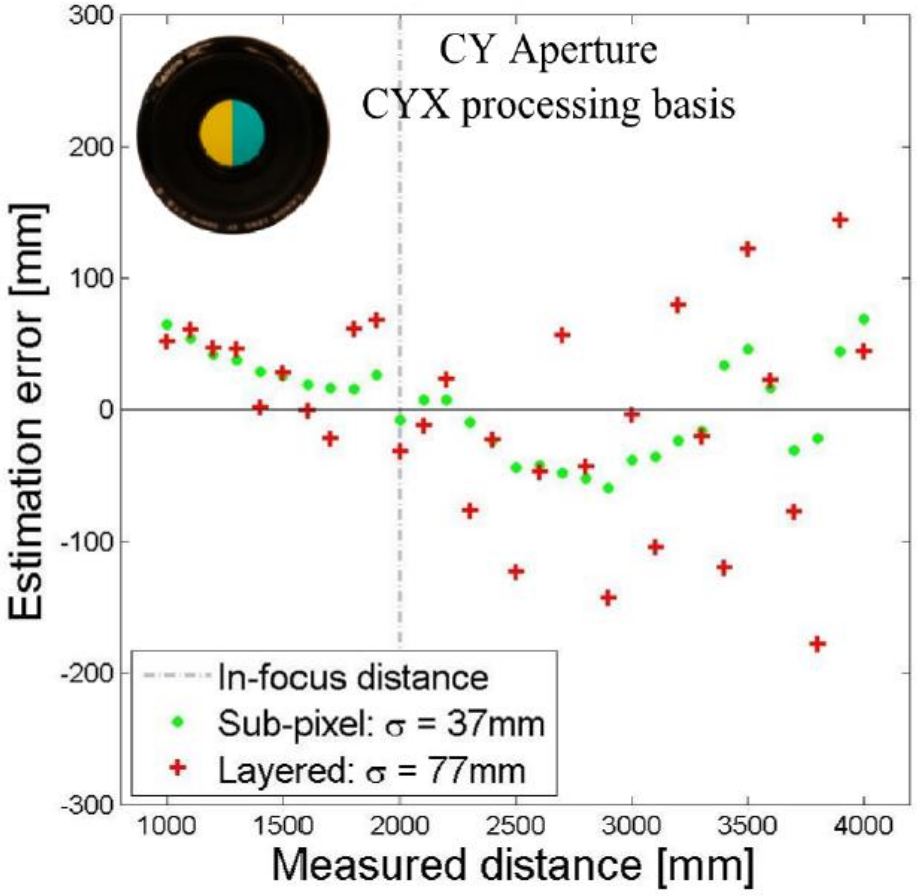
Thank You!

SAMSUNG





SAMSUNG



SAMSUNG

				
central area	0.0	0.9	2.3	14.3
border area	1.5	2.3	3.2	15

SAMSUNG