



Pixel  
Organisation

T. Maugey

Pixel organisation  
problem

360 images

Light fields

Reference

# Master SIF - REP (Part 2)

## Pixel Organisation and Representation

Thomas Maugey  
[thomas.maugey@inria.fr](mailto:thomas.maugey@inria.fr)



*Inria*

Fall 2023



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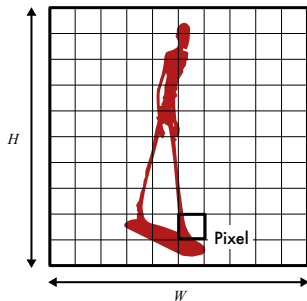
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# Pixels

First pixels in 1965, when the "digital world" moved from a representation of images by lines to an array of *picture elements* called **pixels**.



Aspect ratio =  $W/H$  (4/3, 16/9,...)

Resolution =  $W \times H$

Density (Pixel per Inch, PPI) =  $\frac{\sqrt{W^2+H^2}}{d}$  (where  $d$  is the screen diagonal in "inches")



# Image resolution: $W \times H$

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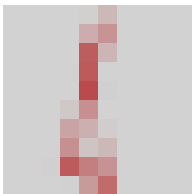
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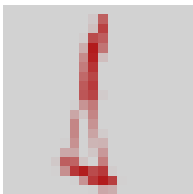
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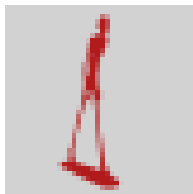
Reference



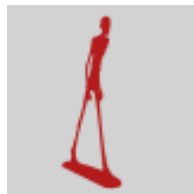
$10 \times 10$



$20 \times 20$



$40 \times 40$



$80 \times 80$



$160 \times 160$



$320 \times 320$



$640 \times 640$



$1280 \times 1280$



# Standard AR and Resolutions

Pixel Organisation

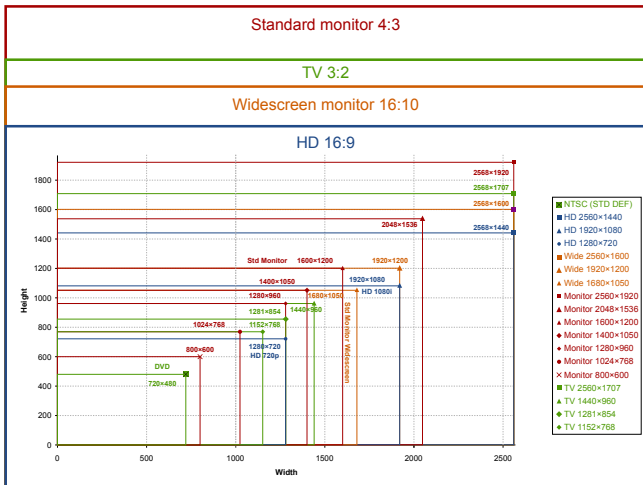
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3840 × 2160 (4K UHDTV), 4096 × 2160 (4K Cinema), 7680 × 4320 (8K UHDTV), 15360 × 8640 (16K Cinema), 61440 × 34560 (64K Cinema)



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# Is matrix organisation always meaningful?

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## Example of omnidirectional capture



How to represent accurately this image?





# Equirectangular representation

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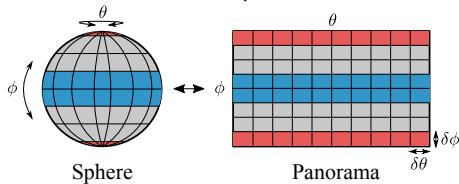
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## Equirectangular or Panorama description



- Most popular
- Suitable for image processing applications

But

- Radial distortions





# Cubemap representation

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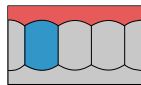
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Sphere



Cube



Cube's faces on the panorama



# Cubemap representation

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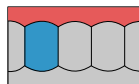
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Cube



Cube's faces on the panorama





# Cubemap representation

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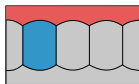
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Cube



Cube's faces on the panorama



- Used by Facebook
- No radial distortion

[Facebook, "Under the hood: building 360 video."  
<https://code.facebook.com/posts/1638767863078802/under-the-hood-building-360-video/>]



# Cubemap representation

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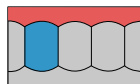
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Cube



Cube's faces on the panorama



- Used by Facebook
- No radial distortion

But

- Lose some connexion informations

[Facebook, "Under the hood: building 360 video."  
<https://code.facebook.com/posts/1638767863078802/under-the-hood-building-360-video/>]



# Pyramidal representation

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Pyramid

Storage of several pyramidal representations corresponding to different directions on the server

[<https://code.fb.com/virtual-reality/next-generation-video-encoding-techniques-for-360-video-and-vr/>]



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Pyramid



Storage of several pyramidal representations corresponding to different directions on the server

[<https://code.fb.com/virtual-reality/next-generation-video-encoding-techniques-for-360-video-and-vr/>]



# Pyramidal representation

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Pyramid



Storage of several pyramidal representations corresponding to different directions on the server

[<https://code.fb.com/virtual-reality/next-generation-video-encoding-techniques-for-360-video-and-vr/>]





# Uniform sampling

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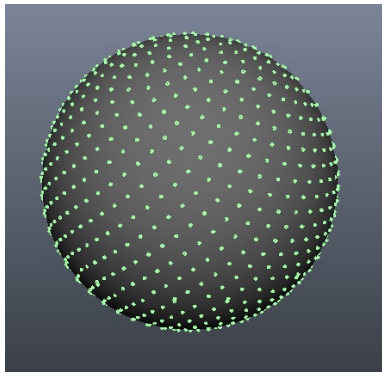
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- Equidistant point
- Connectivity preserved

But

- Not a 2D image anymore



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# Lens

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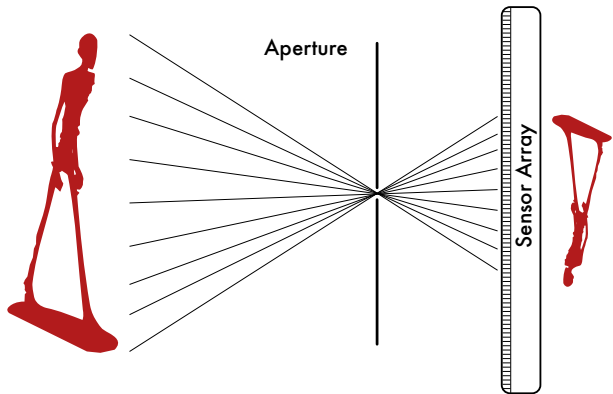
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Aperture does not capture enough light





# Lens

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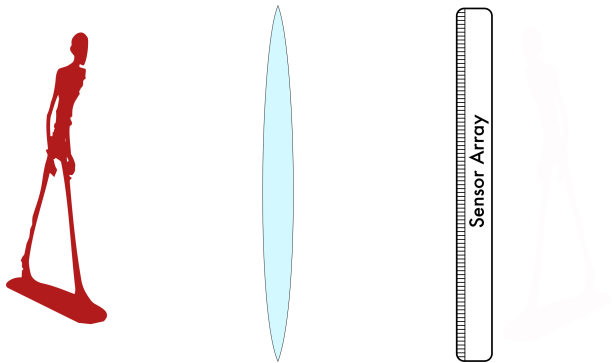
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Aperture is then replaced by a lens





# Lens

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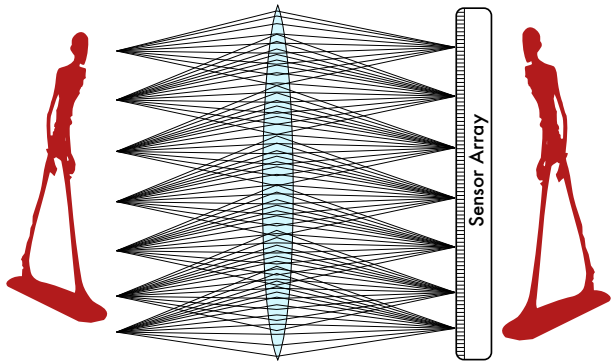
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The lens deviates the light rays





# Lens

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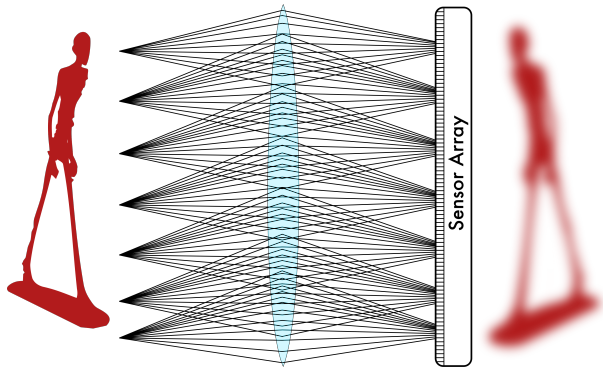
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The rays do not converge to one point, blur appears





# Focus

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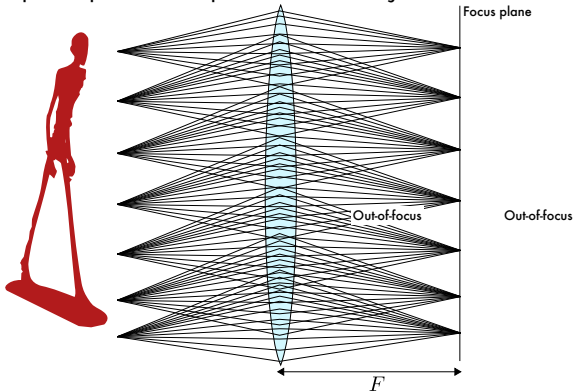
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The focus plane position depends on the object distance.



All the objects whose focus plane is placed at the sensor plane will be **in-focus**, all the other ones are **out-of-focus**



# Examples

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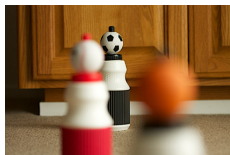
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# Light field

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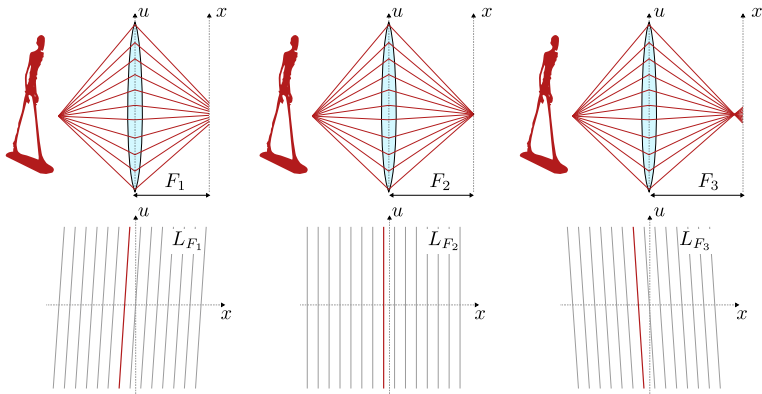
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The light field is parametrized with the two plane coordinates  $(u, v)$  and  $(x, y)$ . It is called  $L_F(x, y, u, v)$  and depends on  $F$ .





# Light field sensing

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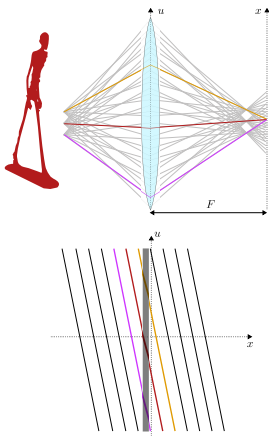
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At the same  $(x, y)$ , there might be several  $L_F(x, y, u, v)$  coming from different  $(u, v)$ .

The value of the light field on the sensor plane at position  $(x, y)$  is equal to

$$E_F^{\text{im}}(x, y) = \frac{1}{F^2} \int_u \int_v L_F(x, y, u, v) dv du$$



# Plenoptic camera

Pixel  
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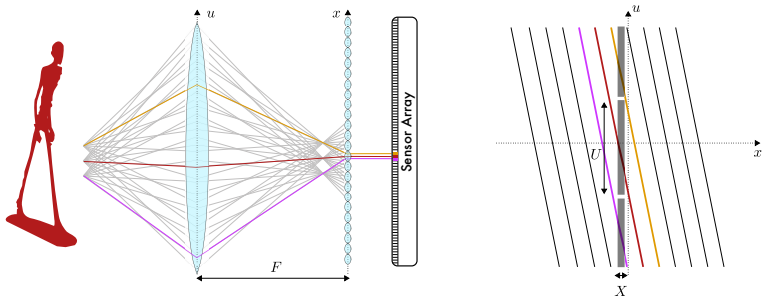
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An array of micro-lenses enables to discriminate the ray directions

$$E_F^{\text{lf}}(x, y, i_u, i_v) = \frac{1}{F^2} \int_{u \in U_{i_u}} \int_{v \in V_{i_v}} L_F(x, y, u, v) dv du$$

In practice,  $(x, y)$  are discretized as well

$$E_F^{\text{lf}}(i_x, i_y, i_u, i_v) = \frac{1}{F^2} \int_{x \in X_{i_x}} \int_{y \in Y_{i_y}} \int_{u \in U_{i_u}} \int_{v \in V_{i_v}} L_F(x, y, u, v) dv du dy dx$$

Often, the indexes are removed and the recorded light field is denoted by  $E_F^{\text{lf}}(x, y, u, v)$ , where  $(x, y, u, v)$  become indices.



# LF capture

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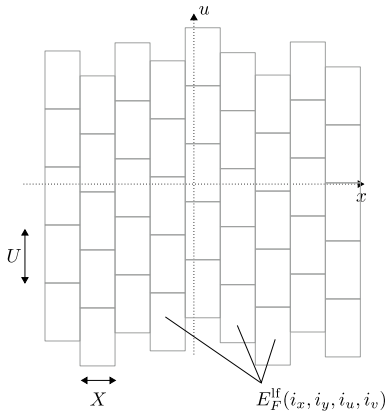
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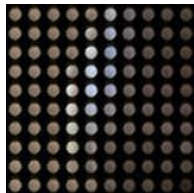
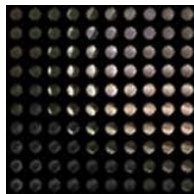
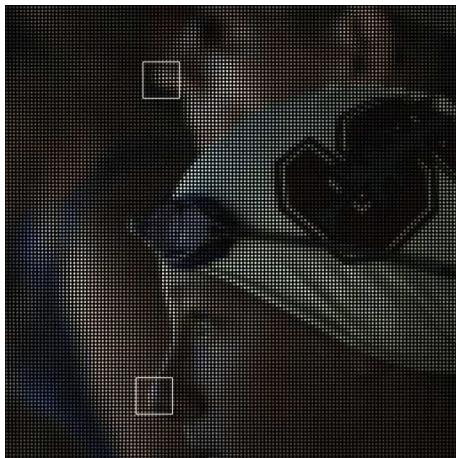
The light field recorded with a distance  $F$  looks like:





# Raw Light field

The pixel array  $E_F(i_x, i_y, i_u, i_v)$  can be represented as it is recorded

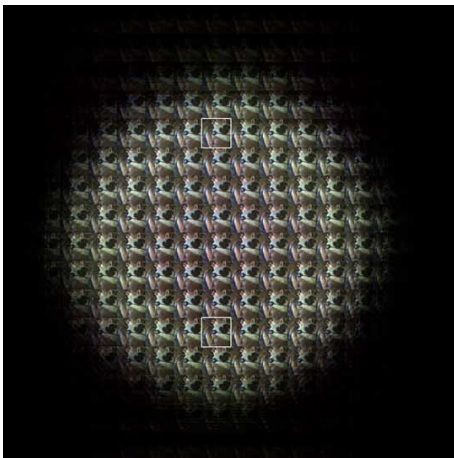


$$(i_x, i_y), (i_u, i_v)$$



# Sub-aperture images

The pixel array  $E_F^{lf}(i_x, i_y, i_u, i_v)$  can be represented by orientations



$$(i_u, i_v), (i_x, i_y)$$



# Epipolar images

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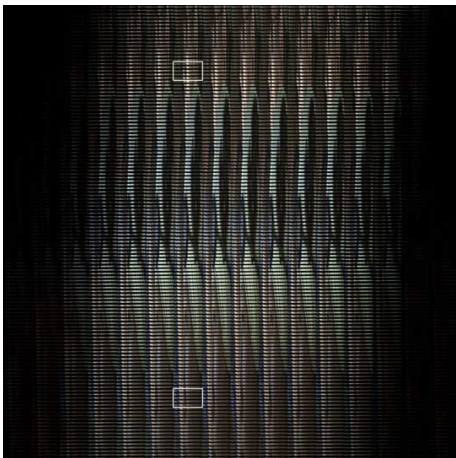
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The pixel array  $E_F^{lf}(i_x, i_y, i_u, i_v)$  can be represented row-by-row



$$(i_x, i_u), (i_y, i_v)$$



# Digital refocusing

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The digital refocusing consists in synthesizing images  $E_{F'}^{\text{im}}$  with the desired focus  $F'$  from a single light field record  $E_F^{\text{lf}}$ .

The generated image is equal to

$$E_{F'}^{\text{im}}(x', y') =$$





# Digital refocusing

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The digital refocusing consists in synthesizing images  $E_{F'}^{\text{im}}$  with the desired focus  $F'$  from a single light field record  $E_F^{\text{lf}}$ .

The generated image is equal to

$$E_{F'}^{\text{im}}(x', y') = \frac{1}{F'^2} \int_u \int_v L_{F'}(x', y', u, v) du dv dx' dy'$$



# Light field's property

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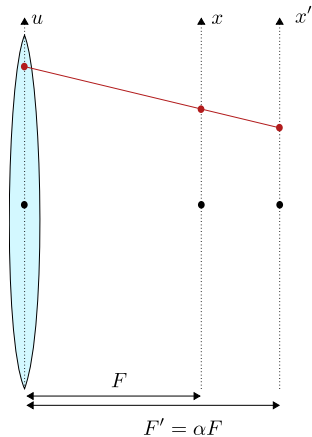
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With a new distance  $F' = \alpha F$

$L_{F'}(x', y', u, v)$  is equal to the value of light field  $L_F$  at position:

$$x =$$

$$y =$$

The acquired image is thus:



# Light field's property

Pixel  
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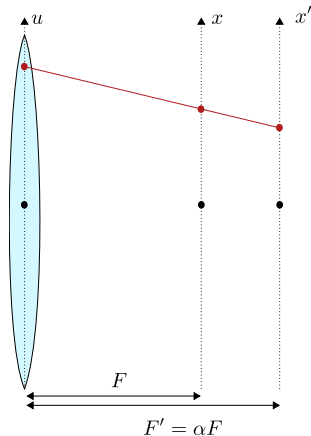
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With a new distance  $F' = \alpha F$

$L_{F'}(x', y', u, v)$  is equal to the value of  
light field  $L_F$  at position:

$$x = u\left(1 - \frac{1}{\alpha}\right) + \frac{x'}{\alpha}$$

$$y = v\left(1 - \frac{1}{\alpha}\right) + \frac{y'}{\alpha}$$

The acquired image is thus:

$$E_{\alpha F}^{\text{im}}(x', y') = \frac{1}{\alpha^2 F^2} \int_u \int_v L_F \left( u\left(1 - \frac{1}{\alpha}\right) + \frac{x'}{\alpha}, v\left(1 - \frac{1}{\alpha}\right) + \frac{y'}{\alpha}, u, v \right) dv du$$



# Digital refocusing

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The generated image is equal to

$$E_{\alpha F}^{\text{im}}(i_{x'}, i_{y'}) = \frac{1}{\alpha^2 F^2} \int_{x' \in X_{i_{x'}}} \int_{y' \in Y_{i_{y'}}} \int_u \int_v L_{F'}(x', y', u, v) du dv dx' dy'$$

Using previous relation between  $L_F$  and  $L_{\alpha F}$ :

$$E_{\alpha F}^{\text{im}}(i_{x'}, i_{y'}) = \frac{1}{\alpha^2 F^2} \int \int \int \int L_F \left( u \left(1 - \frac{1}{\alpha}\right) + \frac{x'}{\alpha}, v \left(1 - \frac{1}{\alpha}\right) + \frac{y'}{\alpha}, u, v \right) du dv dx' dy'$$

We can write (with  $\iota(\cdot)$  equal to the round operation):

$$E_{\alpha F}^{\text{im}}(i_{x'}, i_{y'}) \approx \frac{1}{\alpha^2 F^2} \sum_{i_{x'}} \sum_{i_{y'}} \sum_{i_u} \sum_{i_v} E_F^{\text{lf}} \left( \iota(i_u (1 - \frac{1}{\alpha}) + \frac{i_{x'}}{\alpha}), \iota(i_v (1 - \frac{1}{\alpha}) + \frac{i_{y'}}{\alpha}), i_u, i_v \right)$$



# Digital refocusing

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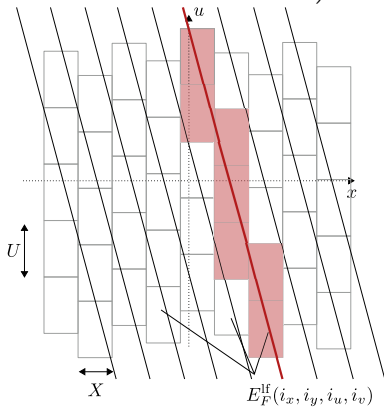
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It comes down to summing along the rays of equations

$$\left( \iota(i_u(1 - \frac{1}{\alpha}) + \frac{i_{x'}}{\alpha}), \iota(i_v(1 - \frac{1}{\alpha}) + \frac{i_{y'}}{\alpha}), i_u, i_v \right)$$



Or simply shifting and summing the sub-aperture images



# Examples

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# Depth Estimation

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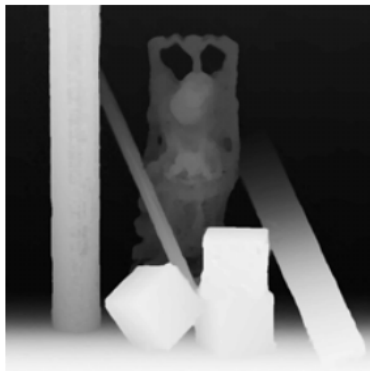
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← Epipolar plane image

[Wanner, S., Goldluecke, B. (2012, June). Globally consistent depth labeling of 4D light fields. In 2012 IEEE Conference on Computer Vision and Pattern Recognition (pp. 41-48). IEEE.]



# Structure Tensor

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Let  $I(\mathbf{p})$  be an image realization at a pixel position  $\mathbf{p}$ .

Let  $\nabla I_x(\mathbf{p})$  and  $\nabla I_y(\mathbf{p})$  be the horizontal and vertical gradients respectively.

We define the tensor structure at position  $\mathbf{p}$  as

$$\mathbf{J}(\mathbf{p}) = \mathbb{E}_{w, \mathbf{p}} \left( [\nabla I_x(\mathbf{r}), \nabla I_y(\mathbf{r})]^\top [\nabla I_x(\mathbf{r}), \nabla I_y(\mathbf{r})] \right)$$

which gives

$$\mathbf{J}(\mathbf{p}) = \begin{pmatrix} \sum_{\mathbf{r}} w(\mathbf{r}) \nabla I_x(\mathbf{p} - \mathbf{r})^2 & \sum_{\mathbf{r}} w(\mathbf{r}) \nabla I_x(\mathbf{p} - \mathbf{r}) \nabla I_y(\mathbf{p} - \mathbf{r}) \\ \sum_{\mathbf{r}} w(\mathbf{r}) \nabla I_x(\mathbf{p} - \mathbf{r}) \nabla I_y(\mathbf{p} - \mathbf{r}) & \sum_{\mathbf{r}} w(\mathbf{r}) \nabla I_y(\mathbf{p} - \mathbf{r})^2 \end{pmatrix}$$

if  $w$  comes from  $G_\sigma$ , a Gaussian kernel centered around  $\mathbf{p}$ , we have

$$\mathbf{J}(\mathbf{p}) = \begin{pmatrix} (G_\sigma * \nabla I_x^2)(\mathbf{p}) & (G_\sigma * \nabla I_x \nabla I_y)(\mathbf{p}) \\ (G_\sigma * \nabla I_x \nabla I_y)(\mathbf{p}) & (G_\sigma * \nabla I_y^2)(\mathbf{p}) \end{pmatrix}$$





# Structure Tensor

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## Tensor's structure property:

The orientation  $\mathbf{n}$  is the solution of the following equation:

$$\mathbf{J}(\mathbf{p})\mathbf{n} = \lambda\mathbf{n}$$

So the eigenvectors of  $\mathbf{J}(\mathbf{p})$  are the major orientation at position  $\mathbf{p}$  and their corresponding energy is given by the eigenvalues  $\lambda_1$  and  $\lambda_2$  (with  $\lambda_1 > \lambda_2$ ).

The major orientation ( $\lambda_1$ ) is given by the first eigenvector

$$\mathbf{n} = \begin{pmatrix} J_{2,2}(\mathbf{p}) - J_{1,1}(\mathbf{p}) \\ 2J_{1,2}(\mathbf{p}) \end{pmatrix}$$

with a level of confidence equal to

$$C = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2} = \frac{(J_{2,2}(\mathbf{p}) - J_{1,1}(\mathbf{p}))^2 + 4J_{1,2}^2}{(J_{1,1}(\mathbf{p}) + J_{2,2}(\mathbf{p}))^2}$$

[Bigun, J. (1987). Optimal orientation detection of linear symmetry.]



# Depth Estimation

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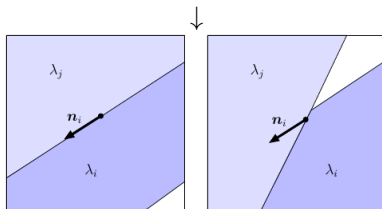
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(a) Allowed

(b) Forbidden





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- C. Grunheit, A. Smolic, and T. Wiegand, "Efficient representation and interactive streaming of high-resolution panoramic views," in International Conference on Image Processing, vol. 3, 2002, pp. 209–212.
- M. Yu, H. Lakshman, and B. Girod, "Content adaptive representations of omnidirectional videos for cinematic virtual reality," in 3rd International Workshop on Immersive Media Experiences. ACM, 2015, p. 16.
- Ren, N. G. (2006). Digital light field photography. Ph. D. thesis Stanford University.
- <http://clim.inria.fr/>