Light Field Processing Using Low-Complexity Multi-Dimensional Linear Filters

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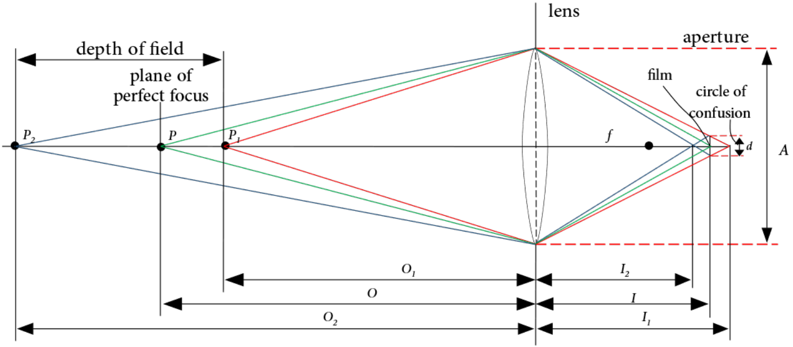
Outline

Introduction

- Let us begin the journey with what we already know:
  - Images (2-D spatial signals)
  - Videos (3-D spatio-temporal signals).

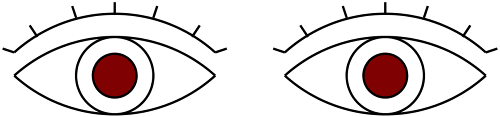
Introduction

- An image provides
  - a projection of a scene in 3-D space
  - only positional information of a light ray.



Introduction

- Let us consider the human visual system.



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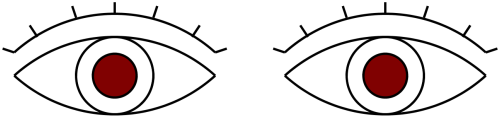
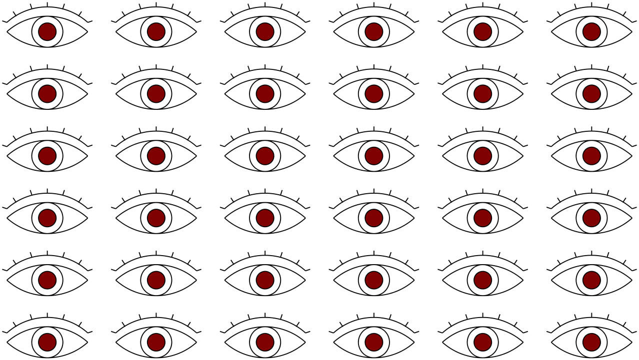


- Human visual system
  - consists of two eyes (cameras)
  - provides both positional and directional information of light rays
  - perceive geometric information, e.g., depth
  - is in fact a 4-D light field video (LFV) system.

Introduction

- What happens if we have a few tens of eyes?



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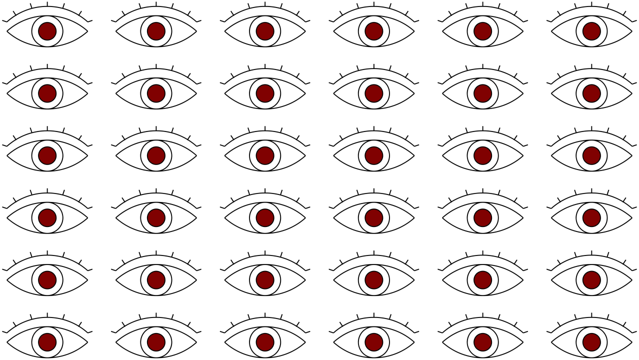

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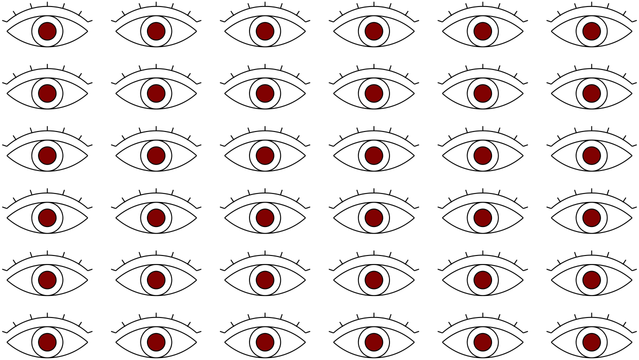
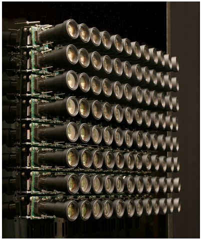


- More information leading to novel tasks (perhaps better than human visual system), e.g., depth filtering
- A 4-D light field (LF)/5-D light field video may be considered as images/videos captured with multiple cameras.

Introduction

- Example LF cameras



(a)

(b)

(c)

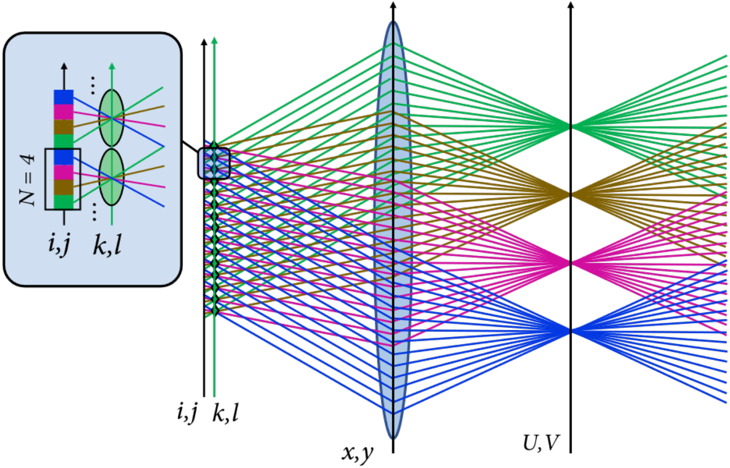
(d)

(e)

Figures: (a) Stanford camera array (Source - http://graphics.stanford.edu/); (b) a light field; (c) a Lytro Illum LF camera (Source - https://www.lytro.com/illum/); (d) a Raytrix LFV camera (Source - http://www.raytrix.de/) (e) Pelican Imaging LF camera (Source - http://lightfield-forum.com).

Introduction

- Internal structure of an LF camera



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- Is an LF/LFV the ultimate description of a scene we can have?

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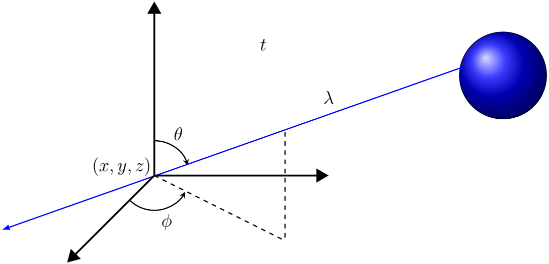
NO

Introduction

- The 7-D plenoptic (*plenus*+*optic*) function [AB91] completely describes the intensity of light rays emanating from a scene
  - at every possible location in the 3-D space (x, y, z)
  - at every possible angle (θ, ϕ)
  - for every wavelength λ
  - at every time t.



[AB91] E. H. Adelson and J. R. Bergen, "The plenoptic function and the elements of early vision," in Computation Models of Visual Processing, M. Landy and J. A. Movshon, Eds. Cambridge, MA: MIT Press, 1991, pp. 3–20.

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- A 4-D LF is a simplified form of the 7-D plenoptic function derived by [ZC04] assuming
  - the intensity of a light ray does not change along its direction of propagation
  - RGB colour components are used instead of the wavelength.
  - the scene is static, so the time dimension can be dropped.

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- For a 5-D LFV, we emloy only the first two assumptions [ZC04].
- 2-D images and 3-D videos are also lower-dimensional forms of the 7-D plenoptic function derived additionally assuming that the viewer has a fixed position [ZC04].

[ZC04] C. Zhang and T. Chen, "A survey on image-based rendering—representation, sampling and compression," Signal Process.: Image Commun., vol. 19, no. 1, pp. 1–28, Jan. 2004.

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Modeling of an LF in the 4-D Space-Angular Domain

- A LF can be parametirized using
  - two-planes (most popular)
  - two spheres
  - a plane and a sphere.

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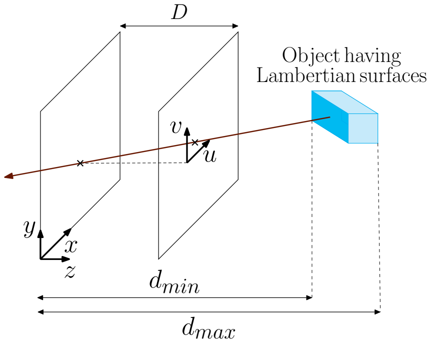
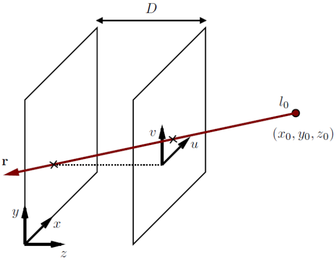
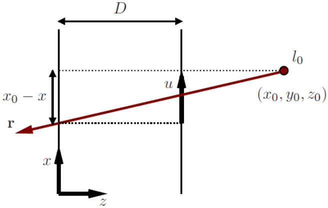
  - a plane and a sphere.
- We employ the two-plane parameterization, where (x, y) is the camera plane and (u, v) is the image plane.



Modeling of an LF in the 4-D Space-Angular Domain Contd.

- We first consider the modeling of a Lambertian point source.



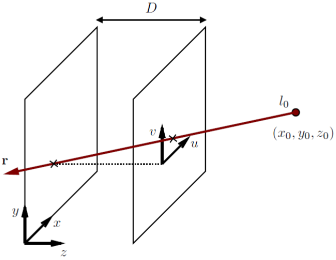


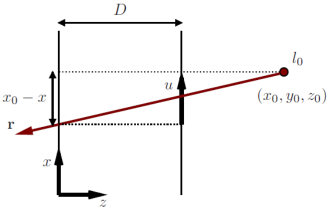
$$mx + u + c_x = 0$$
$$my + v + c_y = 0$$

$$m = \frac{D}{z_0}, c_x = \frac{-Dx_0}{z_0}, c_y = \frac{-Dy_0}{z_0}$$

Modeling of an LF in the 4-D Space-Angular Domain Contd.

- We first consider the modeling of a Lambertian point source.





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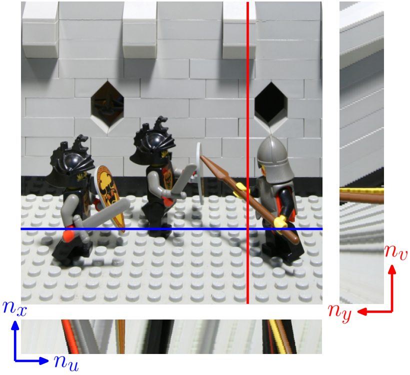
$$m = \frac{D}{z_0}, c_x = \frac{-Dx_0}{z_0}, c_y = \frac{-Dy_0}{z_0}$$

$$l_p^c(x, y, u, v) = l_0 \delta(mx + u + c_x)\delta(my + v + c_y)$$

$$l_p(n_x, n_y, n_u, n_v) = l_0 \delta(mn_x\Delta x + n_u \Delta u + c_x)\delta(mn_y \Delta y + n_v \Delta v + c_y)$$

Modeling of an LF in the 4-D Space-Angular Domain Contd.

- An object located at a constant depth is represented as a plane in 4-D space.
- The orientation of the plane depends on the depth.



A sub-aperture image (SAI) of the "Kinghts" LF of the Stanford dataset and epipolar plane (EPI) representations.

Spectral Representation of LFs

- Now let us move to the spectral representation of LFs.
- First, we will have a review on 1-D and M-D discrete-space Fourier transform.

Definition of the 1-D discrete-time Fourier transform

$$X(e^{j\omega}) = \sum_{n=-\infty}^{\infty} x(n)e^{-j\omega n}$$

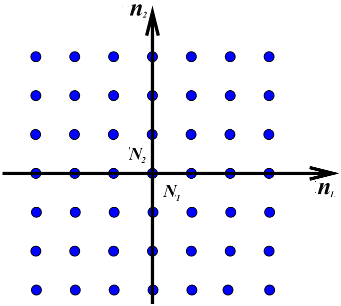
$$x[n] = \frac{1}{2\pi}\int_{-\pi}^{\pi} X(e^{j\omega})e^{j\omega n}\mathrm{d}\omega$$

Spectral Representation of LFs Contd.

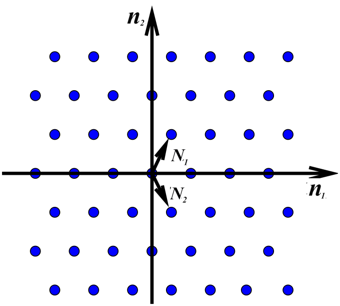
- M-D signals are substantially different from 1-D counterparts in a few ways.

Spectral Representation of LFs Contd.

- M-D signals are substantially different from 1-D counterparts in a few ways.
- For example, different sampling patterns can be employed [DM84], [W06].



Rectangular



Hexagonal

[DM84] D. E. Dudgeon and R. M. Mersereau, Multidimensional Digital Signal Processing, Englewood Cliffs, NJ, Prentice-Hall, 1984.
[W06] J. W. Woods, Multidimensional Signal, Image, and Video Processing and Coding. NY, Academic Press, 2006.

Spectral Representation of LFs Contd.

- Definition of the 2-D discrete-space Fourier transform: Rectangular sampling [DM84], [W06]

$$X(e^{j\omega_1}, e^{j\omega_2}) = \sum_{n_1=-\infty}^{\infty} \sum_{n_2=-\infty}^{\infty} x(n_1, n_2) e^{-j(\omega_1 n_1 + \omega_2 n_2)}$$

$$x(n_1, n_2) = \frac{1}{4\pi^2} \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} X(e^{j\omega_1}, e^{j\omega_2}) e^{j(\omega_1 n_1 + \omega_2 n_2)} \mathrm{d}\omega_1 \mathrm{d}\omega_2$$

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Spectral Representation of LFs Contd.

- Note that a Lambertian point source is modeled as

$$l_p(n_x, n_y, n_u, n_v) = l_0\delta(mn_x\Delta x + n_u\Delta u + c_x)\delta(mn_y\Delta y + n_v\Delta v + c_y),$$

where

$$m = \frac{D}{z_0}, c_x = \frac{-Dx_0}{z_0}, c_y = \frac{-Dy_0}{z_0}.$$

[CTC00] J.-X. Chai, X. Tong, S.-C. Chan, and H.-Y. Shum, "Plenoptic sampling," in Proc. Annu. Conf. Comput. Graph. (SIGGRAPH), 2000, pp. 307–318.

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where

$$m = \frac{D}{z_0}, c_x = \frac{-Dx_0}{z_0}, c_y = \frac{-Dy_0}{z_0}.$$

- The spectrum $L_p(\omega_x, \omega_y, \omega_u, \omega_v)$ of $l(n_x, n_y, n_u, n_v)$ can be obtained as [CT00, DB07]

$$L_p(\omega_x, \omega_y, \omega_u, \omega_v) = 4\pi^2 l_0\delta\left[\omega_x - \left(\frac{m\Delta x}{\Delta u}\right)\omega_u\right] \times \delta\left[\omega_y - \left(\frac{m\Delta y}{\Delta v}\right)\omega_v\right] e^{j(\omega_u c_x + \omega_v c_y)}.$$

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Spectral Representation of LFs Contd.

- The region of support (ROS) $\mathcal{R}_p$ of the spectrum $L(\omega_x, \omega_y, \omega_u, \omega_v)$ inside the Nyquist hypercube $\mathcal{N}$ is given by [CT00, DB07]

$$\mathcal{R}_p = \mathcal{H}_{xu} \cap \mathcal{H}_{yv},$$

where

$$\mathcal{H}_{xu} = \left\{ (\omega_x, \omega_y, \omega_u, \omega_v) \in \mathcal{N} \,\middle|\, \omega_x - \left(\frac{m\Delta x}{\Delta u} \right) \omega_u = 0 \right\}$$

$$\mathcal{H}_{yv} = \left\{ (\omega_x, \omega_y, \omega_u, \omega_v) \in \mathcal{N} \,\middle|\, \omega_y - \left(\frac{m\Delta y}{\Delta v} \right) \omega_u = 0 \right\}.$$

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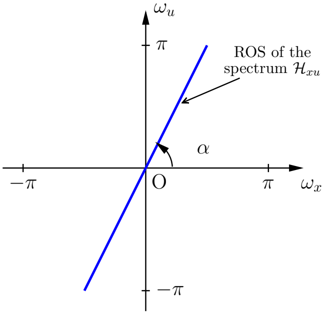

$$\alpha = \tan^{-1}\left(\frac{\Delta}{m}\right) = \tan^{-1}\left(\frac{z_0\Delta}{D}\right),$$

where $\Delta = \frac{\Delta u}{\Delta x} = \frac{\Delta v}{\Delta y}$.

- Note that α varies from 0° to 90° when depth z_0 varies from 0 to ∞.

Spectral Representation of LFs Contd.

- A Lambertian object can be modeled as a compact collection of Lambertian point sources located at a depth range $z_0 \in [z_{min}, z_{max}]$.

$$l_o(n_x, n_y, n_u, n_v) = \sum_{z_0} l_p(n_x, n_y, n_u, n_v).$$

[CTC00] J.-X. Chai, X. Tong, S.-C. Chan, and H.-Y. Shum, "Plenoptic sampling," in Proc. Annu. Conf. Comput. Graph. (SIGGRAPH), 2000, pp. 307–318.

[DB07] D. Dansereau and L. T. Bruton, "A 4-D dual-fan filter bank for depth filtering in light fields," IEEE Trans. Signal Process., vol. 55, no. 2, pp. 542–549, Feb. 2007.

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- In this case, the spectral ROS $\mathcal{R}_o$ inside the Nyquist hypercube $\mathcal{N}$ is given by [CT00, DB07]

$$\mathcal{R}_o = \bigcup_{z_0} \mathcal{R}_p = \bigcup_{z_0} (\mathcal{H}_{xu} \cap \mathcal{H}_{yv})$$

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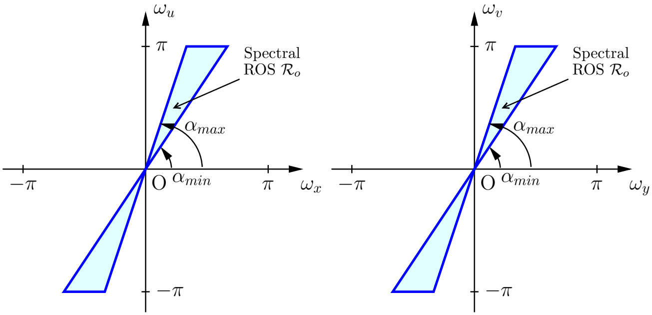
- The spectral ROS $\mathcal{R}_o$ is a hyperfan inside $\mathcal{N}$ [DP15].



$$\alpha_{min} = \tan^{-1}\left(\frac{z_{min}\Delta}{D}\right)$$

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[DP15] D. G. Dansereau, O. Pizarro, and S. B. Williams, "Linear volumetric focus for light field cameras," ACM Trans. Graph., vol. 34, no. 2, pp.15:1–15:20, Feb. 2015.

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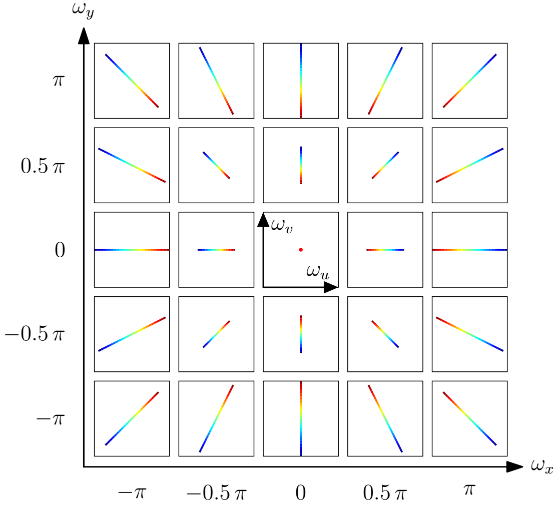

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- Note that the spectral ROS of a Lambertian object is given by

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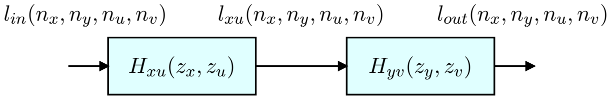
- We design the filter as a cascade of two filters exploiting the partial separability.



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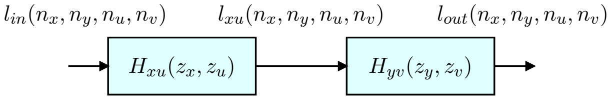


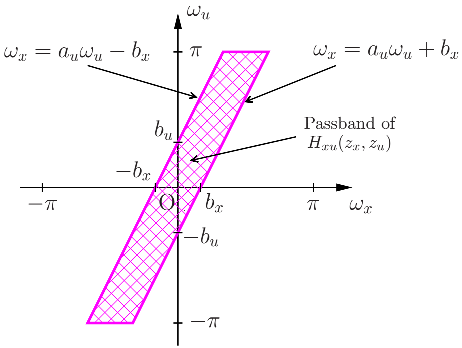
- This structure leads to lower computational complexity:
  - partially separable - $O(N_x N_u + N_y N_v)$
  - nonseparable - $O(N_x N_y N_u N_v)$,

  where (N_x, N_u) $(\in \mathbb{Z}_+^2)$ and (N_y, N_v) $(\in \mathbb{Z}_+^2)$ are the orders of $H_{xu}(z_x, z_u)$ and $H_{yv}(z_y, z_v)$, respectively.

Design of M-D FIR Filters Contd.

- The ideal frequency response of $H_{xu}(z_x, z_u)$, inside the principal Nyquist square of $(\omega_x, \omega_u) \in \mathbb{R}^2$, may be expressed as

$$H_{xu}(e^{j\omega_x}, e^{j\omega_u}) = \begin{cases} 1, & a_u\omega_u - b_x \le \omega_x \le a_u\omega_u + b_x \\ 0, & \text{otherwise.} \end{cases}$$

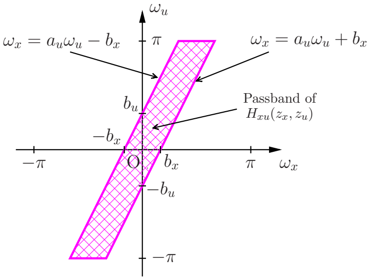


Design of M-D FIR Filters Contd.

- The ideal infinite-extent impulse response $h^I_{xu}(n_x, n_u)$ of $H_{xu}(z_x, z_u)$ can be obtained as

$$h^I_{xu}(n_x, n_u) = \frac{1}{4\pi^2} \iint_{\omega_u,\omega_x=-\pi}^{\pi} H_{xu}(\mathrm{e}^{j\omega_x}, \mathrm{e}^{j\omega_u}) e^{j(\omega_x n_x + \omega_u n_u)}\, \omega_x \omega_u$$

$$= \frac{1}{4\pi^2} \int_{\omega_u=-\pi}^{\pi} \int_{\omega_x=a_u\omega_u-b_x}^{a_u\omega_u+b_x} e^{j(\omega_x n_x + \omega_u n_u)}\, \omega_x \omega_u.$$



Design of M-D FIR Filters Contd.

- After some manipulation, the closed-form expressions for $h^{l}_{xu}(n_x, n_u)$ can be obtained as [EDB15]

$$h^{l}_{xu}(n_x, n_u) = \frac{b_x}{\pi}, \ \ n_x = 0 \ \ \text{and} \ \ n_u = 0$$

$$h^{l}_{xu}(n_x, n_u) = \frac{b_x \sin(n_u \pi)}{n_u \pi^2}, \ \ n_x = 0 \ \ \text{and} \ \ n_u \neq 0$$

$$h^{l}_{xu}(n_x, n_u) = \frac{\sin(b_x n_x)}{n_x \pi}, \ \ n_x \neq 0 \ \ \text{and} \ \ a_u n_x + n_u = 0$$

$$h^{l}_{xu}(n_x, n_u) = \frac{\sin(b_x n_x) \sin[(a_u n_x + n_u)\pi]}{n_x (a_u n_x + n_u)\pi^2}, \quad n_x \neq 0 \ \ \text{and} \ \ a_u n_x + n_u \neq 0.$$

[ED15] C. U. S. Edussooriya, D. G. Dansereau, L. T. Bruton, and P. Agathoklis, “Five-Dimensional Depth-Velocity Filtering for Enhancing Moving Objects in Light Field Videos,” IEEE Transactions on Signal Processing, vol. 63, no. 8, pp. 2151–2163, 2015.

Design of M-D FIR Filters Contd.

- The finite-extent impulse response $h_{xu}(n_x, n_u)$ of $H_{xu}(z_x, z_u)$ (of order $M_x \times M_u$) is obtained as

$$h_{xu}(n_x, n_u) = h^{I}_{xu}(n_x, n_u)\, w(n_x, n_u),$$

where $w(n_x, n_u)$ is a 2-D window function of size $(M_x + 1) \times (M_u + 1)$.

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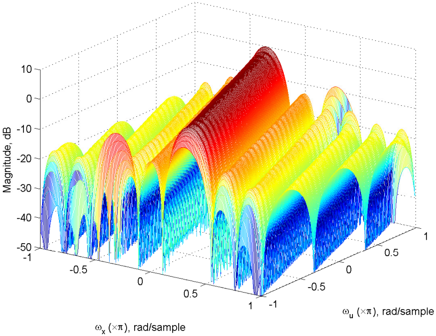
- Magnitude response of $H_{xu}(z_x, z_u)$ of order 8×40 designed with $a_u = 0.33$, $b_x = 0.04$ rad/sample and a 2-D rectangular window.



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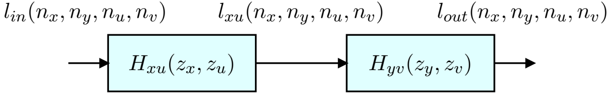

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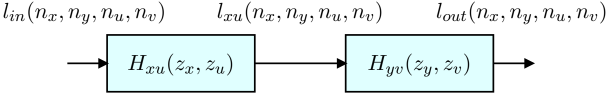
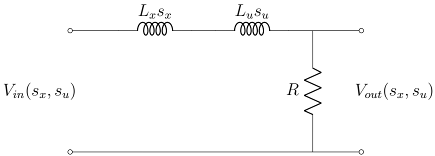


- We consider the first-order 2-D pseudo resistor-inductor network of which the transfer function $H(s_x, s_u)$ can be expressed as [DB04, BB85]

$$H(s_x, s_u) = \frac{V_{out}(s_x, s_u)}{V_{in}(s_x, s_u)} = \frac{R}{R + L_x s_x + L_u s_u}.$$



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- The frequency response of $H(s_x, s_u)$ is

$$H(j\Omega_x, j\Omega_u) = \frac{R}{R + j(L_x\Omega_x + L_y\Omega_u)},$$

where $(\Omega_x, \Omega_u) \in \mathbb{R}^2$ is the 2-D continuous frequency domain.

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  where $(\Omega_x, \Omega_u) \in \mathbb{R}^2$ is the 2-D continuous frequency domain.
- The magnitude response of $H(s_x, s_u)$ is

$$|H(j\Omega_x, j\Omega_u)| = \frac{R}{\left[R^2 + (L_x\Omega_x + L_u\Omega_u)^2\right]^{1/2}}.$$

Design of M-D IIR Filters Contd.

- $|H(j\Omega_x, j\Omega_u)|$ has a maximum value of unity at the resonant plane, given by [BB85]

$$L_x\Omega_x + L_u\Omega_u = 0.$$

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- Furthermore, $|H(j\Omega_x, j\Omega_u)| = 1/\sqrt{2}$ when [BB85]

$$L_x\Omega_x + L_u\Omega_u = \pm R.$$

[BB85] L. T. Bruton and N. R. Bartley, "Three-dimensional image processing using the concept of network resonance," IEEE Trans. Circuits Syst., vol. CAS-32, pp. 664–672, July 1985.

Design of M-D IIR Filters Contd.

- $|H(j\Omega_x, j\Omega_u)|$ has a maximum value of unity at the resonant plane, given by [BB85]

$$L_x\Omega_x + L_u\Omega_u = 0.$$

- Furthermore, $|H(j\Omega_x, j\Omega_u)| = 1/\sqrt{2}$ when [BB85]

$$L_x\Omega_x + L_u\Omega_u = \pm R.$$

- So, the -3 dB bandwidth B of $|H(j\Omega_x, j\Omega_u)|$ is [BB85]

$$B = \frac{R}{(L_x^2 + L_u^2)^{1/2}}.$$

[BB85] L. T. Bruton and N. R. Bartley, "Three-dimensional image processing using the concept of network resonance," IEEE Trans. Circuits Syst., vol. CAS-32, pp. 664–672, July 1985.

Design of M-D IIR Filters Contd.

- We apply bilinear transform

$$s_i = \frac{z_i - 1}{z_i + 1}, \qquad i = x, u.$$

to obtain the 2-D discrete-space filter $H(z_x, z_u)$ as

$$H(z_x, z_u) = \frac{\sum_{i_x=0}^{1} \sum_{i_u=0}^{1} z_x^{-i_x} z_u^{-i_u}}{\sum_{i_x=0}^{1} \sum_{i_u=0}^{1} b_{i_x i_u} z_x^{-i_x} z_u^{-i_u}},$$

which is practically BIBO stable.

[AB83] P. Agathoklis and L. T. Bruton, "Practical-BIBO stability of n-dimensional discrete systems," IEE Proc. G (Electron. Circuits and Syst.), vol. 130, pp. 236–242, Dec. 1983.

Design of M-D IIR Filters Contd.

$$H(z_x, z_u) = \frac{\sum_{i_x=0}^{1} \sum_{i_u=0}^{1} z_x^{-i_x} z_u^{-i_u}}{\sum_{i_x=0}^{1} \sum_{i_u=0}^{1} b_{i_x i_u} z_x^{-i_x} z_u^{-i_u}},$$

- The denominator coefficients are given by [BB85]

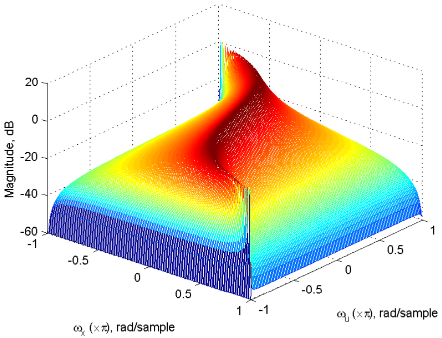
$$b_{i_x i_u} = 1 + \frac{(-1)^{i_x} d_x + (-1)^{i_u} d_u}{B}, \qquad i_x, i_u = 0, 1,$$

where $d_x = \frac{L_x}{(L_x^2 + L_u^2)^{1/2}}$ and $d_u = \frac{L_u}{(L_x^2 + L_u^2)^{1/2}}$.

[BB85] L. T. Bruton and N. R. Bartley, "Three-dimensional image processing using the concept of network resonance," IEEE Trans. Circuits Syst., vol. CAS-32, pp. 664–672, July 1985.

Design of M-D IIR Filters Contd.

- Magnitude response of $H_{xu}(z_x, z_u)$ designed with $d_x = 0.95$, $d_u = 0.32$ and $B = 0.04\pi$ rad/sample.



LF Refocusing using a 4-D Sparse FIR Hyperfan Filter

- Now let us consider the volumetric refocusing of LFs [DP15], [PE18], [SE21].

[DP15] D. G. Dansereau, O. Pizarro, and S. B. Williams, "Linear volumetric focus for light field cameras," ACM Trans. Graph., vol. 34, no. 2, pp.15:1–15:20, Feb. 2015.
[PE18] S. U. Premaratne, C. U. S. Edussooriya, C. Wijenayake, L. T. Bruton, and P. Agathoklis, "A 4-D sparse FIR hyperfan filter for volumetric refocusing of light fields by hard thresholding," in Proc. IEEE Int. Conf. Digital Signal Process., 2018, pp. 1–5.
[SE21] S. S. Jayaweera and C. U. S. Edussooriya and C. Wijenayake and P. Agathoklis and L. T. Bruton, "Multi-Volumetric Refocusing of Light Fields," IEEE Signal Process. Lett., vol.28, pp. 31-35, 2021.

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter

- Now let us consider the volumetric refocusing of LFs [DP15], [PE18], [SE21].
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[SE21] S. S. Jayaweera and C. U. S. Edussooriya and C. Wijenayake and P. Agathoklis and L. T. Bruton, "Multi-Volumetric Refocusing of Light Fields," IEEE Signal Process. Lett., vol.28, pp. 31-35, 2021.

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- We design the 4-D FIR filter in [PE18] using the windowing method [LA92], [DM84], [PJ94].

[DP15] D. G. Dansereau, O. Pizarro, and S. B. Williams, “Linear volumetric focus for light field cameras,” ACM Trans. Graph., vol. 34, no. 2, pp.15:1–15:20, Feb. 2015.

[PE18] S. U. Premaratne, C. U. S. Edussooriya, C. Wijenayake, L. T. Bruton, and P. Agathoklis, “A 4-D sparse FIR hyperfan filter for volumetric refocusing of light fields by hard thresholding,” in Proc. IEEE Int. Conf. Digital Signal Process., 2018, pp. 1–5.

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[LA92] W.-S. Lu and A. Antoniou, Two-Dimensional Digital Filters. NY, Marcel Dekker, 1992.

[DM84] D. E. Dudgeon and R. M. Mersereau, Multidimensional Digital Signal Processing, Englewood Cliffs, NJ, Prentice-Hall, 1984.

[PJ94] S.-C. Pei and S.-B. Jaw, “Two-dimensional general fan-type FIR digital filter design,” Signal Process., vol. 37, no. 2, pp. 265–274, May 1994.

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter

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- We design the 4-D FIR filter in [PE18] using the windowing method [LA92], [DM84], [PJ94].
- Further, we employ the hard thresholding approach to obtain sparse FIR filter [KB03].

[DP15] D. G. Dansereau, O. Pizarro, and S. B. Williams, "Linear volumetric focus for light field cameras," ACM Trans. Graph., vol. 34, no. 2, pp.15:1–15:20, Feb. 2015.

[PE18] S. U. Premaratne, C. U. S. Edussooriya, C. Wijenayake, L. T. Bruton, and P. Agathoklis, "A 4-D sparse FIR hyperfan filter for volumetric refocusing of light fields by hard thresholding," in Proc. IEEE Int. Conf. Digital Signal Process., 2018, pp. 1–5.

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[LA92] W.-S. Lu and A. Antoniou, Two-Dimensional Digital Filters. NY, Marcel Dekker, 1992.

[DM84] D. E. Dudgeon and R. M. Mersereau, Multidimensional Digital Signal Processing, Englewood Cliffs, NJ, Prentice-Hall, 1984.

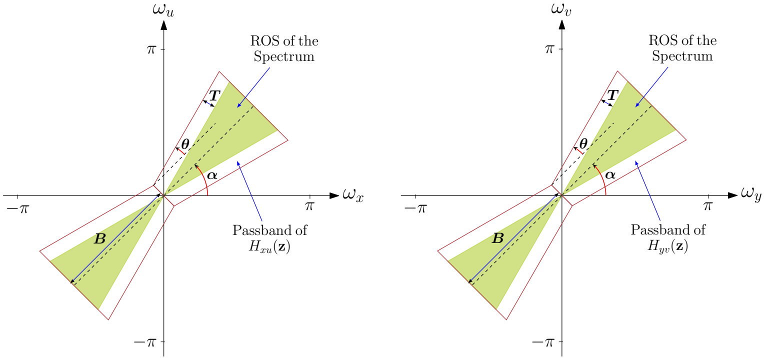
[PJ94] S.-C. Pei and S.-B. Jaw, "Two-dimensional general fan-type FIR digital filter design," Signal Process., vol. 37, no. 2, pp. 265–274, May 1994.

[KB03] L. Khademi and L. T. Bruton, "Reducing the computational complexity of narrowband 2D fan filters using shaped 2D window functions," in Proc. IEEE Int. Symp. Circuits Syst., vol. 3, 2003, pp. III-702–III-705.

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

- The ROS of the passband $\mathcal{R}_{PB}$ ($\supset \mathcal{R}_o$) of the filter is given by

$$\mathcal{R}_{PB} = \Big(\bigcup_{z_0} \mathcal{H}_{xu}\Big) \bigcap \Big(\bigcup_{z_0} \mathcal{H}_{yv}\Big).$$



LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

- Proposed filter is designed using the windowing method [PJ94].

$$h_{xu}(\mathrm{n}) = \left[h^{I}_{xu}(n_x, n_u)\, w_{xu}(n_x, n_u)\right] \delta(n_y)\delta(n_v)$$

$$h_{yv}(\mathrm{n}) = \left[h^{I}_{yv}(n_y, n_v)\, w_{yv}(n_y, n_v)\right] \delta(n_x)\delta(n_u)$$

where, $\mathrm{n} = (n_x, n_y, n_u, n_v) \in \mathbb{Z}^4$.

[PJ94] S.-C. Pei and S.-B. Jaw, "Two-dimensional general fan-type FIR digital filter design," Signal Process., vol. 37, no. 2, pp. 265–274, May 1994.

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

- Proposed filter is designed using the windowing method [PJ94].

$$h_{xu}(\mathrm{n}) = \left[h^{I}_{xu}(n_x, n_u)\, w_{xu}(n_x, n_u)\right] \delta(n_y)\delta(n_v)$$

$$h_{yv}(\mathrm{n}) = \left[h^{I}_{yv}(n_y, n_v)\, w_{yv}(n_y, n_v)\right] \delta(n_x)\delta(n_u)$$

where, $\mathrm{n} = (n_x, n_y, n_u, n_v) \in \mathbb{Z}^4$.

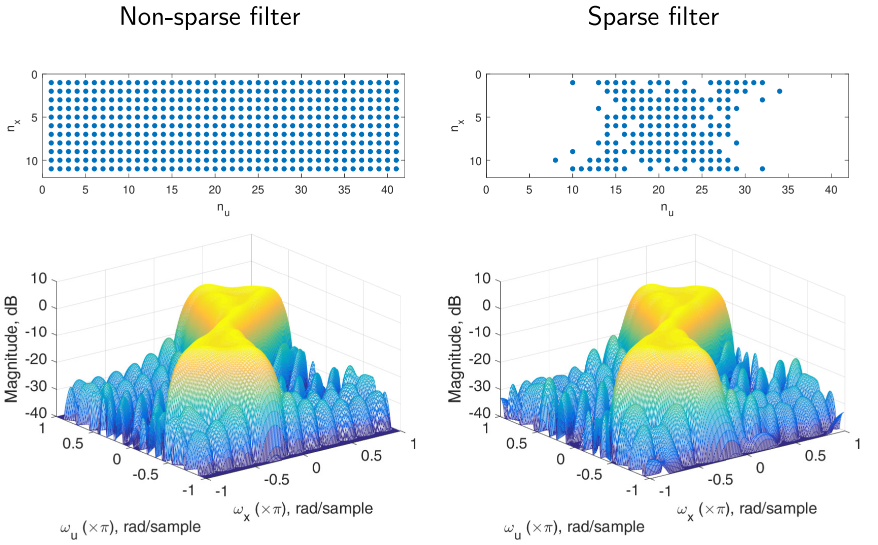
- The sparse coefficients are derived by hard thresholding [KB03].

$$h^{s}_{i}(\mathrm{n}) = \begin{cases} h_i(\mathrm{n}), & \text{if } |h_i(\mathrm{n})| \geq h_{th} \cdot \max |h_i(\mathrm{n})| \\ 0, & \text{otherwise,} \end{cases}$$

where, $i = xu, yv$.

[PJ94] S.-C. Pei and S.-B. Jaw, "Two-dimensional general fan-type FIR digital filter design," Signal Process., vol. 37, no. 2, pp. 265–274, May 1994.
[KB03] L. Khademi and L. T. Bruton, "Reducing the computational complexity of narrowband 2D fan filters using shaped 2D window functions," in Proc. IEEE Int. Symp. Circuits Syst., vol. 3, 2003, pp. III-702–III-705.

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.



$\alpha = 50^\circ$, $\theta = 20^\circ$, $B = 0.9\pi$, $T = 0.08\pi$, filter order$= 10 \times 40$, $h_{th} = 0.01$

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

Filter order - $10 \times 10 \times 40 \times 40$

$\alpha = 50^\circ$, $\theta = 20^\circ$, $B = 0.9\pi$, $T = 0.08\pi$

	Non-sparse filter [DP15]	Sparse filter [PE18]
Multiplications	2712	768
Additions	5400	1512

[DP15] D. G. Dansereau, O. Pizarro, and S. B. Williams, "Linear volumetric focus for light field cameras," ACM Trans. Graph., vol. 34, no. 2, pp.15:1–15:20, Feb. 2015.

[PE18] S. U. Premaratne, C. U. S. Edussooriya, C. Wijenayake, L. T. Bruton, and P. Agathoklis, "A 4-D sparse FIR hyperfan filter for volumetricrefocusing of light fields by hard thresholding," in Proc. IEEE Int. Conf. Digital Signal Process., 2018, pp. 1–5.

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

Filter order - $10 \times 10 \times 40 \times 40$

$\alpha = 50°$, $\theta = 20°$, $B = 0.9\pi$, $T = 0.08\pi$

	Non-sparse filter [DP15]	Sparse filter [PE18]
Multiplications	2712	768
Additions	5400	1512

$h_{th} = 0.005 : 0.005 : 0.05$, $\theta = 5° : 5° : 30°$

	Mean	Standard deviation
Normalized RMSE	1.6%	1.15%
Number of nonzero coeffs.	28.19%	10.39%

[DP15] D. G. Dansereau, O. Pizarro, and S. B. Williams, "Linear volumetric focus for light field cameras," ACM Trans. Graph., vol. 34, no. 2, pp.15:1–15:20, Feb. 2015.

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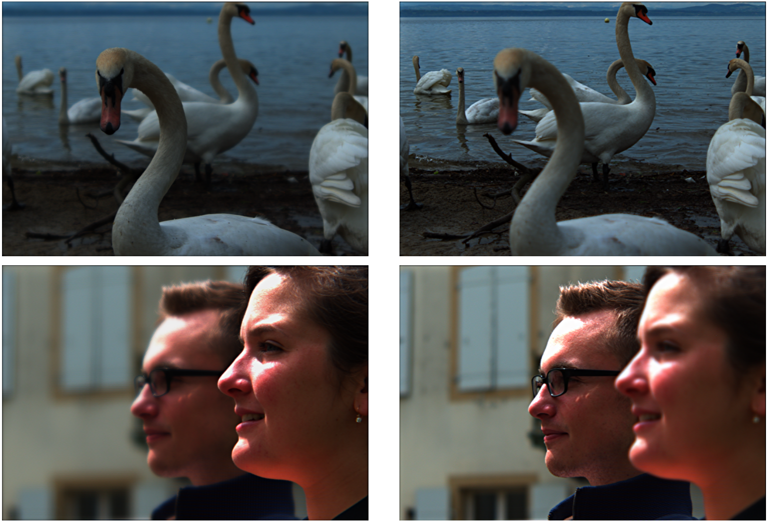
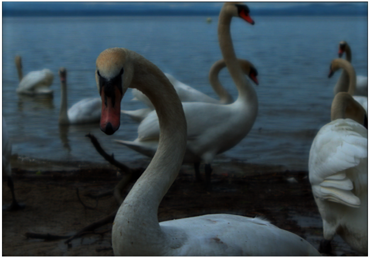
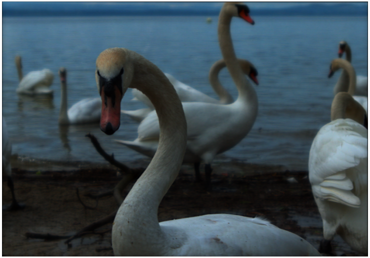
LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

$\alpha = 60^\circ$ $\alpha = 105^\circ$



$\theta = 15^\circ$, filter order $= 10 \times 10 \times 40 \times 40$, $h_{th} = 0.01$

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

Sparse filter	Non-sparse filter	SSIM
		0.9916
		0.9897

$\alpha = 45^\circ, \theta = 35^\circ$, filter order $= 10 \times 10 \times 40 \times 40$, $h_{th} = 0.01$

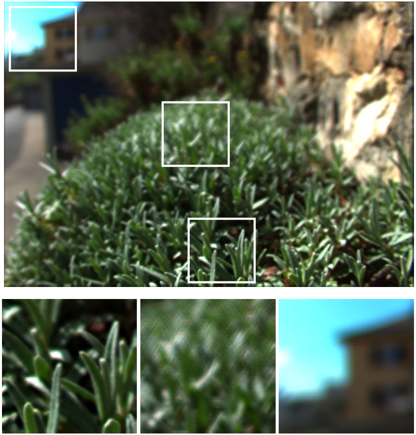
LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.

(a) Planar refocus [NL05]

(b) Volumetric refocus [PE18]

[NL05] R. Ng, M. Levoy, M. Brédif, G. Duval, M. Horowitz, and P. Hanrahan, "Light field photography with a hand-held plenoptic camera," Tech. Rep. CTSR 2005-02, Stanford Univ., Stanford, CA, 2005.
[PE18] S. U. Premaratne, C. U. S. Edussooriya, C. Wijenayake, L. T. Bruton, and P. Agathoklis, "A 4-D sparse FIR hyperfan filter for volumetricrefocusing of light fields by hard thresholding," in Proc. IEEE Int. Conf. Digital Signal Process., 2018, pp. 1–5.

LF Refocusing using a 4-D Sparse FIR Hyperfan Filter Contd.



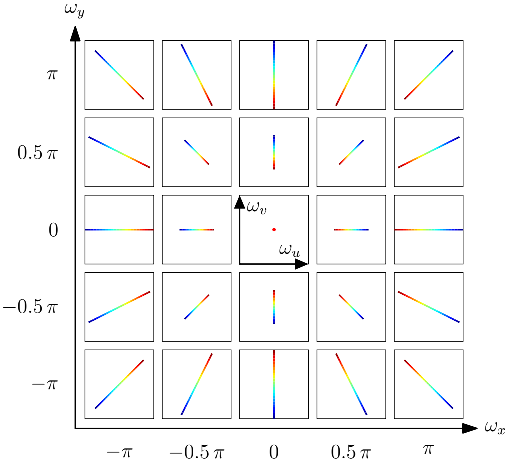
(a) Single volumetric refocus [PE18]

(b) Multi-volumetric refocus [SE21]

[PE18] S. U. Premaratne, C. U. S. Edussooriya, C. Wijenayake, L. T. Bruton, and P. Agathoklis, “A 4-D sparse FIR hyperfan filter for volumetricrefocusing of light fields by hard thresholding,” in Proc. IEEE Int. Conf. Digital Signal Process., 2018, pp. 1–5.
[SE21] S. S. Jayaweera and C. U. S. Edussooriya and C. Wijenayake and P. Agathoklis and L. T. Bruton, “Multi-Volumetric Refocusing of Light Fields,” IEEE Signal Process. Lett., vol.28, pp. 31-35, 2021.

Light Field Denoising Using 4-D Hyperfan Filters

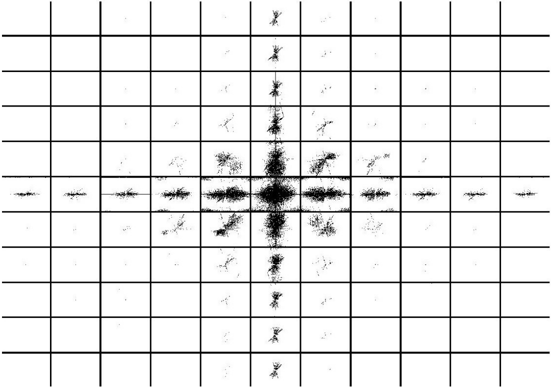
- Recall that the spectral ROS $\mathcal{R}_o$ is a hyperfan inside $\mathcal{N}$ [DP15].



[DP15] D. G. Dansereau, O. Pizarro, and S. B. Williams, "Linear volumetric focus for light field cameras," ACM Trans. Graph., vol. 34, no. 2, pp.15:1–15:20, Feb. 2015.

Light Field Denoising Using 4-D Hyperfan Filters Contd.

- Spectrum of Wheat & Silos LF from the EPFL LF dataset [RE16].

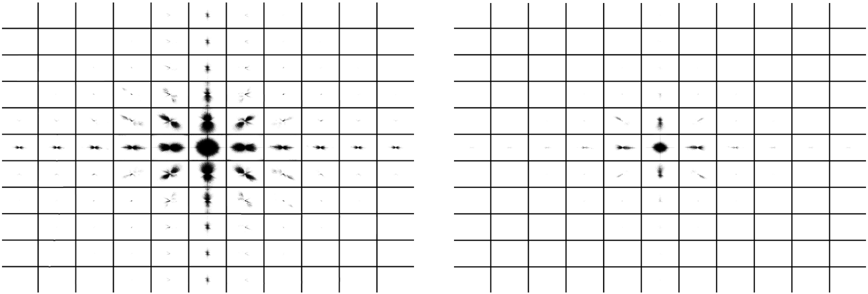


Note - The axes of ω_x, ω_y, ω_u and ω_v are as shown in the figure in the slide 35.

[RE16] M. Rerabek and T. Ebrahimi, "New light field image dataset," in Proc. 8th Int. Conf. Qual. Multimedia Experience, 2016, pp. 1–2. [Online]. Available: http://mmspg.epfl.ch/EPFL-light-field-image-dataset.

Light Field Denoising Using 4-D Hyperfan Filters Contd.

- Spectral Energy of 40 LFs of the EPFL LF dataset [PE20].

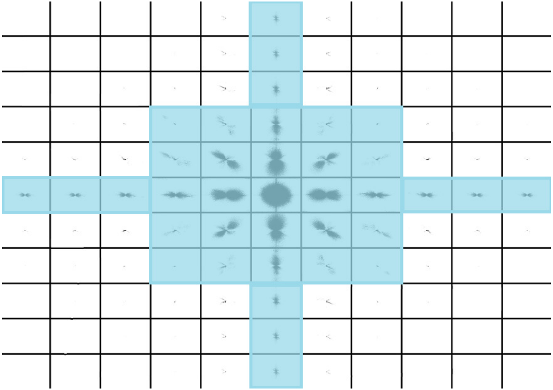


Note - The axes of ω_x, ω_y, ω_u and ω_v are as shown in the figure in the slide 35.

[PE20] S. U. Premaratne, N. Liyanage, C. U. S. Edussooriya, and C. Wijenayake, "Real-time light field denoising using a novel linear 4-D hyperfan filter," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 67, no. 8, pp. 2693–2706, Aug. 2020.

Light Field Denoising Using 4-D Hyperfan Filters Contd.

- Spectral ROS employed for selective filtering with a 4-D hyperfan filter [PE20].



Note - The axes of ω_x, ω_y, ω_u and ω_v are as shown in the figure in the slide 35.

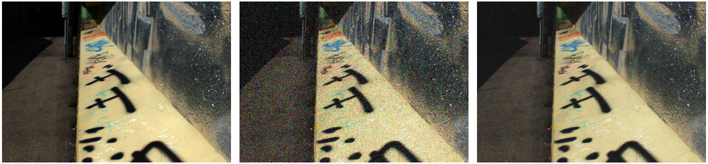
[PE20] S. U. Premaratne, N. Liyanage, C. U. S. Edussooriya, and C. Wijenayake, "Real-time light field denoising using a novel linear 4-D hyperfan filter," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 67, no. 8, pp. 2693–2706, Aug. 2020.

Light Field Denoising Using 4-D Hyperfan Filters Contd.

- Denoisng of Color LFs [PE20].

ground truth | noisy ($\sigma = 0.2$) | denoised

(a) Diplodocus LF (b) 14.74/0.3620 (c) 28.01/0.9129



(d) Graffiti LF (e) 15.11/0.2311 (f) 26.71/0.7654

[PE20] S. U. Premaratne, N. Liyanage, C. U. S. Edussooriya, and C. Wijenayake, "Real-time light field denoising using a novel linear 4-D hyperfan filter," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 67, no. 8, pp. 2693–2706, Aug. 2020.

Light Field Denoising Using 4-D Hyperfan Filters Contd.

- Denoisng of Reeds (top) and Red and White Building (bottom) LFs [PE20].

(a) 14.03/ 0.05 (b) 26.83/ 0.67 (c) 30.08/ 0.69

(d) 13.95/ 0.11 (e) 25.91/ 0.79 (f) 28.19/ 0.74

Noisy LF ($\sigma = 0.2$) FPGA implementation Software implementation

[PE20] S. U. Premaratne, N. Liyanage, C. U. S. Edussooriya, and C. Wijenayake, "Real-time light field denoising using a novel linear 4-D hyperfan filter," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 67, no. 8, pp. 2693–2706, Aug. 2020.

Light Field Denoising Using 4-D Hyperfan Filters Contd.

- Real-time denoisng of LFs: average results for grayscale 10 LFs in the EPFL dataset.

Method	$\sigma = 0.1$			$\sigma = 0.2$			$\sigma = 0.3$		
	PSNR	SSIM	Time	PSNR	SSIM	Time	PSNR	SSIM	Time
Hyperfan [PE20]	31.89	0.8615	3.36	28.38	0.7334	3.33	24.13	0.6174	3.33
Hyperfan [DB13]	29.80	0.7577	10.86	26.83	0.6140	11.07	23.13	0.4688	10.99
Planar [DB04]	30.15	0.8622	10.23	27.33	0.7578	10.37	23.96	0.6498	10.36

[PE20] S. U. Premaratne, N. Liyanage, C. U. S. Edussooriya, and C. Wijenayake, "Real-time light field denoising using a novel linear 4-D hyperfan filter," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 67, no. 8, pp. 2693–2706, Aug. 2020.
[DB13] D. G. Dansereau, D. L. Bongiorno, O. Pizarro, and S. B. Williams, "Light field image denoising using a linear 4D frequency-hyperfan all-in-focus filter," in Proc. SPIE Comput. Imag. XI, vol. 8657, 2013, pp. 86 570P–1–86 570P–14.
[DB04] D. Dansereau and L. Bruton, "A 4D frequency-planar IIR filter and its application to light field processing," in Proc. IEEE Int. Symp. Circuits Syst., vol. 4, 2003, pp. IV–476–IV–479.

Light Field Denoising Using 4-D Hyperfan Filters Contd.

- Real-time denoisng of LFs: average results for grayscale 10 LFs in the EPFL dataset.

Method	$\sigma = 0.1$			$\sigma = 0.2$			$\sigma = 0.3$		
	PSNR	SSIM	Time	PSNR	SSIM	Time	PSNR	SSIM	Time
Hyperfan [PE20]	31.89	0.8615	3.36	28.38	0.7334	3.33	24.13	0.6174	3.33
Hyperfan [DB13]	29.80	0.7577	10.86	26.83	0.6140	11.07	23.13	0.4688	10.99
Planar [DB04]	30.15	0.8622	10.23	27.33	0.7578	10.37	23.96	0.6498	10.36

- Throughput of the FPGA implementation: 25 LFs/s with a Xilinx Vertex-7 FPGA for grayscale LFs of size $11 \times 11 \times 625 \times 434$.

[PE20] S. U. Premaratne, N. Liyanage, C. U. S. Edussooriya, and C. Wijenayake, "Real-time light field denoising using a novel linear 4-D hyperfan filter," IEEE Trans. Circuits Syst. I, Reg. Papers, vol. 67, no. 8, pp. 2693–2706, Aug. 2020.

[DB13] D. G. Dansereau, D. L. Bongiorno, O. Pizarro, and S. B. Williams, "Light field image denoising using a linear 4D frequency-hyperfan all-in-focus filter," in Proc. SPIE Comput. Imag. XI, vol. 8657, 2013, pp. 86 570P–1–86 570P–14.

[DB04] D. Dansereau and L. Bruton, "A 4D frequency-planar IIR filter and its application to light field processing," in Proc. IEEE Int. Symp. Circuits Syst., vol. 4, 2003, pp. IV–476–IV–479.

Applications of Linear Filters in LF/LFV Processing

- Depth filtering of LFs [IM00], [DB07], [LW20].

[IM00] A. Isaksen, L. McMillan, and S. J. Gortler, “Dynamically reparameterized light fields,” in Proc. Annu. Conf. Comput. Graph. (SIGGRAPH), 2000, pp. 297–306.
[DB07] D. Dansereau and L. T. Bruton, “A 4-D dual-fan filter bank for depth filtering in light fields,” IEEE Trans. Signal Process., vol. 55, no. 2, pp. 542–549, Feb. 2007.
[LW20] N. Liyanage, C. Wijenayake, C. Edussooriya, A. Madanayake, P. Agathoklis, L. T. Bruton, and E. Ambikairajah, “Multi-depth filtering and occlusion suppression in 4-D light fields: Algorithms and architectures,” Signal Process., vol. 167, pp. 1–13, Feb. 2020.

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- Depth filtering of LFs [IM00], [DB07], [LW20].
- Depth-velocity filtering of LFVs [ED15], [EB17], [WL19].

[IM00] A. Isaksen, L. McMillan, and S. J. Gortler, “Dynamically reparameterized light fields,” in Proc. Annu. Conf. Comput. Graph. (SIGGRAPH), 2000, pp. 297–306.

[DB07] D. Dansereau and L. T. Bruton, “A 4-D dual-fan filter bank for depth filtering in light fields,” IEEE Trans. Signal Process., vol. 55, no. 2, pp. 542–549, Feb. 2007.

[LW20] N. Liyanage, C. Wijenayake, C. Edussooriya, A. Madanayake, P. Agathoklis, L. T. Bruton, and E. Ambikairajah, “Multi-depth filtering and occlusion suppression in 4-D light fields: Algorithms and architectures,” Signal Process., vol. 167, pp. 1–13, Feb. 2020.

[ED15] C. U. S. Edussooriya, D. G. Dansereau, L. T. Bruton, and P. Agathoklis, “Five-Dimensional Depth-Velocity Filtering for Enhancing Moving Objects in Light Field Videos,” IEEE Transactions on Signal Processing, vol. 63, no. 8, pp. 2151–2163, 2015.

[EB17] C. U. S. Edussooriya, L. T. Bruton, and P. Agathoklis, “A novel 5-D depth-velocity filter for enhancing noisy light field videos,” Multidim. Syst. Signal Process., vol. 28, no. 1, pp. 353–369, Jan. 2017.

[WL19] C. Wijenayake, N. Liyanage, C. U. S. Edussooriya, H. Seatang, P. Agathoklis, and L. Bruton, “Design and implementation of 5-D IIR depth velocity filters for light field video processing,” IEEE Trans. Circuits Syst. II, vol. 66, no. 7, pp. 1267–1271, Jul. 2019.

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- Review article on real-time LF processing using linear filters [EW21].

[IM00] A. Isaksen, L. McMillan, and S. J. Gortler, "Dynamically reparameterized light fields," in Proc. Annu. Conf. Comput. Graph. (SIGGRAPH), 2000, pp. 297–306.

[DB07] D. Dansereau and L. T. Bruton, "A 4-D dual-fan filter bank for depth filtering in light fields," IEEE Trans. Signal Process., vol. 55, no. 2, pp. 542–549, Feb. 2007.

[LW20] N. Liyanage, C. Wijenayake, C. Edussooriya, A. Madanayake, P. Agathoklis, L. T. Bruton, and E. Ambikairajah, "Multi-depth filtering and occlusion suppression in 4-D light fields: Algorithms and architectures," Signal Process., vol. 167, pp. 1–13, Feb. 2020.

[ED15] C. U. S. Edussooriya, D. G. Dansereau, L. T. Bruton, and P. Agathoklis, "Five-Dimensional Depth-Velocity Filtering for Enhancing Moving Objects in Light Field Videos," IEEE Transactions on Signal Processing, vol. 63, no. 8, pp. 2151–2163, 2015.

[EB17] C. U. S. Edussooriya, L. T. Bruton, and P. Agathoklis, "A novel 5-D depth-velocity filter for enhancing noisy light field videos," Multidim. Syst. Signal Process., vol. 28, no. 1, pp. 353–369, Jan. 2017.

[WL19] C. Wijenayake, N. Liyanage, C. U. S. Edussooriya, H. Seatang, P. Agathoklis, and L. Bruton, "Design and implementation of 5-D IIR depth velocity filters for light field video processing," IEEE Trans. Circuits Syst. II, vol. 66, no. 7, pp. 1267–1271, Jul. 2019.

[EW21] C. U. S. Edussooriya, C. Wijenayake, A. Madanayake, N. Liyanage, S. Premaratne, J. T. Vorhies, D. G. Dansereau, P. Agathoklis, and L. T. Bruton, "Real-time light field signal processing using 4D/5D linear digital filter FPGA circuits," IEEE Trans. Circuits Syst. II, to be published in Apr 2021.

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QUESTIONS ???