ATTENUATION-BASED LIGHT FIELD DISPLAYS

Bachelor Thesis

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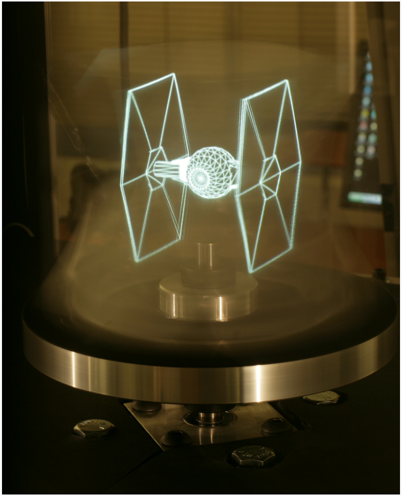
OUTLINE

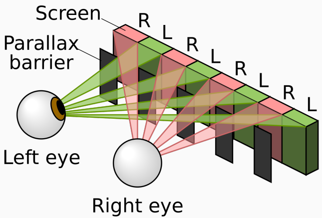
1. Introduction
2. Light Fields
3. Attenuation Display
4. Spectral Analysis
5. Conclusion

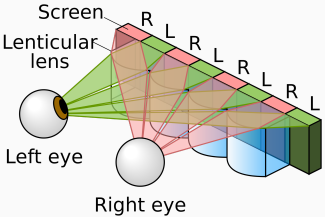
INTRODUCTION

EXISTING 3D DISPLAYS



Jones et al. [2007]

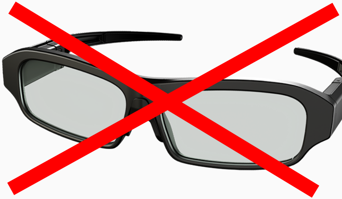




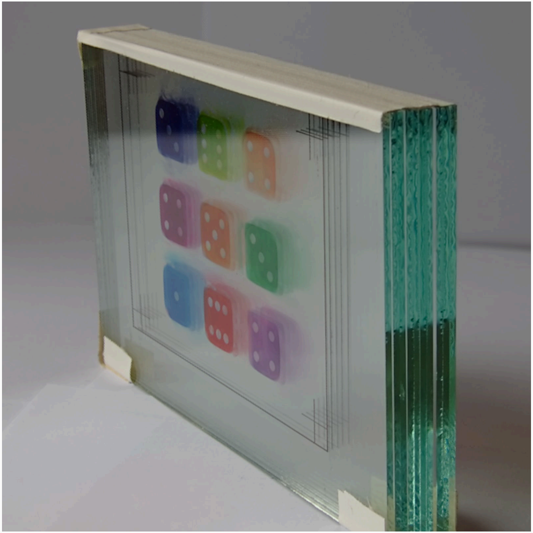
en.wikipedia.org/wiki/Autostereoscopy

EXISTING 3D DISPLAYS

EXISTING 3D DISPLAYS



TODAY



LAYERED 3D

Layered 3D: Tomographic Image Synthesis for Attenuation-based Light Field and High Dynamic Range Displays

Wetzstein et al. [2011]

Layered 3D: Tomographic Image Synthesis for Attenuation-based Light Field and High Dynamic Range Displays

Gordon Wetzstein[1] Douglas Lanman[2] Wolfgang Heidrich[1] Ramesh Raskar[2]
[1]University of British Columbia [2]MIT Media Lab

Figure 1: *Inexpensive, glasses-free light field display using volumetric attenuators. (Left) A stack of spatial light modulators (e.g., printed masks) recreates a target light field (here for a car) when illuminated by a backlight. (Right) The target light field is shown in the upper left, together with the optimal five-layer decomposition, obtained with iterative tomographic reconstruction. (Middle) Oblique projections for a viewer standing to the top left (magenta) and bottom right (cyan). Corresponding views of the target light field and five-layer prototype are shown on the left and right, respectively. Such attenuation-based 3D displays allow accurate, high-resolution depiction of motion parallax, occlusion, translucency, and specularity, being exhibited by the trunk, the fender, the window, and the roof of the car, respectively.*

Abstract

We develop tomographic techniques for image synthesis on displays composed of compact volumes of light-attenuating material. Such volumetric attenuators recreate a 4D light field or high-contrast 2D image when illuminated by a uniform backlight. Since arbitrary oblique views may be inconsistent with any single attenuator, iterative tomographic reconstruction minimizes the difference between the emitted and target light fields, subject to physical constraints on attenuation. As multi-layer generalizations of conventional parallax barriers, such displays are shown, both by theory and experiment, to exceed the performance of existing dual-layer architectures. For 3D display, spatial resolution, depth of field, and brightness are increased, compared to parallax barriers. For a plane at a fixed depth, our optimization also allows optimal construction of high dynamic range displays, confirming existing heuristics and providing the first extension to multiple, disjoint layers. We conclude by demonstrating the benefits and limitations of attenuation-based light field displays using an inexpensive fabrication method: separating multiple printed transparencies with acrylic sheets.

Keywords: computational displays, light fields, autostereoscopic 3D displays, high dynamic range displays, tomography

Links: DL PDF WEB VIDEO

1 Introduction

3D displays are designed to replicate as many perceptual depth cues as possible. As surveyed by Lipton [1982], these cues can be classified by those that require one eye (monocular) or both eyes (binocular). Artists have long exploited monocular cues, including perspective, shading, and occlusion, to obtain the illusion of depth with 2D media. Excluding motion parallax and accommodation, existing 2D displays provide the full set of monocular cues. As a result, 3D displays are designed to provide the lacking binocular cues of disparity and convergence, along with these missing monocular cues.

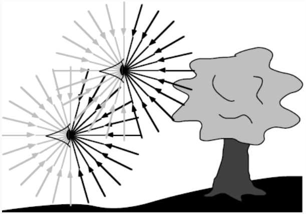
Current 3D displays preserve disparity, but require special eyewear (e.g., LCD shutters, polarizers, or color filters). In contrast, automultiscopic displays replicate disparity and motion parallax without encumbering the viewer. As categorized by Favalora [2005], such glasses-free displays include parallax barriers [Ives 1903; Kanolt 1918] and integral imaging [Lippmann 1908], volumetric displays [Blundell and Schwartz 1999], and holograms [Slinger et al. 2005]. Holograms present all depth cues, but are expensive and primarily restricted to static scenes viewed under controlled illumination [Klug et al. 2001]. Research is addressing these issues [Blanche et al. 2010], yet parallax barriers and volumetric displays remain practical alternatives, utilizing well-established, low-cost fabrication. Furthermore, volumetric displays can replicate similar depth cues with flicker-free refresh rates [Favalora 2005].

This paper considers automultiscopic displays comprised of compact volumes of light-attenuating material, which we dub "Layered 3D" displays. Differing from volumetric displays with light-emitting layers, overlaid attenuation patterns allow objects to appear beyond the display enclosure and for the depiction of motion parallax, occlusion, and specularity. While our theoretical contributions apply equally well to dynamic displays, such as stacks of liquid crystal display (LCD) panels, our prototype uses static printing to demonstrate the principles of tomographic image synthesis. Specifically, we produce multi-layer attenuators using 2D printed transparencies, separated by acrylic sheets (see Figures 1 and 2).

LIGHT FIELDS

THE PLENOPTIC FUNCTION

- Measures light in the world
- Position, viewing direction
- Time, Wavelength
- $P(x, y, z, \theta, \phi, t, \lambda)$
- 7D



Adelson and Bergen [1991]

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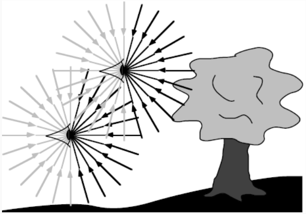

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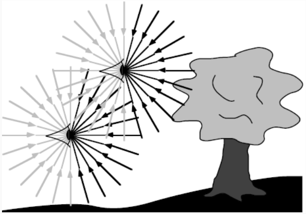

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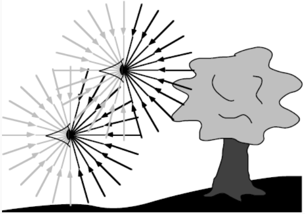

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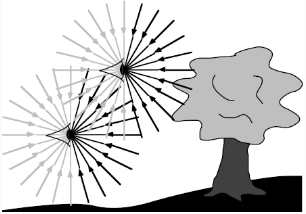

Adelson and Bergen [1991]

THE 4D LIGHT FIELD

- Reduce dimensions of P
- $L(u, v, s, t)$
- Defined by two planes

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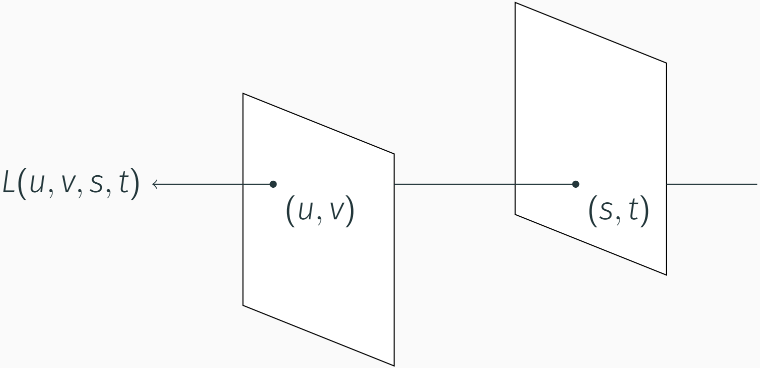


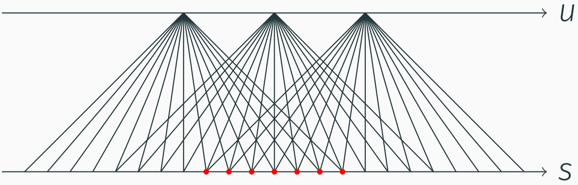
LIGHT FIELD ACQUISITION

Stanford camera array. Source: lightfield.stanford.edu

Lego gantry. Source: lightfield.stanford.edu

Lytro plenoptic camera. Source: de.wikipedia.org/wiki/Lytro

RE-PARAMETERIZATION TO GLOBAL COORDINATES



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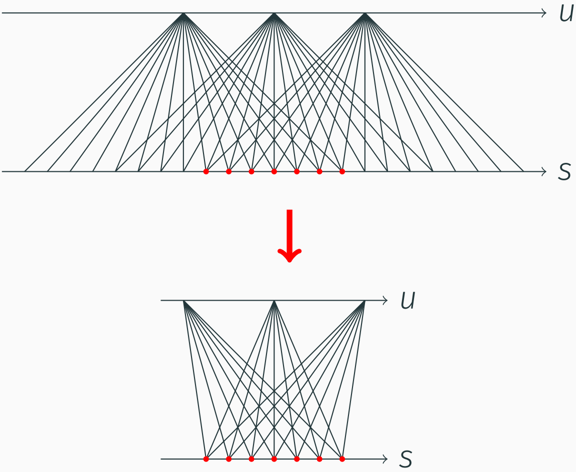


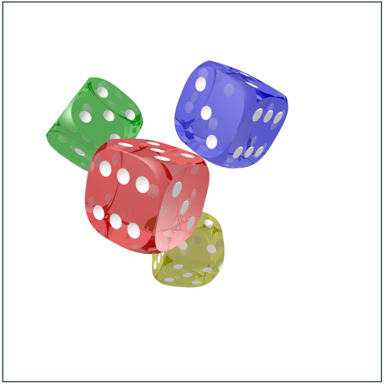
RE-PARAMETERIZATION TO GLOBAL COORDINATES

Raw

Rectified

RE-PARAMETERIZATION TO GLOBAL COORDINATES

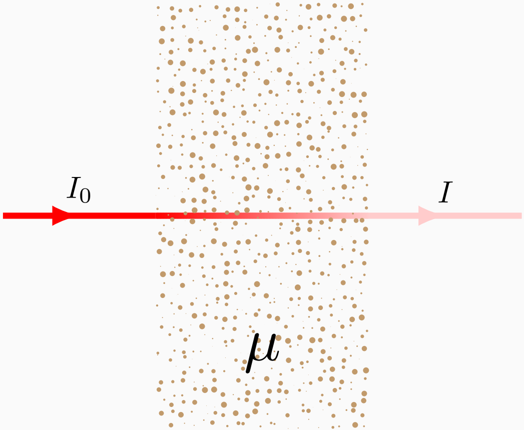
Raw



Rectified

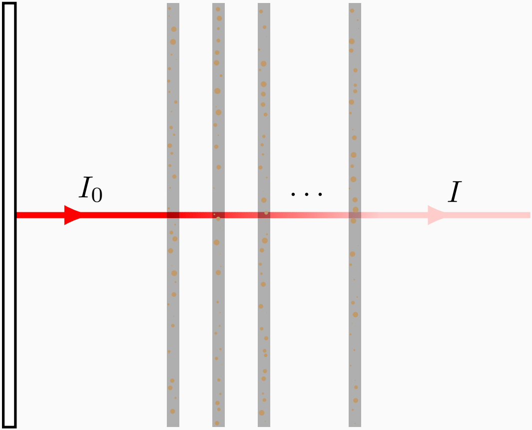
ATTENUATION DISPLAY

THE BEER-LAMBERT LAW



$$\frac{I}{I_0} = \exp\left(-\int_{\mathcal{R}} \mu(r)\mathrm{d}r\right)$$

THE BEER-LAMBERT LAW



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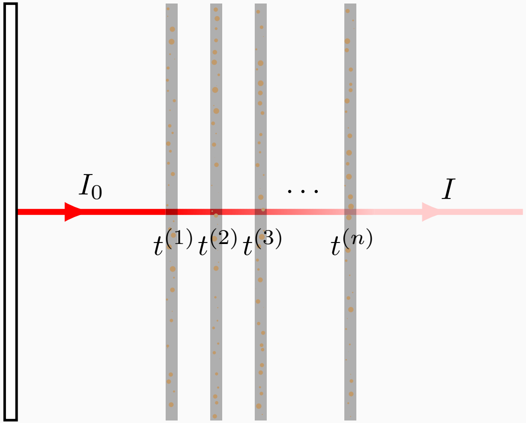
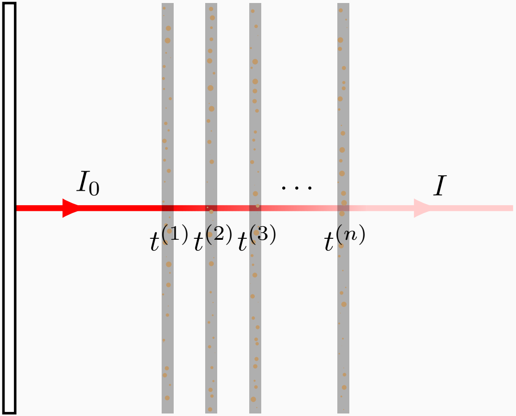


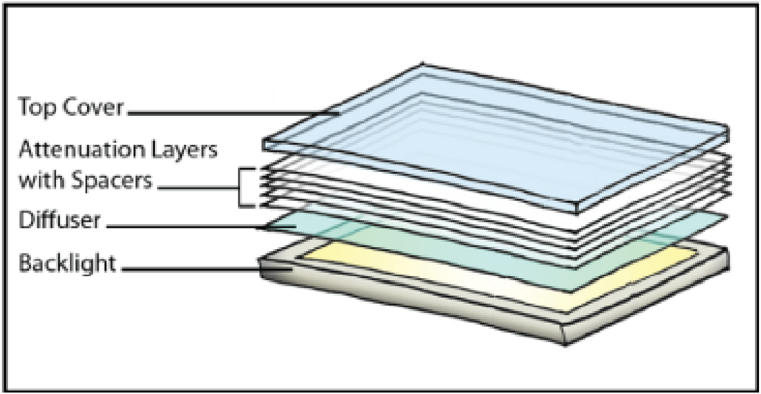
$$\frac{I}{I_0} = \exp\left(-\int_{\mathcal{R}} \mu(r)\mathrm{d}r\right) = \prod_i t^{(i)}$$

THE BEER-LAMBERT LAW



$$\frac{I}{I_0} = \exp\left(-\int_{\mathcal{R}} \mu(r)\mathrm{d}r\right) = \prod_i t^{(i)} = \exp\left(-\sum_i a^{(i)}\right)$$

DISPLAY ARCHITECTURE

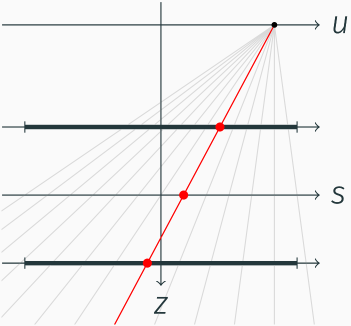


Wetzstein et al. [2011]

PROBLEM STATEMENT

Given a light field

Produce layers that attenuate light from backlight such that display creates the given light field



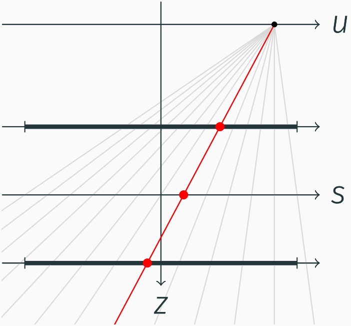
$$L_m = L_0 \prod_{n=1}^{N} t^{(n)}(h(m,n))$$

L_m Color of ray m

t Transmission

h Intersection

LIGHT TRANSMISSION



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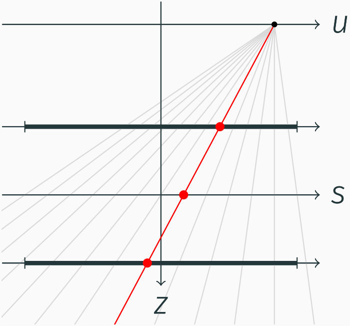

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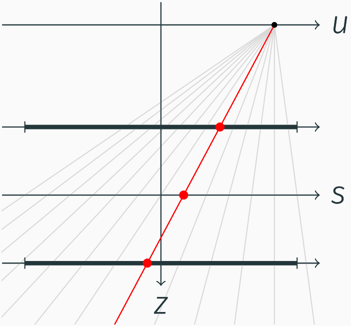

$$L_m = L_0 \prod_{n=1}^{N} t^{(n)}(h(m,n))$$

L_m Color of ray m

t Transmission

h Intersection

From now on: $L_0 = 1$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown

$$L_m = \prod_{n=1}^{N} t^{(n)}(h(m, n))$$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays

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FROM TRANSMISSION TO ABSORBANCE

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- This is hard

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FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays
- This is hard
- Transform to log-domain

$$L_m = \prod_{n=1}^{N} t^{(n)}(h(m,n))$$

$$\Big\downarrow \quad t = e^{-a}$$

$$\log(L_m) = -\sum_{n=1}^{N} a^{(n)}(h(m,n))$$

FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays
- This is hard
- Transform to log-domain
- Solve for absorbance

$$L_m = \prod_{n=1}^{N} t^{(n)}(h(m,n))$$

$$\big\downarrow \quad t = e^{-a}$$

$$\log(L_m) = -\sum_{n=1}^{N} a^{(n)}(h(m,n))$$

RAY CASTING

- One linear constraint per ray
- Create a big matrix P
- Matrix encodes intersections

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$$
P = \begin{array}{cc}
 & \begin{array}{cccccccccc} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & \alpha_6 & \alpha_7 & \alpha_8 & \alpha_9 & \alpha_{10} \end{array} \\
\begin{array}{c} \bar{L}_1 \\ \bar{L}_2 \\ \bar{L}_3 \\ \bar{L}_4 \\ \bar{L}_5 \\ \bar{L}_6 \\ \bar{L}_7 \\ \bar{L}_8 \\ \bar{L}_9 \\ \bar{L}_{10} \\ \bar{L}_{11} \\ \bar{L}_{12} \end{array} &
\left(\begin{array}{ccccc|ccccc}
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\end{array}\right)
\end{array}
$$

$$\log(L) = -P\alpha$$

- $\log(L)$ Vectorized log light field
- α Vector holding unkowns

THE EQUATION

$$\log(L) = -P\alpha$$

- $\log(L)$ Vectorized log light field
- α Vector holding unkowns

OPTIMIZATION PROBLEM

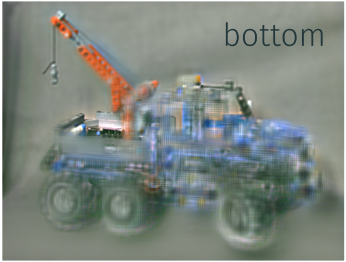
$$\begin{aligned} \underset{\alpha}{\operatorname{argmin}} \quad & \|P\alpha + \log(L)\|^2 \\ \text{subject to} \quad & \alpha \geq 0. \end{aligned}$$

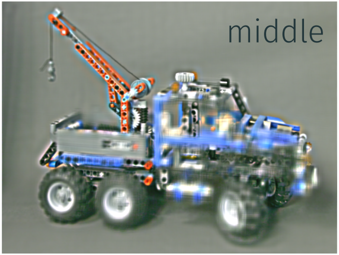
- Proposed by Wetzstein et al. [2011]
- System is overdetermined
- Need iterative solver

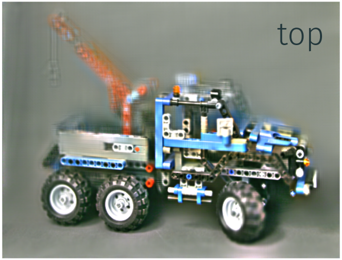
THE CONSTRAINT $\alpha \geq 0$

- Negative absorption ($\alpha < 0$) is physically not possible
- The theoretical model supports negative absorption
- Constraint reduces the space of possible solutions

EXAMPLE: LEGO TRUCK







$6 \times 6 \times 480 \times 640$

~ 2 minutes

EXAMPLE: LEGO TRUCK

Goal: Simulate viewing experience before assembly

$$I = e^{-P\alpha}$$

Original

Simulation

Light field courtesy: Stanford Light Field Archive

Original

Simulation

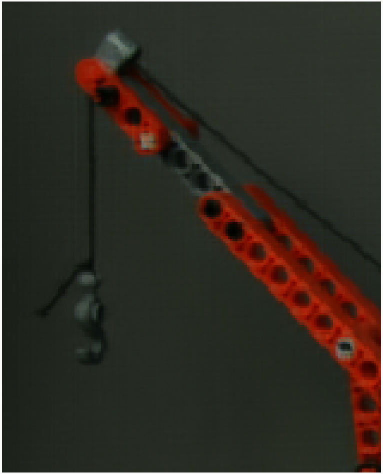
5 LAYERS

Original

Simulation

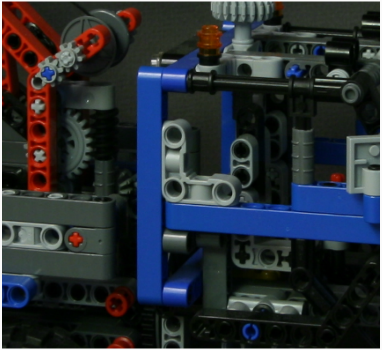
Original

Simulation

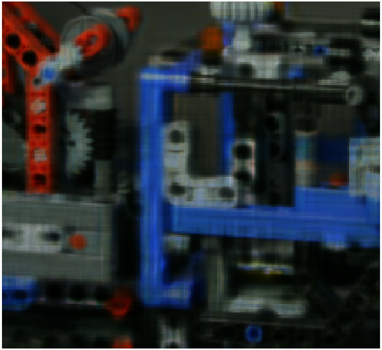


3 LAYERS

Original

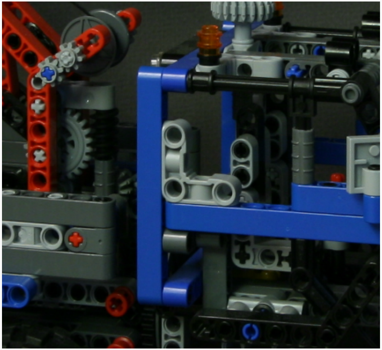


Simulation



5 LAYERS

Original



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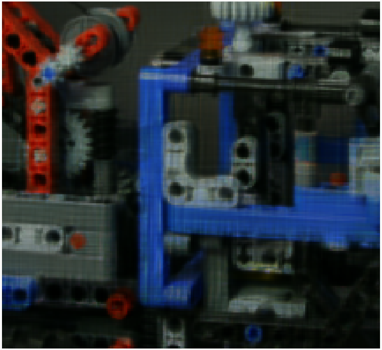
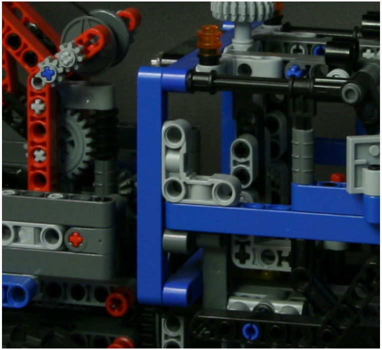
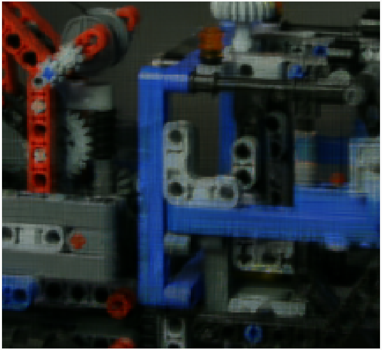


10 LAYERS

Original

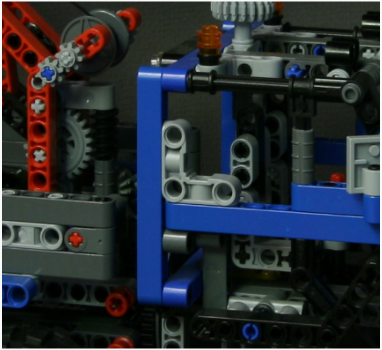


Simulation



10 LAYERS, HIGHER ANGULAR RESOLUTION

Original



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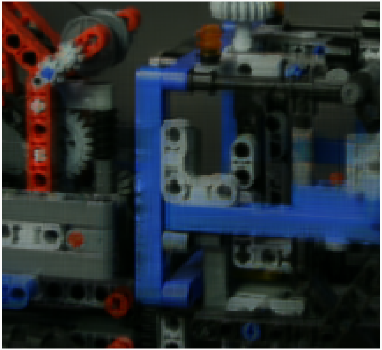
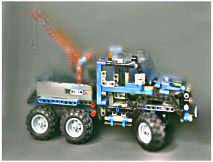


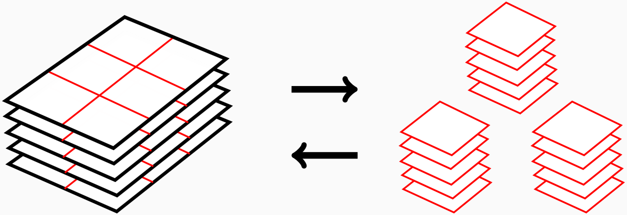
EXAMPLE: LEGO TRUCK



- A lot of memory is needed:
    - Light field (uncompressed)
    - Propagation matrix (? nnz entries)
    - Additional matrices for solver
- Memory usage grows with resolution
- Solution: Slice the attenuator

ATTENUATOR TILING

1. Slice attenuator into smaller pieces
2. Solve optimization problem for every slice
3. Reconnect the slices



ATTENUATOR TILING

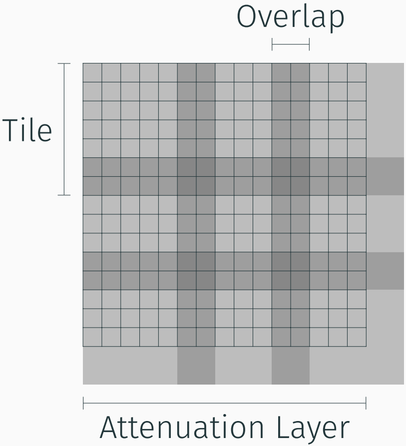
- Problem: Rays can overlap with multiple slices at borders
- Slices need to overlap too
- Blend slices with mask

Original

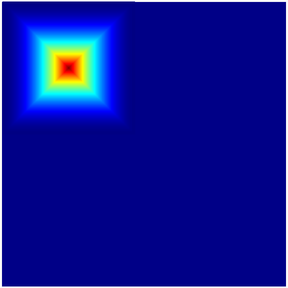
Simulation

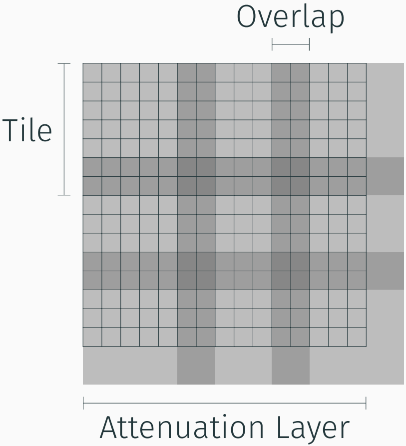
Light field courtesy: Stanford Light Field Archive

TILE BLENDING

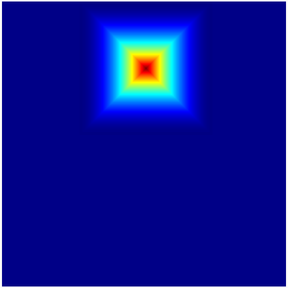


*

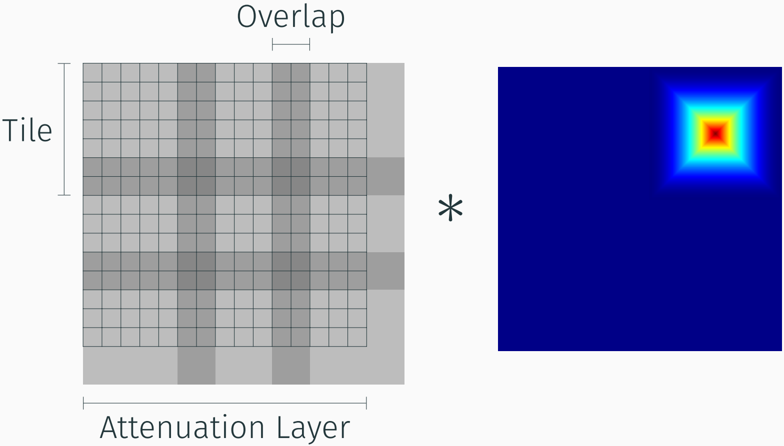



Overlap
Tile
Attenuation Layer

*



TILE BLENDING

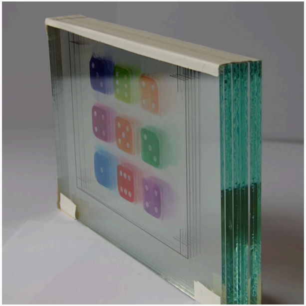


No overlap

30% overlap

THE FINISHED PRODUCT

- Finally, print images on transparent sheets
- Glass plates hold sheets in place
- Combine with backlight



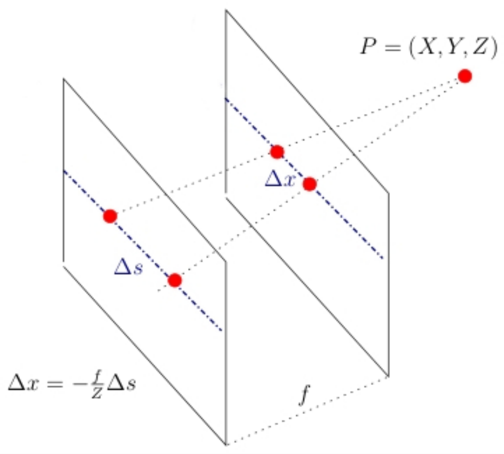
THE FINISHED PRODUCT

QUESTIONS

- Impact of more layers?
- Does thickness of display matter?
- Is it possible to show objects outside the display?
- What are the limitations?

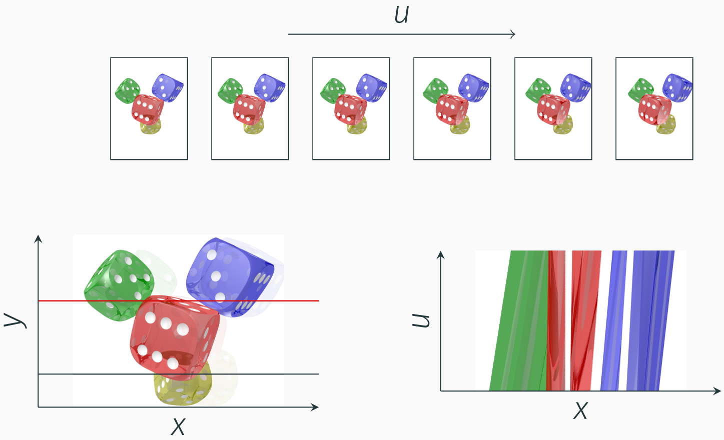
SPECTRAL ANALYSIS

EPIPOLAR PLANE GEOMETRY

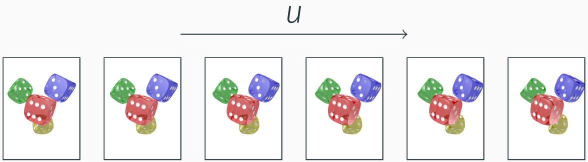


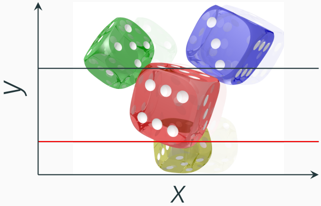
Source: klimt.iwr.uni-heidelberg.de

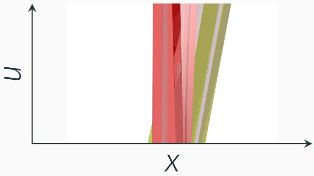
EPIPOLAR PLANE IMAGE



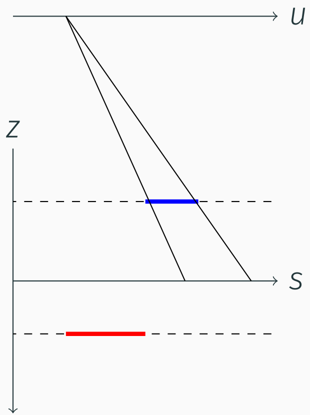
EPIPOLAR PLANE IMAGE

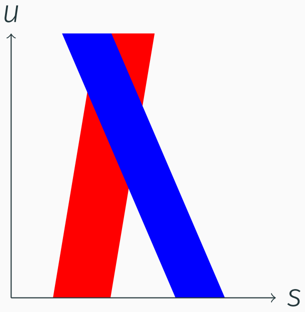






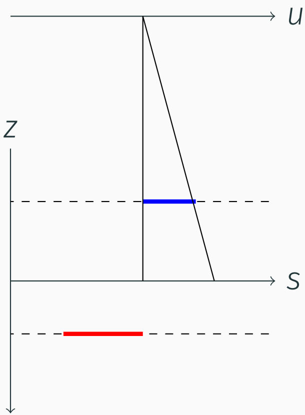
EPIPOLAR PLANE IMAGE

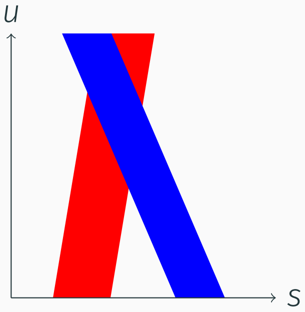




$$\frac{\mathrm{d}u}{\mathrm{d}s} = \frac{z - Z_u}{z - Z_s}$$

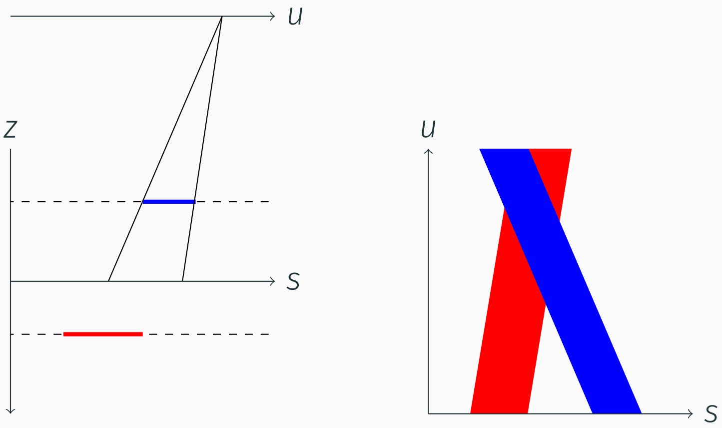
EPIPOLAR PLANE IMAGE





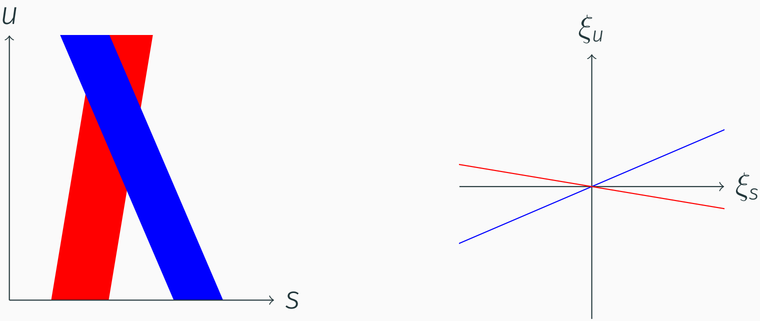
$$\frac{\mathrm{d}u}{\mathrm{d}s} = \frac{z - Z_u}{z - Z_s}$$

EPIPOLAR PLANE IMAGE



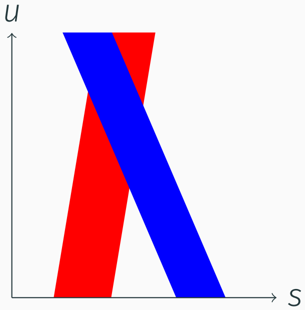
$$\frac{\mathrm{d}u}{\mathrm{d}s} = \frac{z - Z_u}{z - Z_s}$$

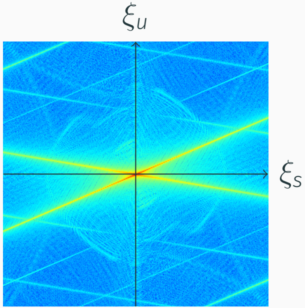
SPECTRAL PROPERTIES OF LIGHT FIELDS



Frequency Response
(Amplitude)

SPECTRAL PROPERTIES OF LIGHT FIELDS

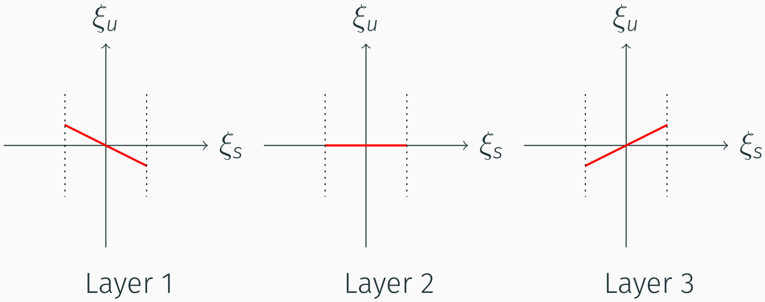




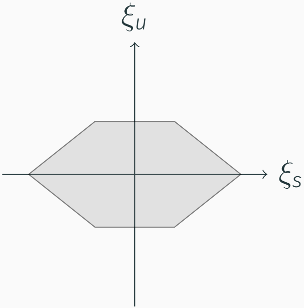
Frequency Response
(Amplitude)

SPECTRAL PROPERTIES OF DISPLAY

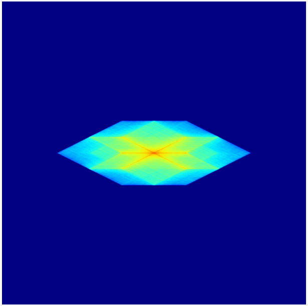
- Every layer creates a light field L_n
- Stack of layers creates $L' = L_0 \cdot L_1 \cdots L_N$
- What does L' look like in frequency domain?



SPECTRAL PROPERTIES OF DISPLAY

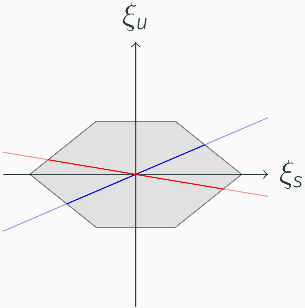


Spectral Support

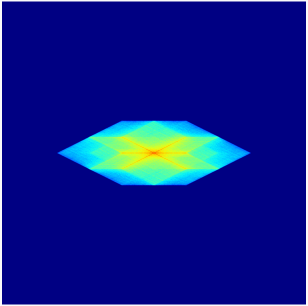


Frequency Response (Amplitude)

SPECTRAL PROPERTIES OF DISPLAY



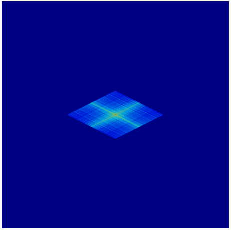
Spectral Support



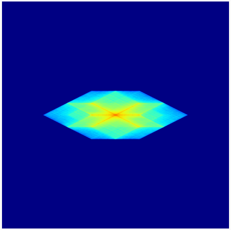
Frequency Response (Amplitude)

SPECTRAL PROPERTIES OF DISPLAY

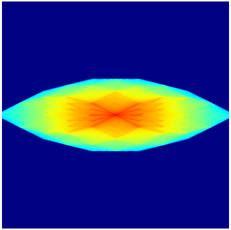
- Spectral support increases with more layers
- Highest response in center



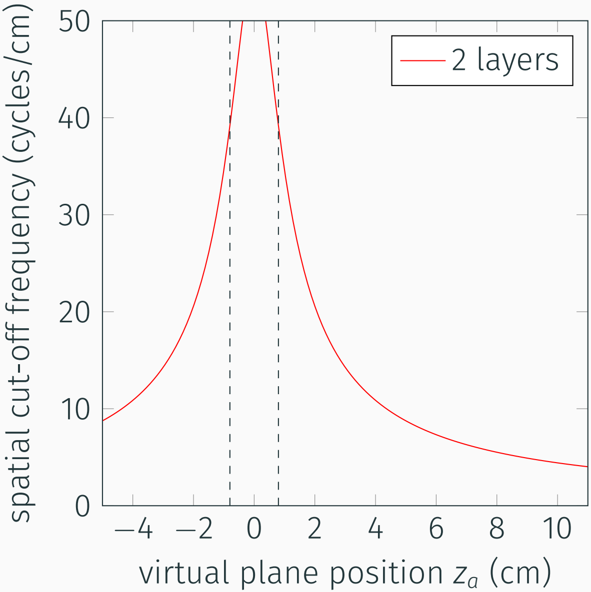
2 Layers



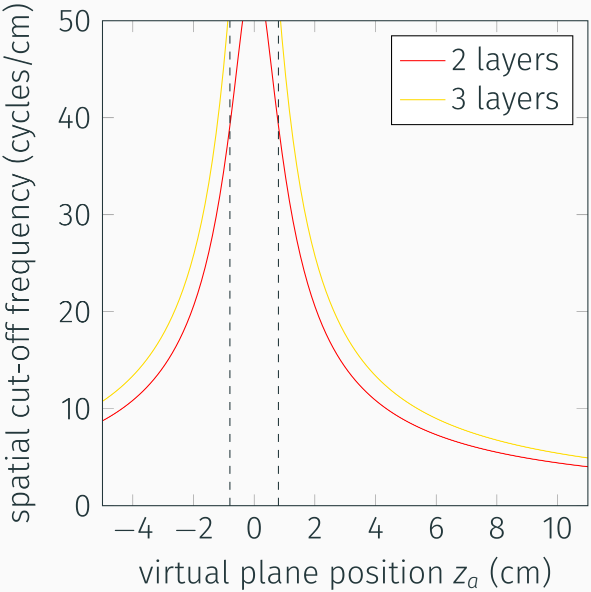
3 Layers



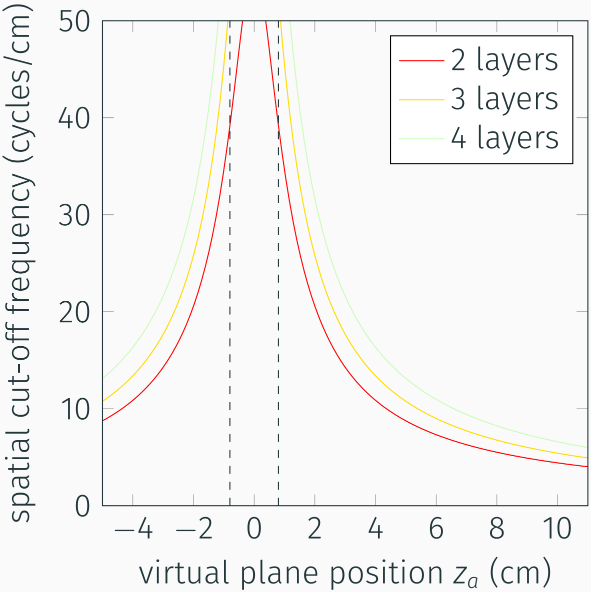
5 Layers


50
40
30
20
10
0
spatial cut-off frequency (cycles/cm)
−4
−2
0
2
4
6
8
10
virtual plane position z_a (cm)
2 layers

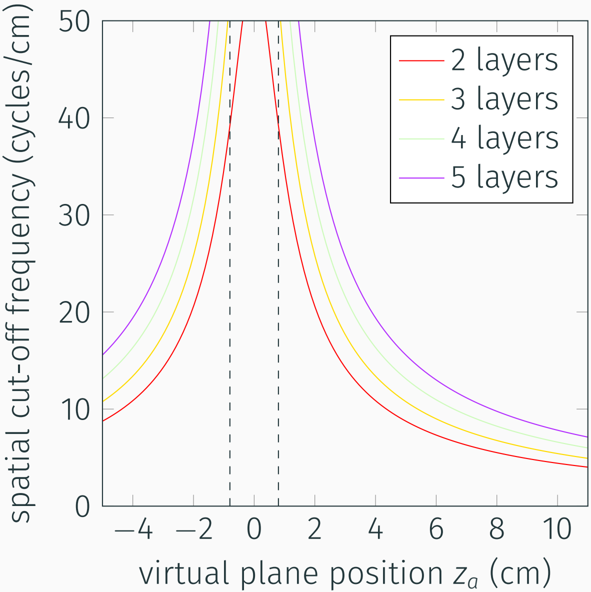
DEPTH OF FIELD



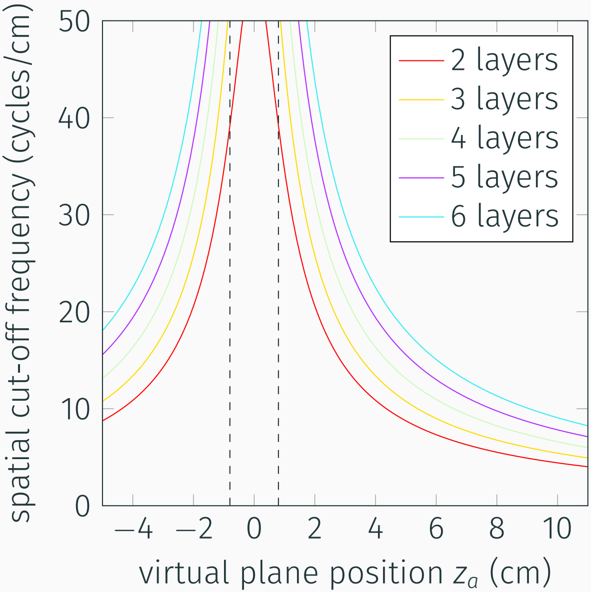
DEPTH OF FIELD



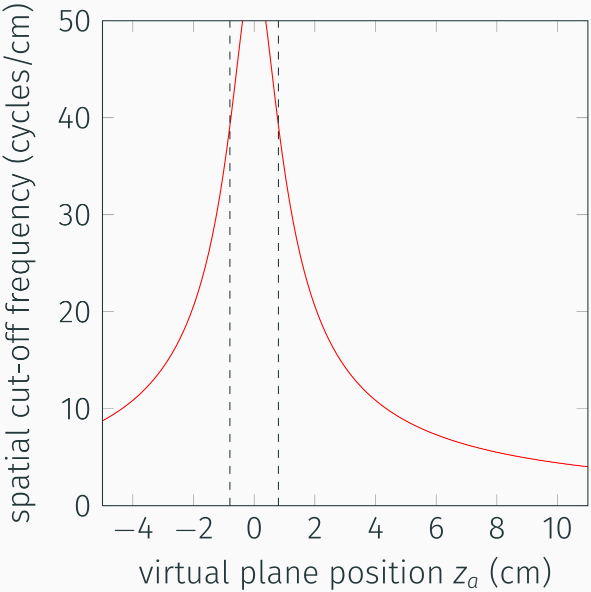
DEPTH OF FIELD



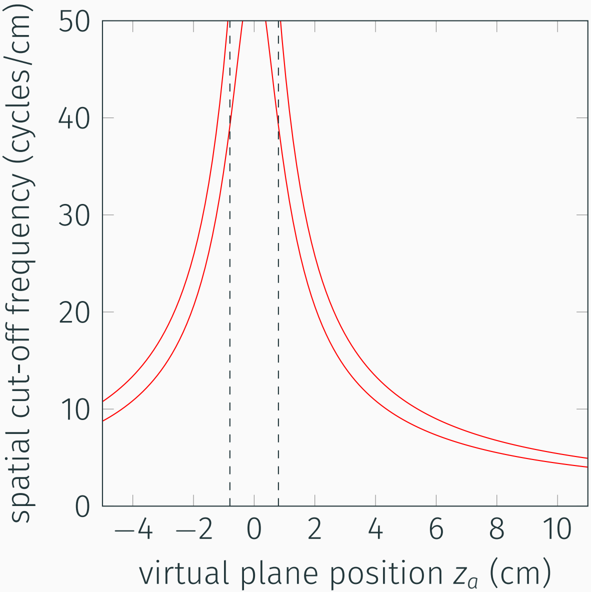
DEPTH OF FIELD

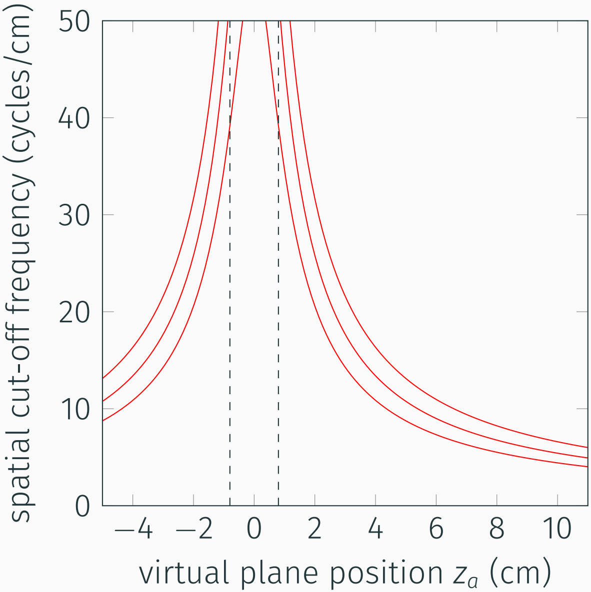


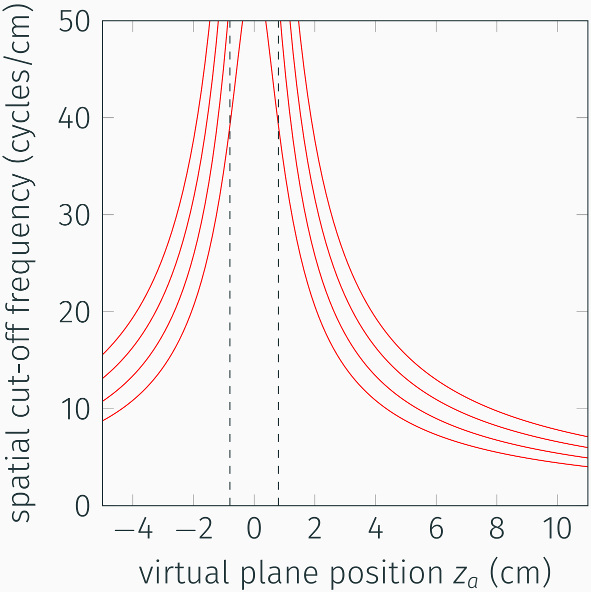
DEPTH OF FIELD



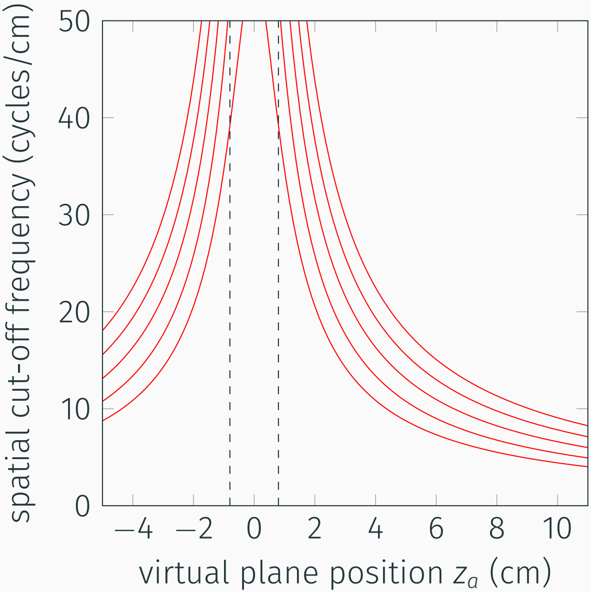
DEPTH OF FIELD




spatial cut-off frequency (cycles/cm)
50
40
30
20
10
0
−4
−2
0
2
4
6
8
10
virtual plane position z_a (cm)


spatial cut-off frequency (cycles/cm)
virtual plane position z_a (cm)
0
10
20
30
40
50
−4
−2
0
2
4
6
8
10

DEPTH OF FIELD



CONCLUSION

THE GOOD

- No trade-off between angular- and spatial resolution
- Extended spectral support
- Works with different types of light fields
    - Oblique Projections (synthetic scenes)
    - Perspective Projections (cameras)
    - Lytro

THE BAD

- Very small viewing angles
- Depth of field highly dependent on thickness
    - Light field's depth of field needs to match
    - For fixed thickness, need to squeeze baseline
- Need many layers to eliminate halo artefacts
- Manual layer alignment is hard

Your Questions

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Supervision by

Prof. Dr. Matthias Zwicker
Siavash Bigdeli

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Thesis and Resources

github.com/awaelchli/bachelor_thesis

REFERENCES

E. H. Adelson and J. Bergen. The plenoptic function and the elements of early vision. *Computational Models of Visual Processing*, pages 3–20, 1991.

A. Jones, I. McDowall, H. Yamada, M. Bolas, and P. Debevec. Rendering for an interactive 360° light field display. In *ACM SIGGRAPH 2007 Papers*, SIGGRAPH '07, New York, NY, USA, 2007. ACM.

G. Wetzstein, D. Lanman, W. Heidrich, and R. Raskar. Layered 3D: Tomographic image synthesis for attenuation-based light field and high dynamic range displays. *ACM Trans. Graph.*, 30(4):95:1–95:12, 2011.