Light-fields: Beyond the Lambertian

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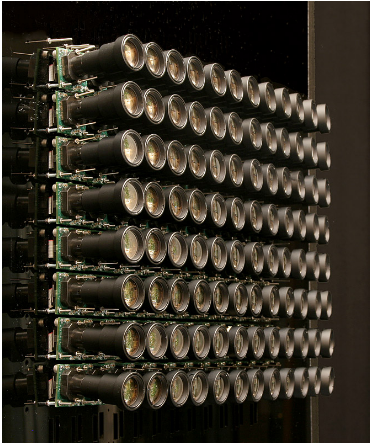
Recording Light Fields



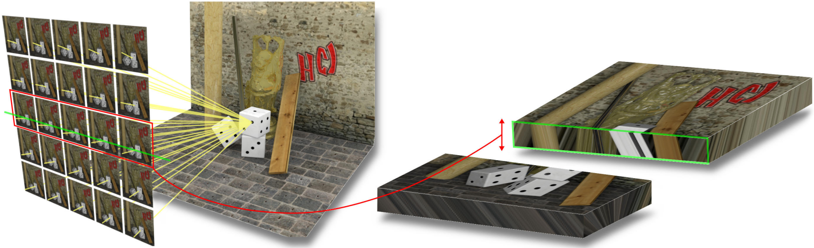
Lytro Illum

Standford Camera Array

Changing focus - focus in front

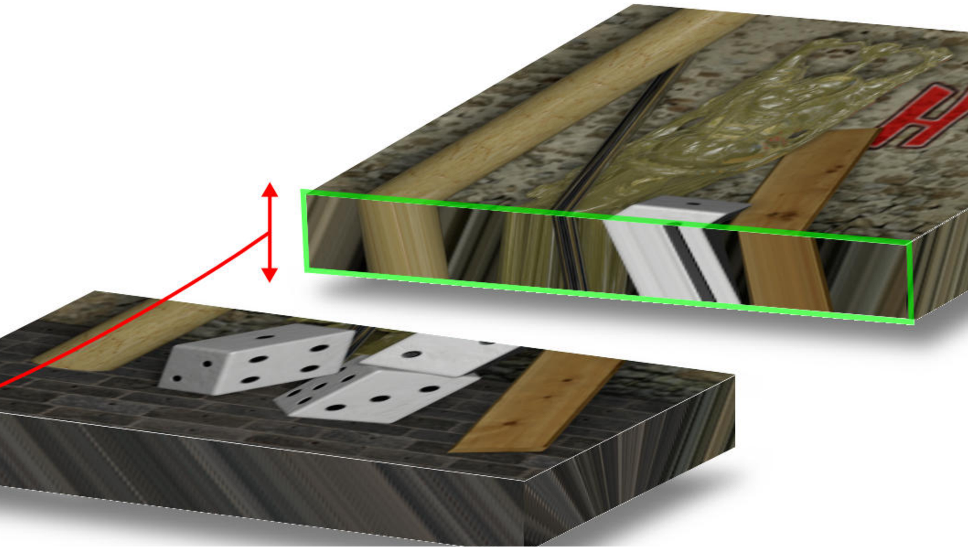
Changing focus - focus in back

Light Fields

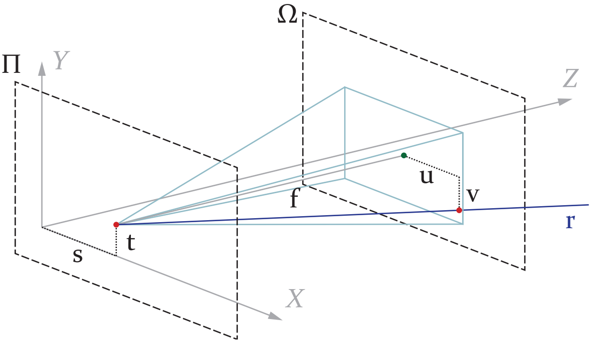


[Figure: Wanner and Goldluecke 2012]

Light Fields



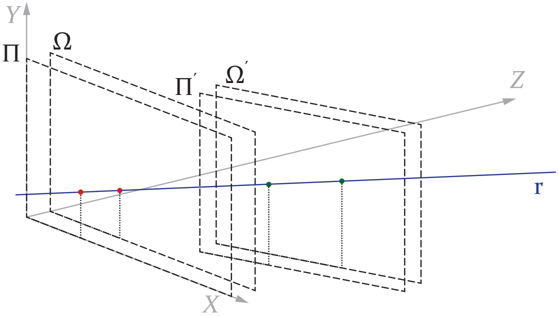
Light Field Parametrization



- Angular coordinates on *focal plane* $(s, t, 0) \in \Pi$
- Spatial coordinates on *image plane* $(u, v, f) \in \Omega$
- Light field coordinates $\mathbf{l} = [u, v, s, t]^T$

Structure from Motion in Light fields

- How to find extrinsic parameters between two cameras?
- How find features in light fields?
- How to make refocusable light-field panoramas?

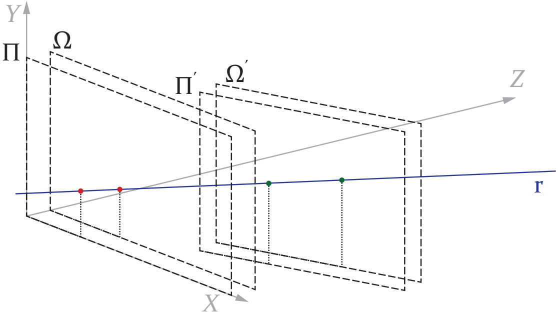


[Johannsen, Sulc and Goldluecke, ICCV 2015]

Rigid transform in Plücker coordinates

- No easy way to transform light field coordinates $\mathbf{l}$.
- We can represent rays $\mathbf{l}$ as homogeneous Plücker rays $(\mathbf{q}, \mathbf{m})$

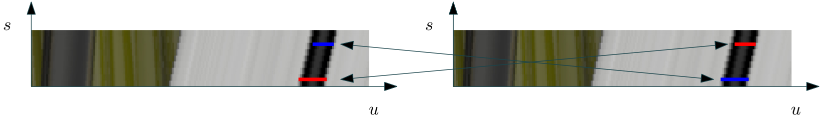
$$\begin{bmatrix} \mathbf{q}' \\ \mathbf{m}' \end{bmatrix} = \begin{bmatrix} R\mathbf{q} \\ R\mathbf{m} + E\mathbf{q} \end{bmatrix} \tag{1}$$



[Pless 2003]

Generalized Epipolar Constraint

Consider n-to-m **ray-to-ray** matches $(\mathbf{q}, \mathbf{m}) \leftrightarrow (\mathbf{q}_i, \mathbf{m}_i)$



- $(\mathbf{q}, \mathbf{m}) \leftrightarrow (\mathbf{q}_i, \mathbf{m}_i)$ in the same coordinate frame intersect iff

$$\mathbf{q}^T \mathbf{m}_i + \mathbf{m}^T \mathbf{q}_i = 0 \qquad (2)$$

- $(\mathbf{q}_i, \mathbf{m}_i)$ is in a coordinate frame R, t
  - Transform the $(\mathbf{q}', \mathbf{m}') = (R\mathbf{q}, R\mathbf{m} + E\mathbf{q})$
  - By plugging $(\mathbf{q}', \mathbf{m}')$ into Eq. 2 we get:

$$\mathbf{q}_i^T E\mathbf{q} + \mathbf{q}_i^T R\mathbf{m} + \mathbf{m}_i^T R\mathbf{q} = 0 \qquad (3)$$

- The Eq. 3 is called *Generalized Epipolar Constraint (GEC)*
- Huge system of ray-to-ray matches $\mathcal{O}(nm)$

[Pless 2003]

Features in Light fields

A 3D point is projected into multiple sub-aperture views (s, t)

$$\{\mathbf{I}_i\}_{i=1\ldots n} = \{[u_i, v_i, s_i, t_i]^T\}_{i=1\ldots n}$$

Light field subspace constraint

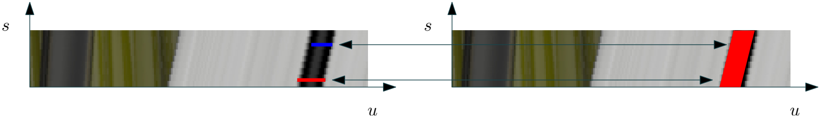
- Pinhole projection equations impose an affine relationship between (u, v) and (s, t)
- Rays $\{\mathbf{l}_i\}_{i=1\ldots n}$ which are intersecting the same 3D point $\mathbf{X}$ form a linear 2D subspace $M\mathbf{l}_i = 0$

$$\underbrace{\begin{bmatrix} 1 & 0 & \frac{f}{Z} & 0 & -\frac{fX}{Z} \\ 0 & 1 & 0 & \frac{f}{Z} & -\frac{fX}{Z} \end{bmatrix}}_{M(\mathbf{X},f)} \begin{bmatrix} u \\ v \\ s \\ t \\ 1 \end{bmatrix} = 0 \quad (4)$$

Our method

Consider n-to-m **ray-to-subspace** matches

$$M \leftrightarrow (\mathbf{q}_i, \mathbf{m}_i)$$



- M and $\mathbf{l}$ represent the same 3D point iff

$$M\mathbf{l} = 0$$

- No straightforward way to transform light field coordinates in different coordinate frames **but**
- A $\mathbf{l}$ as Plücker $(\mathbf{q}, \mathbf{m})$ ray can be transformed

$$M' P(f) \begin{bmatrix} R\mathbf{q} \\ R\mathbf{m} + E\mathbf{q} \end{bmatrix} = 0$$

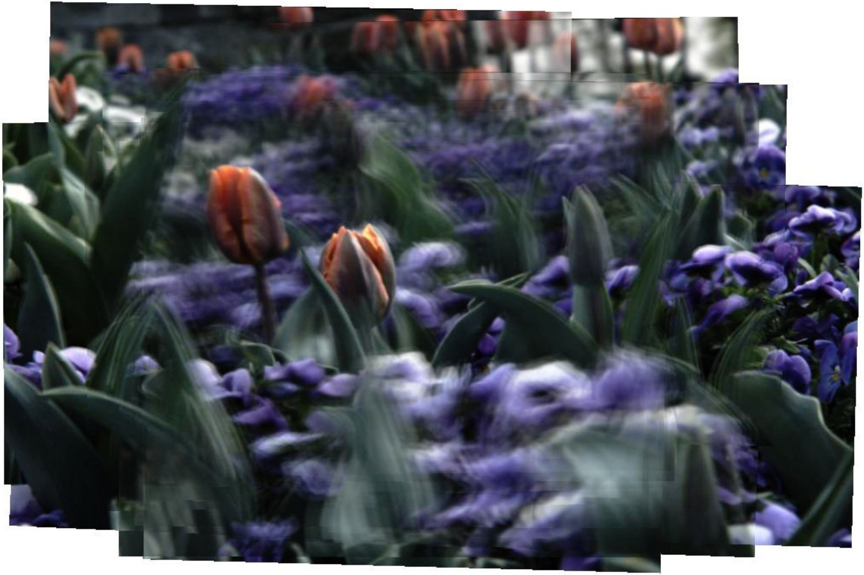
- ray-to-subspace matches $\mathcal{O}(m+n)$

[Johannsen, Sulc and Goldluecke, ICCV 2015]

Our method

- Direct utilization of light field geometry.
- Linear complexity $\mathcal{O}(m+n)$ with number n, m rays (matches)
- Robust (a lot of outliers can be removed in M estimation)

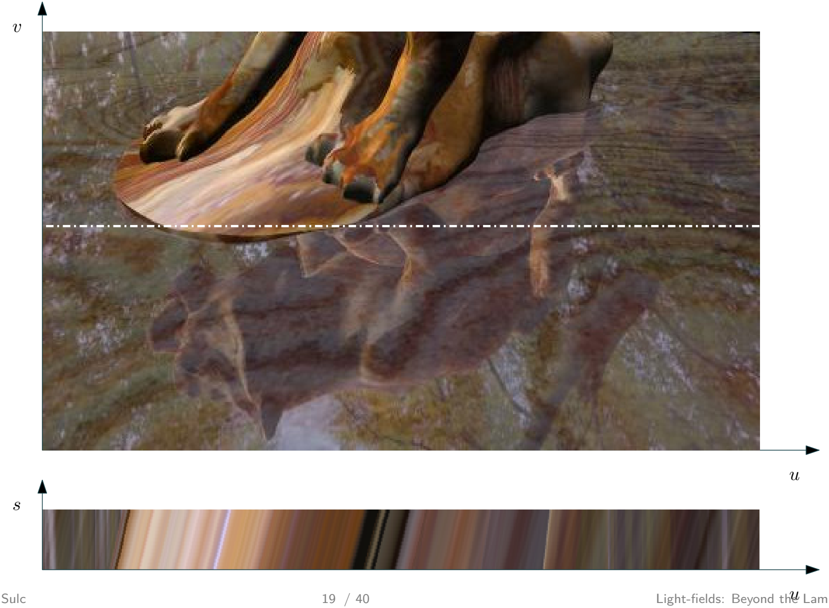
Method	Rotation error	Translation error	Time	Complexity
3DPC	1.31	9.49	**0.00**	
R2R	1.55	2.37	0.07	$\mathcal{O}(mn)$
Ours	**0.58**	**1.22**	0.04	$\mathcal{O}(m+n)$



Non-Lambertian surfaces

- How to calculate depth of a reflective/transparent surface.
- How to find a reflection mask.
- How to separate foreground from reflection.

Non-Lambertian surfaces in light-fields



Depth estimation - Structure tensor

First order structure tensor:

$$f\left(x\right)=f\left(x+\alpha\mathbf{v}\right) \tag{5}$$

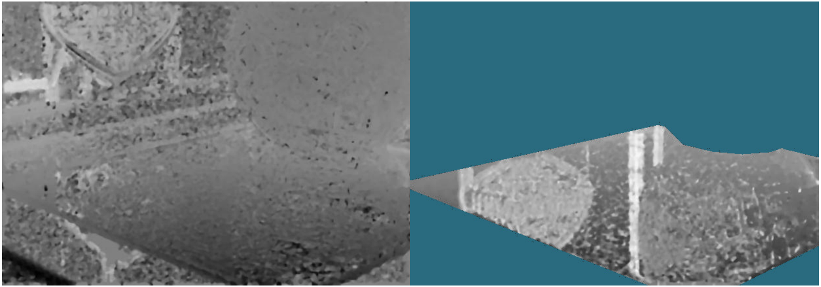
Second order structure tensor:

What if $f = f_u + f_v$?

$$\mathbf{u}\nabla f_u = 0 \quad \text{and} \quad \mathbf{v}\nabla f_v = 0 \tag{6}$$

Eigensystem analysis of the second order structure tensor

[Aach et.al. 2006; Wanner and Goldluecke 2013]

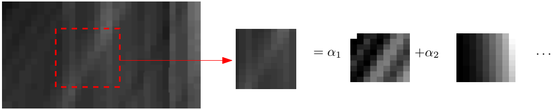


[Johannsen, Sulc and Goldluecke, VMV 2015]

Robust depth estimation - Sparse codes

- Structure tensor is very sensitive to noise and texture-less regions

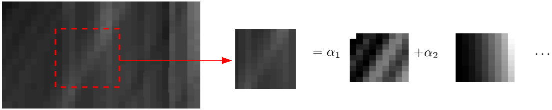
- **Idea** Represent EPI patches as a linear combination of atoms with fixed disparity



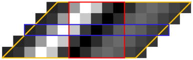
[Johannsen, Sulc and Goldluecke, CVPR 2016]

Robust depth estimation - Sparse codes

Each patch in EPI can be represented as a linear combination of atoms with fixed disparity.



- **Dictionary** consists of sheared center view patches a with fixed (known) disparity.

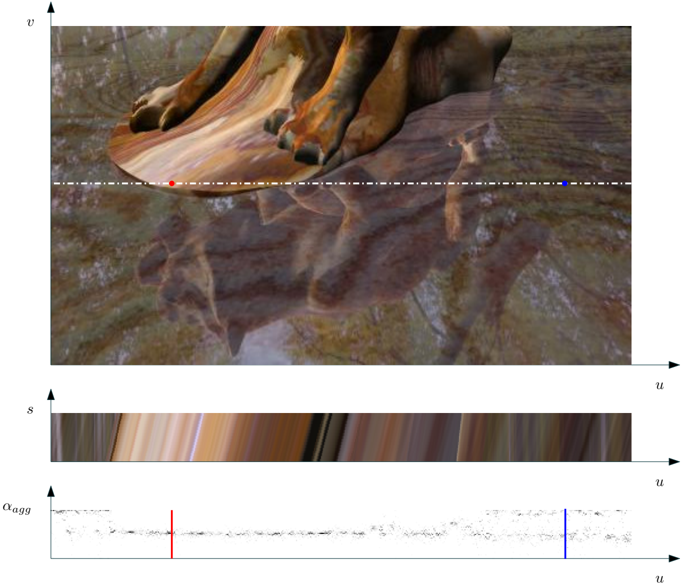


- **Disparity** is weighted average of patch disparities from *sparse codes* α (lasso, L_1)

$$\arg\min_{\alpha} \|\mathbf{x} - D\alpha\|_2^2 + \|\alpha\|_1 \tag{7}$$

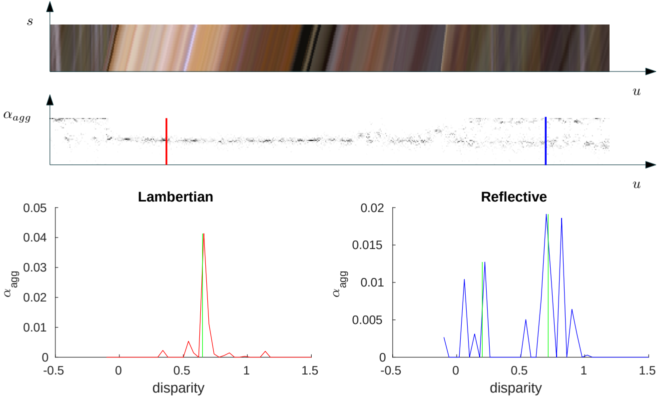
[Johannsen, Sulc and Goldluecke, CVPR 2016]

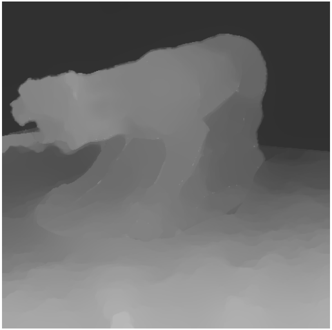
Robust depth estimation - Sparse codes

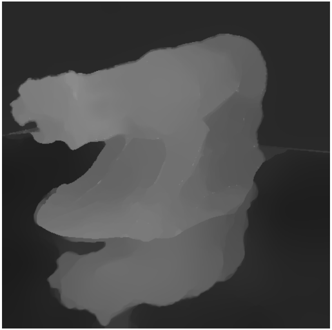


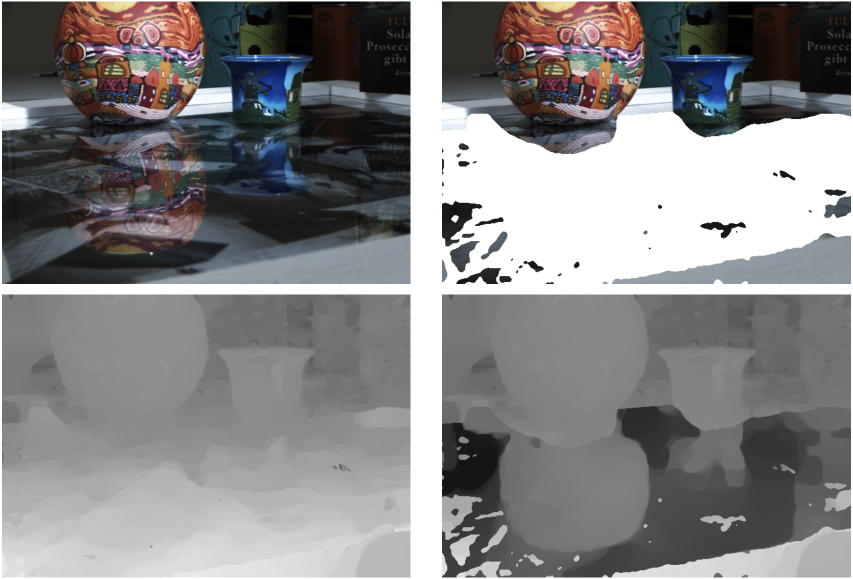
Robust depth estimation - Sparse codes

- Classes of aggregated sparse codes:
  - One peak - Lambertian surface
  - Two peaks - Reflective/Transparent surface
  - Uniform - Textureless region



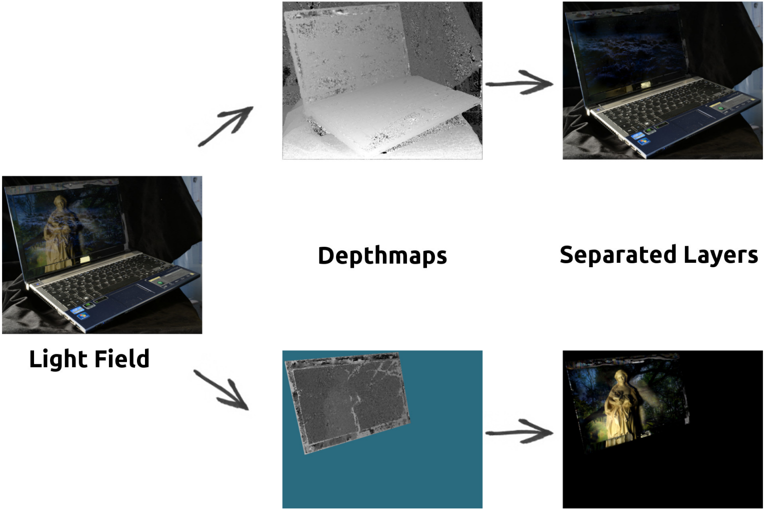






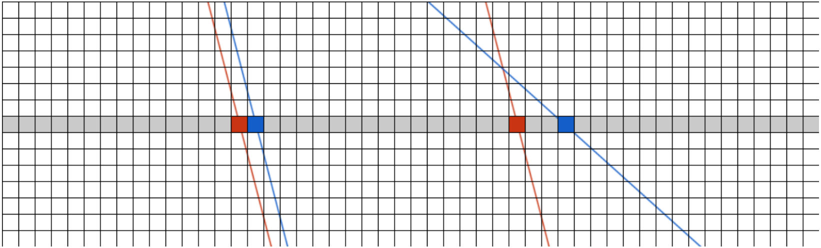
How to separate light-field images with reflection or transparent surface

Layer separation



[Johannsen, Sulc and Goldluecke, VMV 2015]

Generative Model for EPIs: Lambertian Surface



Depth dependent linear relation between center view and full EPI

Variational Inverse Problem: Dataterm

f	input EPI
u, v	center view layers restricted to this EPI
d_u, d_v	layer disparities restricted to this EPI
G_{d_u}, G_{d_v}	matrices to compute full EPI from layers

$$D_{EPI}(u, v) = \| G_{d_u} u + G_{d_v} v - f \|_p^p$$

$G_{d_u} u$ $G_{d_v} v$ f

[Johannsen, Sulc and Goldluecke, VMV 2015]

Variational Inverse Problem

- **Dataterm:** Goes though horizontal (W) and vertical (H) EPIs

$$D(u,v) = \sum_{x=1}^{W} D_x(u_x, v_x) + \sum_{y=1}^{H} D_y(u_y, v_y) \qquad (8)$$

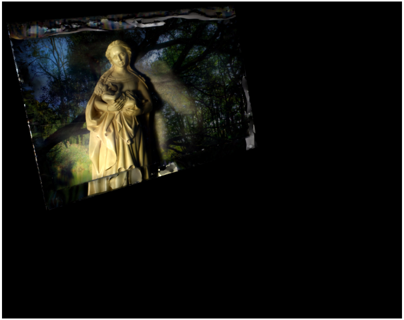
- **Regularization:** TGV favors linear solutions

$$\lambda(J(u) + J(v)) \qquad (9)$$

- **Energy**:

$$\boxed{E(u,v) = D(u,v) + \lambda(J(u) + J(v))}$$

Solved by primal-dual algorithm [Chambolle and Pock 2010]

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Conclusion

- LF Light field samples luminance of a subset of **rays which go though aperture**.
- SfM Rays from a 3D point form a **2D subspace**.
- SfM Linear algorithm for SfM with **ray-to-subspace** matches.
- ST Structure tensor can find a **disparity of two superimposed** light fields but is too sensitive.
- DL Distribution of grouped **sparse codes encode disparities**.
- LS Knowing **disparity and mask** of respective light field components, light field can be **separated in two components**.

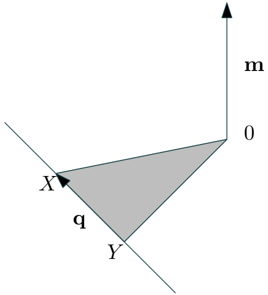
Thank you for your attention

Joint work of Ole Johannsen and Prof. Bastian Goldluecke

Funded by ERC grant *Light Field Imaging and Analysis*

Notes : Plücker coordinates

- Direction $\mathbf{q} \in \mathbb{R}^3 - \{0\}$
- Moment $\mathbf{m} \in \mathbb{R}^3$
- A point $X \in \mathbb{R}^3$ lies on the $(\mathbf{q}, \mathbf{m})$ ray iff $\mathbf{m} = X \times \mathbf{q}$



Two coordinates $(\mathbf{q}_1, \mathbf{m}_1)$ and $(\mathbf{q}_2, \mathbf{m}_2)$ represent the same ray iff
$\exists w \neq 0 : \mathbf{q}_1 = w\mathbf{q}_1$ and $\mathbf{m}_1 = w\mathbf{m}_2$

Note : Light Field Subspace constraint

$$\underbrace{\begin{bmatrix} 1 & 0 & \frac{f}{Z} & 0 & -\frac{fX}{Z} \\ 0 & 1 & 0 & \frac{f}{Z} & -\frac{fX}{Z} \end{bmatrix}}_{M(\mathbf{X},f)} \begin{bmatrix} u \\ v \\ s \\ t \\ 1 \end{bmatrix} = 0 \tag{10}$$

$$\begin{bmatrix} u + s\frac{f}{Z} - \frac{fX}{Z} \\ v + t\frac{f}{Z} - \frac{fX}{Z} \end{bmatrix} = 0 \tag{11}$$

$$\begin{bmatrix} (u - sd) - x \\ (v - td) - y \end{bmatrix} = 0 \tag{12}$$