Accurate Depth and Normal Maps from Occlusion-Aware Focal Stack Symmetry

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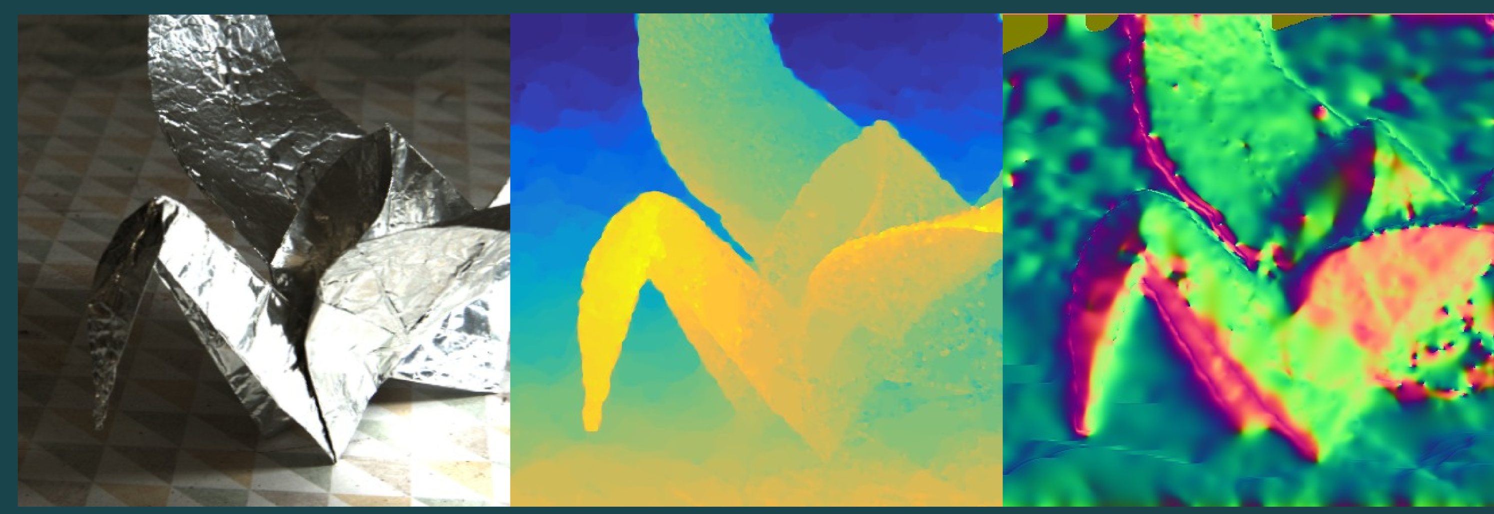
Contributions

- Novel way to handle occlusions when constructing cost volumes based on focal stack symmetry
- Joint regularization of depth and normals for smooth normal maps consistent with depth estimate



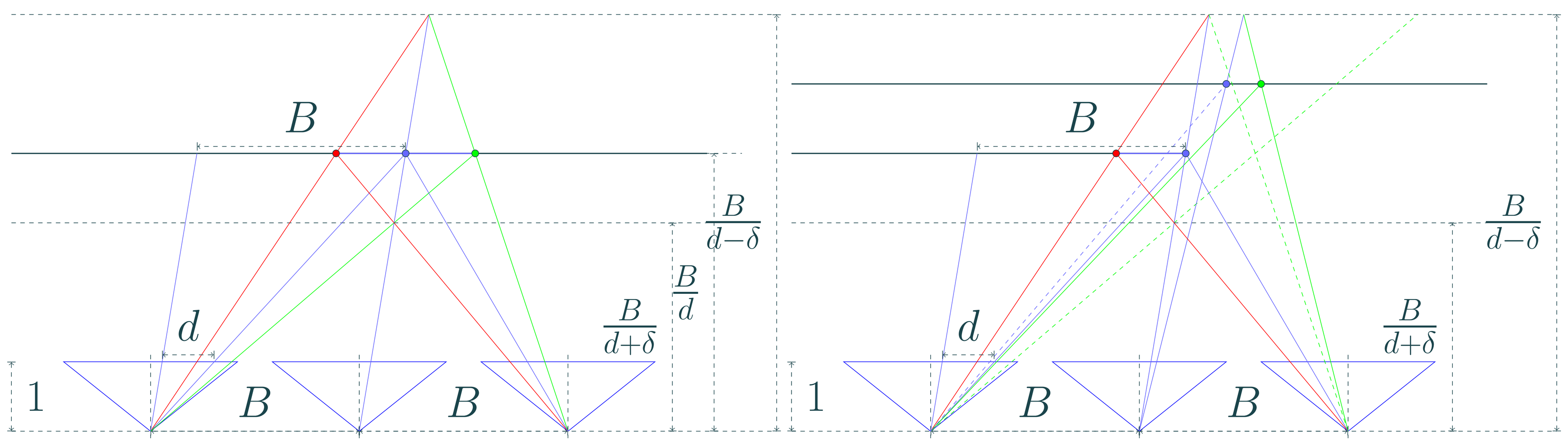
Light field structure and focal stacks

Light fields are defined as 4D function $L : \Pi \times \Omega \to \mathbb{R}$ on ray space, where rays are given by intersection points with the focal plane Π and the image plane Ω.
Refocusing to disparity α: aperture filter σ over subaperture views $\boldsymbol{v} = (s,t)$,

$$\varphi_{\boldsymbol{p}}(\alpha) = \int_{\Pi} \sigma(\boldsymbol{v}) L(\boldsymbol{p} + \alpha \boldsymbol{v}, \boldsymbol{v}) \, d\boldsymbol{v}. \quad (1)$$

Lin et al. [6]: **in absence of occlusion**, the focal stack is symmetric around the ground truth disparity. Assignment cost for disparities measures symmetry,

$$s^{\varphi}_{\boldsymbol{p}}(\alpha) = \int_0^{\delta_{\max}} \rho(\varphi_{\boldsymbol{p}}(\alpha - \delta) - \varphi_{\boldsymbol{p}}(\alpha + \delta)) \, d\delta. \quad (2)$$



Occlusion-aware focal stack symmetry

Problem: Focal stack at occlusions not symmetric around true disparity
Our assumption: occlusions only in one half-plane of view points
Then we can prove symmetry in partial focal stacks,

$$\varphi^-_{\boldsymbol{e},\boldsymbol{p}}(d+\delta) = \varphi^+_{\boldsymbol{e},\boldsymbol{p}}(d-\delta), \qquad \text{where} \quad \varphi^-_{\boldsymbol{e},\boldsymbol{p}}(\alpha) = \int_{-\infty}^{0} L(\boldsymbol{p} + \alpha s\boldsymbol{e}, s\boldsymbol{e}) \, ds$$
$$\varphi^+_{\boldsymbol{e},\boldsymbol{p}}(\alpha) = \int_{0}^{\infty} L(\boldsymbol{p} + \alpha s\boldsymbol{e}, s\boldsymbol{e}) \, ds. \quad (3)$$

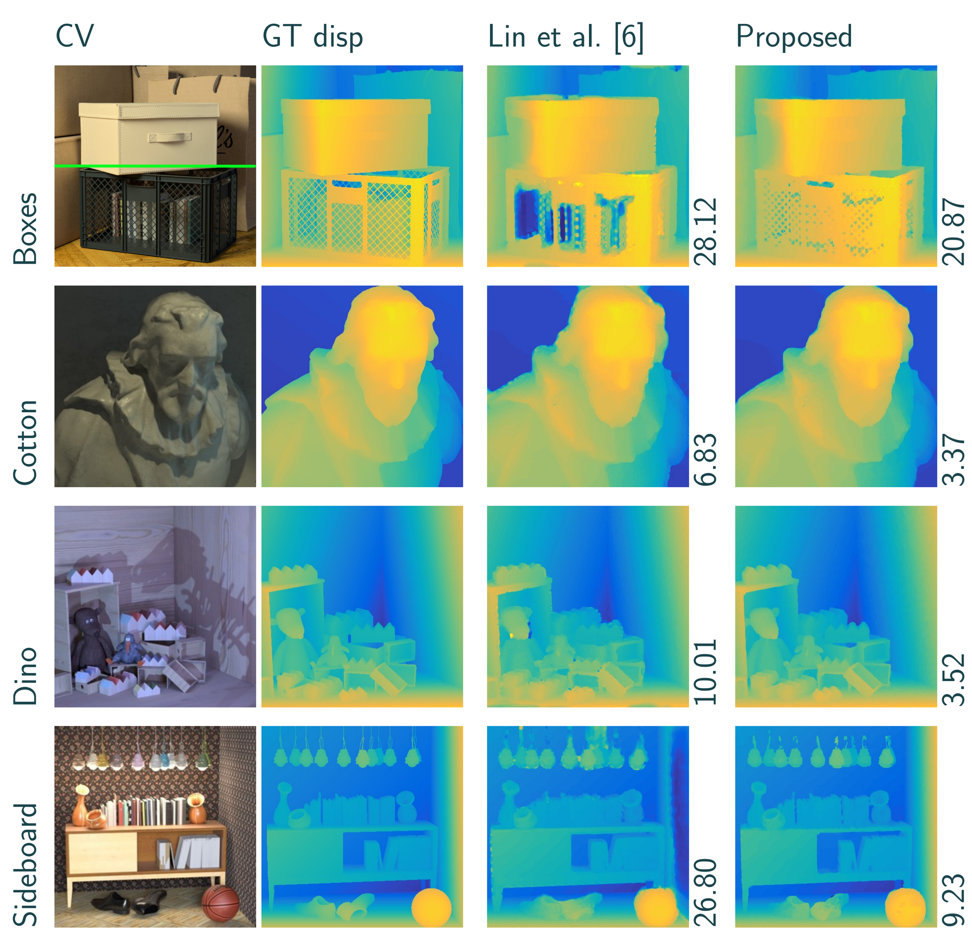
Our new disparity cost encourages symmetry for partial horizontal and vertical stacks:

$$s^{\varphi}_{\boldsymbol{p}}(\alpha) = \int_0^{\delta_{\max}} \min\big(\rho(\varphi^-_{(1,0),\boldsymbol{p}}(\alpha+\delta) - \varphi^+_{(1,0),\boldsymbol{p}}(\alpha-\delta)), \rho(\varphi^-_{(0,1),\boldsymbol{p}}(\alpha+\delta) - \varphi^+_{(0,1),\boldsymbol{p}}(\alpha-\delta))\big) \, d\delta. \quad (4)$$

(a) slice through focal stack φ from [6]

(b) slice through φ^+

(c) slice through φ^-



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Joint depth and normal map optimization

Problem: global optimal solution obtained with sublabel relaxation [7] locally flat.
Our approach: novel prior on normal maps which enforces correct relation to depth as well as smoothness of the normal field:

$$E(\zeta, \boldsymbol{n}) = \min_{\alpha > 0} \int_{\Omega} \rho(\zeta, x) + \lambda \|N\zeta - \alpha \boldsymbol{n}\|_2 \, dx + R(\boldsymbol{n}) \, dx \quad (5)$$

where $R(\boldsymbol{n})$ is a regularizer for the normal field given as

$$R(\boldsymbol{n}) = \sup_{\boldsymbol{w} \in C^1_c(\Omega, \mathbb{R}^{n \times m})} \int_{\Omega} \alpha \|\boldsymbol{w} - D\boldsymbol{n}\| + \gamma g \|D\boldsymbol{w}\|_F \, dx \quad (6)$$

and reparametrized depth $\zeta := \frac{1}{2} z^2$ is related to normals by a linear operator $N(\zeta)$ [2].

Optimization for depth: Terms not dependent on ζ are removed, resulting in saddle point problem:

$$\min_{\zeta, \alpha > 0} \max_{\|\boldsymbol{p}\|_2 \le \lambda, |\xi| \le 1} \big\{ (\boldsymbol{p}, N\zeta - \alpha \boldsymbol{n}) + (\xi, \rho|_{\zeta_0} + (\zeta - \zeta_0)\partial_\zeta \rho|_{\zeta_0}) \big\}. \quad (7)$$

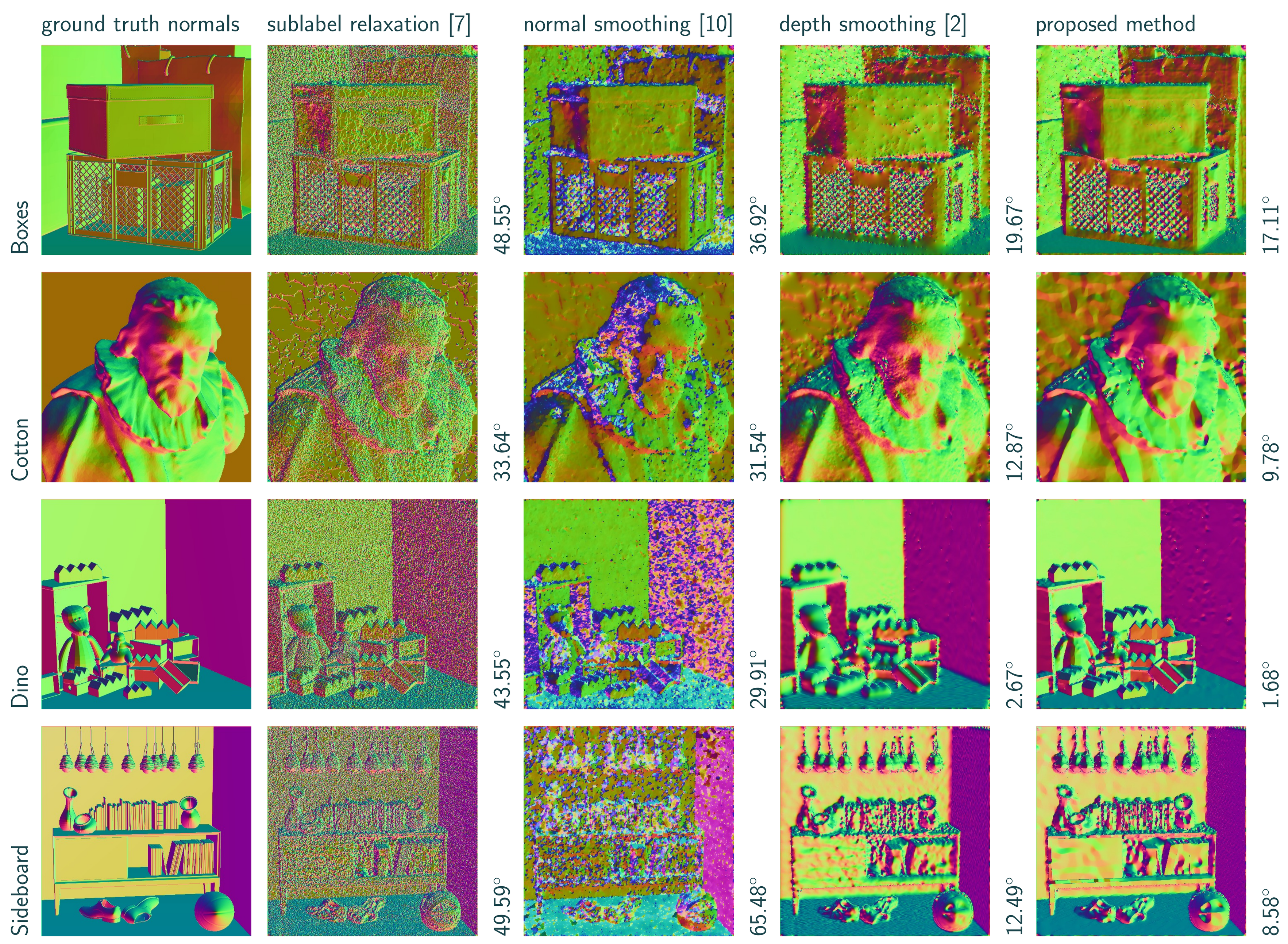
Solved using the primal-dual algorithm [1].

Optimization for normals: Removing all terms not depending on $\boldsymbol{n}$: L^1 denoising problem

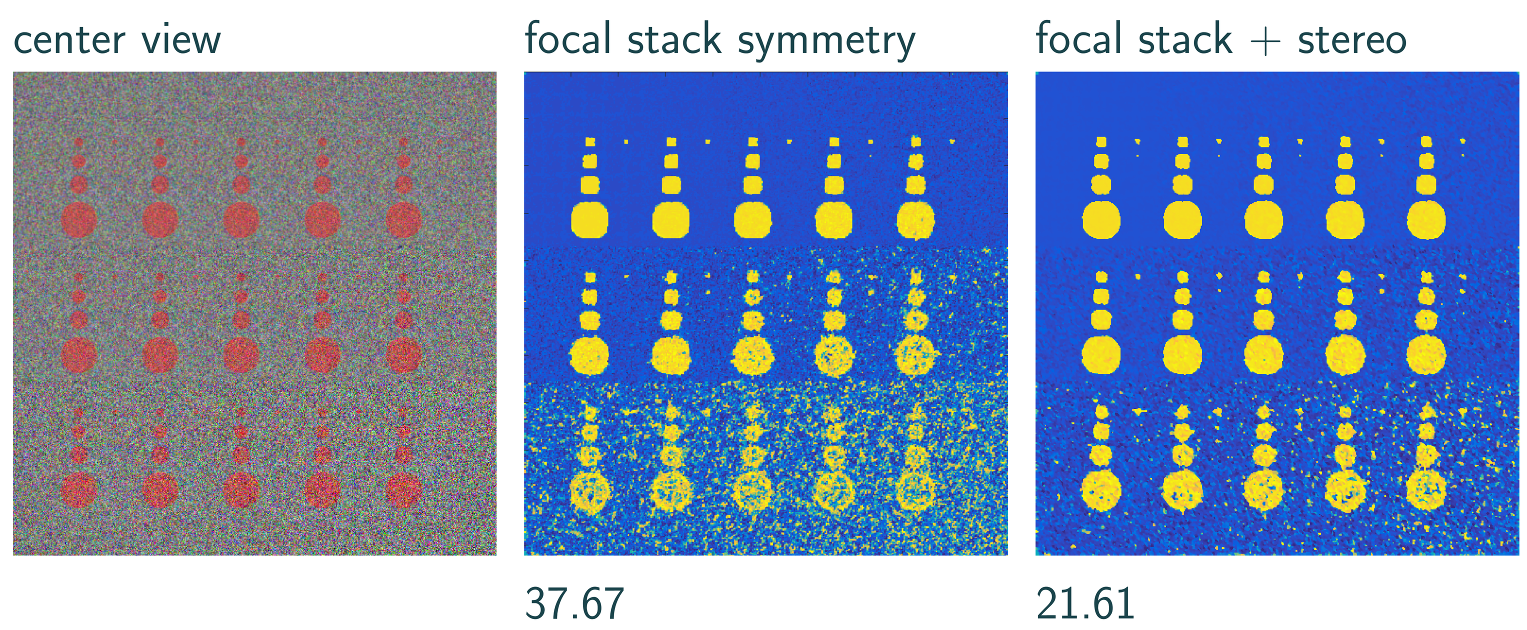
$$\min_{\|\boldsymbol{n}\|=1} \int_{\Omega} \lambda \|N\zeta\| \, \|\boldsymbol{w} - \boldsymbol{n}\| \, dx + R(\boldsymbol{n}). \quad (8)$$

Nonconvex due to $\|\boldsymbol{n}\| = 1$: adoption of ideas from [10] for solution (local parameterization of tangent space, effective linearization).

Comparison of normal maps for different methods



Combining cost terms can improve robustness



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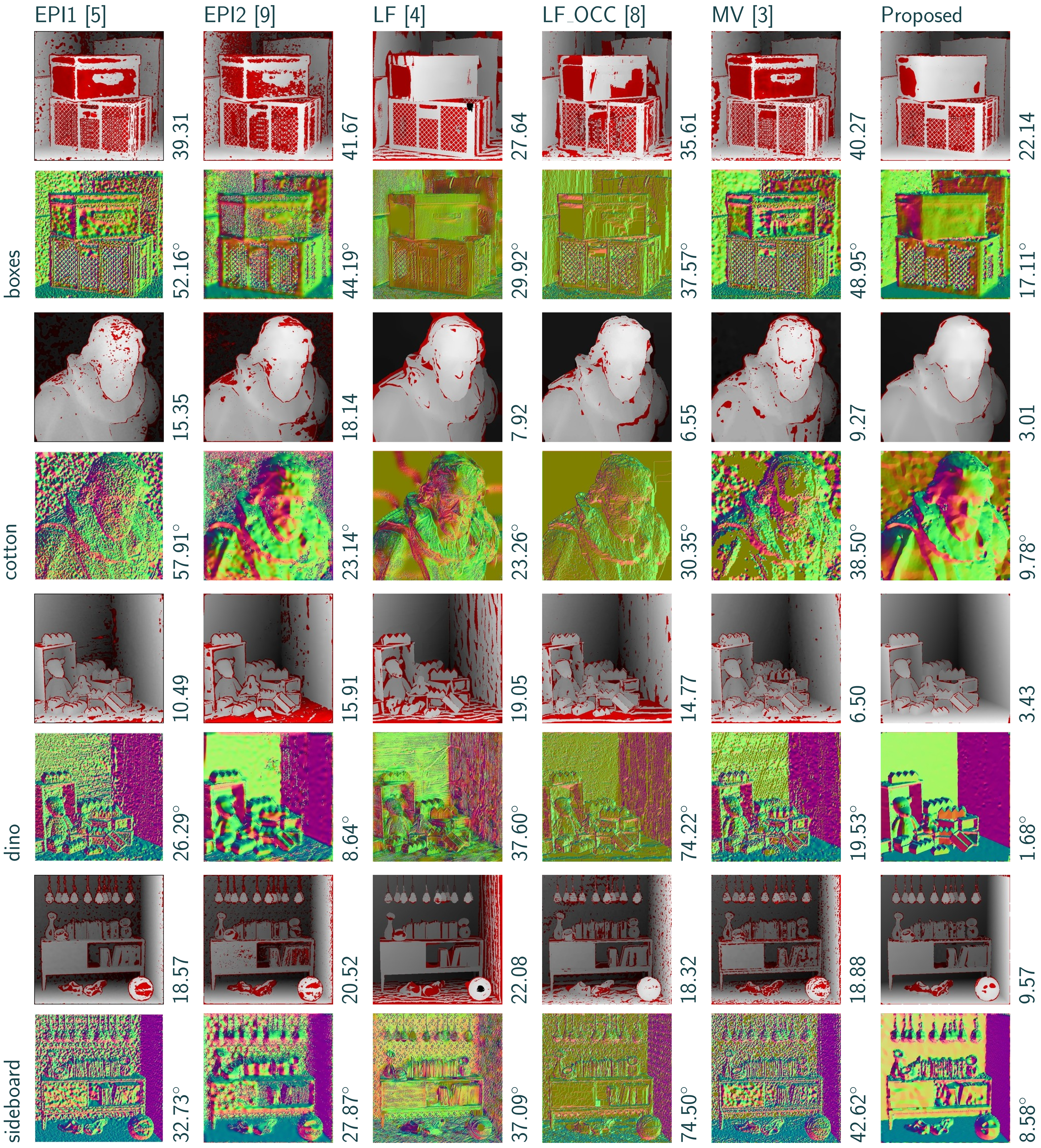
Experiments

Results on benchmark [3]



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Real-world results