On Evaluation of 6D Object Pose Estimation

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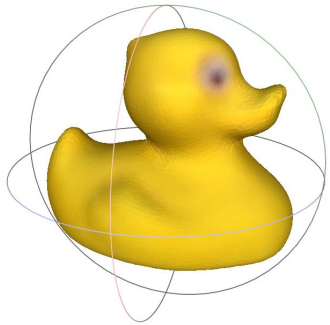
2nd International Workshop on Recovering 6D Object Pose (ECCV 2016)
9th October 2016, Amsterdam

How to Evaluate a 6D Object Pose Estimate?

Test RGB-D image

Evaluated 6D pose estimator



Training data
(e.g. a 3D model)

Evaluator

How good is the pose?

Images and model from dataset:
Hinterstoisser et al. (ACCV 2012)

Standard Approaches

Estimated pose: $\hat{\mathbf{P}} = (\hat{\mathbf{R}}, \hat{\mathbf{t}})$

Ground truth pose: $\bar{\mathbf{P}} = (\bar{\mathbf{R}}, \bar{\mathbf{t}})$

1. Translational and rotational error

Shotton et al., Scene Coordinate Regression Forests for Camera Relocalization in RGB-D Images, CVPR 2013

$$e_{\mathrm{TE}}(\hat{\mathbf{t}}, \bar{\mathbf{t}}) = \left\| \bar{\mathbf{t}} - \hat{\mathbf{t}} \right\|_2$$

$$e_{\mathrm{RE}}(\hat{\mathbf{R}}, \bar{\mathbf{R}}) = \arccos\left(\left(\mathrm{Tr}(\hat{\mathbf{R}}\bar{\mathbf{R}}^{-1}) - 1 \right) / 2 \right)$$

2. Average distance of corresponding model points

Hinterstoisser et al., Model Based Training, Detection and Pose Estimation of Texture-Less 3D Objects in Heavily Cluttered Scenes, ACCV 2012

$$e_{\mathrm{ADD}}(\hat{\mathbf{P}}, \bar{\mathbf{P}}; \mathcal{M}) = \operatorname*{avg}_{\mathbf{x} \in \mathcal{M}} \left\| \bar{\mathbf{P}}\mathbf{x} - \hat{\mathbf{P}}\mathbf{x} \right\|_2$$

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Intuitive, until pose ambiguity enters the game...

Pose Ambiguity

Due to **object symmetries**, multiple poses may be **indistinguishable**

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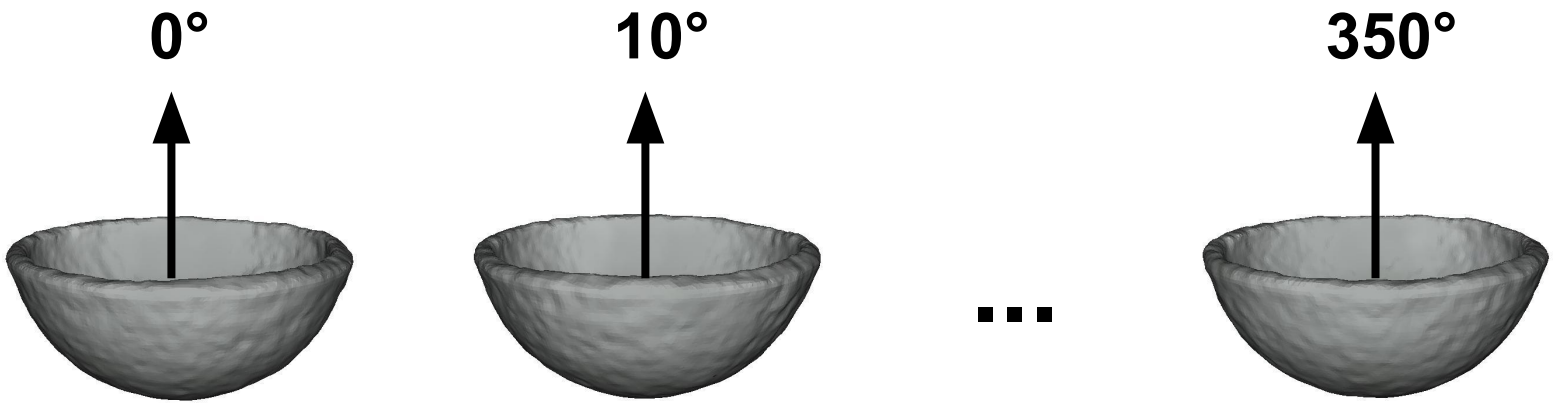

Rotational symmetry

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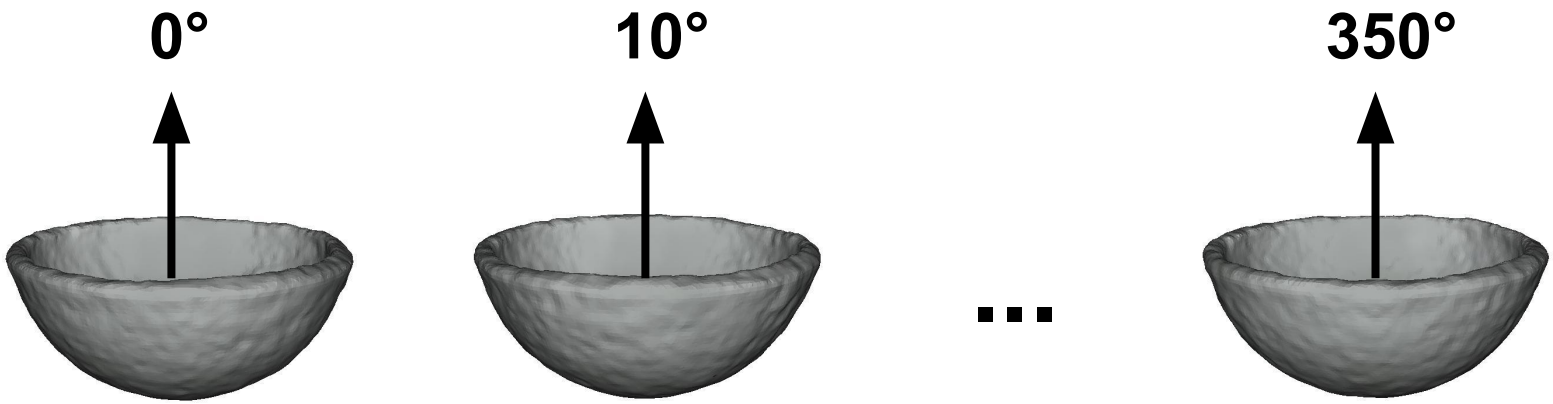

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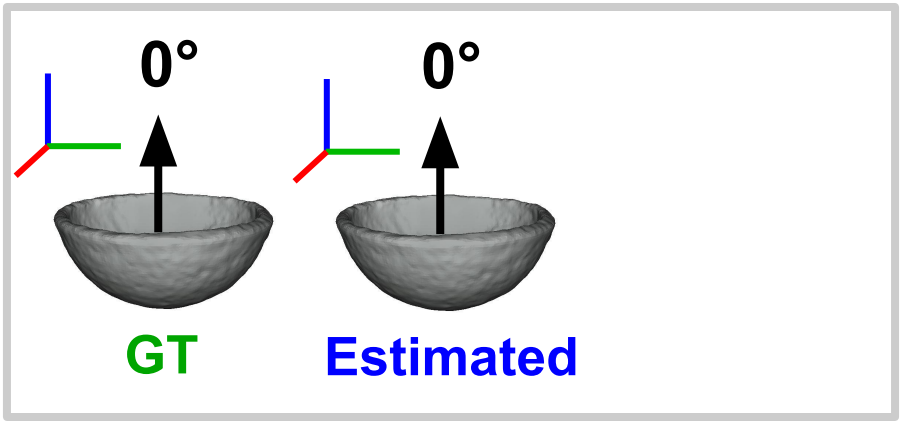

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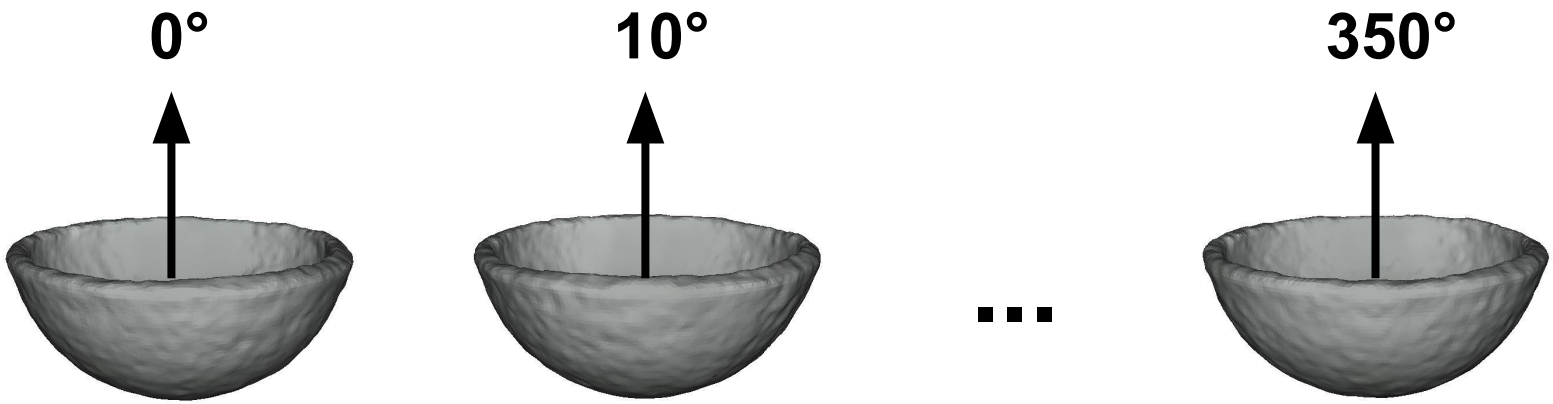

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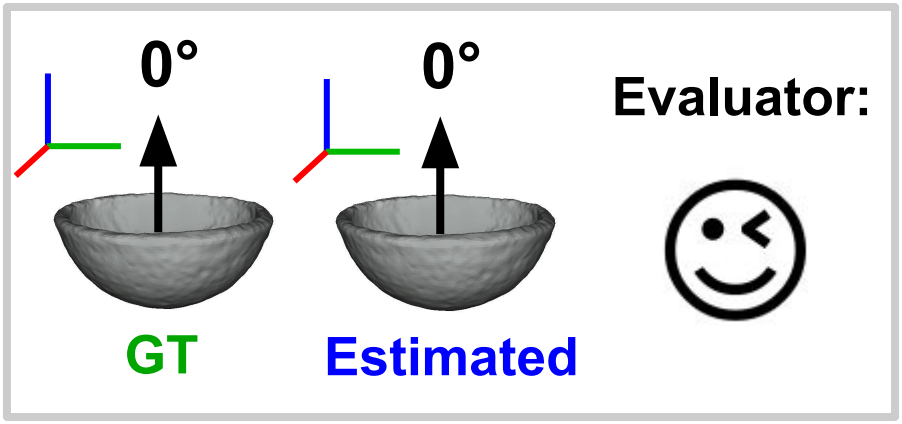

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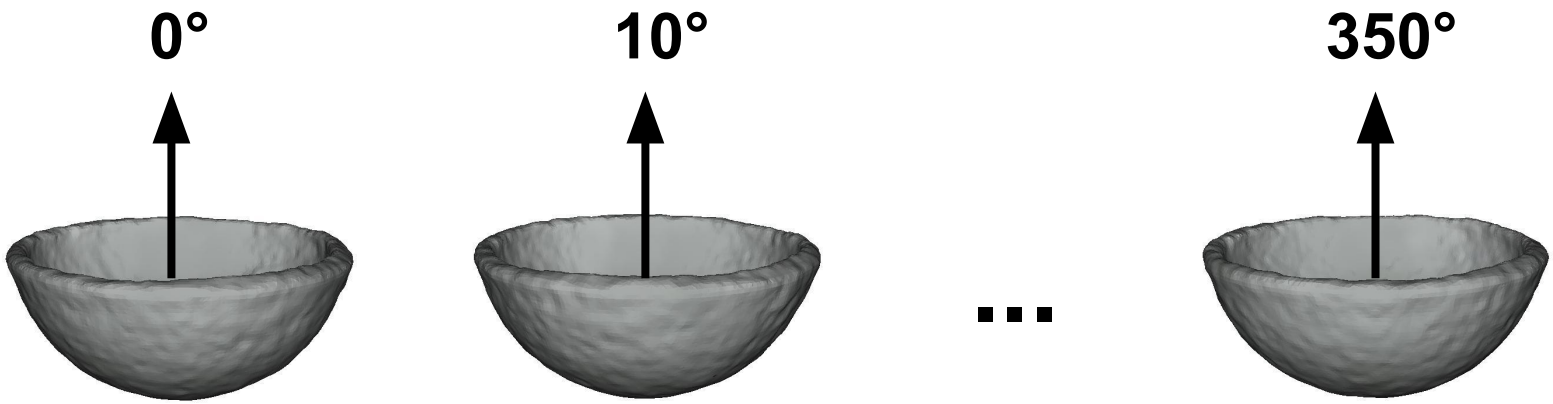

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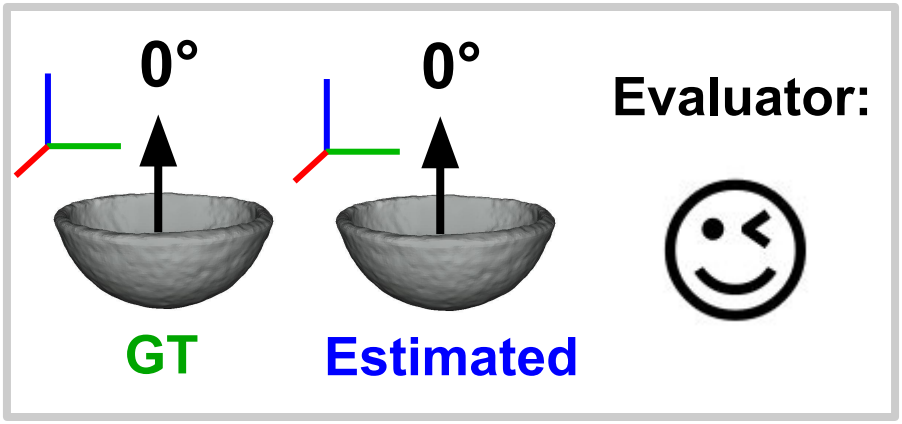

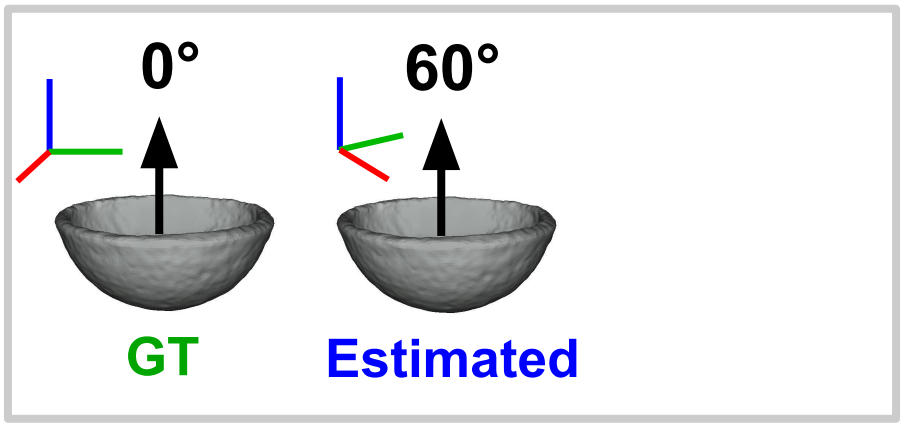

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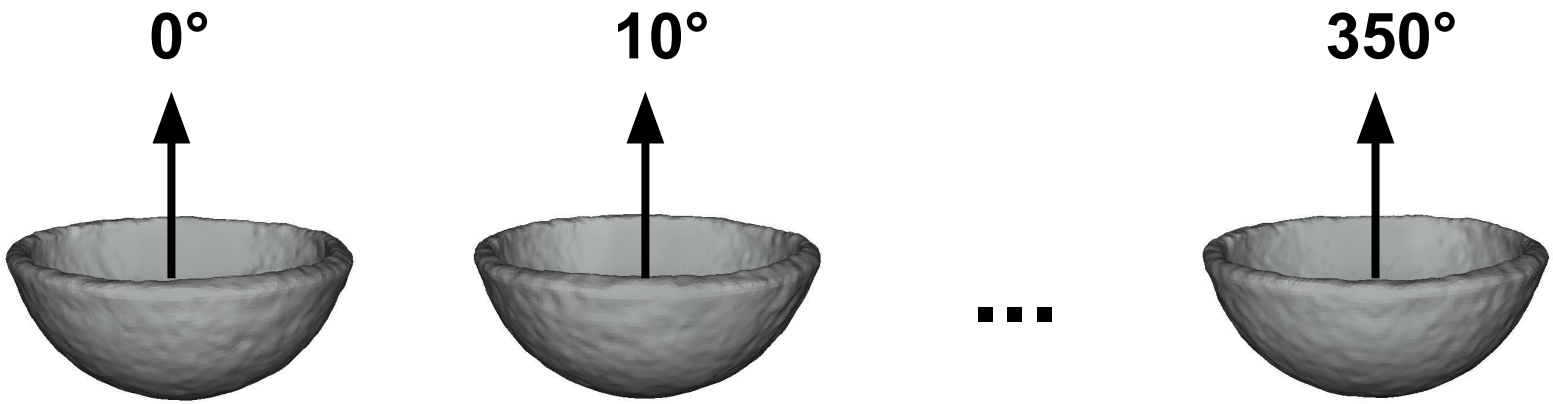

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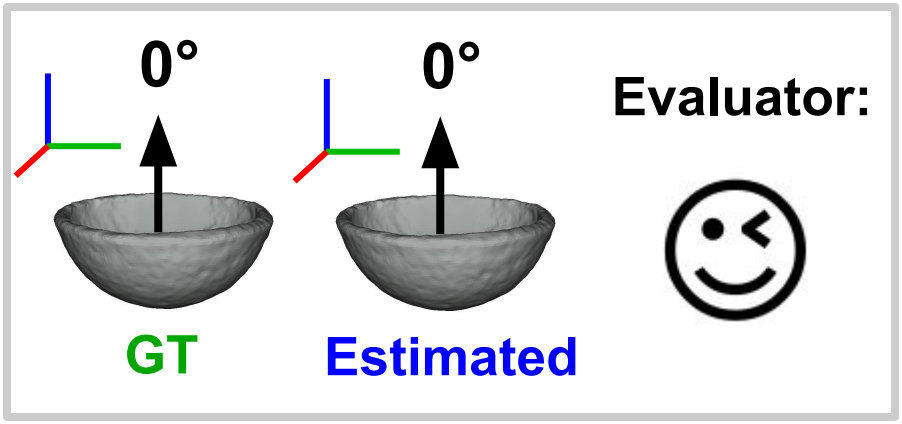

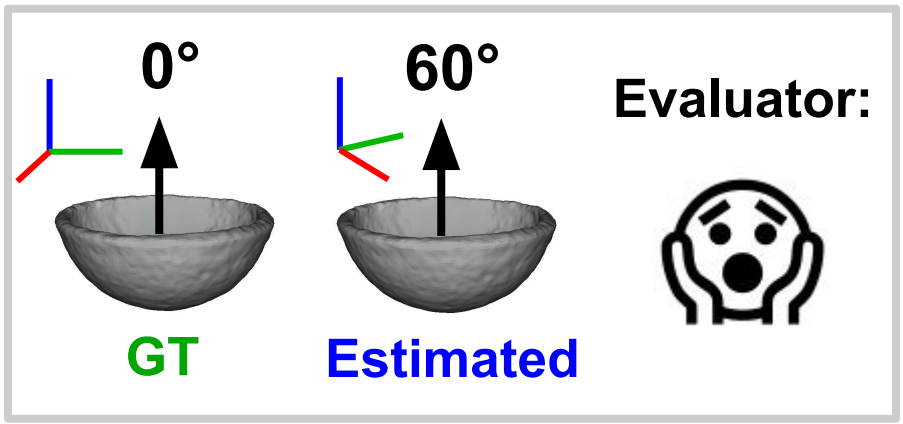

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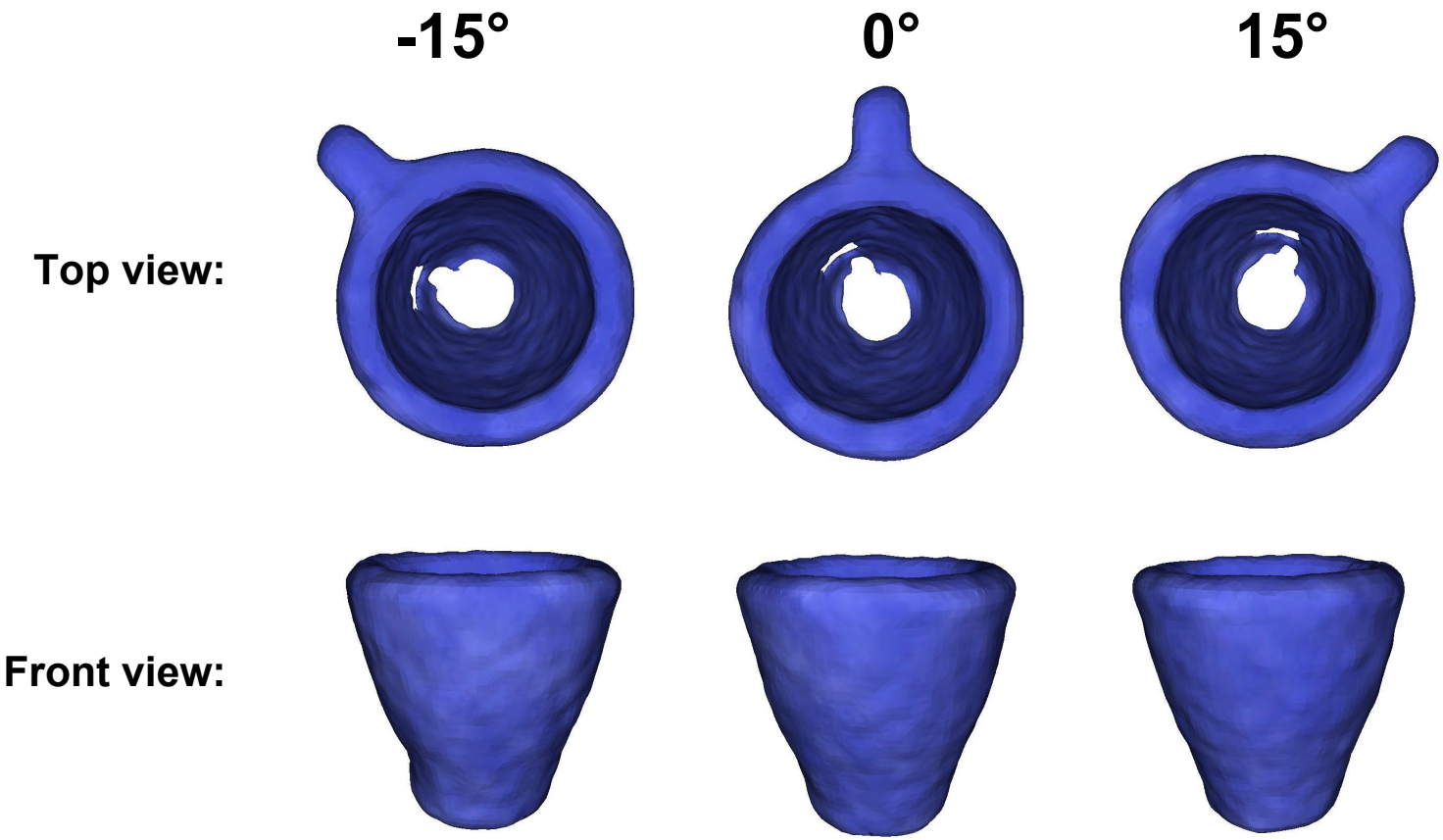

Partial symmetry - self-occlusion

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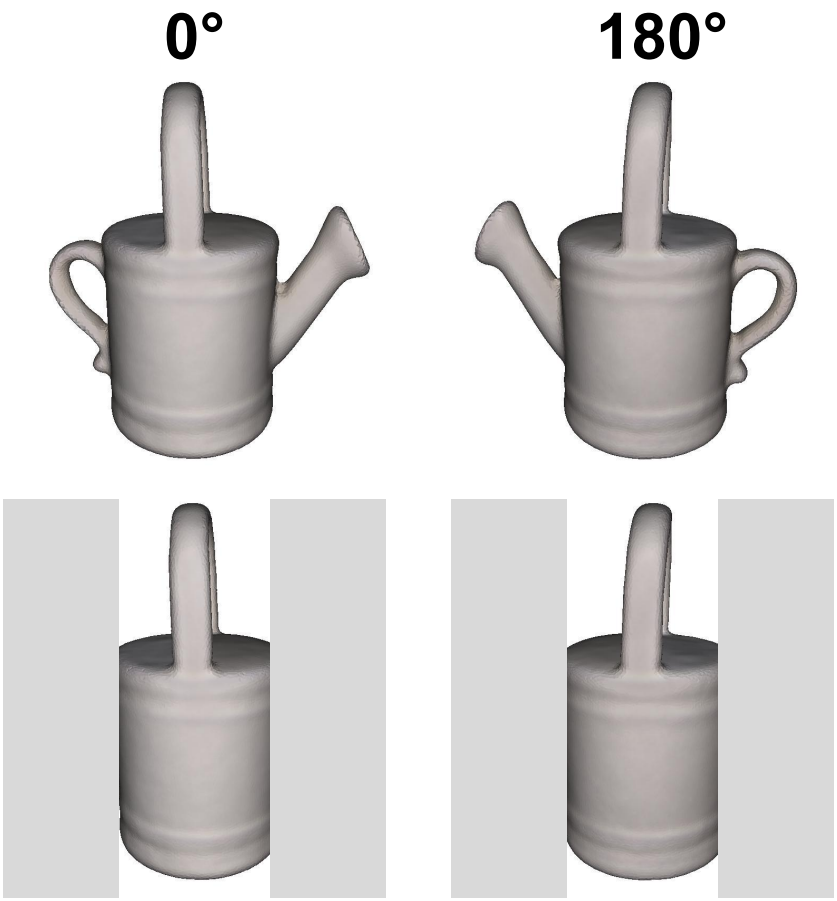

Partial symmetry - occlusion

Extension of the Standard Errors

1. **Find the indistinguishable poses**
2. Final error given by e.g. **minimum error** over the indistinguishable set

The indistinguishable poses could be found by e.g.:

1. Identification of the visible part of the object surface
2. Finding repetitions of the visible part on the full object surface using:

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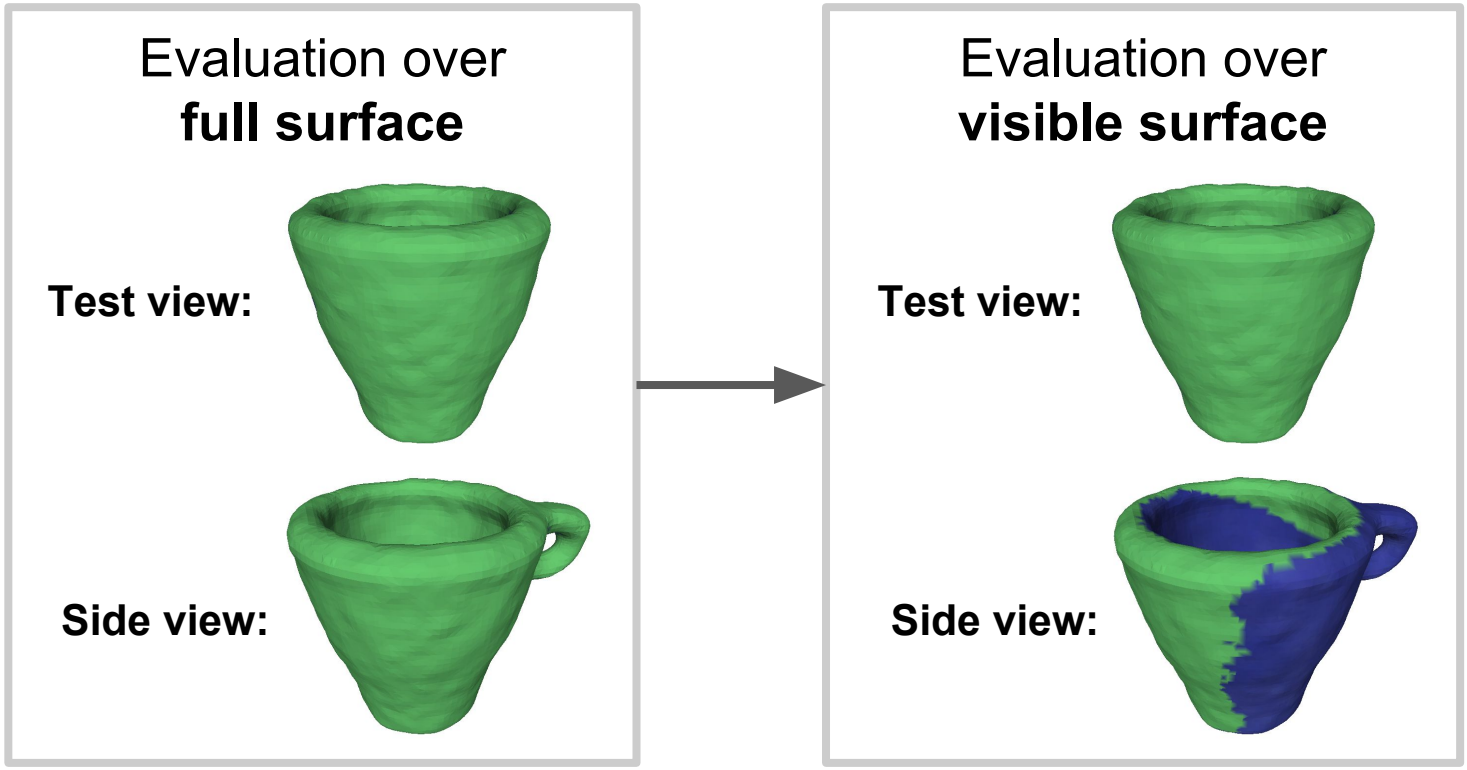
Disadvantages:

- Complicates and slows down the evaluation process
- Problems with representation of sets of poses

Proposal: Evaluate over Visible Surface

Measure the pose error only over the visible part of the object surface



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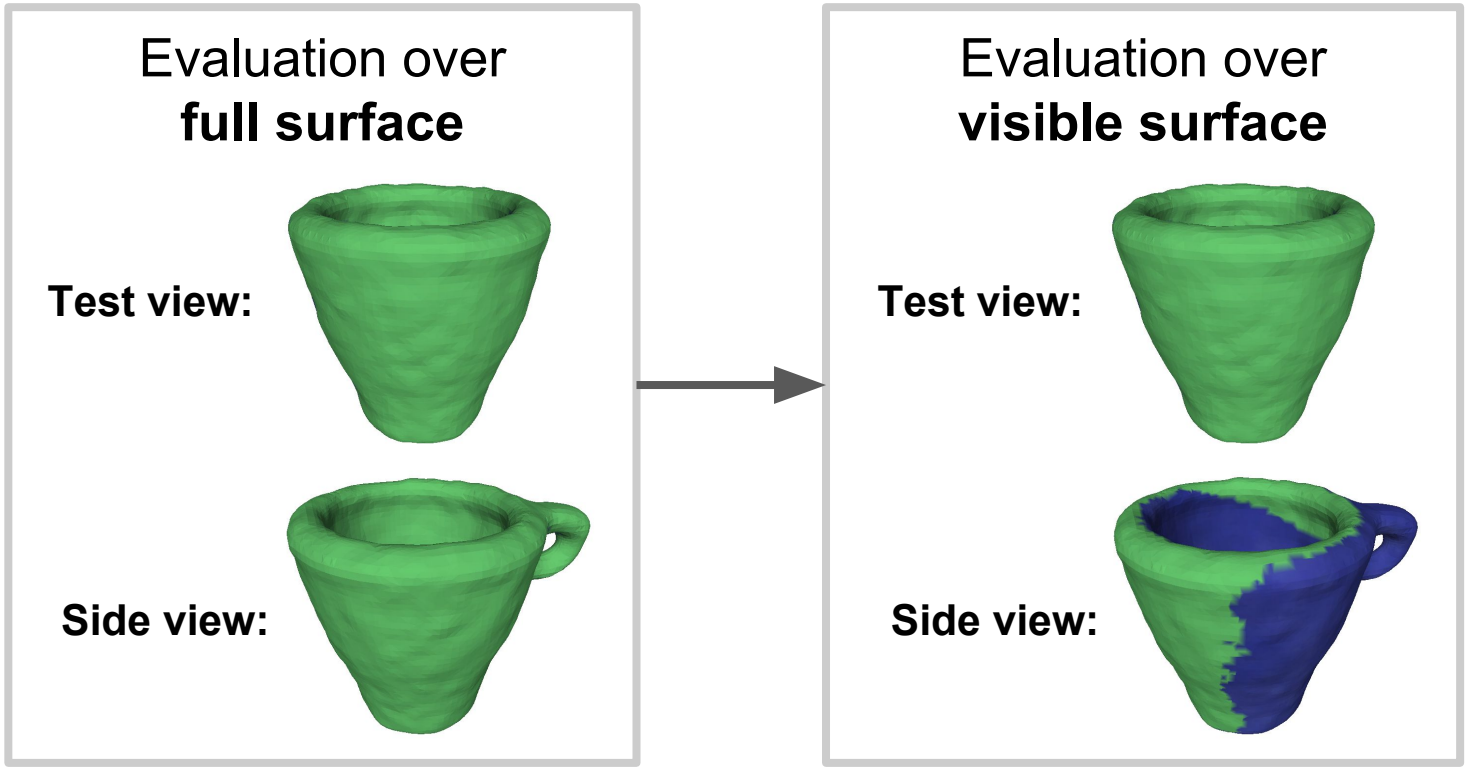

- Inherently invariant under pose ambiguity (the visible surface is the same in all indistinguishable poses)

Visibility

Object surface at a pixel is visible if it is **in front of the scene surface, or at most by a tolerance δ behind**

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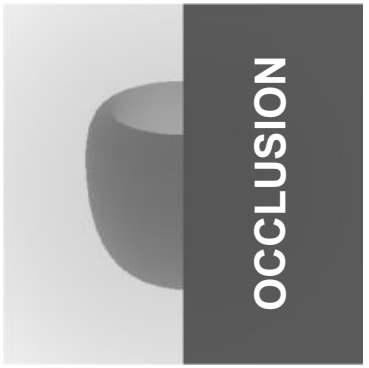

Test depth im.

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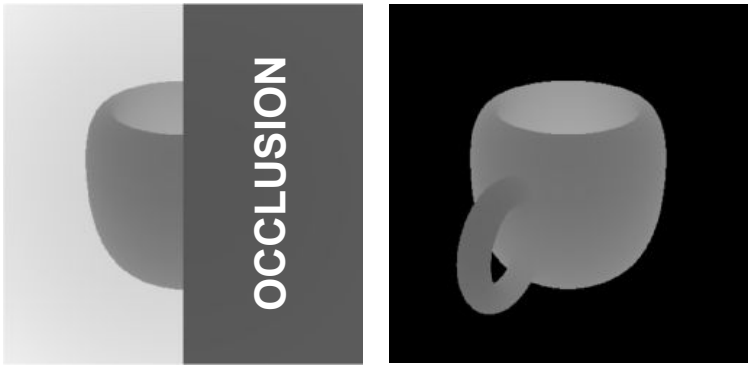

Test depth im. **Rendered pose**

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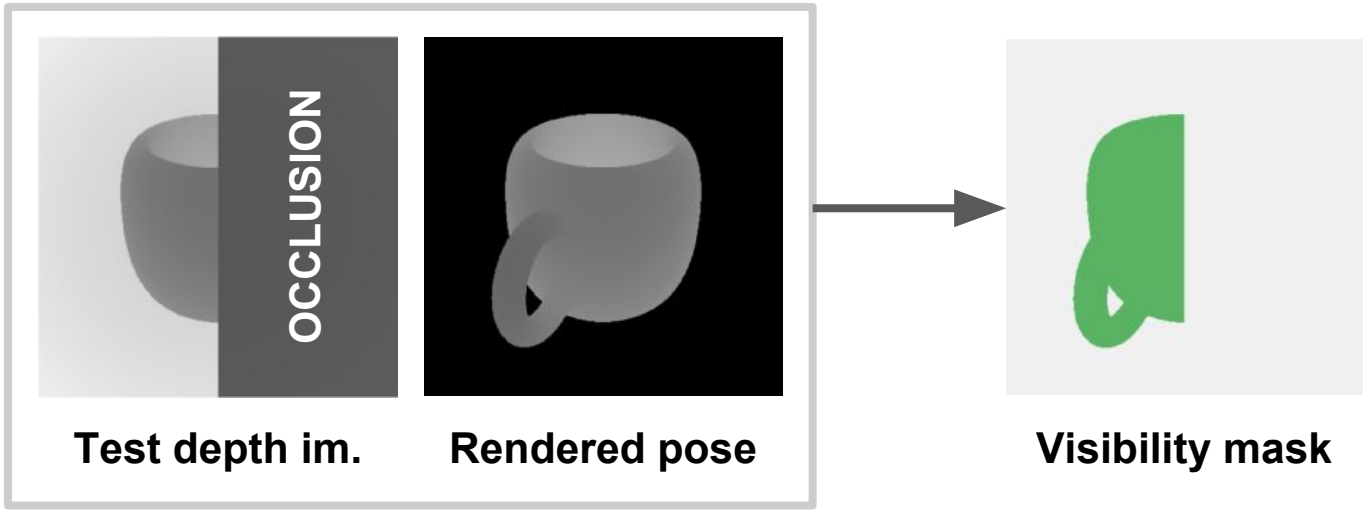

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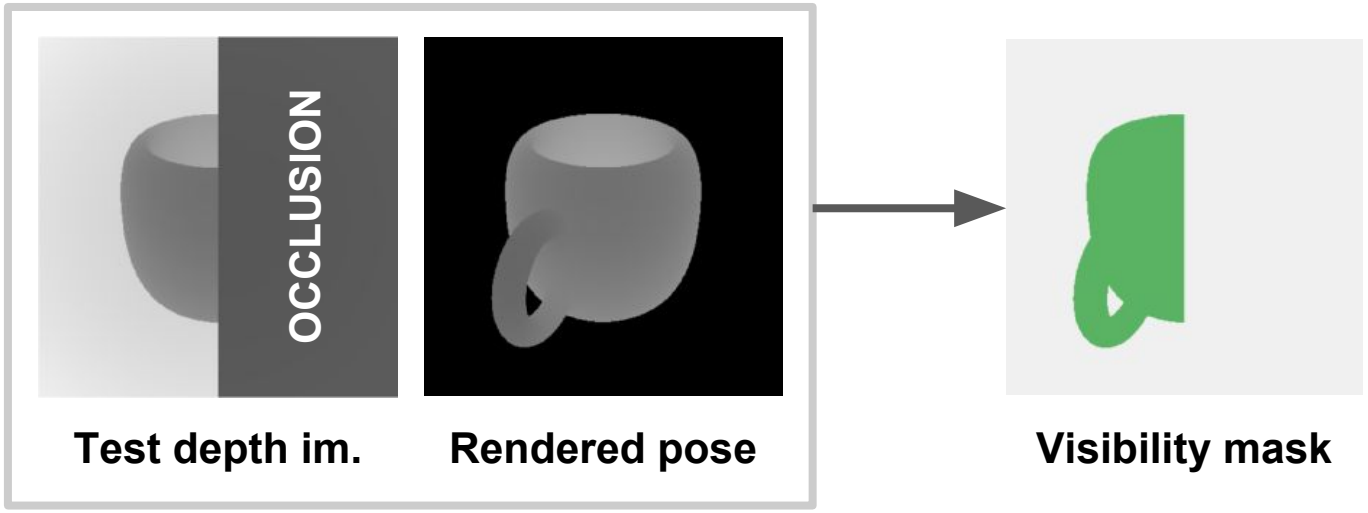
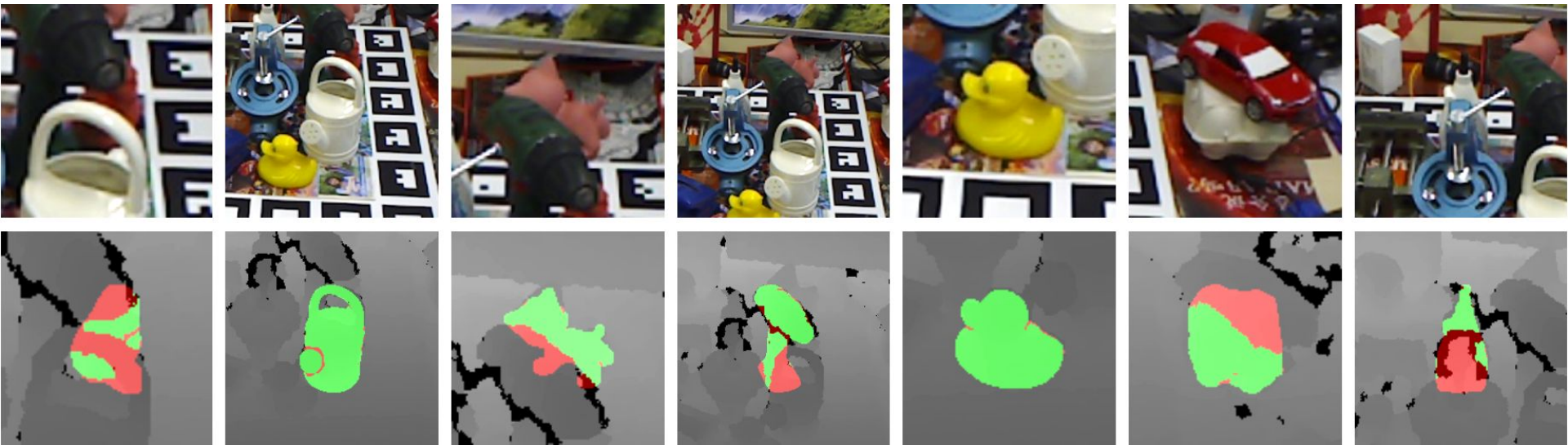




Visible Surface Discrepancy (VSD)

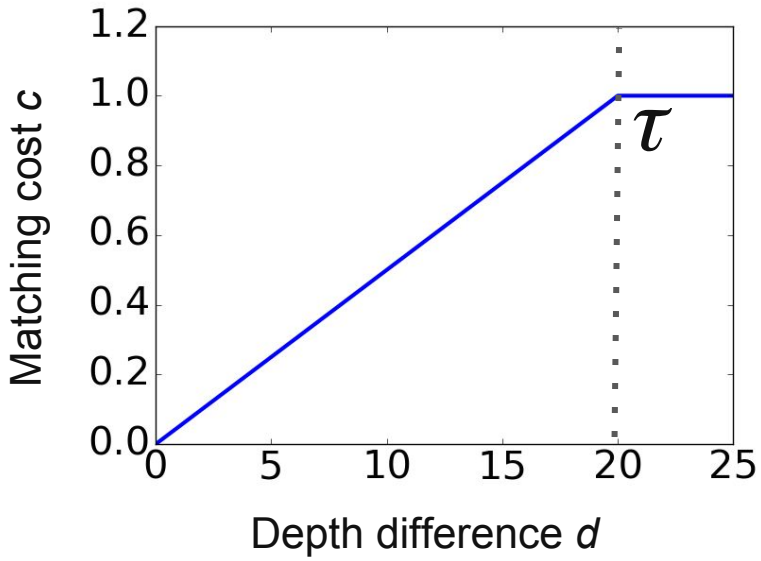
The average pixel-wise matching cost over union of the visibility masks:

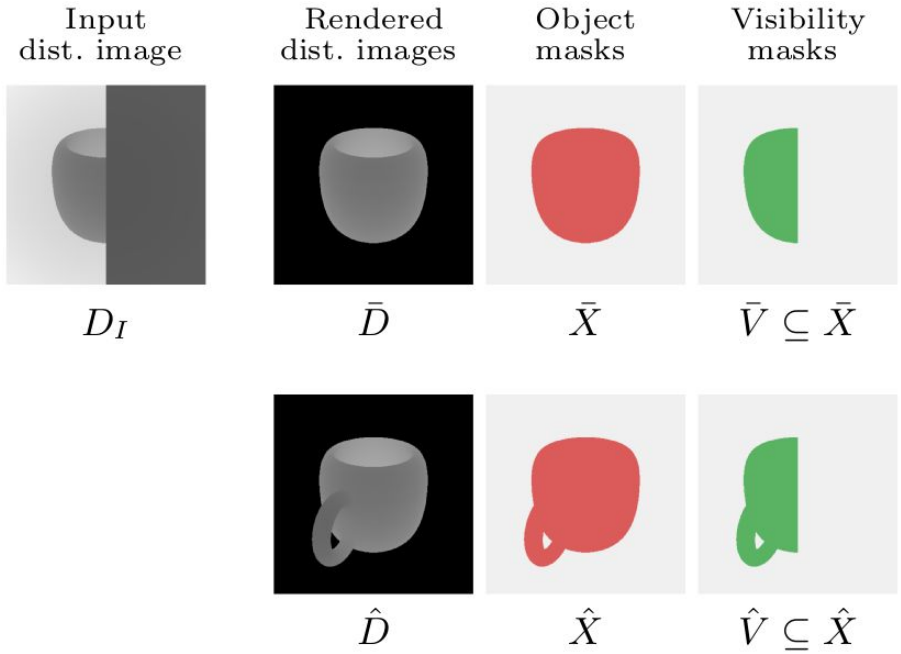
$$e_{\text{VSD}}(\hat{\mathbf{P}}, \bar{\mathbf{P}}; \mathcal{M}, I, \delta, \tau) = \underset{p \in \hat{V} \cup \bar{V}}{\text{avg}} \; c(p, \hat{D}, \bar{D}, \tau)$$

Pixel-wise matching cost:

$$c(p, \hat{D}, \bar{D}, \tau) = \begin{cases} d \,/\, \tau & \text{if } p \in \hat{V} \cap \bar{V} \wedge d < \tau \\ 1 & \text{otherwise,} \end{cases}$$

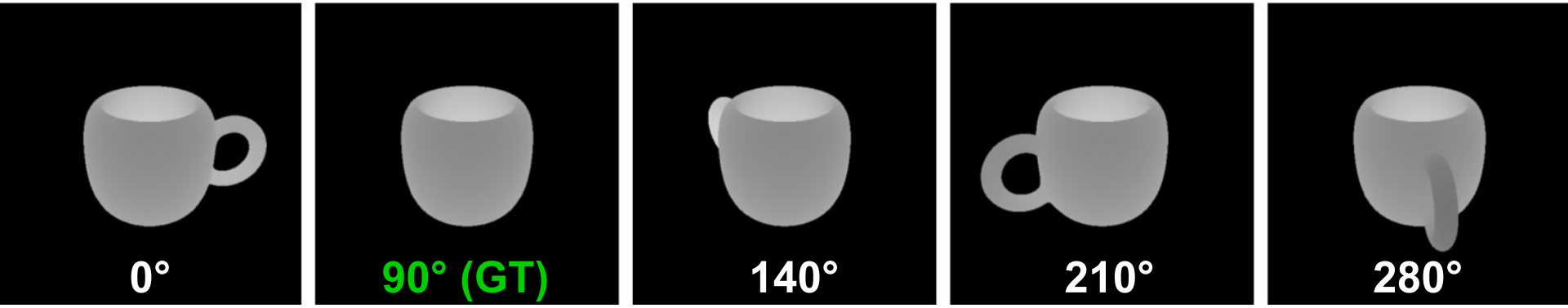
$$d = |\hat{D}(p) - \bar{D}(p)|$$

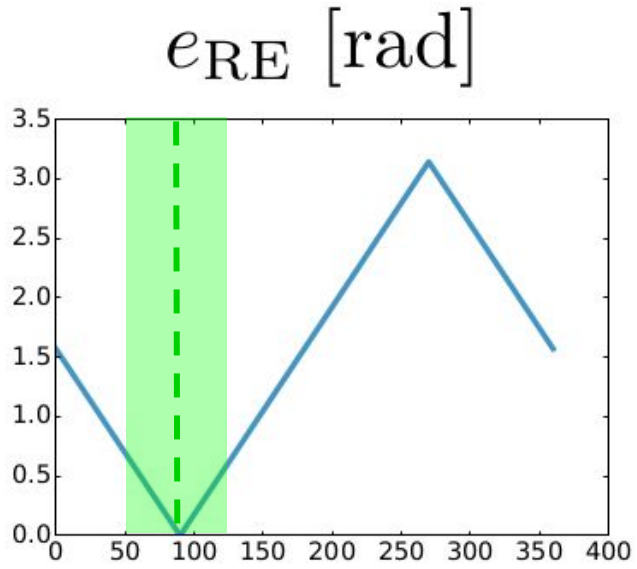


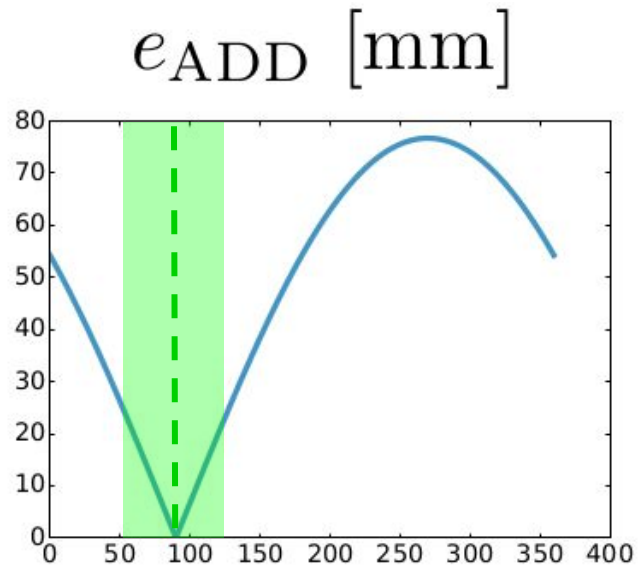


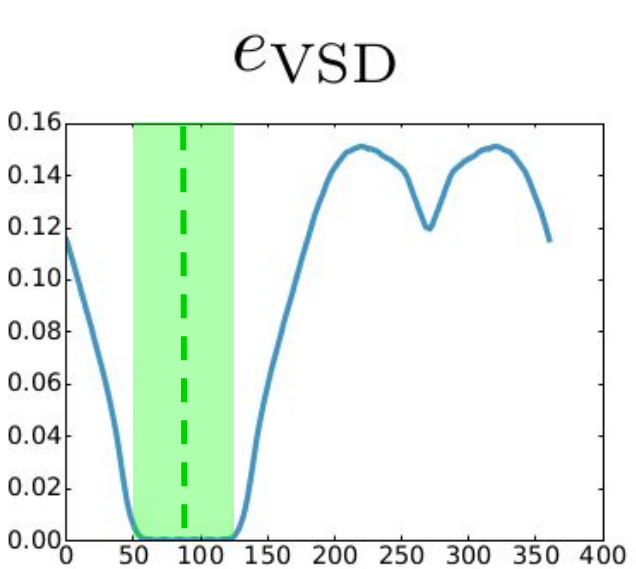
Comparison of Pose Error Functions

- Synthetic sequence (P_0, P_1, …, P_{359}) of 6D poses of a rotating cup
- Pose P_i represents a rotation by i°
- The poses were evaluated against P_{90}, which was set to be the GT







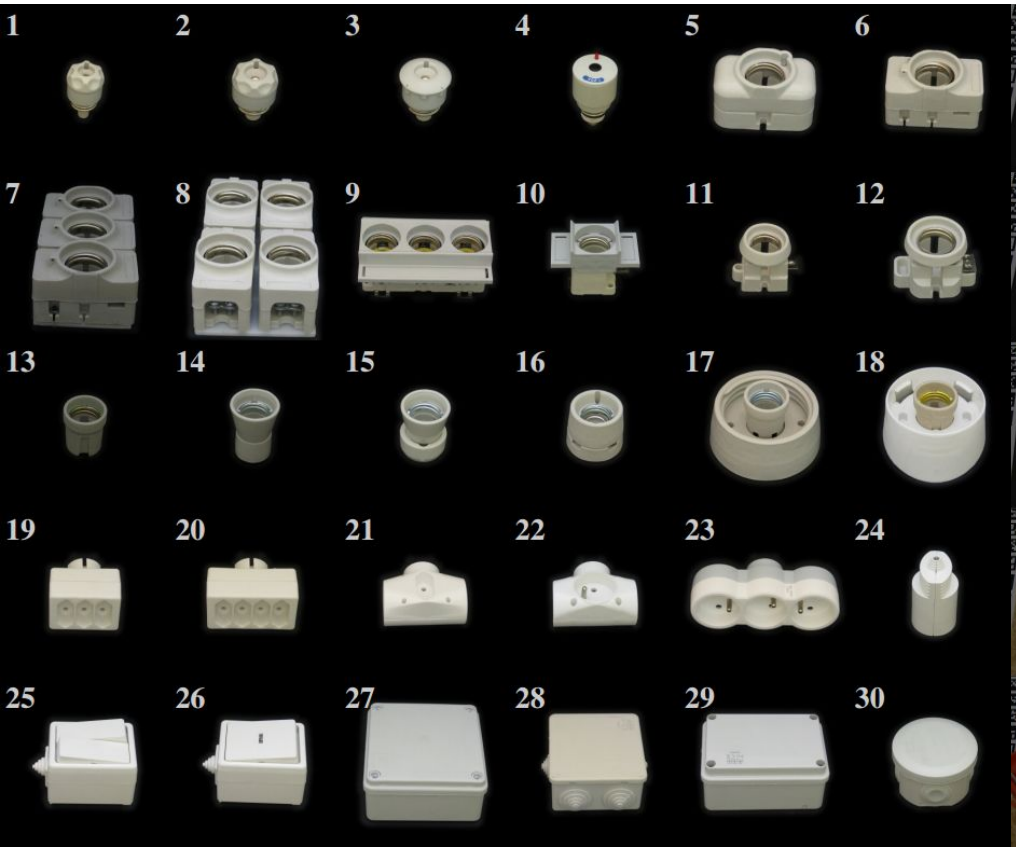


T-LESS

An RGB-D Dataset for 6D Pose Estimation of Texture-less Objects

http://cmp.felk.cvut.cz/**t-less**

- **30 Industry-relevant objects:** No discriminative color, no texture, often similar in shape, some objects are parts of others
- **Training data provided in several forms:** 1) RGB-D templates annotated with 6D object poses, 2) 3D CAD models, and 3) automatically reconst. 3D models
- **Test data includes RGB-D images of 20 scenes with accurate ground truth poses**
- **All images captured with three synchronized sensors:** Primesense CARMINE 1.09, Microsoft Kinect v2, and Canon IXUS 950 IS



Thank you!

Extension of the Standard Errors?

Minimum over: $Q = [\hat{\mathbf{P}}]_{\mathcal{M},I,\varepsilon} \times [\bar{\mathbf{P}}]_{\mathcal{M},I,\varepsilon}$

Indistinguishable poses of the estimated pose

Indistinguishable poses of the ground truth pose

$$e_{\mathrm{ACPD}}(\hat{\mathbf{P}}, \bar{\mathbf{P}}; \mathcal{M}, I, \varepsilon) = \min_{(\hat{\mathbf{P}}', \bar{\mathbf{P}}') \in Q} \operatorname*{avg}_{\mathbf{x} \in \mathcal{M}} \left\| \bar{\mathbf{P}}'\mathbf{x} - \hat{\mathbf{P}}'\mathbf{x} \right\|_2$$

The sets of indistinguishable poses could be found by e.g.:

1. Identification of the visible part of the object surface
2. Finding repetitions of the visible part on the whole object surface using:
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Who Finds the Indistinguishable Poses?

Option #1: **The estimator provides the set of indistinguishable poses, instead of a point estimate**

- Relevant to robotic manipulation tasks
- Not provided by the current SOTA methods

Option #2: **The evaluation system finds the indistinguishable poses**

- No extra requirements on the methods
- Slows down and complicates the evaluation process

But do we really need to find the poses?