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Multiframe Scene Flow with Piecewise Rigid Motion

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Scene Flow

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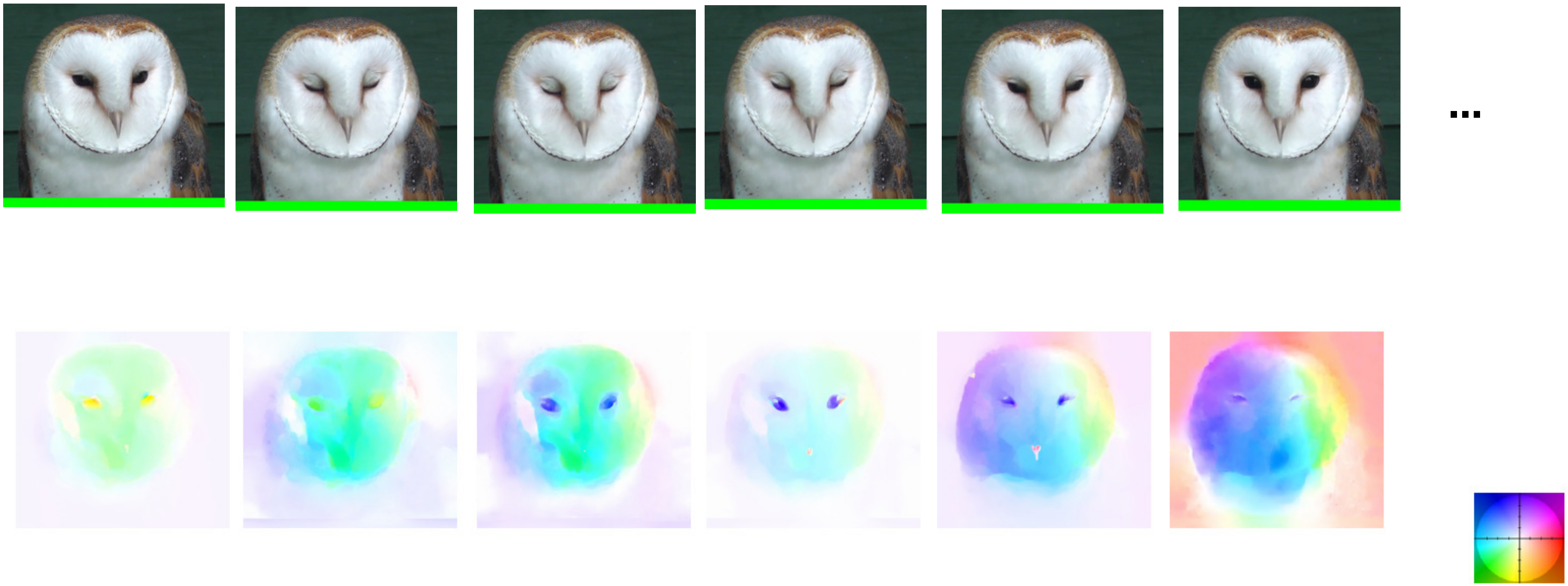
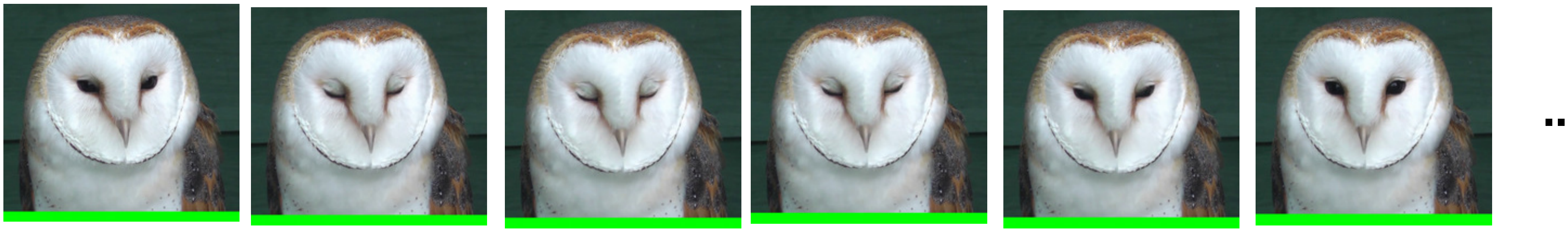
Scene Flow



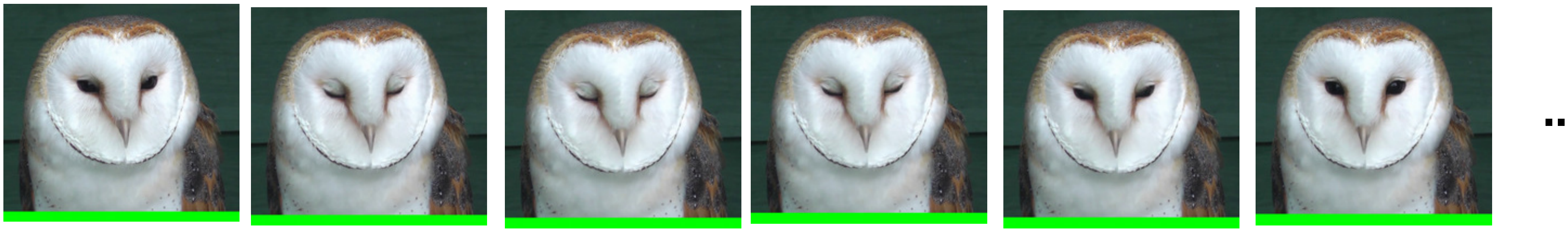
Scene Flow



Scene Flow Estimation:

- input: image sequence (RGB or RGB-D)
- output: 3D displacement field between underlying 3D scene states

Scene Flow



Scene Flow Estimation:

- input: image sequence (RGB or RGB-D)
- output: 3D displacement field between underlying 3D scene states

Overview

input RGB-D frames (overlayed)

ground truth optical flow

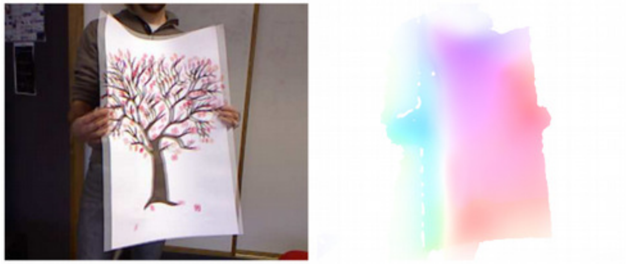
oversegmentation of the reference frame

segmentation transfer into the current frame

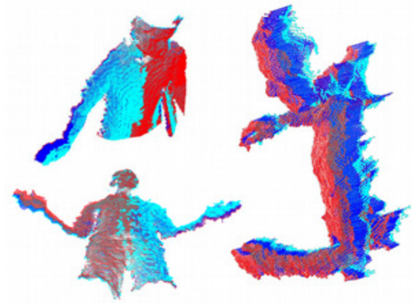
our MSF result (projected)

Overview

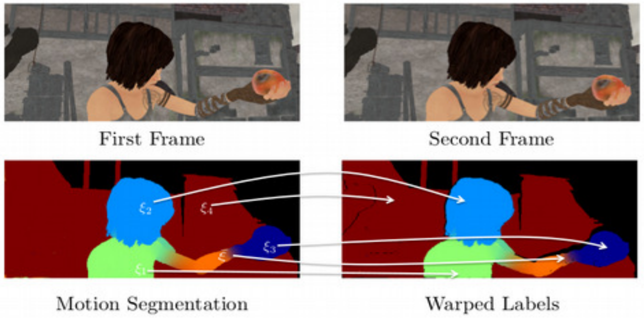
Vogel *et al. ICCV, 2013.*



Quiroga *et al. ECCV, 2014.*



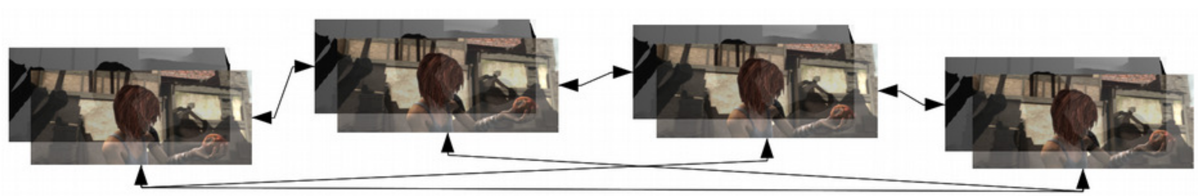
Jaimez *et al. ICRA, 2015.*

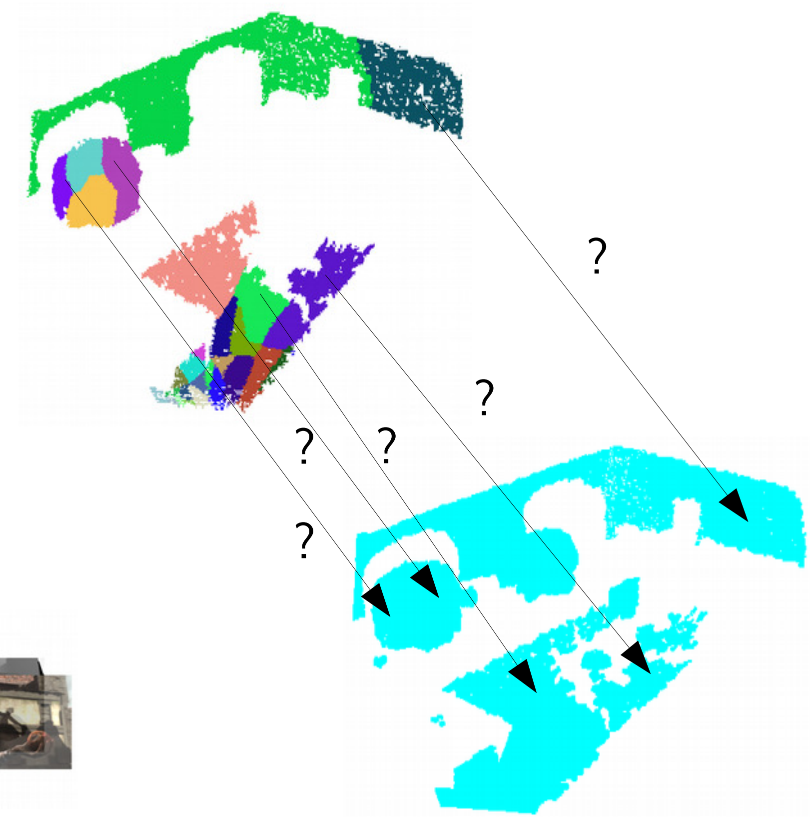


Jaimez *et al. 3DV, 2015.*

C. Vogel *et al.* Piecewise rigid scene flow. In ICCV, 2013.
J. Quiroga *et al.* Dense semi-rigid scene flow estimation from RGBD images. In ECCV, 2014.
M. Jaimez *et al.* A primal-dual framework for real-time dense rgb-d scene flow. In ICRA, 2015.
M. Jaimez *et al.* Motion cooperation: Smooth piece-wise rigid scene flow from rgb-d images. In 3DV, 2015.

Proposed Approach





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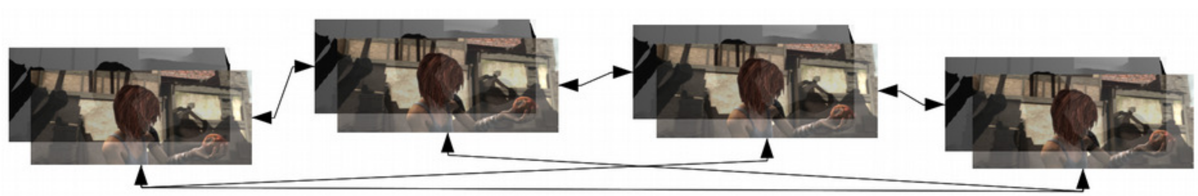
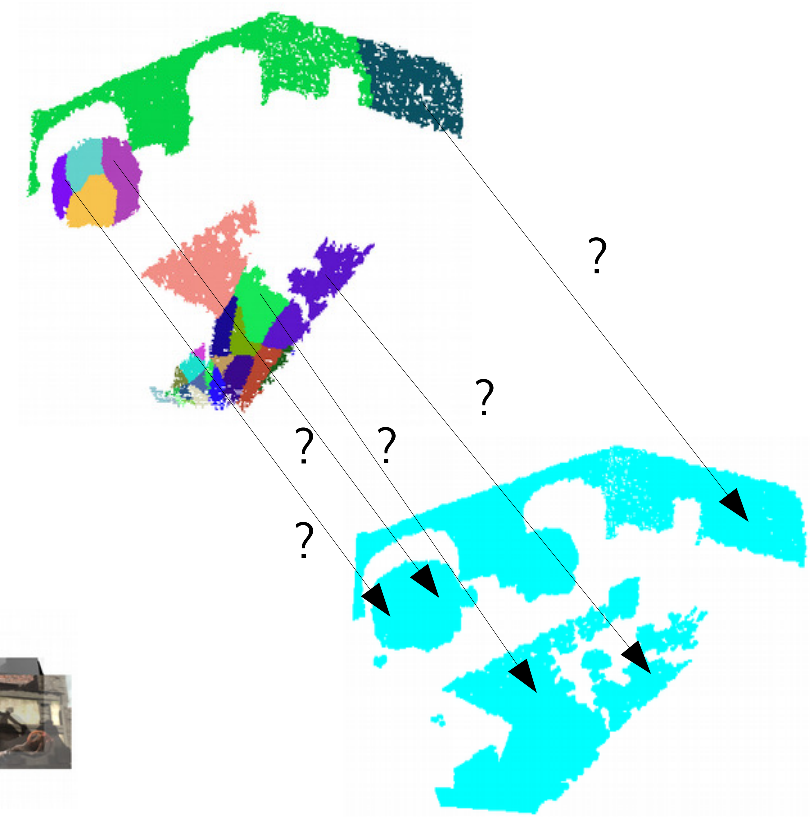
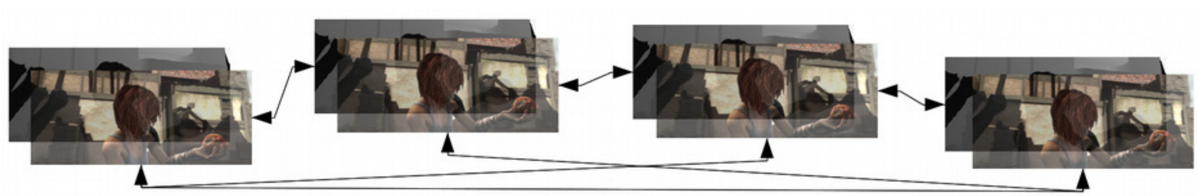
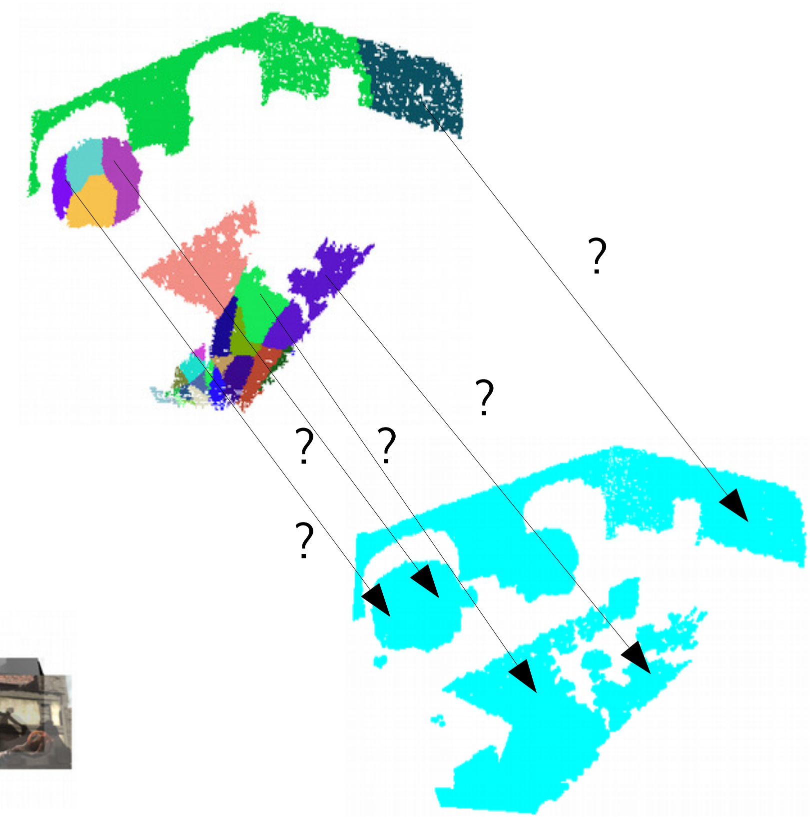




- **depth channel** is used to obtain oversegmentation of the scene
- segmentation of a scene is kept **fixed**
- a global scene-flow formulation over **multiple frames**

Proposed Approach





- take advantage of **point set registration** (**projective point-to-plane ICP term**)
- **lifting function** for coherent segment transformations

Proposed Approach

$$\mathfrak{E}(\mathbf{T}^1, \mathbf{T}^2, \ldots, \mathbf{T}^{|Z|}, \mathbf{w}) = \sum_{\zeta \in Z} \alpha_\zeta \, \mathfrak{E}_{\text{data}}(\mathbf{T}^\zeta) +$$

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Proposed Approach

vector of frame-to-frame segment transformations

$$\mathfrak{E}(\mathbf{T}^1, \mathbf{T}^2, \ldots, \mathbf{T}^{|Z|}, \mathbf{w}) = \sum_{\zeta \in Z} \alpha_\zeta \, \mathfrak{E}_{\text{data}}(\mathbf{T}^\zeta) + \sum_{\zeta \in Z} \beta_\zeta \, \mathfrak{E}_{\text{pICP}}(\mathbf{T}^\zeta) + \sum_{\zeta \in Z} \gamma_\zeta \, \mathfrak{E}_{\text{l.reg.}}(\mathbf{T}^\zeta, \mathbf{w}) + \eta \, \mathfrak{E}_{\text{r.opt.}}(\mathbf{w}) + \sum_{\zeta=3}^{|Z|} \lambda_\zeta \, \mathfrak{E}_{\text{c.}}(\mathbf{T}^\zeta).$$

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Proposed Approach

vector of frame-to-frame segment transformations

segment-to-segment connectivity weights

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Proposed Approach

vector of frame-to-frame segment transformations

segment-to-segment connectivity weights

brightness constancy

$$
\begin{aligned}
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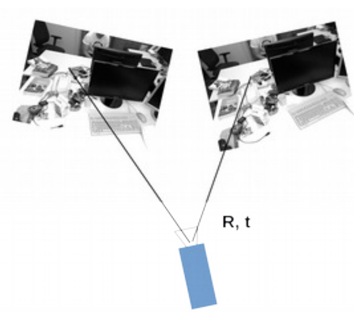
$$



Proposed Approach

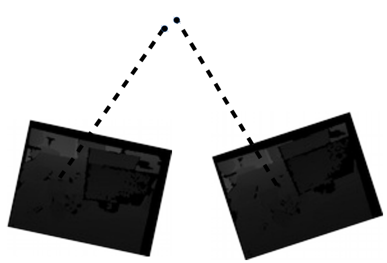
vector of frame-to-frame segment transformations

segment-to-segment connectivity weights

brightness constancy

projective ICP

$$\mathfrak{E}(\mathbf{T}^1, \mathbf{T}^2, \ldots, \mathbf{T}^{|Z|}, \mathbf{w}) = \sum_{\zeta \in Z} \alpha_\zeta \, \mathfrak{E}_{\text{data}}(\mathbf{T}^\zeta) + \\ + \sum_{\zeta \in Z} \beta_\zeta \, \mathfrak{E}_{\text{pICP}}(\mathbf{T}^\zeta) + \sum_{\zeta \in Z} \gamma_\zeta \, \mathfrak{E}_{\text{l.reg.}}(\mathbf{T}^\zeta, \mathbf{w}) + \\ + \eta \, \mathfrak{E}_{\text{r.opt.}}(\mathbf{w}) + \sum_{\zeta=3}^{|Z|} \lambda_\zeta \, \mathfrak{E}_{\text{c.}}(\mathbf{T}^\zeta).$$



Proposed Approach

vector of frame-to-frame segment transformations

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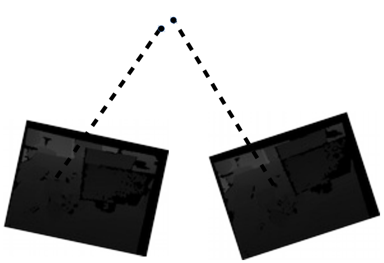
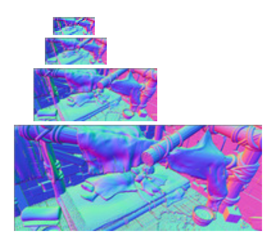
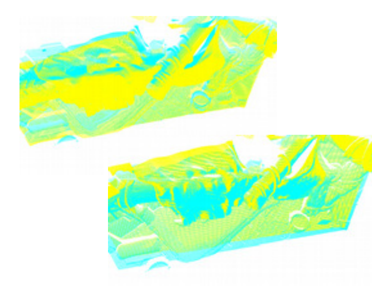


input frames



a pyramid with visualized normals



result of pICP

Proposed Approach

vector of frame-to-frame segment transformations

segment-to-segment connectivity weights

brightness constancy

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lifted segment pose regularizer

$$+ \eta \, \mathfrak{E}_{\text{r.opt.}}(\mathbf{w}) + \sum_{\zeta=3}^{|Z|} \lambda_\zeta \, \mathfrak{E}_{\text{c.}}(\mathbf{T}^\zeta).$$

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robust weight optimizer

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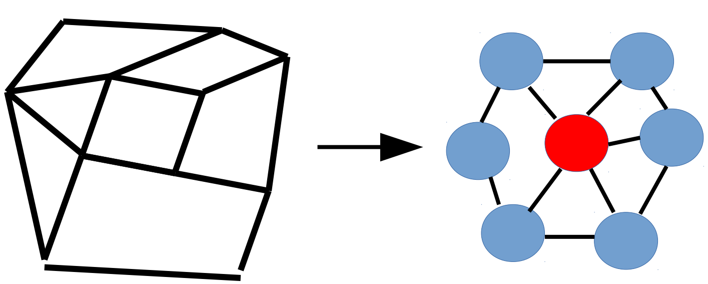
projective ICP

lifted segment pose regularizer

robust weight optimizer



compute oversegmentation

build a connectivity graph

	-1	
-1	4	-1
	-1	

Laplace

Proposed Approach

vector of frame-to-frame segment transformations

segment-to-segment connectivity weights

brightness constancy

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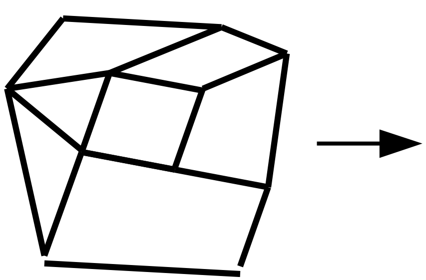
projective ICP

lifted segment pose regularizer

robust weight optimizer



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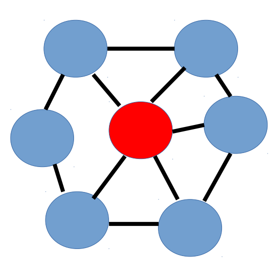

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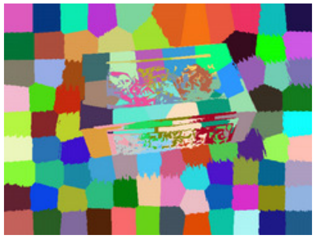

oversegmentation

segment connectivity

Proposed Approach

vector of frame-to-frame segment transformations

segment-to-segment connectivity weights

brightness constancy

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projective ICP

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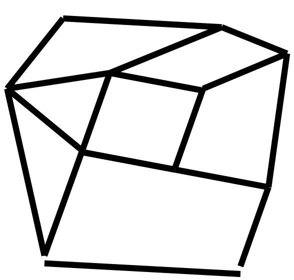
robust weight optimizer



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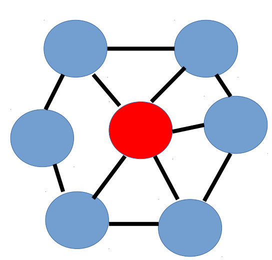

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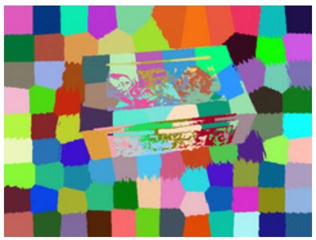

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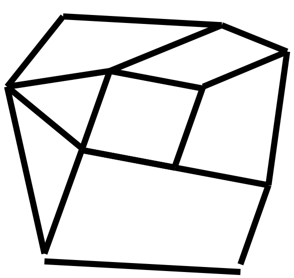

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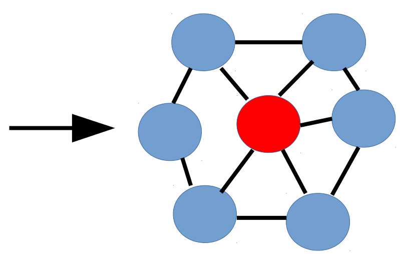

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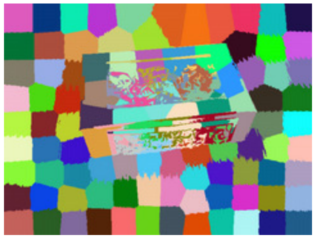

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robust weight optimizer

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projective ICP

lifted segment pose regularizer

robust weight optimizer

lifting function $\mathscr{F}(\cdot, \mathbf{w}) = \sum (w_i^2(\cdot) + (1 - w_i^2))$

Proposed Approach

vector of frame-to-frame segment transformations

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projective ICP

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robust weight optimizer

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projective ICP

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multiframe pose concatenation

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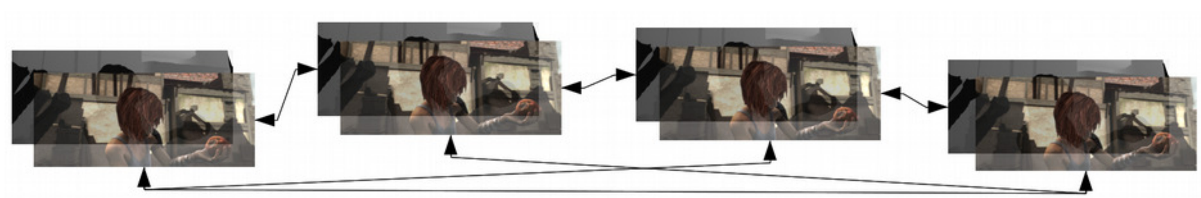
multiframe pose concatenation



optimization over multiple frames

Proposed Approach

vector of frame-to-frame segment transformations

segment-to-segment connectivity weights

brightness constancy

$$\mathfrak{E}(\mathbf{T}^1, \mathbf{T}^2, \ldots, \mathbf{T}^{|Z|}, \mathbf{w}) = \sum_{\zeta \in Z} \alpha_\zeta \, \mathfrak{E}_{\text{data}}(\mathbf{T}^\zeta) + \sum_{\zeta \in Z} \beta_\zeta \, \mathfrak{E}_{\text{pICP}}(\mathbf{T}^\zeta) + \sum_{\zeta \in Z} \gamma_\zeta \, \mathfrak{E}_{\text{l.reg.}}(\mathbf{T}^\zeta, \mathbf{w}) + \eta \, \mathfrak{E}_{\text{r.opt.}}(\mathbf{w}) + \sum_{\zeta=3}^{|Z|} \lambda_\zeta \, \mathfrak{E}_{\text{c.}}(\mathbf{T}^\zeta).$$

projective ICP

lifted segment pose regularizer

robust weight optimizer

multiframe pose concatenation

Huber norm:

$$\|a^2\|_\epsilon = \begin{cases} \frac{1}{2}a^2, & \text{for } |a| \leq \epsilon \\ \epsilon(|a| - \frac{1}{2}\epsilon), & \text{otherwise,} \end{cases}$$

Results

In the experimental evaluation we use:
- MPI SINTEL [1]
- virtual KITTI [2]
- Bonn multibody data set [3]
- own RGB-D recordings

… and compare the following methods:
- Primal-Dual Flow [4]
- Semi-Rigid Scene Flow [5]
- Multi-Frame Optical FLow [6]
- tv-l1 optical flow [7]

[1] D. J. Butler *et al.* A naturalistic open source movie for optical flow evaluation. In ECCV, 2012.
[2] A. Gaidon *et al.* Virtual worlds as proxy for multi-object tracking analysis. In CVPR, 2016.
[3] J. Stueckler and S. Behnke. Efficient dense rigid-body motion segmentation and estimation in rgb-d video. IJCV, 2015.

[4] M. Jaimez *et al.* A primal-dual framework for real-time dense rgb-d scene flow. In ICRA, 2015.
[5] J. Quiroga *et al.* Dense semi-rigid scene flow estimation from RGBD images. In ECCV, 2014.
[6] B. Taetz *et al.* Occlusion-aware video registration for highly non-rigid objects. In WACV, 2016.
[7] C. Zach *et al.* A duality based approach for realtime tv-l1 optical flow. In GCPR, 2007.

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End Point Error is defined as $\|(u - u_{\mathrm{GT}}), (v - v_{\mathrm{GT}})\|$

$(u, v)^{\mathsf{T}}$ is a projected flow vector

$(u_{\mathrm{GT}}, v_{\mathrm{GT}})^{\mathsf{T}}$ is a ground truth vector

[1] D. J. Butler *et al.* A naturalistic open source movie for optical flow evaluation. In ECCV, 2012.
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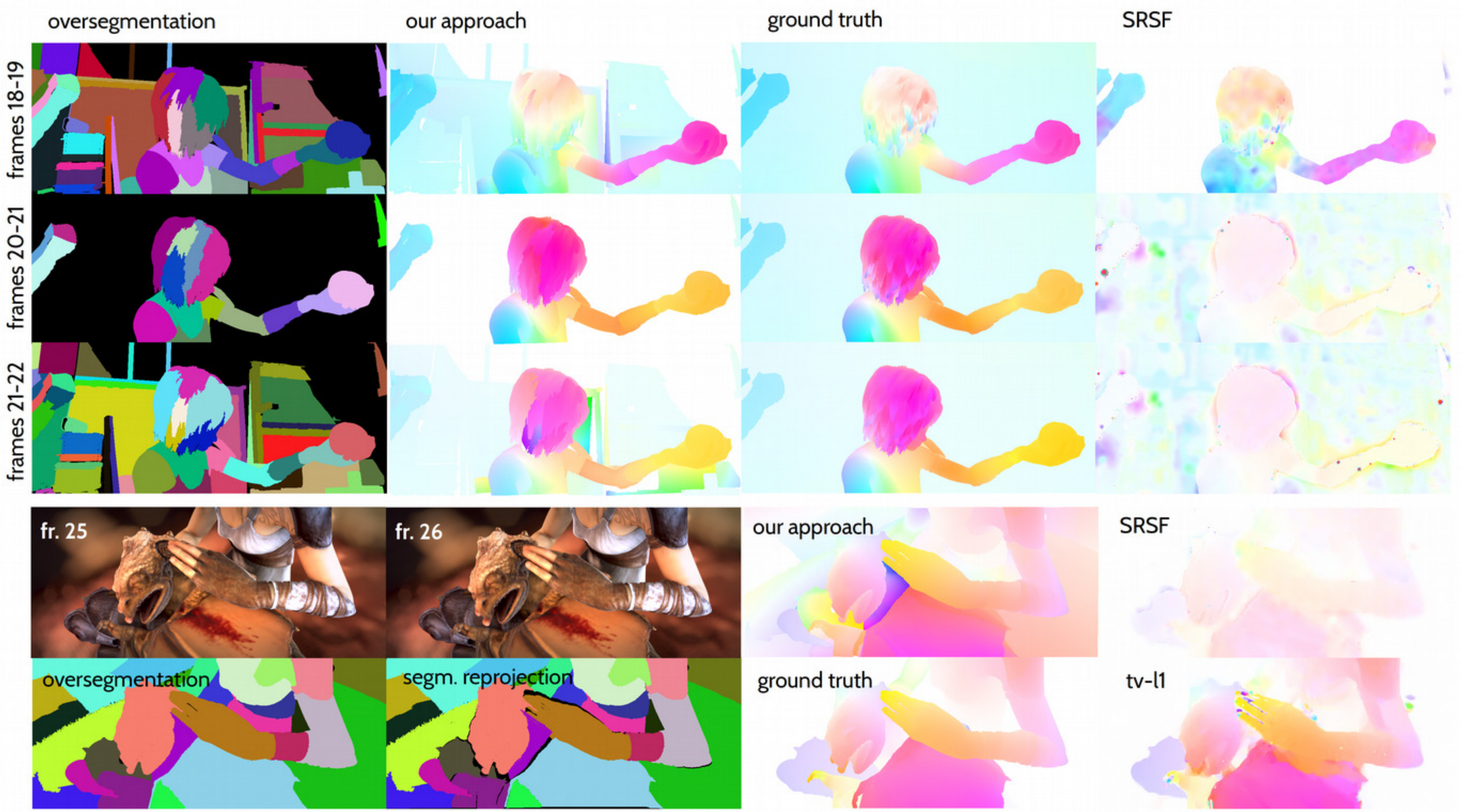
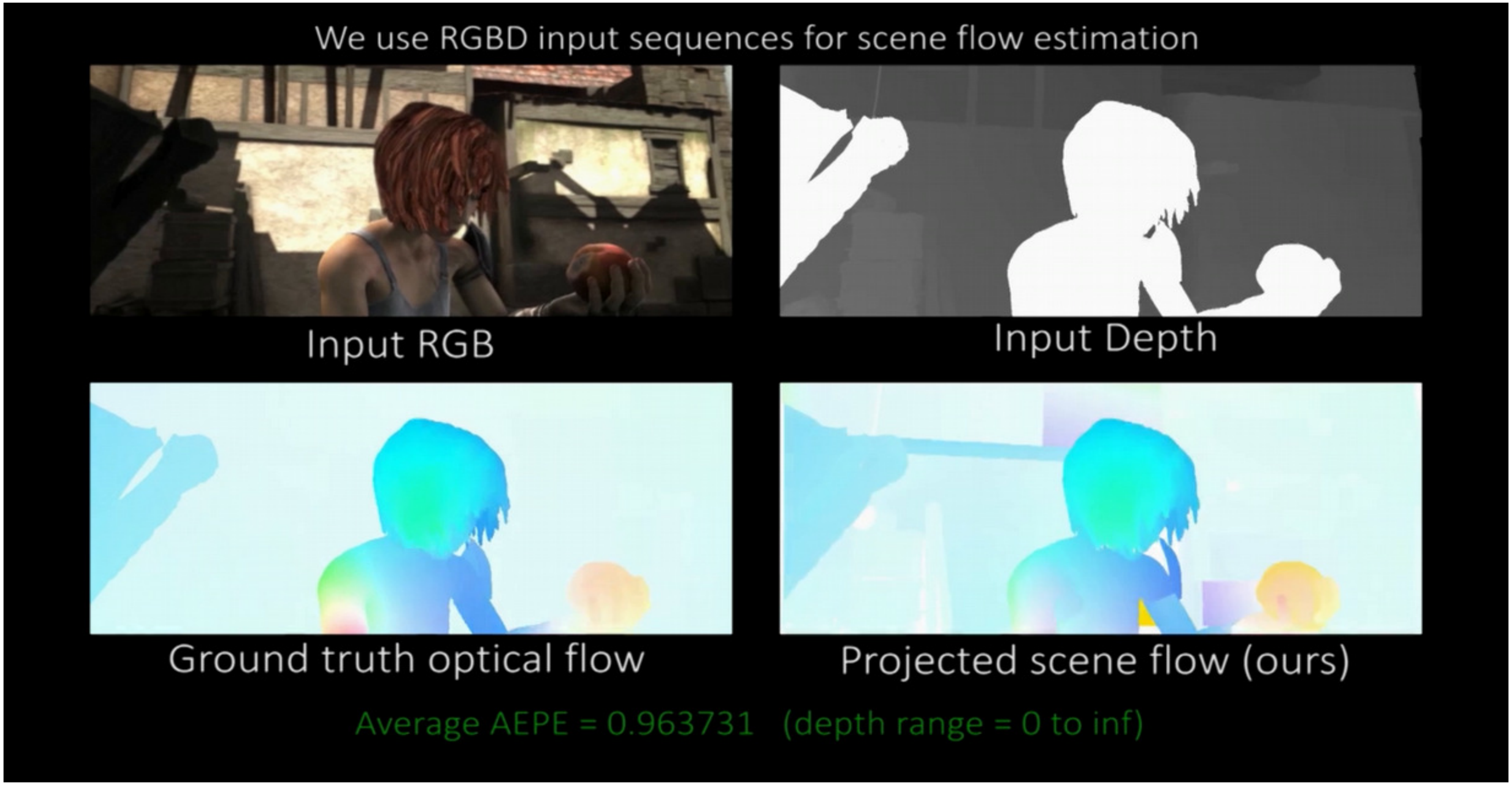
Results



	alley1	*bandage1*	*sleeping2, rigid*
SRSF [5]	2.46122/2.40833	2.47801/2.46389	1.13584
MSF	0.740127	1.69865	0.307526

...

Results


We use RGBD input sequences for scene flow estimation
Input RGB
Input Depth
Ground truth optical flow
Projected scene flow (ours)
Average AEPE = 0.963731 (depth range = 0 to inf)

Conclusions and Future Work

We propose a new multiframe RGB-D scene flow approach

Main novelties:

- **segmentation is obtained on the depth channel and kept fixed**
- **projective ICP term**
- **lifted segment pose regularizer**

Next: combine MSF with semantic segmentation, test other energy terms

Thank you for your attention!

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