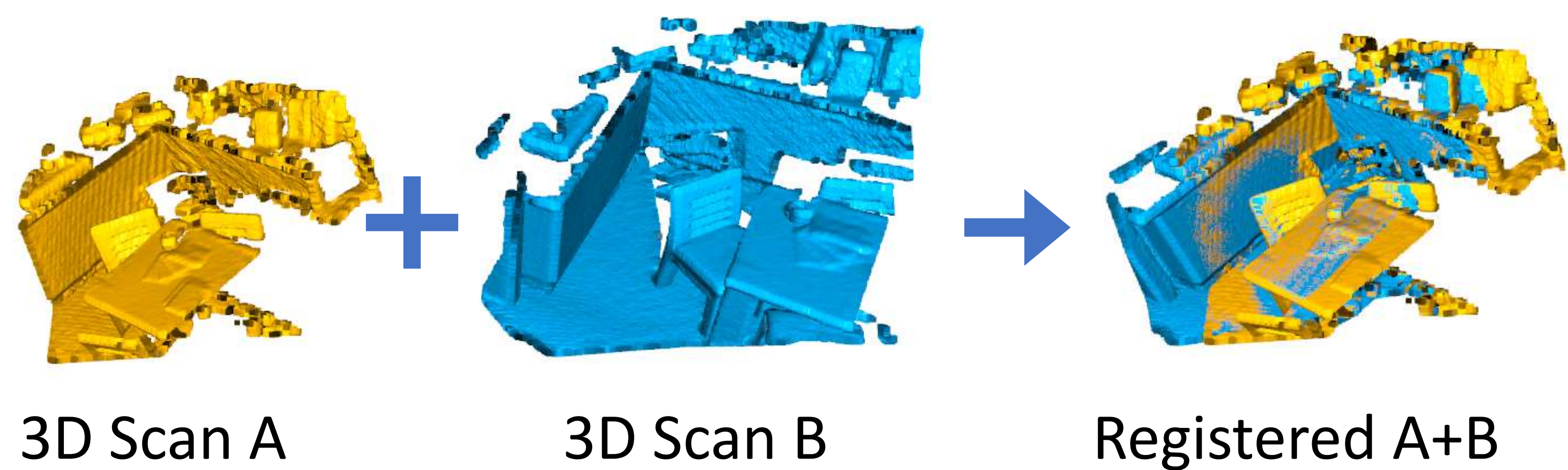


Task: 3D Registration



- Classical methods**
 - ICP
 - RANSAC, FGR
- Learned registration networks**
 - Deep Closest Points
 - PointNetLK

Deep Global Registration

- Convolutional feature extraction and matching
- Convolutional inlier detection
 - Failure case prediction and safeguard registration
- Weighted Procrustes analysis for pose estimation
- Differentiable robust pose refinement

Sparse Tensors for High Dimensional Learning

- Extension of sparse matrices

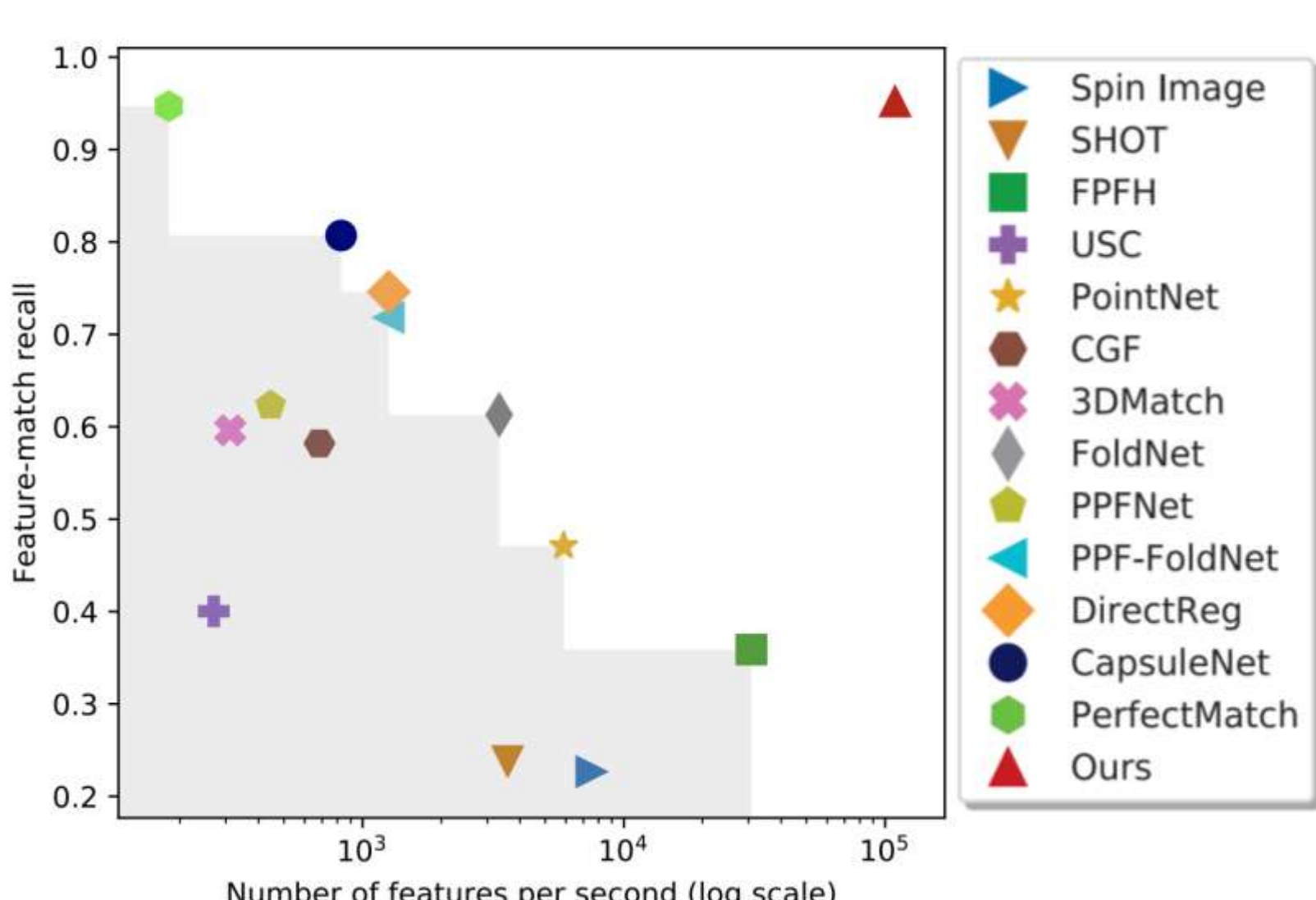
$$\mathcal{T}[\mathbf{x}_i] = \begin{cases} \mathbf{f}_i & \text{if } \mathbf{x}_i \in \mathcal{C} \\ 0 & \text{otherwise} \end{cases}$$

$$\mathcal{C} = \{\mathbf{x}_i \mid \mathbf{x}_i \in \mathbb{Z}^D, \mathcal{T}[\mathbf{x}_i] \neq \mathbf{0}\}_{i=1}^N$$

$$\mathbf{x}'(\mathbf{u}) = \sum_{\mathbf{i} \in \mathcal{N}(\mathbf{u}) \cap \mathcal{C}^{\text{in}}} W_i \mathbf{x}(\mathbf{u} + \mathbf{i}) \text{ where } \mathbf{u} \in \mathcal{C}^{\text{out}}$$

Fully Convolutional Geometric Features

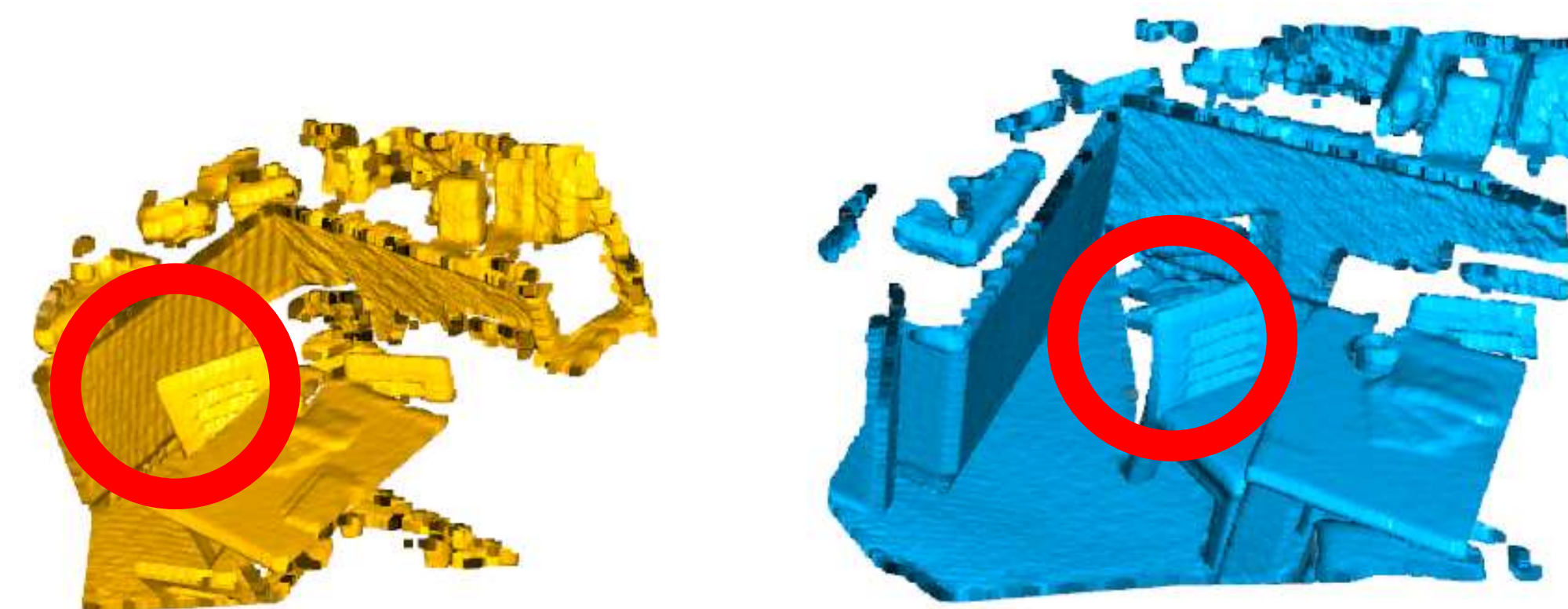
- Fast and accurate features [1]



Method	3DMatch		with Rot. Aug.		Feat. Dim.	Time (ms)
	FMR	STD	FMR	STD		
Spin [16]	0.227	0.114	0.227	0.121	153	0.133
SHOT [26]	0.238	0.109	0.234	0.095	352	0.279
USC	0.359	0.134	0.364	0.136	33	0.032
PointNet	0.400	0.125	-	-	1980	3.712
CGF	0.471	0.127	-	-	256	0.171
PointNet [21]	0.582	0.142	0.585	0.140	32	1.463
CGF [17]	0.596	0.088	0.011	0.012	512	3.210
3DMatch [36]	0.613	0.087	0.023	0.010	512	0.352
Folding [33]	0.623	0.108	0.003	0.005	64	2.257
PPFNet [7]	0.718	0.105	0.731	0.104	512	0.794
PPF-Fold [6]	0.746	0.094	-	-	512	0.794
DirectReg [8]	0.807	0.062	0.807	0.062	512	1.208
CapsuleNet [37]	0.947	0.027	0.949	0.024	32	5.515
PerfectMatch [11]	0.952	0.029	0.953	0.033	32	0.009
Ours	0.952	0.029	0.953	0.033	32	0.009

6D Euclidean Space for Correspondences

- 6D Representation of Correspondences

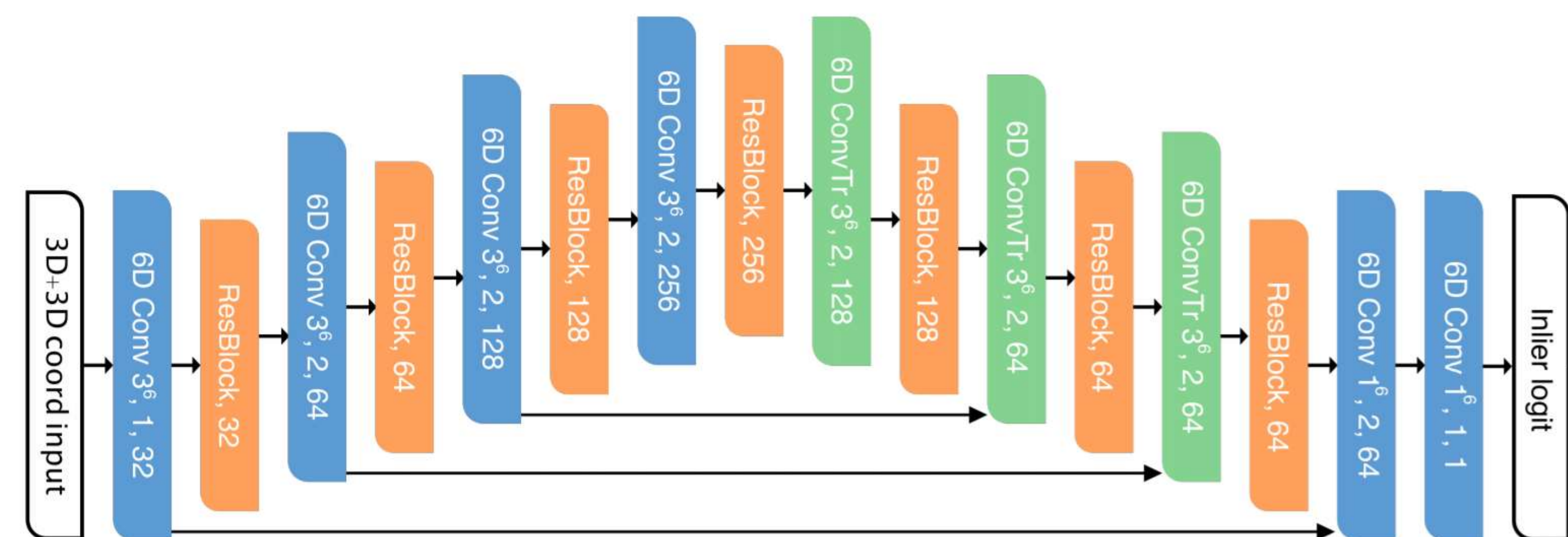


$$\{((x_1, y_1, z_1)_i, (x_2, y_2, z_2)_i)\}_i$$

- Inliers: 3D plane in 6D space [2] $[R \quad -I] \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} + \mathbf{t} = 0$

6D ConvNet for Inlier Detection

- Foreground (inlier) background (outlier) segmentation



Weighted Procrustes Registration

- Closed-form SVD-based solution
- Gradient passed through predicted weights

$$\operatorname{argmin}_{R, \mathbf{t}} \sum_i w_i (R\mathbf{x}_1^i + \mathbf{t} - \mathbf{x}_2^i)^2$$

Robust Refinement

- 1st order optimization
- Gradient passed through estimated poses

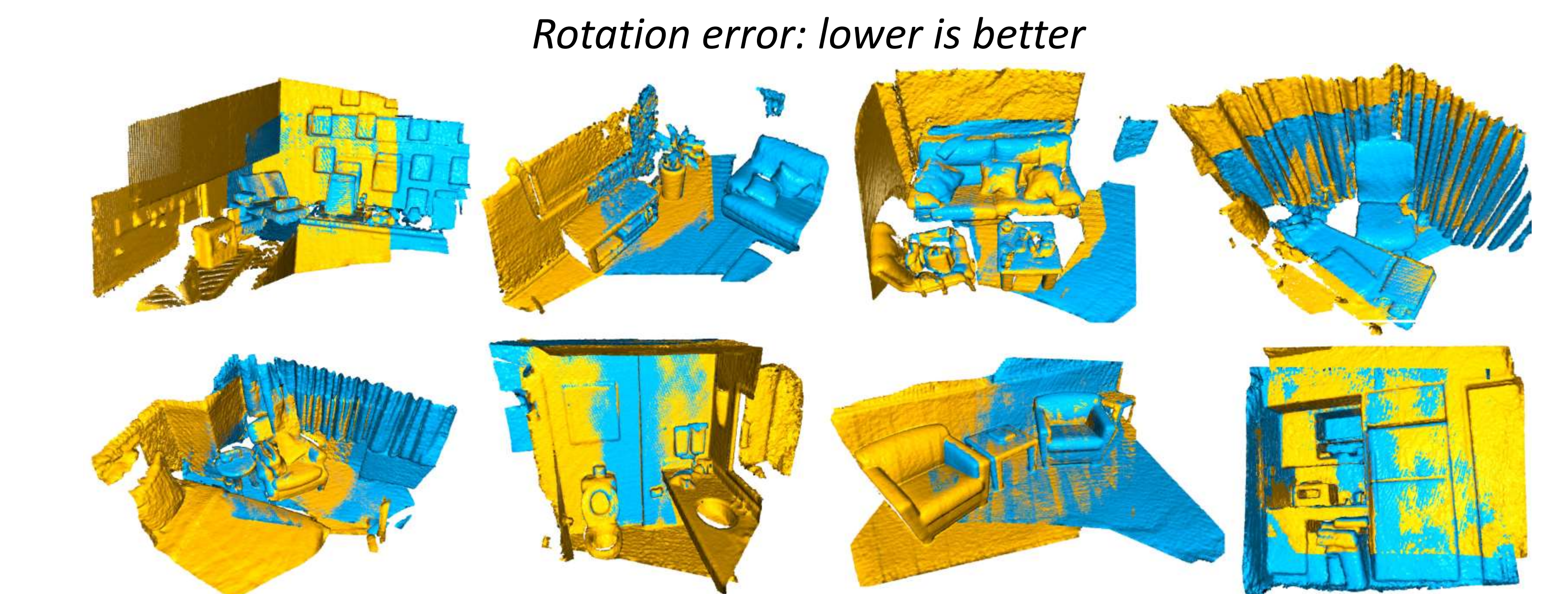
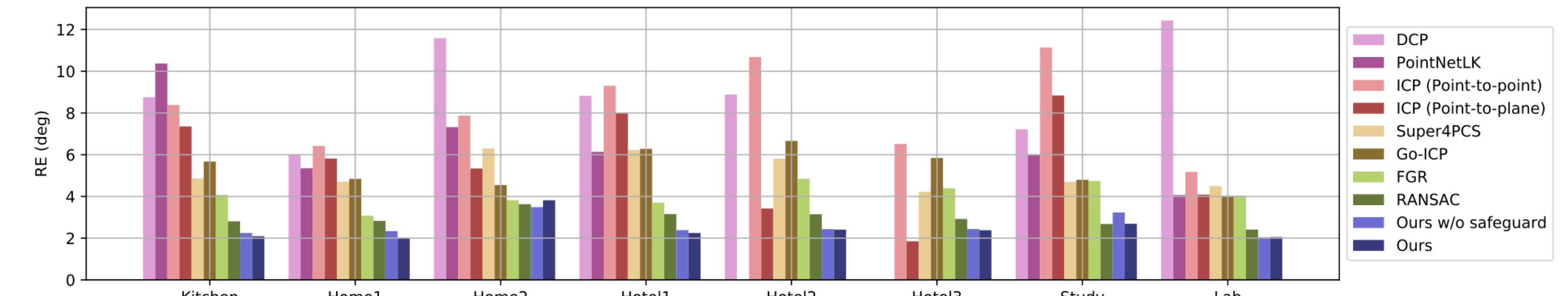
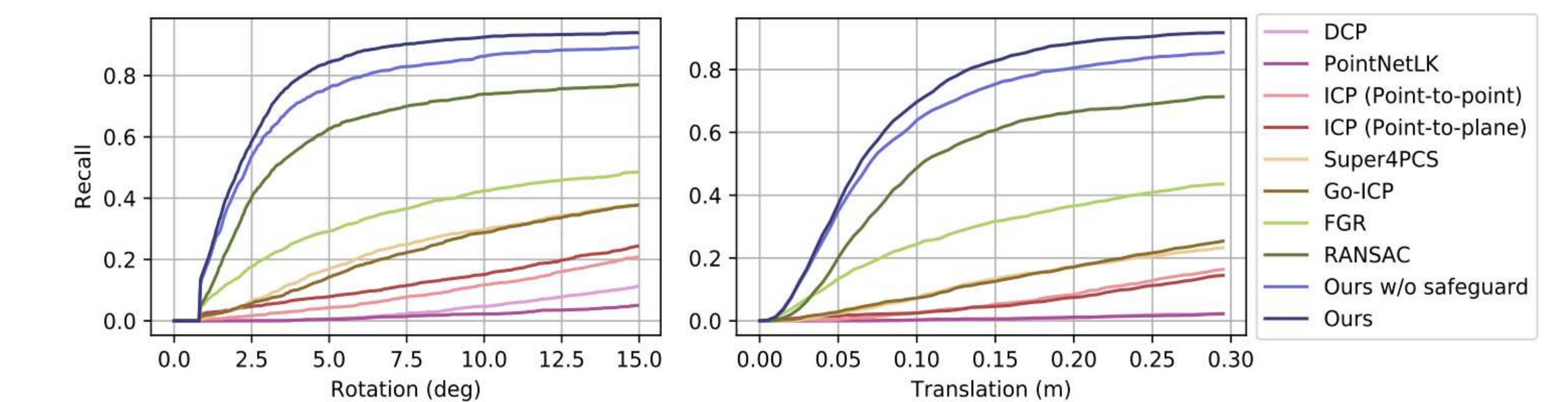
$$\operatorname{argmin}_{R, \mathbf{t}} \sum_i \phi(w_i) L(R\mathbf{x}_1^i + \mathbf{t}, \mathbf{x}_2^i)$$

References

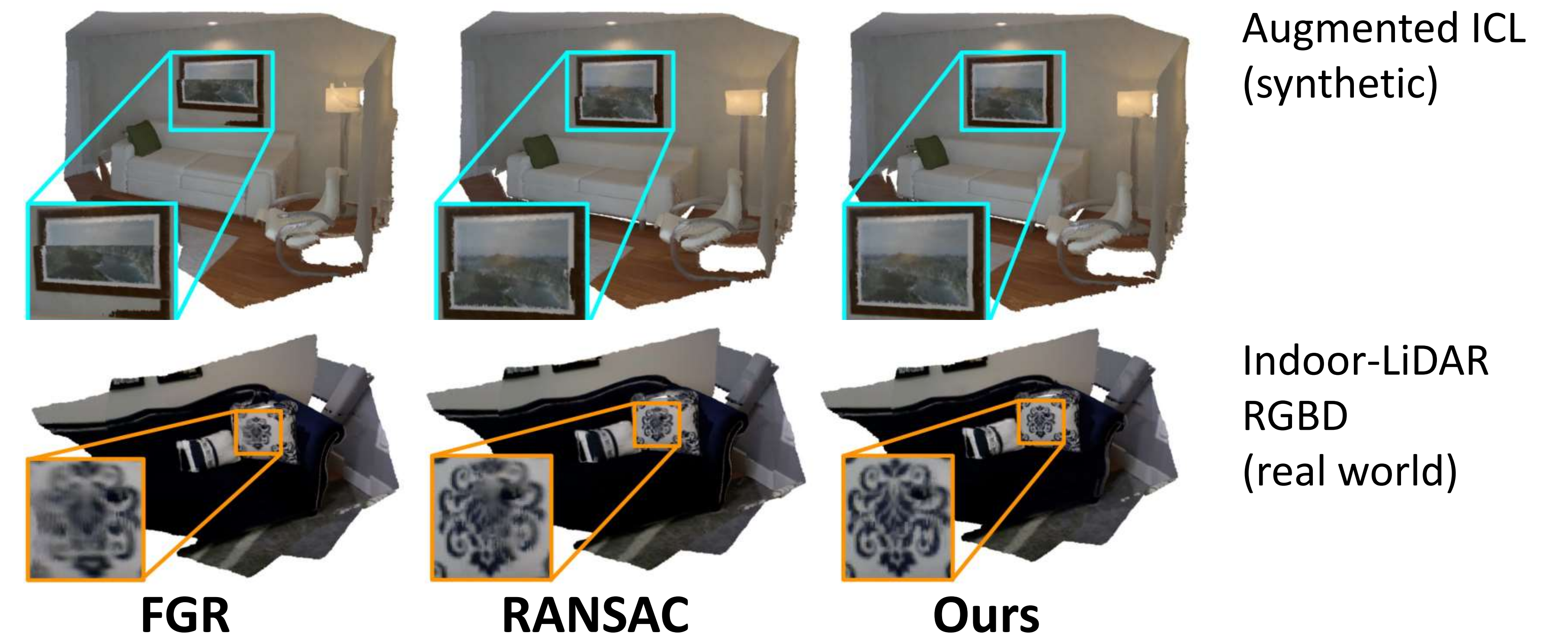
- [1] Choy, et al., Fully Convolutional Geometric Features, ICCV'19
- [2] Choy et al., High-Dimensional Convolutional Networks for Geometric Pattern Recognition, CVPR'20

Indoor RGB-D Registration

- Outperforms learning-based and classical methods on 3DMatch



- Generalizes to Augmented-ICL (synthetic) and Indoor LiDAR RGBD (real world) datasets with finer registrations



Outdoor LiDAR Registration

- Comparable to state-of-the-art methods on KITTI

	Recall	TE (cm)	RE (deg)	Time (s)
FGR [50]	0.2%	40.7	1.02	1.42
RANSAC [35]	34.2%	25.9	1.39	1.37
FCGF [9]	98.2%	10.2	0.33	6.38
Ours	96.9%	21.7	0.34	2.29
Ours + ICP	98.0	3.46	0.14	2.51