Registration is a Powerful Rotation-Invariance Learner for 3D Anomaly Detection

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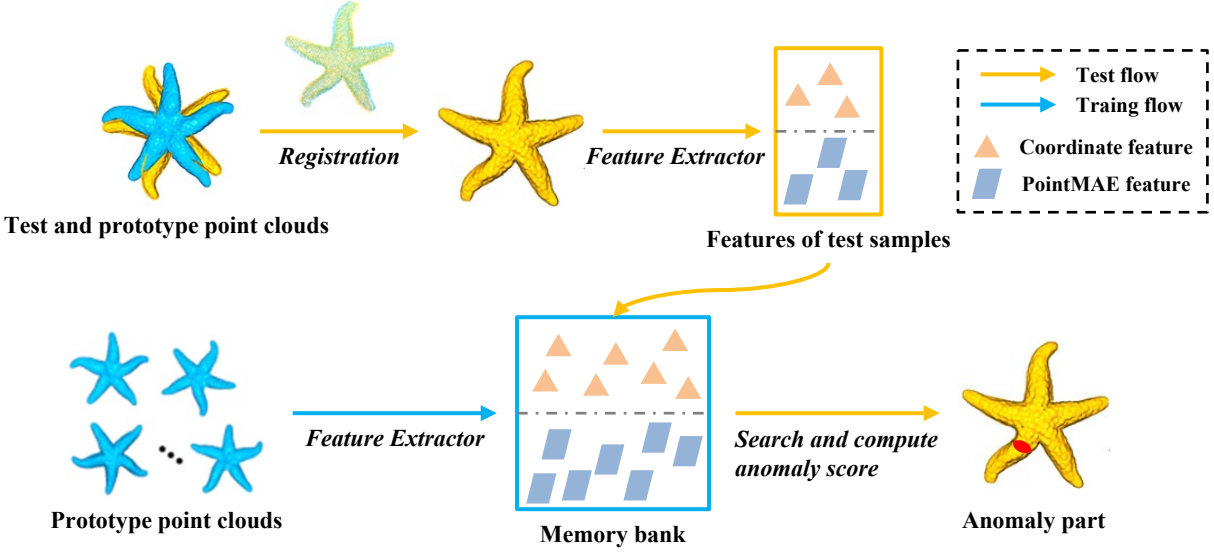
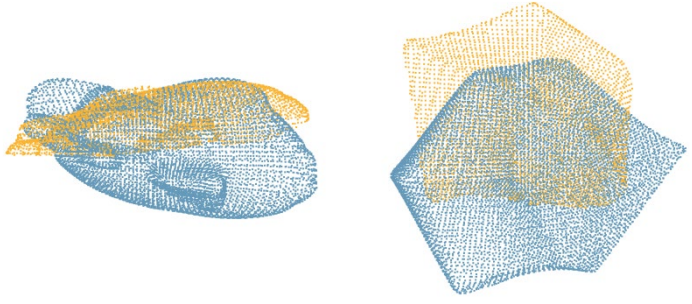
Motivation

Memory bank-based 3DAD methods follow **three** key steps: 1. Build memory bank (from prototypes); 2. ***Register*** test point cloud; 3. ***Feature extraction*** and comparison.

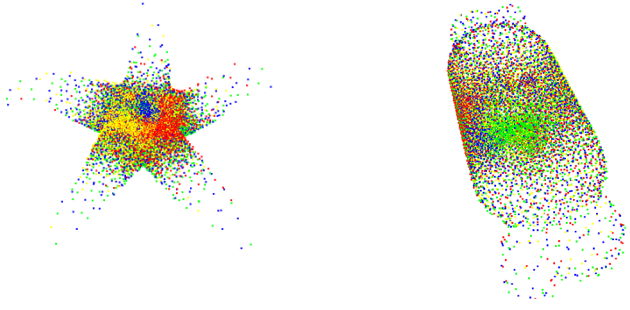


Motivation: Challenges

Unreliable Registration



Weak Feature Representation



Motivation: Rethinking Registration in Anomaly Detection

--To address the challenges we discussed earlier

Conventional Pipeline:

Registration → Feature Extractor → Anomaly Detection

Shared Core Capabilities

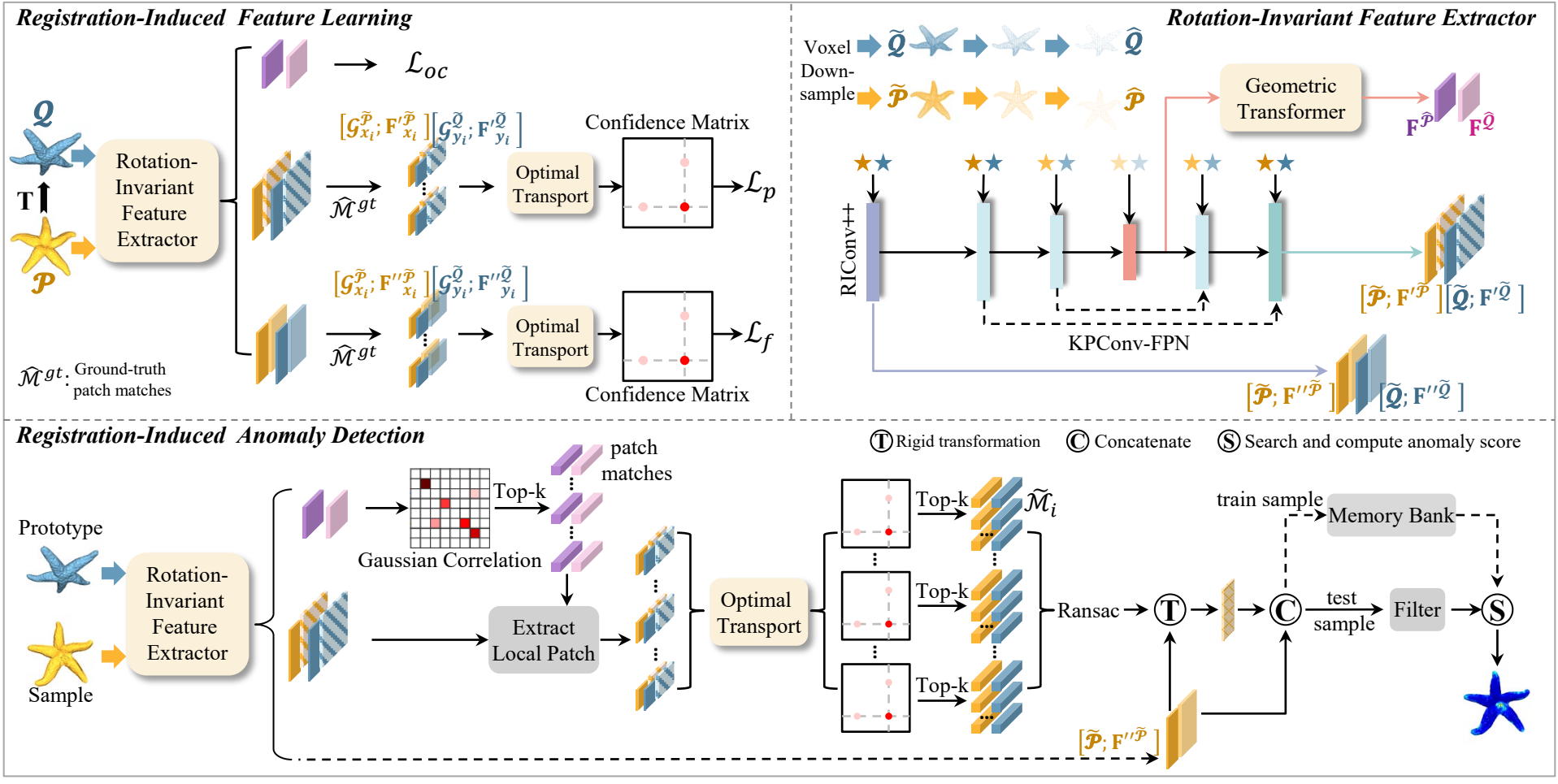
Registration		Anomaly Detection
Rotation-invariant	↔	Robust under rotations
Local structure modeling	↔	Fine-grained local details
Structural discrimination	↔	Consistent feature comparison

- Rotation-invariant, structurally consistent features;
- Better handle geometric variations and structural defects;
- Naturally improve memory-based anomaly detection

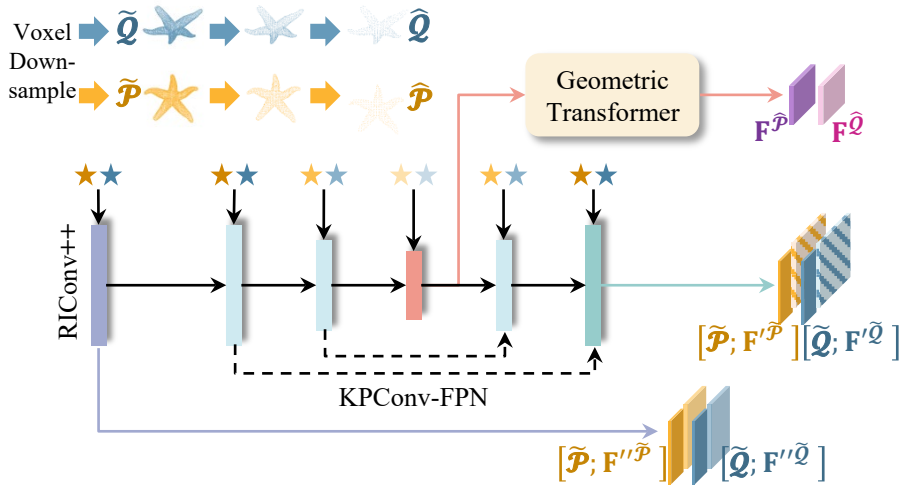
Our Pipeline:

【Registration ↔ Feature Extractor】 → Anomaly Detection

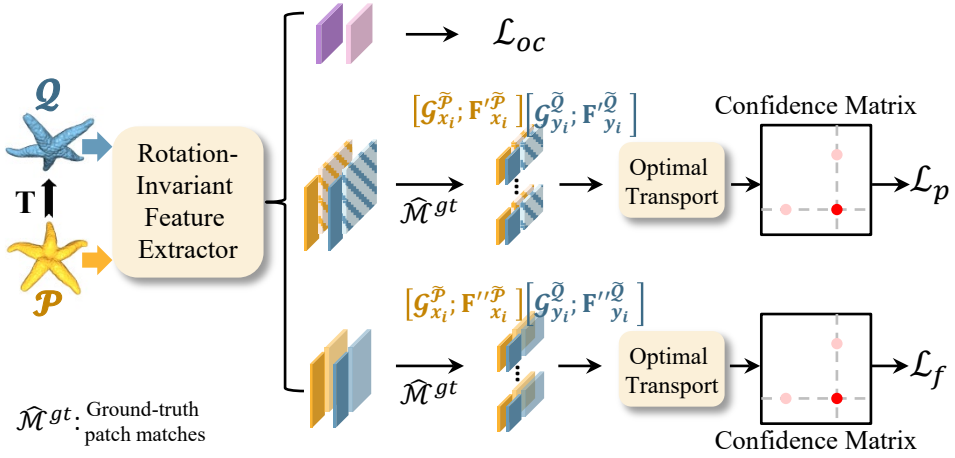
Method: Reg2Inv



Method: Rotation-Invariant Feature Extractor



Method: Registration-Induced Feature Learning

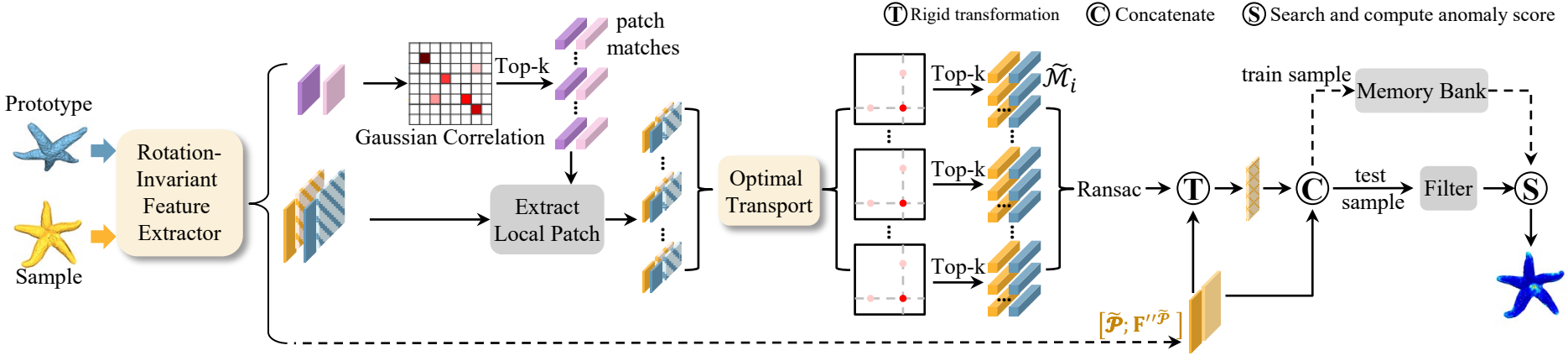


$$\mathcal{L}_{oc} = \left(\mathcal{L}^{\mathcal{P}}_{oc} + \mathcal{L}^{\mathcal{Q}}_{oc}\right)/2, \quad \mathcal{L}^{\mathcal{P}}_{oc} = \frac{1}{|\mathcal{A}|}\sum_{\mathcal{G}^{\mathcal{P}}_i \in \mathcal{A}} \log\left[1 + \sum_{\mathcal{G}^{\mathcal{Q}}_j \in \varepsilon^i_p} e^{\lambda^j_i \beta^{i,j}_p \left(d^j_i - \Delta_p\right)} \cdot \sum_{\mathcal{G}^{\mathcal{Q}}_k \in \varepsilon^i_n} e^{\beta^{i,k}_n \left(\Delta_n - d^k_i\right)}\right],$$ the same applies to $\mathcal{L}^{\mathcal{Q}}_{oc}$ in $\mathcal{Q}$

$$\mathcal{L}_p = \frac{1}{N_g}\sum_{i=1}^{N_g}\{-\sum_{(x,y)\in\widetilde{\mathcal{M}}^{gt}_i} \log z'^{*}_{i,x,y} - \sum_{x\in\mathcal{I}_i} \log z''^{*}_{i,x,m_i+1} - \sum_{y\in\mathcal{J}_i} \log z'^{*}_{i,n_i+1,y}\}$$

$$\mathcal{L}_f = \frac{1}{N_g}\sum_{i=1}^{N_g}\{-\sum_{(x,y)\in\widetilde{\mathcal{M}}^{gt}_i} \log z''^{*}_{i,x,y} - \sum_{x\in\mathcal{I}_i} \log z''^{*}_{i,x,m_i+1} - \sum_{y\in\mathcal{J}_i} \log z''^{*}_{i,n_i+1,y}\}$$

Method: Registration-Induced Anomaly Detection



Experiments

Table 1: Comparison of AUROC results at the object and point levels (%) of various methods on Real3D-AD. The best result in red and the second-best in blue for each category. (Raw) denotes the raw point coordinates used as input to the method. (FPFH) and (PMAE) denote configurations using Fast Point Feature Histograms [8] and PointMAE [10] as feature extractors. The top three methods are reconstruction-based, while the remaining ones are memory bank-based.

O-AUROC(↑) / P-AUROC(↑)

Method	Airplane	Car	Candy	Chicken	Diamond	Duck	Fish
IMRNet	76.2 /	71.1 /	75.5 /	78.0 /	90.5 /	51.7 /	88.0 /
R3D-AD	77.2 /	69.3 /	71.3 /	71.4 /	68.5 /	90.9 /	69.2 /
PO3AD	80.4 /	65.4 /	78.5 /	68.6 /	80.1 /	82.0 /	85.9 /
BTF(RAW)	73.0 / 56.4	64.7 / 64.7	53.9 / 73.5	78.9 / 60.9	70.7 / 56.3	69.1 / 60.1	60.2 / 51.4
BTF(FPFH)	52.0 / 73.8	56.0 / 70.8	63.0 / 86.4	43.2 / 73.5	54.5 / 88.2	78.4 / 87.5	54.9 / 70.9
M3DM	43.4 / 54.7	54.1 / 60.2	55.2 / 67.9	68.3 / 67.8	60.2 / 60.8	43.3 / 66.7	54.0 / 60.6
PatchCore(FPFH)	88.2 / 56.2	59.0 / 75.4	54.1 / 78.0	83.7 / 42.9	57.4 / 82.8	54.6 / 26.4	67.5 / 82.9
PatchCore(PMAE)	72.6 / 56.9	49.8 / 60.9	66.3 / 62.7	82.7 / 72.9	78.3 / 71.8	48.9 / 52.8	63.0 / 71.7
CPMF	70.1 / 61.8	55.1 / 83.6	55.2 / 73.4	50.4 / 55.9	52.3 / 75.3	58.2 / 71.9	55.8 / 98.8
Reg3D-AD	71.6 / 63.1	69.7 / 71.8	68.5 / 72.4	85.2 / 67.6	90.0 / 83.5	58.4 / 50.3	91.5 / 82.6
Group3AD	74.4 / 63.6	72.8 / 74.5	84.7 / 73.8	78.6 / 75.9	93.2 / 86.2	67.9 / 63.1	97.6 / 83.6
ISMP	85.8 / 75.3	73.1 / 83.6	85.2 / 90.7	71.4 / 79.8	94.8 / 92.6	71.2 / 87.6	94.5 / 88.6
Ours	81.8 / 92.3	75.8 / 94.4	100. / 96.9	94.4 / 91.0	100. / 97.9	75.0 / 93.7	67.2 / 84.6

Method	Gemstone	Seahorse	Shell	Starfish	Toffees	Average
IMRNet	67.4 /	60.4 /	66.5 /	67.4 /	77.4 /	72.5 /
R3D-AD	66.5 /	72.0 /	84.0 /	70.1 /	70.3 /	73.4 /
PO3AD	69.3 /	75.6 /	80.0 /	75.8 /	77.1 /	76.5 /
BTF(RAW)	68.6 / 59.7	59.6 / 52.0	39.6 / 48.9	53.0 / 39.2	70.3 / 62.3	63.5 / 57.1
BTF(FPFH)	64.8 / 89.1	77.9 / 51.2	75.4 / 57.1	57.5 / 50.1	46.2 / 81.5	60.3 / 73.3
M3DM	64.4 / 67.4	49.5 / 56.0	69.4 / 73.8	55.1 / 53.2	45.0 / 68.2	55.2 / 63.1
PatchCore(FPFH)	37.0 / 91.0	50.5 / 73.9	58.9 / 73.9	44.1 / 60.6	56.5 / 74.7	59.3 / 68.2
PatchCore(PMAE)	37.4 / 44.4	53.9 / 63.3	50.1 / 70.9	51.9 / 58.0	58.5 / 58.0	59.4 / 62.0
CPMF	58.9 / 44.9	72.9 / 96.2	65.3 / 72.5	70.0 / 80.0	39.0 / 95.9	58.6 / 75.8
Reg3D-AD	41.7 / 54.5	76.2 / 81.7	58.3 / 81.1	50.6 / 61.7	82.7 / 75.9	70.4 / 70.5
Group3AD	53.9 / 56.4	84.1 / 82.7	58.5 / 79.8	56.2 / 62.5	79.6 / 80.3	75.1 / 73.5
ISMP	46.8 / 85.7	72.9 / 81.3	62.3 / 83.9	66.0 / 64.1	84.2 / 89.5	75.7 / 83.6
Ours	73.5 / 90.7	53.2 / 64.5	69.2 / 90.6	84.1 / 84.0	62.6 / 73.7	78.0 / 87.8

Experiments

Table 2: Comparison of AUROC results at the object and point levels (%) of various methods on Anomaly-ShapeNet.

O-AUROC(↑) / P-AUROC(↑)

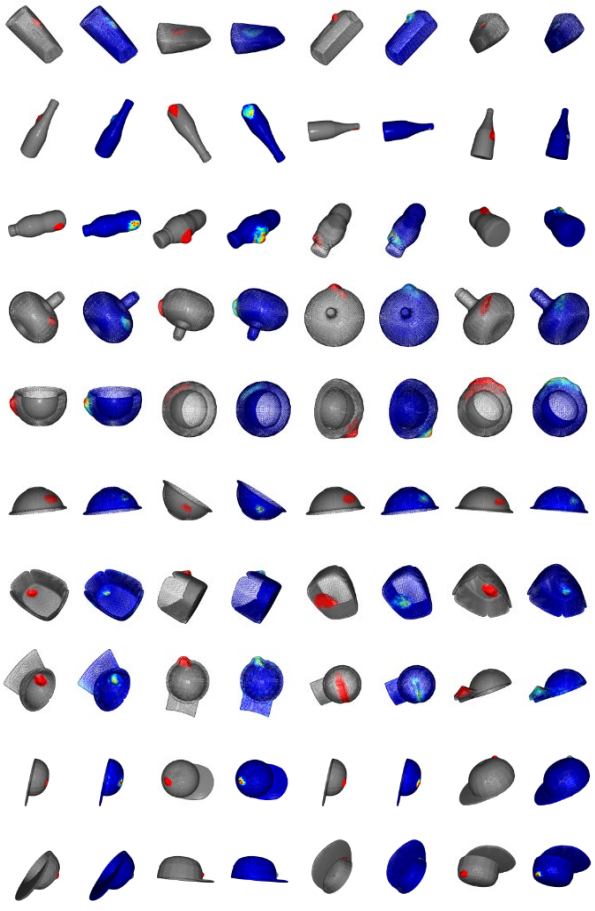
Method	ashtray0	bag0	bottle0	bottle1	bottle3	bowl0	bowl1	bowl2	bowl3	bowl4	bowl5
IMRNet	67.1 / 67.1	66.0 / 66.8	55.2 / 55.6	70.0 / 70.2	64.0 / 64.1	68.1 / 78.1	70.2 / 70.5	68.5 / 68.4	59.9 / 59.9	67.6 / 57.6	71.0 / 71.5
R3D-AD	83.3 /	72.0 /	73.3 /	73.7 /	78.1 /	81.9 /	77.8 /	74.1 /	76.7 /	74.4 /	65.6 /
PO3AD	100. / 96.2	83.3 / 94.9	90.0 / 91.2	93.3 / 84.4	92.6 / 88.0	92.2 / 97.8	82.9 / 91.4	83.3 / 91.8	88.1 / 93.5	98.1 / 96.7	84.9 / 94.1
BTF(RAW)	57.8 / 51.2	41.0 / 43.0	59.7 / 55.1	51.0 / 49.1	56.8 / 72.0	56.4 / 52.4	26.4 / 46.4	52.5 / 42.6	38.5 / 68.5	66.4 / 56.3	41.7 / 51.7
BTF(FPFH)	42.0 / 62.4	54.6 / 74.6	34.4 / 64.1	54.6 / 54.9	32.2 / 62.2	50.9 / 71.0	66.8 / 76.8	51.0 / 51.8	49.0 / 59.0	60.9 / 67.9	69.9 / 69.9
M3DM	57.7 / 57.7	53.7 / 63.7	57.4 / 66.3	63.7 / 63.7	54.1 / 53.2	63.4 / 65.8	66.3 / 66.3	68.4 / 69.4	61.7 / 65.7	46.4 / 62.4	40.9 / 48.9
PatchCore(FPFH)	58.7 / 59.7	57.1 / 57.4	60.4 / 65.4	66.7 / 68.7	57.2 / 51.2	50.4 / 52.4	63.9 / 53.1	61.5 / 62.5	53.7 / 32.7	49.4 / 72.0	55.8 / 35.8
PatchCore(PMAE)	59.1 / 49.5	60.1 / 67.4	51.3 / 55.3	60.1 / 60.6	65.0 / 65.3	52.3 / 52.7	62.9 / 52.4	45.8 / 51.5	57.9 / 58.1	50.1 / 50.1	59.3 / 56.2
CPMF	35.3 / 61.5	64.3 / 65.5	52.0 / 52.1	48.2 / 57.1	40.5 / 43.5	78.3 / 74.5	63.9 / 48.8	62.5 / 63.5	65.8 / 64.1	68.3 / 68.3	68.5 / 68.4
Reg3D-AD	59.7 / 69.8	70.6 / 71.5	48.6 / 88.6	69.5 / 69.6	52.5 / 52.5	67.1 / 77.5	52.5 / 61.5	49.0 / 59.3	34.8 / 65.4	66.3 / 80.0	59.3 / 69.1
ISMP	/ 60.3	/ 74.7	/ 77.0	/ 56.8	/ 77.5	/ 85.1	/ 54.6	/ 73.6	/ 77.3	/ 74.0	/ 53.4
Ours	90.0 / 78.5	100. / 99.1	100. / 99.5	100. / 84.9	100. / 81.7	100. / 98.3	80.7 / 82.8	65.6 / 82.2	58.5 / 76.1	85.2 / 78.8	81.8 / 82.4

Method	bucket0	bucket1	cap0	cap3	cap4	cap5	cup0	cup1	eraser0	headset0	headset1
IMRNet	58.0 / 58.5	77.1 / 77.4	73.7 / 71.5	77.5 / 70.6	65.2 / 75.3	65.2 / 74.2	64.3 / 64.3	75.7 / 68.8	54.8 / 54.8	72.0 / 70.5	67.6 / 47.6
R3D-AD	68.3 /	75.6 /	82.2 /	73.0 /	68.1 /	67.0 /	77.6 /	75.7 /	89.0 /	73.8 /	79.5 /
PO3AD	85.3 / 75.5	78.7 / 89.9	87.7 / 95.7	85.9 / 94.8	79.2 / 94.0	67.0 / 86.4	87.1 / 90.9	83.3 / 93.2	99.5 / 97.4	80.8 / 82.3	92.3 / 90.7
BTF(RAW)	61.7 / 61.7	32.1 / 68.6	66.8 / 52.4	52.7 / 68.7	46.8 / 46.9	37.3 / 37.3	40.3 / 63.2	52.1 / 56.1	52.5 / 63.7	37.8 / 57.8	51.5 / 47.5
BTF(FPFH)	40.1 / 40.1	63.3 / 63.3	61.8 / 73.0	52.2 / 65.8	52.0 / 52.4	58.6 / 58.6	58.6 / 79.0	61.0 / 61.9	71.9 / 71.9	52.0 / 62.0	49.0 / 59.1
M3DM	30.9 / 69.8	50.1 / 69.9	55.7 / 53.1	42.3 / 60.5	77.7 / 71.8	63.9 / 65.5	53.9 / 71.5	55.6 / 55.6	62.7 / 71.0	57.7 / 58.1	61.7 / 58.5
PatchCore(FPFH)	46.9 / 45.9	55.1 / 57.1	58.0 / 47.2	45.3 / 65.3	75.7 / 59.5	79.0 / 79.5	60.0 / 65.5	58.6 / 59.6	65.7 / 81.0	58.3 / 58.3	63.7 / 46.4
PatchCore(PMAE)	59.3 / 58.6	56.1 / 57.4	58.9 / 54.4	47.6 / 48.8	72.7 / 72.5	53.8 / 54.5	61.0 / 51.0	55.6 / 85.6	67.7 / 37.8	59.1 / 57.5	62.7 / 42.3
CPMF	48.2 / 48.6	60.1 / 60.1	60.1 / 60.1	55.1 / 55.1	55.3 / 55.3	69.7 / 55.1	49.7 / 49.7	49.9 / 50.9	68.9 / 68.9	64.3 / 69.9	45.8 / 45.8
Reg3D-AD	61.0 / 61.9	75.2 / 75.2	69.3 / 63.2	72.5 / 71.8	64.3 / 81.5	46.7 / 46.7	51.0 / 68.5	53.8 / 69.8	34.3 / 75.5	53.7 / 58.0	61.0 / 62.6
ISMP	/ 52.4	/ 67.2	/ 86.5	/ 73.4	/ 75.3	/ 67.8	/ 86.9	/ 60.0	/ 70.6	/ 58.0	/ 70.2
Ours	81.3 / 61.0	90.2 / 85.5	65.9 / 86.1	86.3 / 94.5	68.1 / 86.4	90.2 / 97.0	73.3 / 79.8	93.3 / 88.1	100. / 98.0	100. / 94.6	84.3 / 97.0

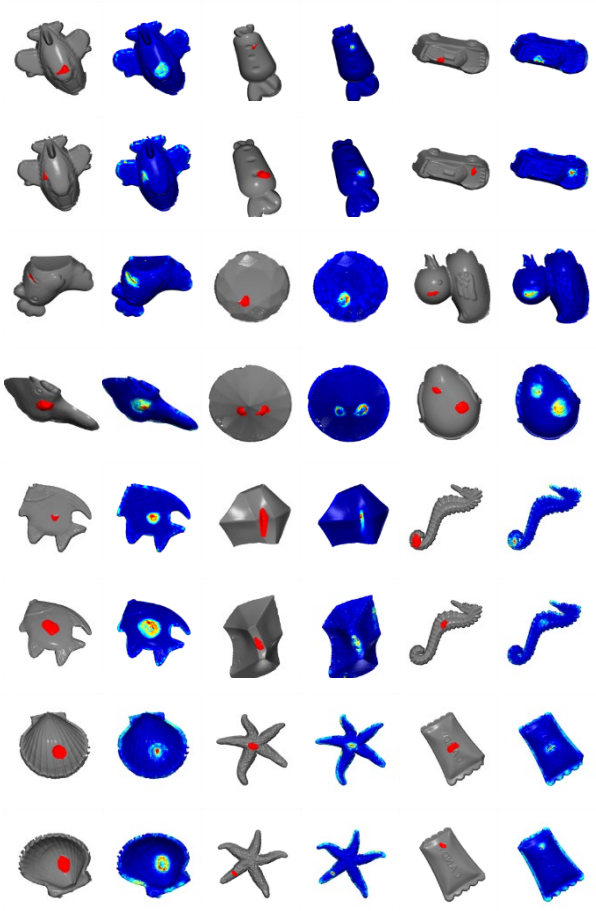
Method	helmet0	helmet1	helmet2	helmet3	jar0	phone	shelf0	tap0	tap1	vase0	vase1
IMRNet	59.7 / 59.8	60.0 / 60.4	64.1 / 64.4	57.3 / 66.3	78.0 / 76.5	75.5 / 74.2	60.3 / 60.5	67.6 / 68.1	69.6 / 69.9	53.3 / 53.5	75.7 / 68.5
R3D-AD	75.7 /	72.0 /	63.3 /	70.7 /	83.8 /	76.2 /	69.6 /	73.6 /	90.0 /	78.8 /	72.9 /
PO3AD	76.2 / 87.8	96.1 / 94.8	86.9 / 93.2	75.4 / 84.6	86.6 / 87.1	77.6 / 81.0	57.3 / 66.3	74.5 / 78.3	68.1 / 69.2	85.8 / 95.5	74.2 / 88.2
BTF(RAW)	55.3 / 50.4	34.9 / 44.9	60.2 / 60.5	52.6 / 70.0	42.0 / 42.3	56.3 / 58.3	16.4 / 46.4	52.5 / 52.7	57.3 / 56.4	53.1 / 61.8	54.9 / 54.9
BTF(FPFH)	57.1 / 57.5	71.9 / 74.9	54.2 / 64.3	44.4 / 72.4	42.4 / 42.7	67.1 / 67.5	60.9 / 61.9	56.0 / 56.8	54.6 / 59.6	34.2 / 64.2	21.9 / 61.9
M3DM	52.6 / 59.9	42.7 / 42.7	62.3 / 62.3	37.4 / 65.5	44.1 / 54.1	35.7 / 35.8	56.4 / 55.4	75.4 / 65.4	73.9 / 71.2	42.3 / 60.8	42.7 / 60.2
PatchCore(FPFH)	54.6 / 54.8	48.4 / 48.9	42.5 / 45.5	40.4 / 73.7	47.2 / 47.8	38.8 / 48.8	49.4 / 61.3	75.3 / 73.3	76.6 / 76.8	45.5 / 65.5	42.3 / 45.3
PatchCore(PMAE)	55.6 / 58.0	55.2 / 56.2	44.7 / 65.1	42.4 / 61.5	48.3 / 48.7	48.8 / 88.6	52.3 / 54.3	45.8 / 85.8	53.8 / 54.1	44.7 / 67.7	55.2 / 55.1
CPMF	55.5 / 55.5	58.9 / 54.2	46.2 / 51.5	52.0 / 52.0	61.0 / 61.1	50.9 / 54.5	68.5 / 78.3	35.9 / 45.8	69.7 / 65.7	45.1 / 45.8	34.5 / 48.6
Reg3D-AD	60.0 / 60.0	38.1 / 62.4	61.4 / 82.5	36.7 / 62.0	59.2 / 59.9	41.4 / 59.9	68.8 / 68.8	67.6 / 58.9	64.1 / 74.1	53.3 / 54.8	70.2 / 60.2
ISMP	/ 68.3	/ 62.2	/ 84.4	/ 72.2	/ 82.3	/ 66.1	/ 68.7	/ 52.2	/ 55.2	/ 66.1	/ 84.3
Ours	81.7 / 92.5	98.6 / 90.6	87.5 / 89.1	87.6 / 95.6	100. / 98.2	100. / 99.2	57.7 / 63.2	94.8 / 91.8	80.4 / 86.9	99.6 / 98.0	60.5 / 70.5

Method	vase2	vase3	vase4	vase5	vase7	vase8	vase9	Average
IMRNet	61.4 / 61.4	70.0 / 40.1	52.4 / 52.4	67.6 / 68.2	63.5 / 59.3	63.0 / 63.5	59.4 / 69.1	66.1 / 65.0
R3D-AD	75.2 /	74.2 /	63.0 /	75.7 /	77.1 /	72.1 /	71.8 /	74.9 /
PO3AD	95.2 / 97.8	82.1 / 88.4	67.5 / 90.2	85.2 / 93.7	96.6 / 98.2	73.9 / 95.0	83.0 / 95.2	83.9 / 89.8
BTF(RAW)	41.0 / 40.3	71.7 / 60.2	42.5 / 61.3	58.5 / 58.5	44.8 / 57.8	42.4 / 55.0	56.4 / 56.4	49.3 / 55.0
BTF(FPFH)	54.6 / 64.6	69.9 / 69.9	51.0 / 71.0	40.9 / 42.9	51.8 / 54.0	66.8 / 66.2	26.8 / 56.8	52.8 / 62.8
M3DM	73.7 / 73.7	43.9 / 65.8	47.6 / 65.5	31.7 / 64.2	65.7 / 51.7	66.3 / 55.1	66.3 / 66.3	55.2 / 61.6
PatchCore(FPFH)	72.1 / 72.1	44.9 / 43.0	50.6 / 50.5	41.7 / 44.7	69.3 / 69.3	66.2 / 57.5	66.0 / 66.3	56.8 / 58.0
PatchCore(PMAE)	74.1 / 74.2	46.0 / 46.5	51.6 / 52.3	57.9 / 57.2	65.0 / 65.1	66.3 / 36.4	62.9 / 42.3	56.2 / 57.7
CPMF	58.2 / 58.2	58.2 / 58.2	51.4 / 51.4	61.8 / 65.1	39.7 / 50.4	52.9 / 52.9	60.9 / 54.5	55.9 / 57.3
Reg3D-AD	60.5 / 40.5	65.0 / 51.1	50.0 / 75.5	52.0 / 62.4	46.2 / 88.1	62.0 / 81.1	59.4 / 69.4	57.2 / 66.8
ISMP	/ 73.3	/ 76.2	/ 54.5	/ 47.2	/ 70.1	/ 85.1	/ 61.5	/ 69.1
Ours	100. / 99.7	84.5 / 84.4	81.8 / 92.7	100. / 87.9	64.3 / 86.3	81.8 / 93.4	87.3 / 97.1	86.1 / 88.2

Experiments



Qualitative results of localization on the Anomaly-Shapenet dataset.



Qualitative results of localization on the Real3D-AD dataset.

THANK YOU FOR YOUR ATTENTION