CVPR 2023, VANCOUVER, CANADA

3D Registration with Maximal Cliques

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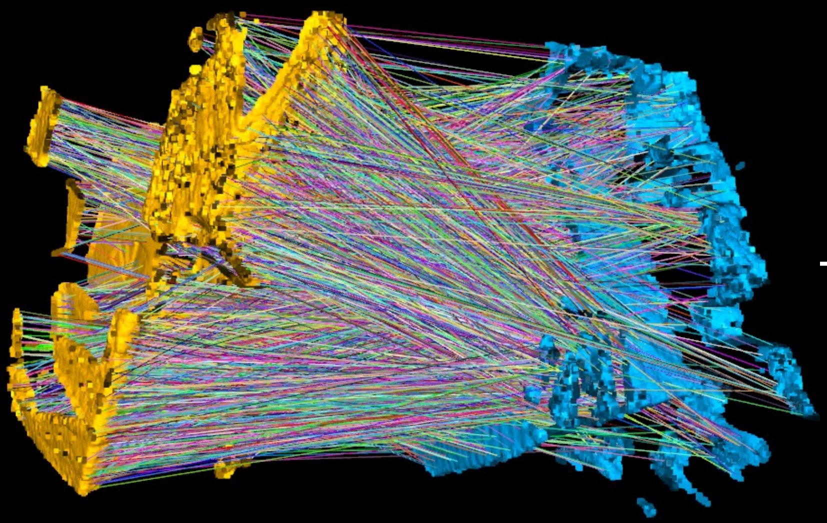
1. Problem definition

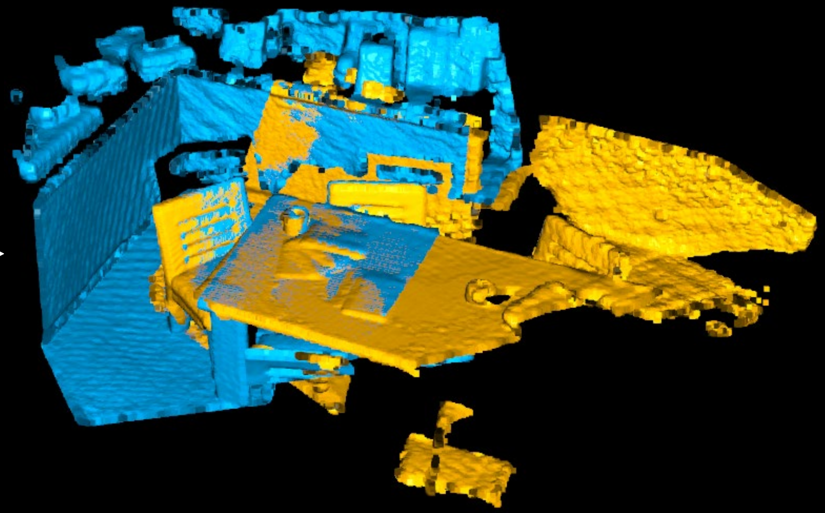
- Given putative correspondences, 3D registration aims at estimating the six-degree-of-freedom (6-DoF) pose between two point clouds
- Correspondences can be generated by matching geometric or deep learned 3D features



$\mathbf{R} \in SO(3)$

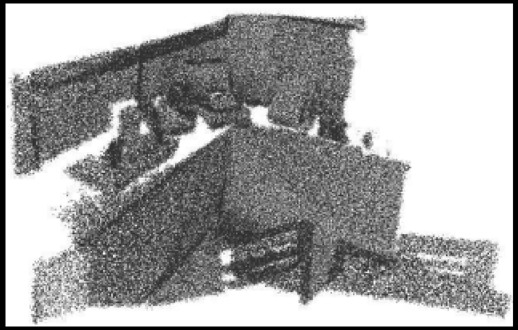
$\mathbf{t} \in \mathbb{R}^3$

6DoF pose transformation

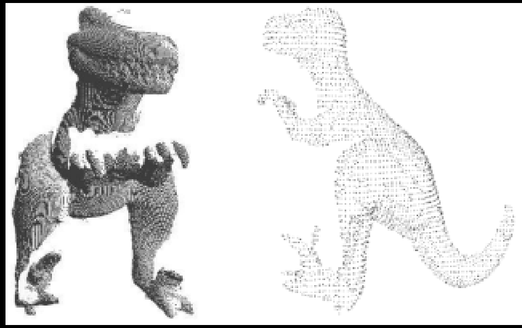


2. Challenges

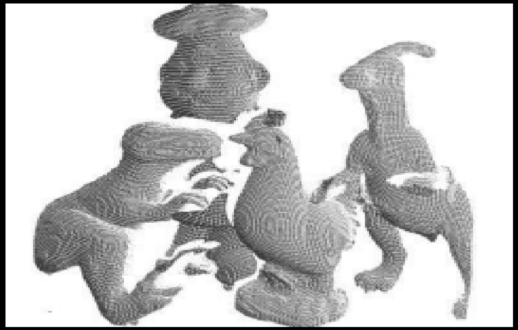
- Outliers are the main concern
  - Data nuisances (noise, resolution variation, limited overlap, etc)
  - Limited distinctiveness of point cloud features



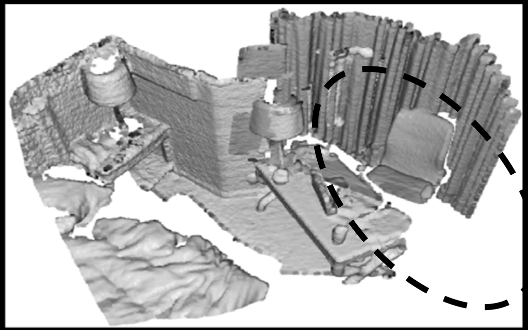
Noise



Resolution Variation

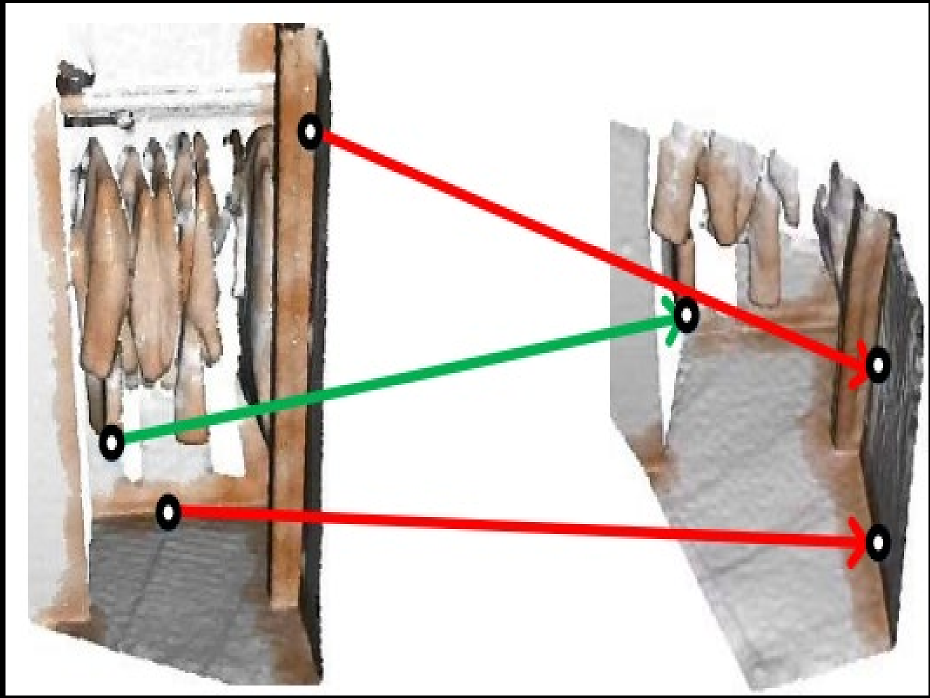


Occlusion



Limited Overlap

Data nuisances

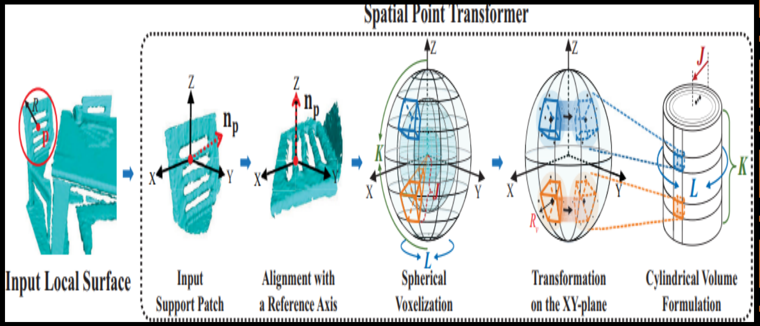
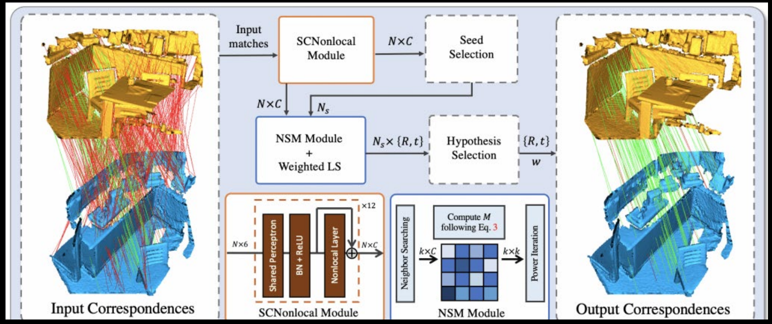
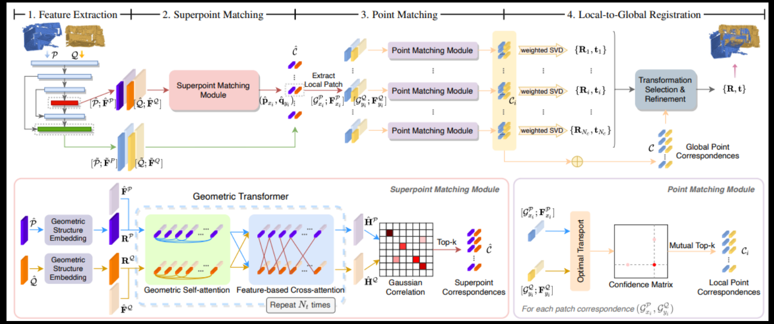


Feature limitation

3. Existing solutions

- Two main categories

1. Deep learned

SpinNet, CVPR2021	PointDSC, CVPR2021	GeoTransformer, CVPR2022
		
Learn features	Learn to find inliers	End-to-end registration

- Massive training data (with labels)
- Not lightweight, requiring GPU resource
- Weak generalization ability

3. Existing solutions

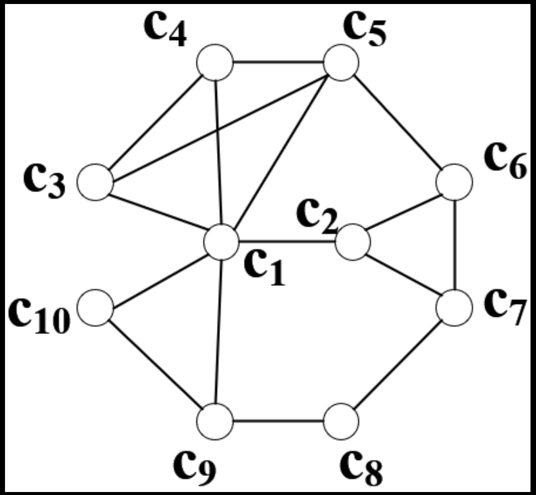
- Two main categories

  2. Traditional: Maximum clique based methods are dominating

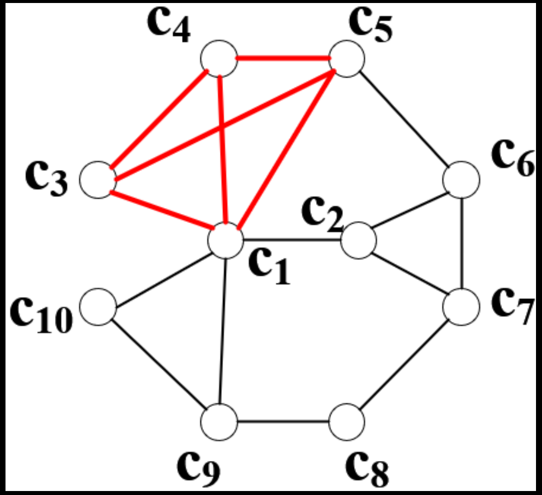
Prior: Inliers are compatible with each other

① First construct a compatibility graph

② Find the maximum clique



①

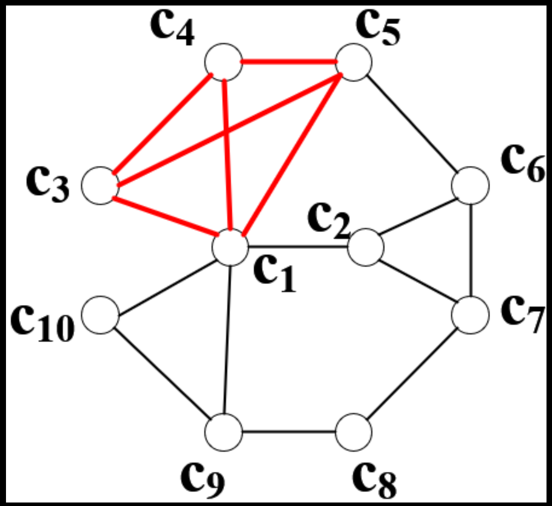


②

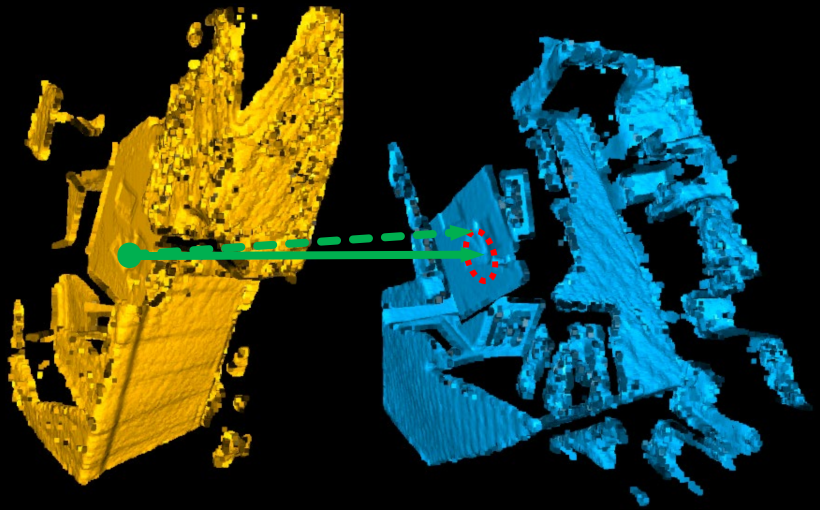
- Still sensitive to heavy outliers

4. Our insight

- **Loosen the maximum clique constraint**
  - We do not have a "perfect" compatibility metric
  - Inliers are not "perfect" inliers, they not always form the maximum clique
  - Mine more local consensus information in the graph



Compatible?



Inliers also suffer errors

5. Our contributions

- A novel 6-DoF pose hypothesis representation: **Maximal Cliques (MAC)**
- A novel correspondence-based 3D registration method based on MAC
- Surprisingly effective: 1) SOTA in registration recall and accuracy; 2) Friendly to deep learned methods (MAC is a booster for learned ones)

6. Details of MAC

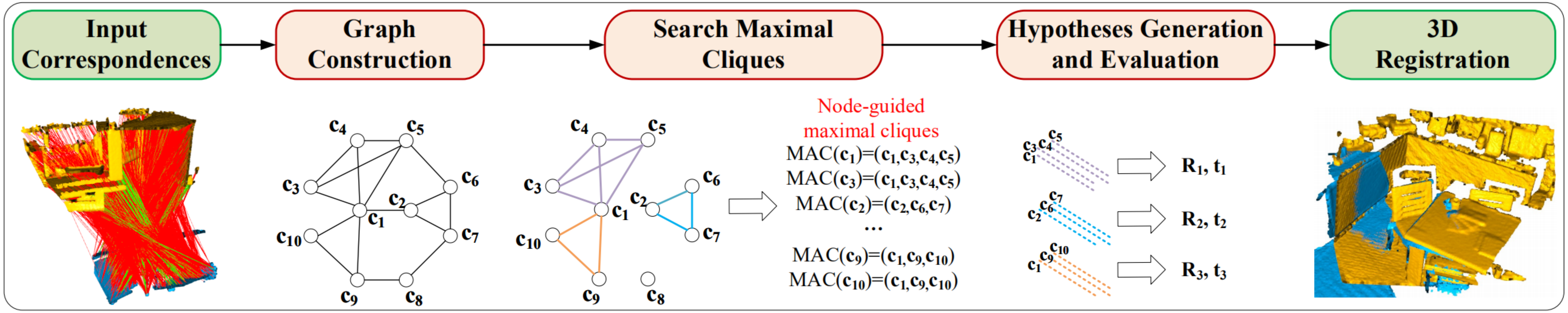
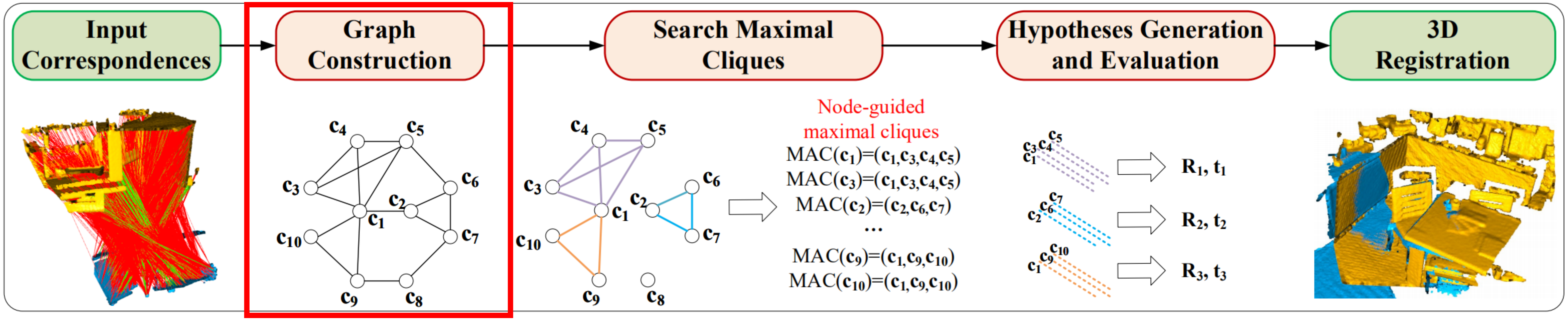


Figure 2. **Pipeline of MAC**. **1.** Construct a graph for the initial correspondence set. **2.** Select a set of maximal cliques from the graph as the consistent sets. **3.** Generate and evaluate the hypotheses according to the consistent sets. **4.** Select the best hypothesis to perform 3D registration.

MAC is technically very simple, which performs hypothesis generation & verification (like RANSAC) in a graph space

6. Details of MAC



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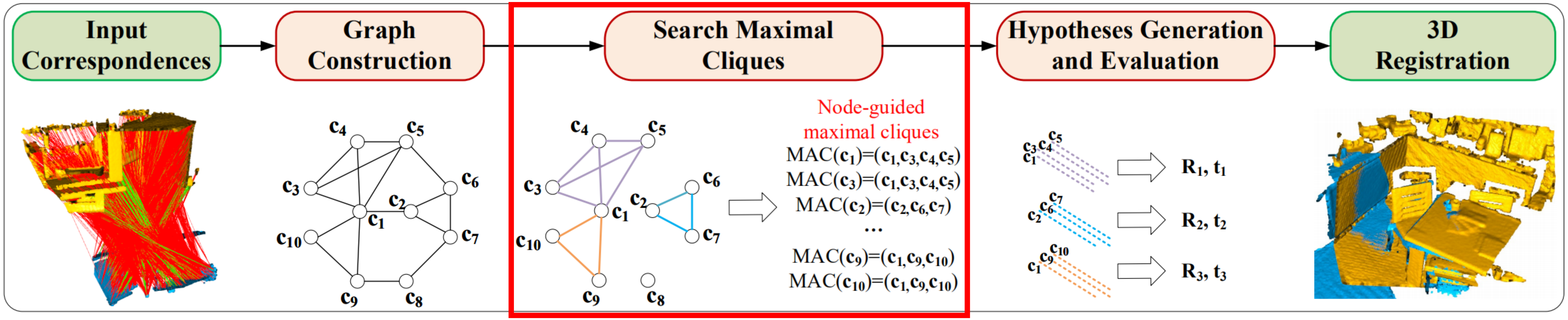
Step 1: Graph construction

1) Node: correspondences
2) Edge: compatible correspondences, measure with a compatibility metric

Motivation: The graph space can more accurately depict the affinity relationship between correspondences than the Euclidean space

6. Details of MAC



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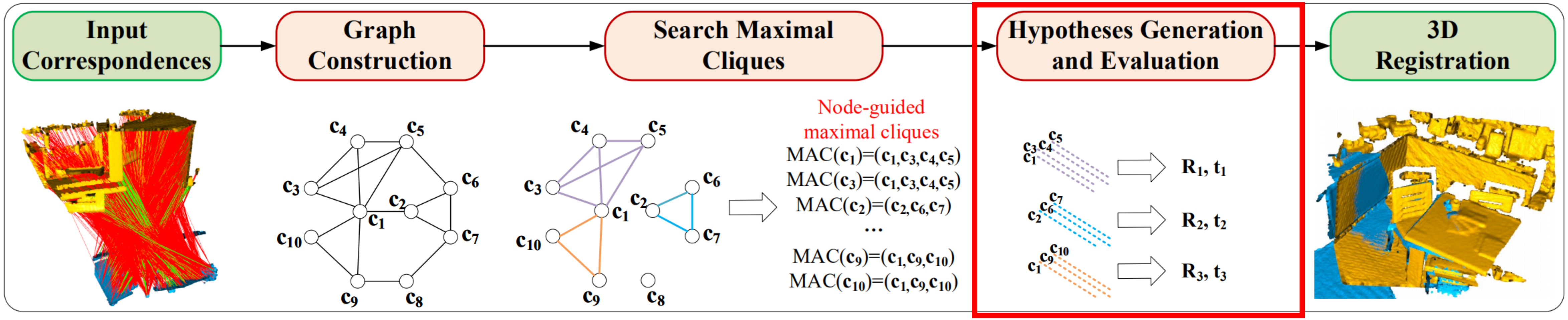
Step 2: Search maximal cliques

1) Quick search with a *igraph* C++ library
2) Node-guided selection: i) there are too many MACs in a graph (>10,000); ii) representative MACs are selected based on node-guided selection, i.e., the 'best' MAC associated with a node is kept for that node

6. Details of MAC



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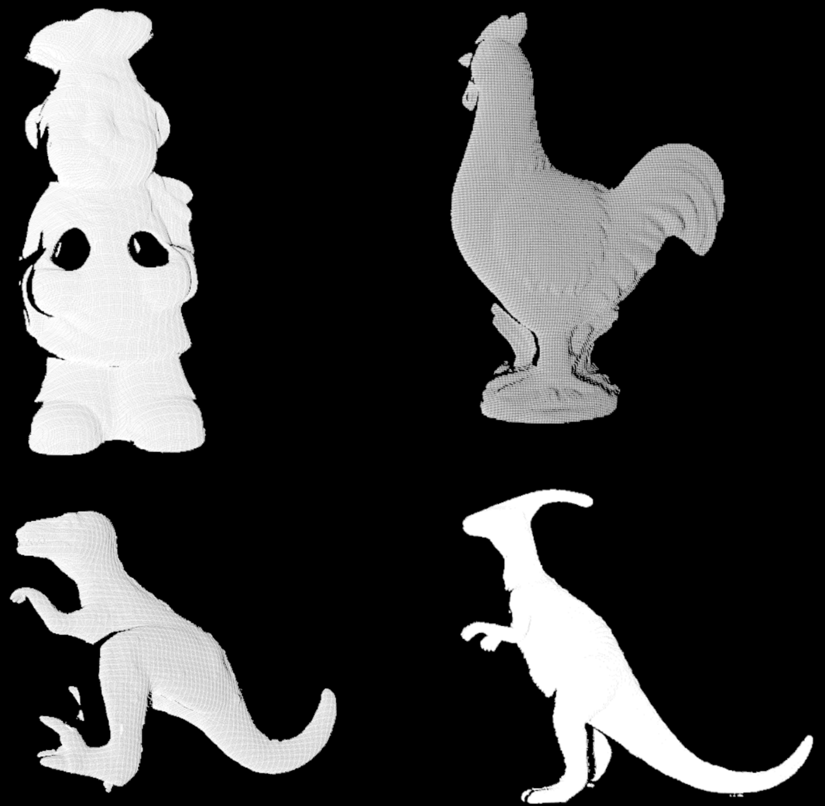
Step 3: Hypotheses generation & evaluation

1) Hypotheses generation: Each MAC generates one hypothesis with SVD
2) Hypotheses evaluation: metrics in RASNAC, such as inlier count, MAE, MSE, are employed to find the best hypothesis

7. Experiments-comparative exp.

1. U3M dataset: an object-scale dataset



U3M object dataset

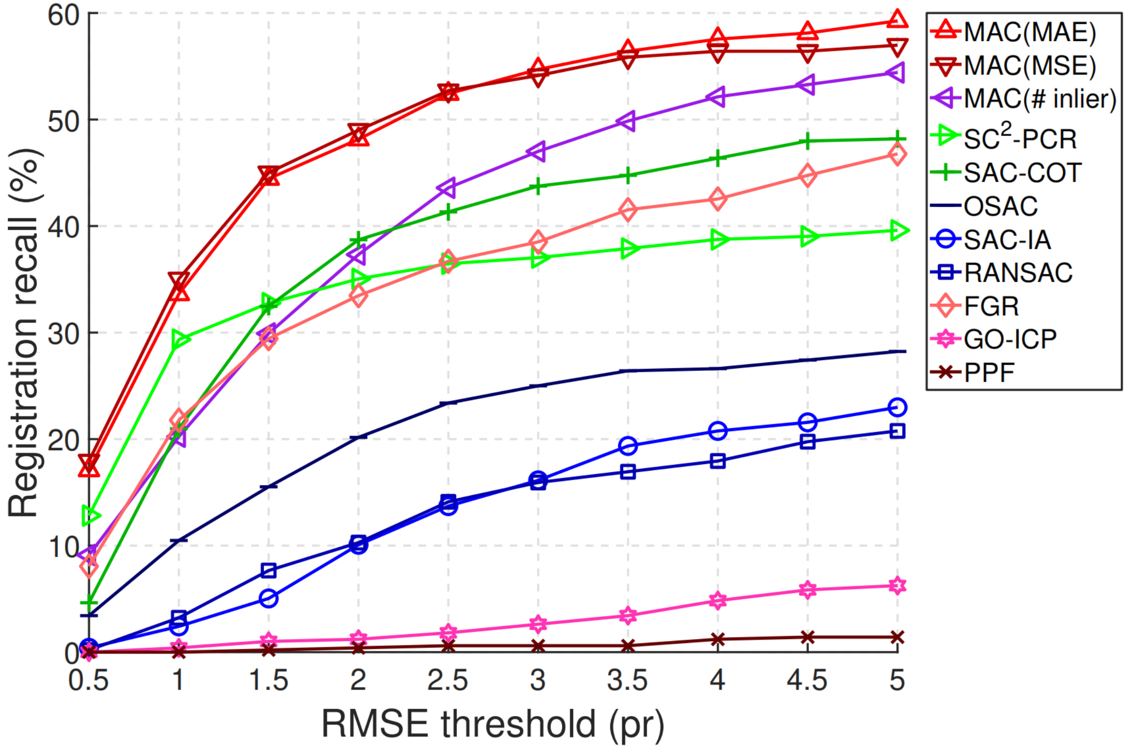


Figure 3. Registration performance of tested point cloud registration methods on U3M.

7. Experiments-comparative exp.

2. 3DMatch/3DLoMatch dataset: an indoor scene dataset

	FPFH			FCGF		
	RR(%)	RE(°)	TE(cm)	RR(%)	RE(°)	TE(cm)
i) Traditional						
SM [20]	55.88	2.94	8.15	86.57	2.29	7.07
FGR [45]	40.91	4.96	10.25	78.93	2.90	8.41
RANSAC-1M [13]	64.20	4.05	11.35	88.42	3.05	9.42
RANSAC-4M [13]	66.10	3.95	11.03	91.44	2.69	8.38
GC-RANSAC [5]	67.65	2.33	6.87	92.05	2.33	7.11
TEASER++ [36]	75.48	2.48	7.31	85.77	2.73	8.66
CG-SAC [30]	78.00	2.40	6.89	87.52	2.42	7.66
SC^2-PCR [8]	83.73	2.18	6.70	93.16	2.09	6.51
ii) Deep learned						
3DRegNet [27]	26.31	3.75	9.60	77.76	2.74	8.13
DGR [9]	32.84	2.45	7.53	88.85	2.28	7.02
DHVR [19]	67.10	2.78	7.84	91.93	2.25	7.08
PointDSC [3]	72.95	2.18	6.45	91.87	2.10	6.54
MAC	**84.10**	**1.96**	**6.18**	**93.72**	**1.89**	**6.03**

Table 1. Registration results on 3DMatch dataset.

	FPFH			FCGF		
	RR(%)	RE(°)	TE(cm)	RR(%)	RE(°)	TE(cm)
i) Traditional						
RANSAC-1M [13]	0.67	10.27	15.06	9.77	7.01	14.87
RANSAC-4M [13]	0.45	10.39	20.03	10.44	6.91	15.14
TEASER++ [36]	35.15	4.38	10.96	46.76	4.12	12.89
SC^2-PCR [8]	38.57	4.03	10.31	58.73	3.80	10.44
ii) Deep learned						
DGR [9]	19.88	5.07	13.53	43.80	4.17	10.82
PointDSC [3]	20.38	4.04	10.25	56.20	3.87	10.48
MAC	**40.88**	**3.66**	**9.45**	**59.85**	**3.50**	**9.75**

Table 2. Registration results on 3DLoMatch dataset.

7. Experiments-comparative exp.

2. 3DMatch/3DLoMatch dataset: MAC can boost deep –learned methods.

# Samples	3DMatch RR(%)					3DLoMatch RR(%)				
	5000	2500	1000	500	250	5000	2500	1000	500	250
FCGF [10]	85.1	84.7	83.3	81.6	71.4	40.1	41.7	38.2	35.4	26.8
SpinNet [1]	88.6	86.6	85.5	83.5	70.2	59.8	54.9	48.3	39.8	26.8
Predator [18]	89.0	89.9	90.6	88.5	86.6	59.8	61.2	62.4	60.8	58.1
CoFiNet [43]	89.3	88.9	88.4	87.4	87.0	67.5	66.2	64.2	63.1	61.0
GeoTransformer [29]	92.0	91.8	91.8	91.4	91.2	75.0	74.8	74.2	74.1	73.5
FCGF+MAC	91.3	92.2	91.6	90.4	85.6	57.2	56.0	52.6	42.4	32.1
	6.2↑	7.5↑	8.3↑	8.8↑	14.2↑	17.1↑	14.3↑	14.4↑	7.0↑	5.3↑
SpinNet+MAC	95.3	95.1	93.3	91.4	81.2	72.8	69.9	59.2	54.8	32.1
	6.7↑	8.5↑	7.8↑	7.9↑	11.0↑	13.0↑	15.0↑	10.9↑	15.0↑	5.3↑
Predator+MAC	94.6	94.4	94.0	93.5	92.3	70.9	70.4	69.8	67.2	64.1
	5.6↑	4.5↑	3.4↑	5.0↑	5.7↑	11.1↑	9.2↑	7.4↑	6.4↑	6.0↑
CoFiNet+MAC	94.1	94.4	94.5	93.8	92.7	71.6	71.5	70.6	69.2	68.1
	4.8↑	5.5↑	6.1↑	6.4↑	5.7↑	4.1↑	5.3↑	6.4↑	6.1↑	7.1↑
GeoTransformer+MAC	**95.7**	**95.7**	**95.2**	**95.3**	**94.6**	**78.9**	**78.7**	**78.2**	**77.7**	**76.6**
	3.7↑	3.9↑	3.4↑	3.9↑	3.4↑	3.9↑	3.9↑	4.0↑	3.6↑	3.1↑

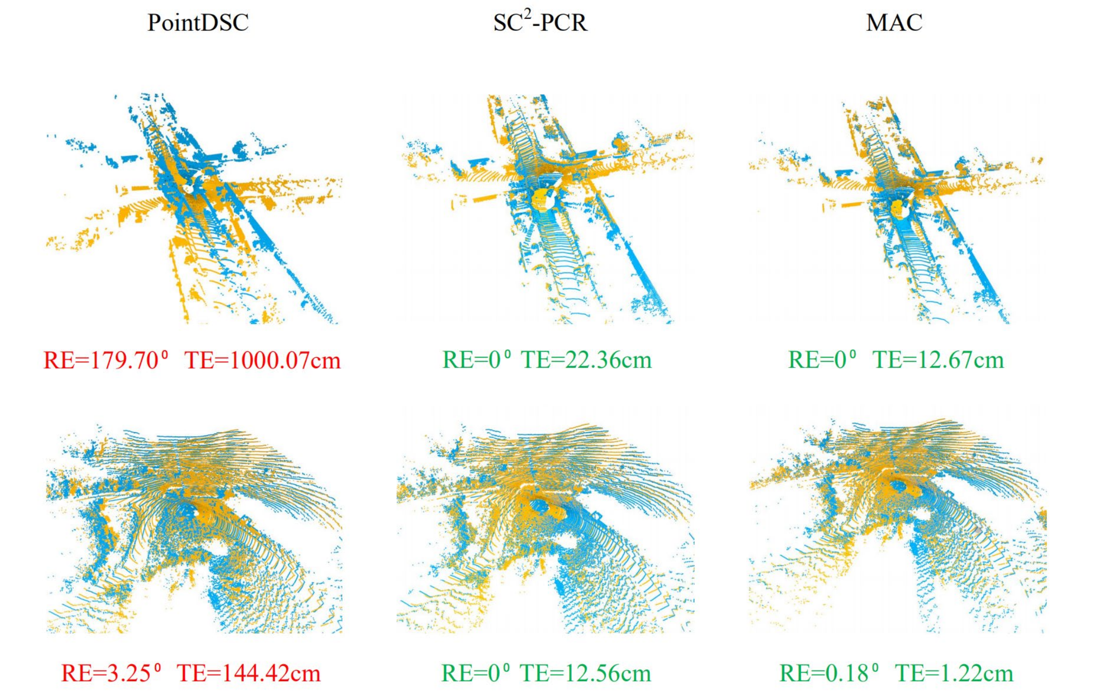
Table 3. Performance boosting for deep-learned methods when combined with MAC.

7. Experiments-comparative exp.

3. KITTI dataset: an outdoor scene dataset

	FPFH			FCGF		
	RR(%)	RE(°)	TE(cm)	RR(%)	RE(°)	TE(cm)
i) Traditional						
FGR [45]	5.23	0.86	43.84	89.54	0.46	25.72
TEASER++ [36]	91.17	1.03	17.98	94.96	0.38	**13.69**
RANSAC [13]	74.41	1.55	30.20	80.36	0.73	26.79
CG-SAC [30]	74.23	0.73	14.02	83.24	0.56	22.96
SC^2-PCR [8]	99.28	0.39	8.68	**97.84**	**0.33**	20.58
ii) Deep learned						
DGR [9]	77.12	1.64	33.10	96.90	0.34	21.70
PointDSC [3]	98.92	**0.38**	**8.35**	**97.84**	**0.33**	20.32
MAC	**99.46**	0.40	8.46	**97.84**	0.34	19.34

Table 4. Registration results on KITTI dataset.



7. Experiments-analysis exp.

1. The quality of MAC hypotheses

# hypotheses	3DMatch				3DLoMatch			
	RANSAC		MAC		RANSAC		MAC	
	FCGF	FPFH	FCGF	FPFH	FCGF	FPFH	FCGF	FPFH
100	10.45	0.76	61.94	50.67	1.25	0.05	30.47	12.22
200	20.76	1.50	119.20	89.27	2.52	0.09	55.57	17.59
500	51.74	3.68	269.06	162.41	6.21	0.21	109.32	23.32
1000	103.65	7.39	456.18	217.32	12.43	0.41	156.11	26.02
2000	208.24	14.90	669.32	254.13	24.80	0.81	202.12	29.31

Table 6. Comparison of the number of correct hypotheses generated by MAC and RANSAC on 3DMatch and 3DLoMatch.

7. Experiments-analysis exp.

2. The upper bound of MAC

	3DMatch RR(%)	3DLoMatch RR(%)
MAC-1	98.46	91.24
MAC-5	97.10	83.32
MAC-10	96.43	77.93
MAC-20	94.70	70.47
MAC-50	91.13	56.37
MAC-origin	93.72	59.85

Table 7. Registration recall on 3DMatch with FCGF setting based on judging MAC's hypotheses. MAC-n: a point cloud pair is considered alignable if at least n hypotheses are correct.

Comparison with current SOTA: 98.46%/91.24% vs ~94%/58%

7. Experiments-analysis exp.

3. Efficiency analysis

# Corr.	250	500	1000	2500	5000
PointDSC	32.24±0.81	78.38±0.89	240.46±2.18	1401.97±12.24	5504.11±10.32
TEASER++	6.40±1.88	6.68±0.66	16.74±1.21	104.24±0.53	484.93±1.87
SC^2-PCR	19.34±0.63	63.23±0.55	215.98±1.24	1282.73±4.05	5210.17±8.30
MAC	7.32±0.55	23.32±0.38	56.45±1.41	282.67±7.83	3259.38±12.66

Table 4. Comparisons on average time consumption (ms).

# Corr.	250	500	1000	2500	5000
PointDSC	3531.46	3538.26	3582.57	3634.22	3736.10
TEASER++	1631.92	1634.77	2029.22	2266.84	2484.83
SC^2-PCR	448.01	453.18	508.40	621.27	690.22
MAC	15.59	17.43	23.49	52.79	150.86

Table 5. Comparisons on average memory consumption (MB).

8. Conclusion

1. MAC's advantages

Simple

- Technically simple
- A few parameters
- Learning-free

Effective

- SOTA performance
- Light-weight
- Robust to outliers

General

- Cross-dataset 1st
- Booster for learning
- Various scenarios

8. Conclusion

2. MAC's limitations & future work

- MAC can generate high-quality hypotheses, but may still fail to find them
- A better hypothesis evaluation metric is desired

	3DMatch RR(%)	3DLoMatch RR(%)
MAC-1	98.46	91.24
MAC-5	97.10	83.32
MAC-10	96.43	77.93
MAC-20	94.70	70.47
MAC-50	91.13	56.37
MAC-origin	93.72	59.85

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Final Remark

Handcrafted methods can be great again.

Paper **Code**

Github: https://github.com/zhangxy0517/3D-Registration-with-Maximal-Cliques

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