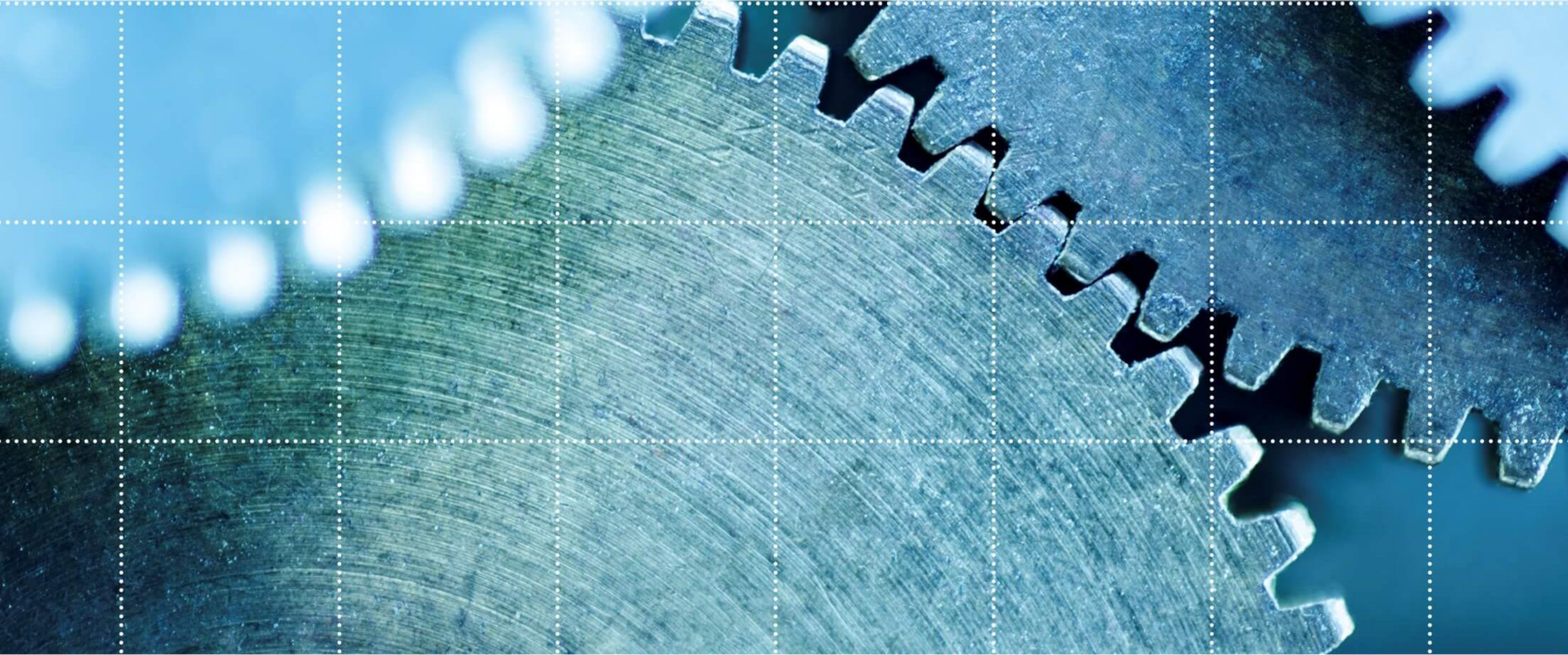
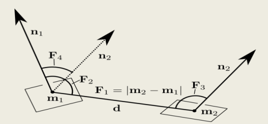


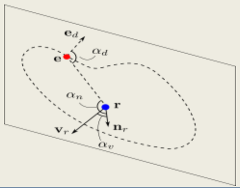
Detecting Geometric Primitives in 3D Data

Background: Building Blocks for Point-Pair-Voting

Feature

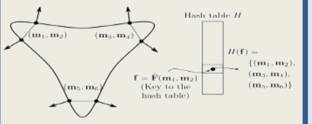
3D Point Pairs





Feature Matching

Implicit Model Description



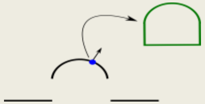
$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) \in \mathbb{R} \times [\pi/2 - \delta_\angle, \pi/2 + \delta_\angle] \times [\pi/2 - \delta_\angle, \pi/2 + \delta_\angle] \times [0, 2\delta_\angle]$$

$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) = (2r\sin(\alpha/2), (\pi - \alpha)/2, (\pi + \alpha)/2, \alpha)$$

$$\begin{aligned}\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) &= (|\mathbf{d}|, \angle(\mathbf{n}_1, \mathbf{d}), \pi - \mathbf{F}_2, \alpha) \\ &= (\sqrt{s^2 + l^2}, \\ &\quad \angle((1,0,0)^T, (r(1-\cos\alpha), r\sin\alpha, l)^T), \\ &\quad \pi - \mathbf{F}_2, \alpha)\end{aligned}$$

Parameter Space

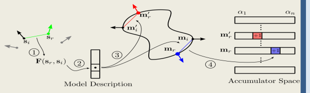
Local, Data-Driven Parameters

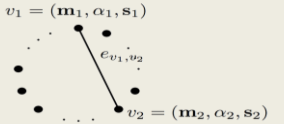


	Number of parameters		
Shape	Rigid	Local	Shape
Free-form	6	3	0
Plane	3	0	0
Sphere	3	0	1 (radius)
Cylinder	4	1	1 (radius)

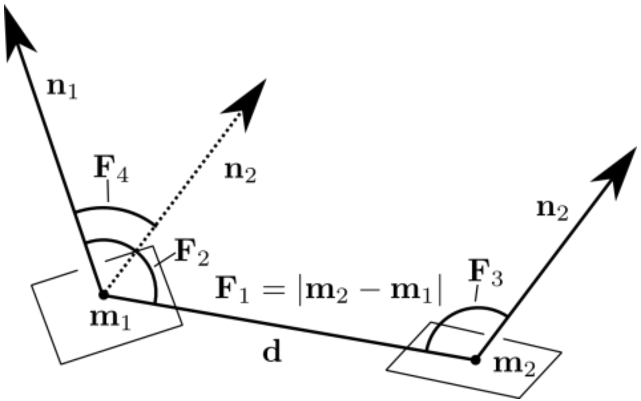
Detection

Voting Scheme





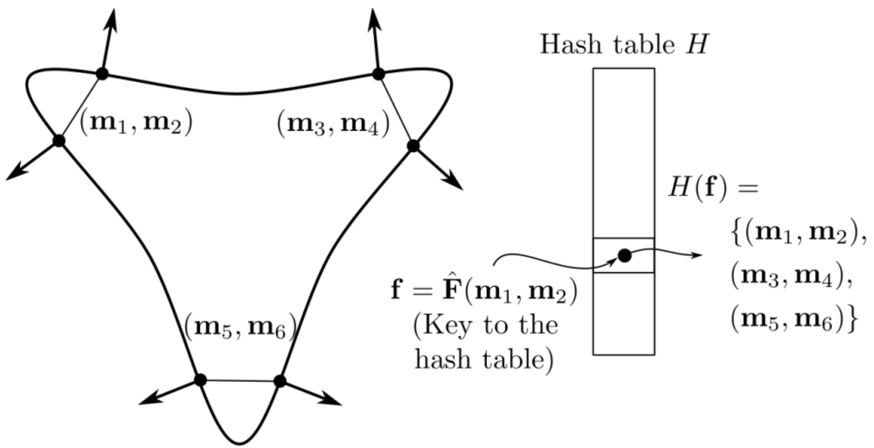
Background: Point Pair Features



$$\mathbf{F}(\mathbf{m}_1, \mathbf{m}_2) = (|\mathbf{d}|, \angle(\mathbf{n}_1, \mathbf{d}), \angle(\mathbf{n}_2, \mathbf{d}), \angle(\mathbf{n}_1, \mathbf{n}_2))$$

Fast, invariant, discriminative,
define local reference frame

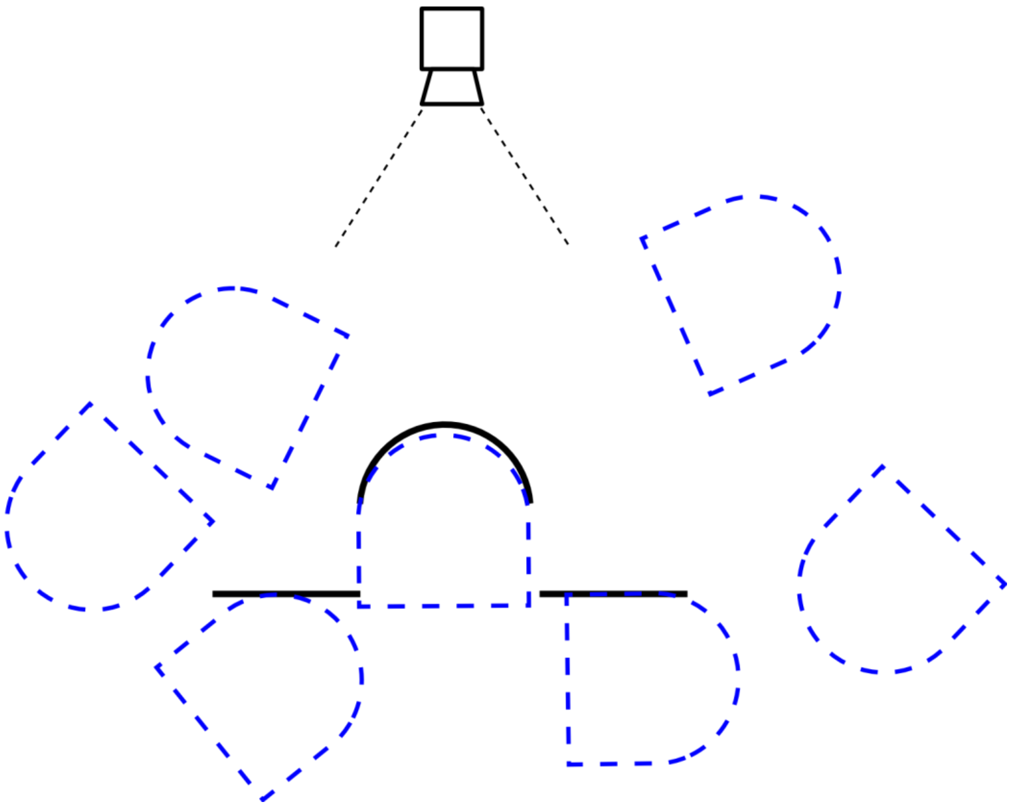
Background: Point Pair Feature Database



$$\hat{\mathbf{F}} = \left(\left\lfloor \frac{F_1}{d_{\text{dist}}} \right\rfloor, \left\lfloor \frac{F_2}{d_{\text{angle}}} \right\rfloor, \left\lfloor \frac{F_3}{d_{\text{angle}}} \right\rfloor, \left\lfloor \frac{F_4}{d_{\text{angle}}} \right\rfloor \right) \in \mathbb{Z}^4$$

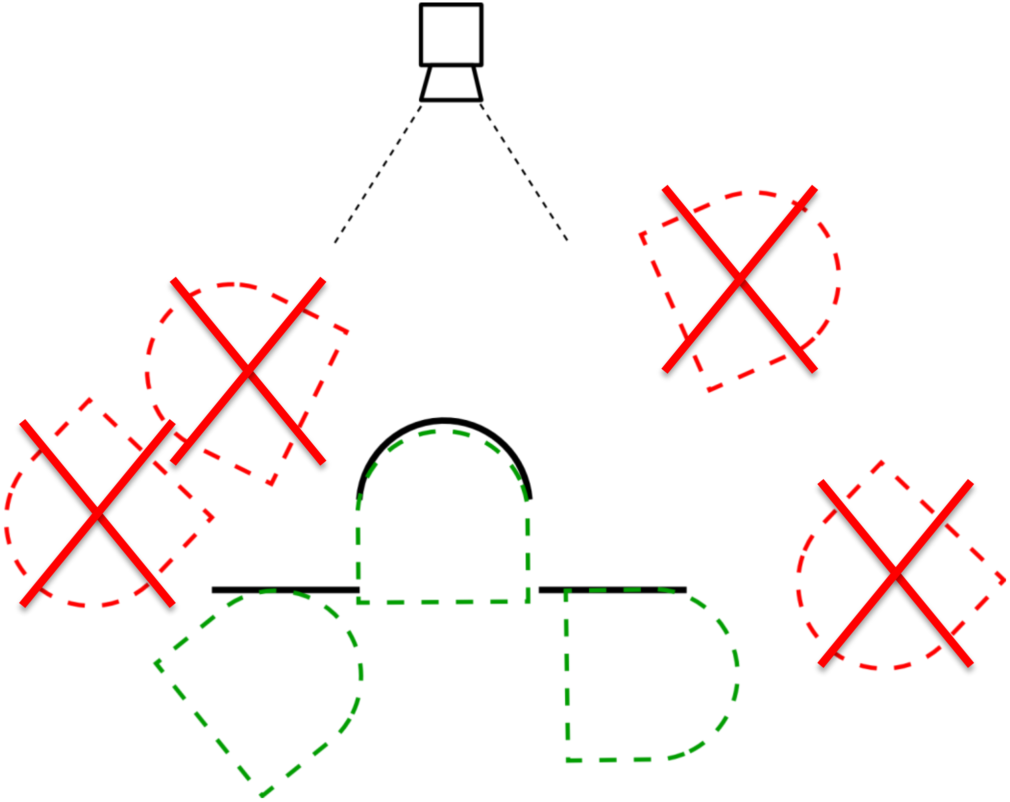
Find similar point pairs in O(1)

Background: Local Pose Parameters



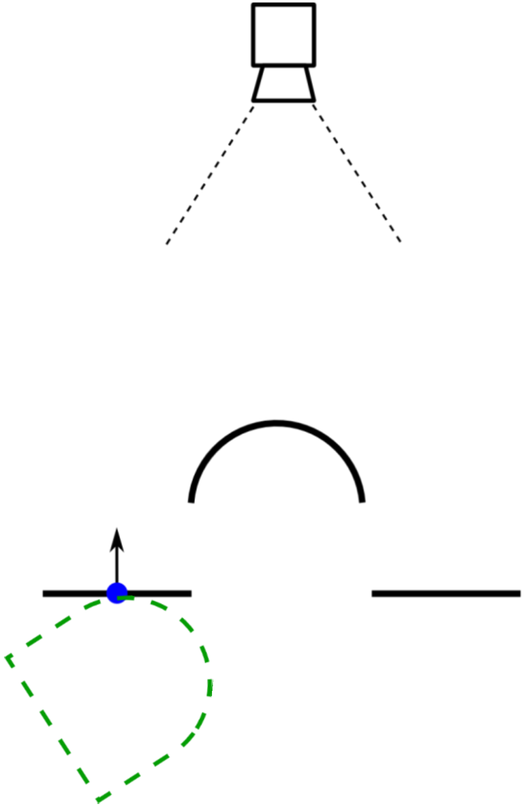
- **Rigid 6D pose: Large, complex parameter space**

Background: Local Pose Parameters



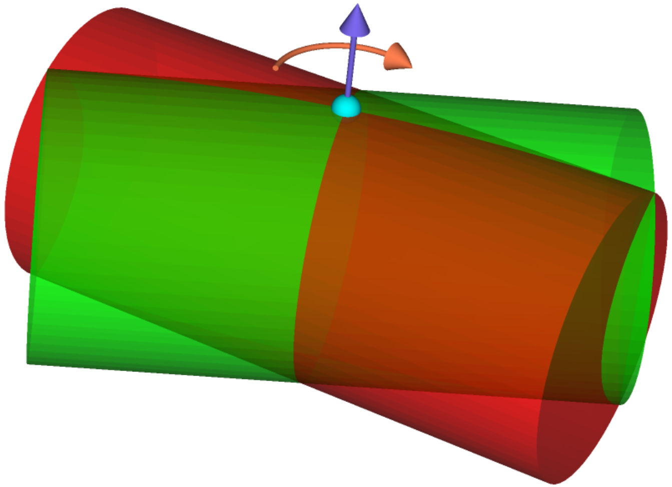
- Rigid 6D pose: Large, complex parameter space
- Assume one 3D point to be aligned

Background: Local Pose Parameters



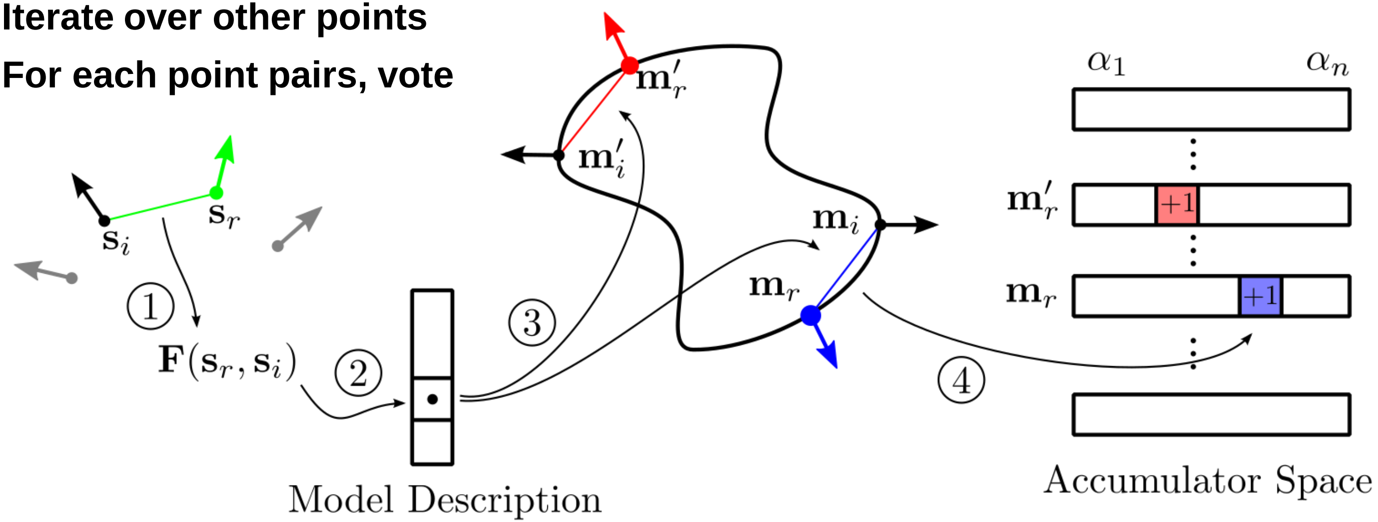
- Rigid 6D pose: Large, complex parameter space
- Assume one 3D point to be aligned
- Fix scene point (“reference point”)
- Find corresponding model point and rotation around normal vector

Background: Local Pose Parameters



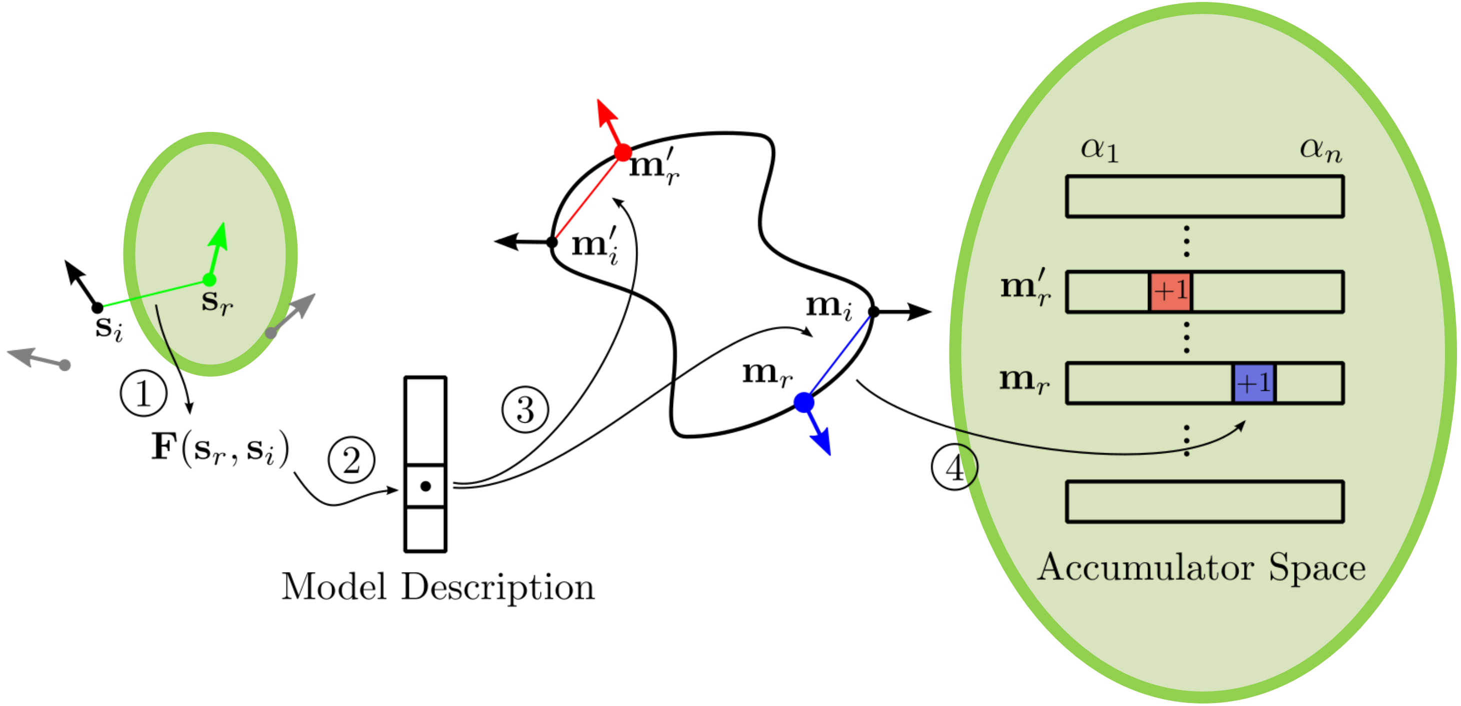
Voting Scheme

- For each scene point, find best local parameters (corresponding model point, rotation angle) through voting
  - Initialize accumulator array with zeros
  - Iterate over other points
  - For each point pairs, vote



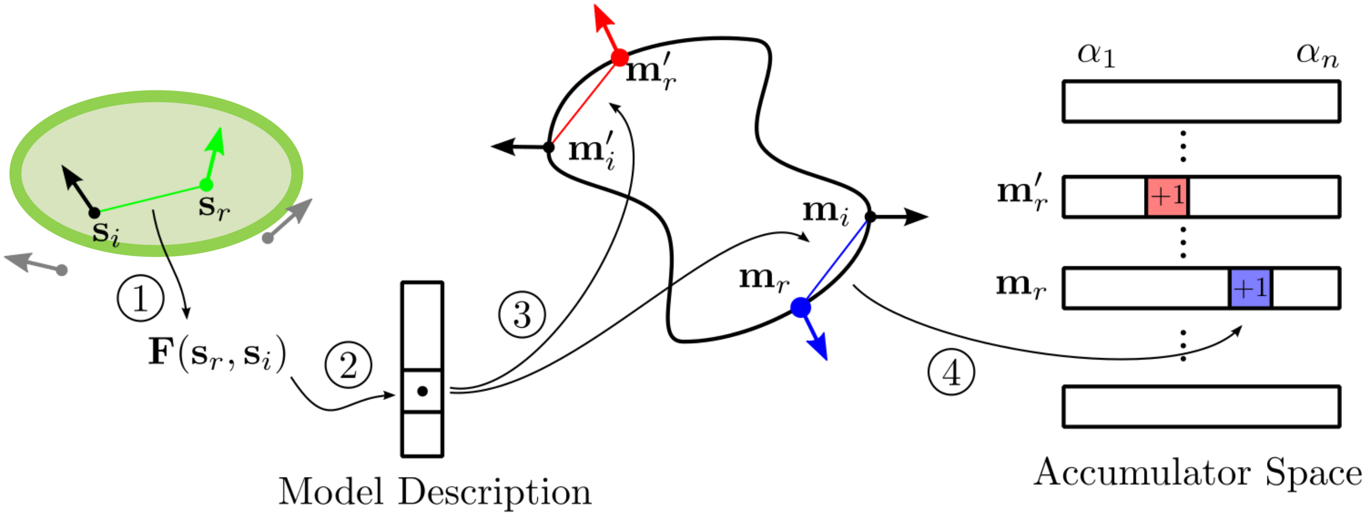
Voting Scheme

- Select a 3D scene point, create the local voting space



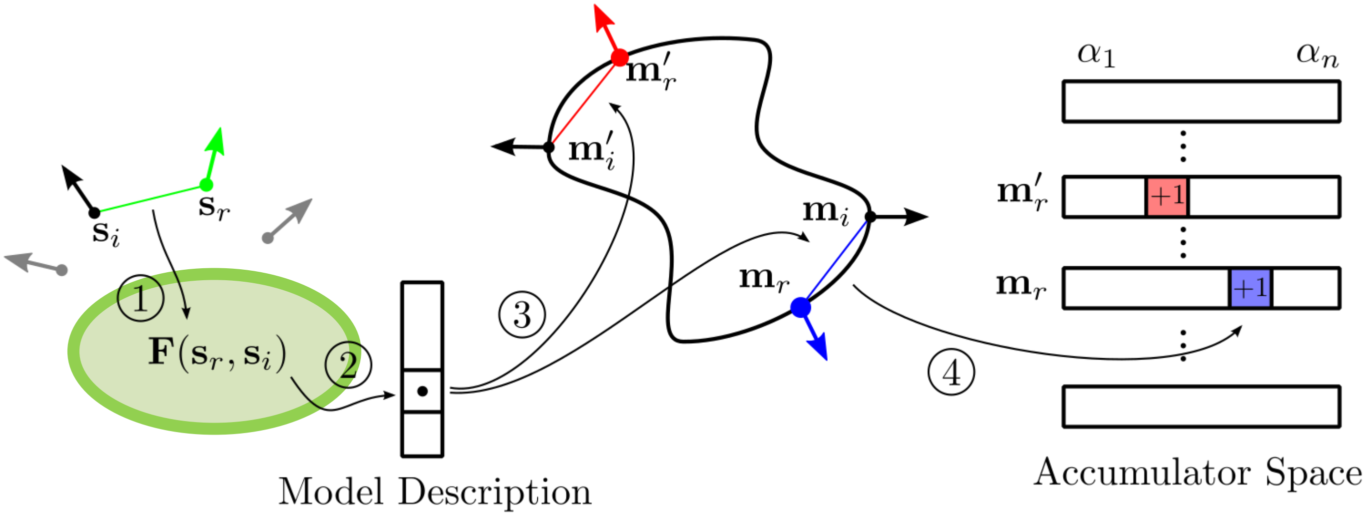
Voting Scheme

- **Pair the 3D point with all other 3D points**



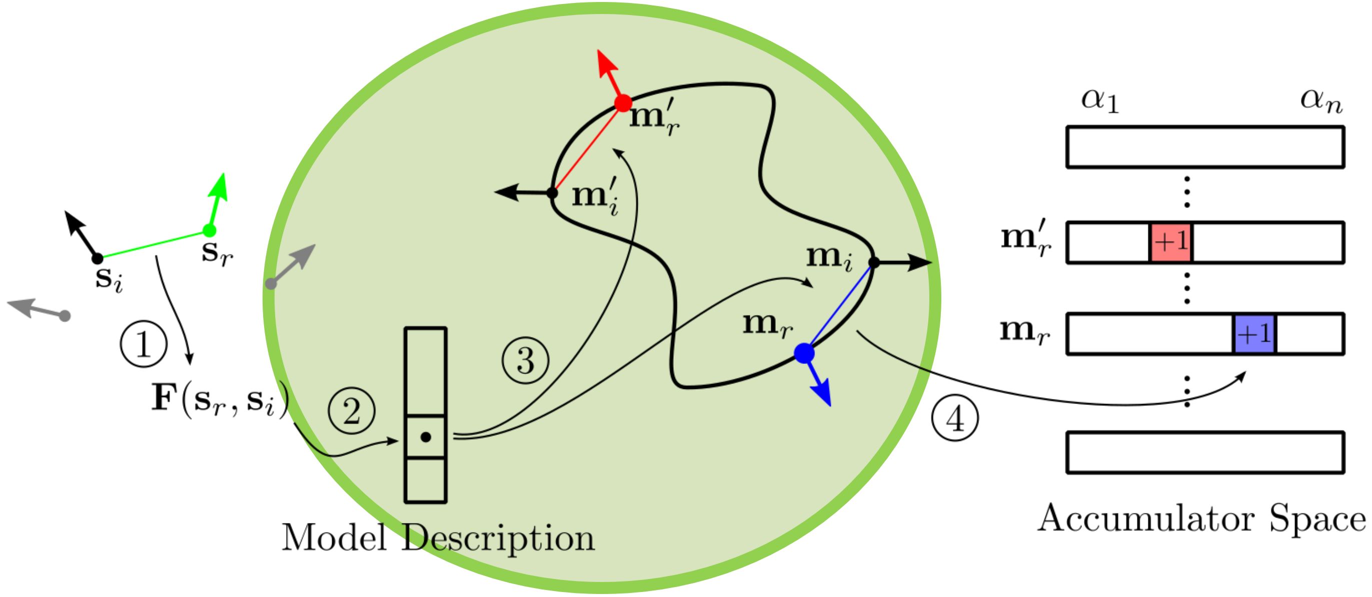
Voting Scheme

- **Compute the point pair feature**



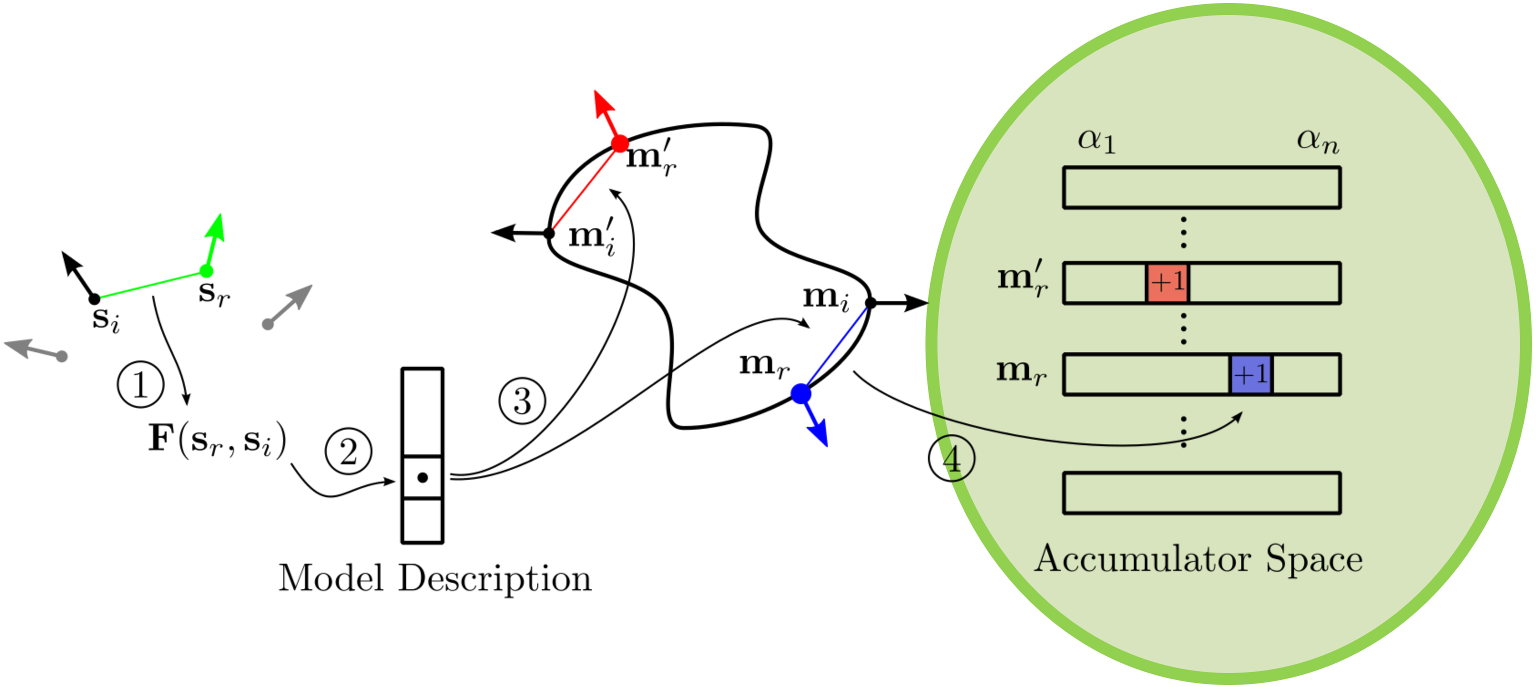
Voting Scheme

- Find corresponding point pairs on the model



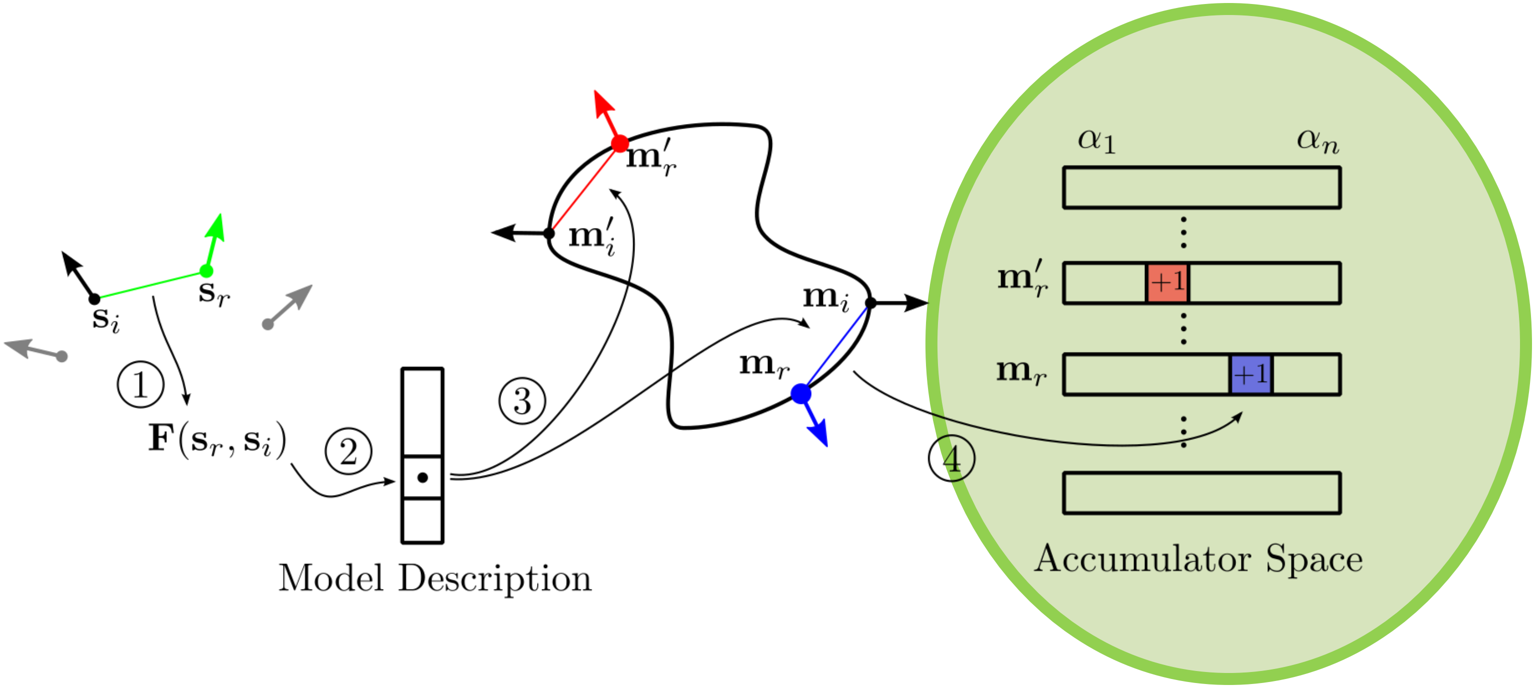
Voting Scheme

- Vote for every possible correspondence



Voting Scheme

- Maximum in the voting space is the locally optimal pose



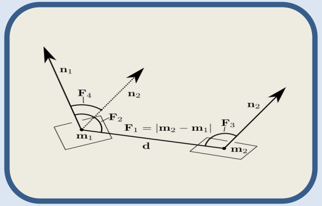
Geometric Primitives

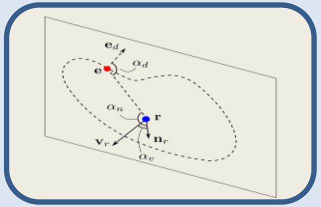
- Geometric primitives often arise in practical applications
  - Calibration using spheres
  - Find background planes
    - Navigation
    - Remove background plane before object detection
  - Raw cylinders with varying radii (rigid shape is too constraining)
- The base method works for primitives, but local parameters contain redundancies that make the voting slower
- Propose to adapt the method to
  - Remove redundancies
  - Exploit explicit nature of primitives for faster feature matching
  - Add shape parameters (radius / scale)

Optimizations for Geometric Primitives

Feature

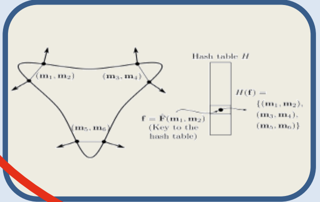
3D Point Pairs





Feature Matching

Implicit Model Description



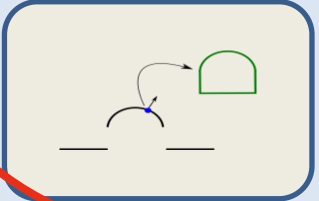
$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) \in \mathbb{R} \times [\pi/2 - \delta_\angle, \pi/2 + \delta_\angle] \times [\pi/2 - \delta_\angle, \pi/2 + \delta_\angle] \times [0, 2\delta_\angle]$$

$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) = (2r\sin(\alpha/2), (\pi - \alpha)/2, (\pi + \alpha)/2, \alpha)$$

$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) = (|\mathbf{d}|, \angle(\mathbf{n}_1, \mathbf{d}), \pi - \mathbf{F}_2, \alpha) = (\sqrt{s^2 + l^2}, \angle((1,0,0)^T, (r(1 - \cos\alpha), r\sin\alpha, l)^T), \pi - \mathbf{F}_2, \alpha)$$

Parameter Space

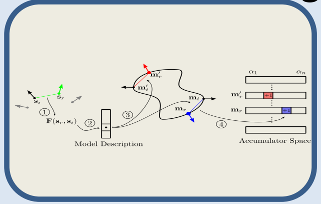
Local, Data-Driven Parameters

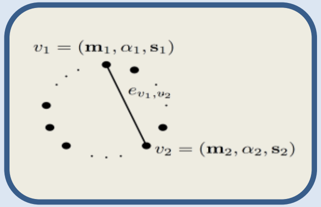


	Number of parameters		
Shape	Rigid	Local	Shape
Free-form	6	3	0
Plane	3	0	0
Sphere	3	0	1 (radius)
Cylinder	4	1	1 (radius)

Detection

Voting Scheme



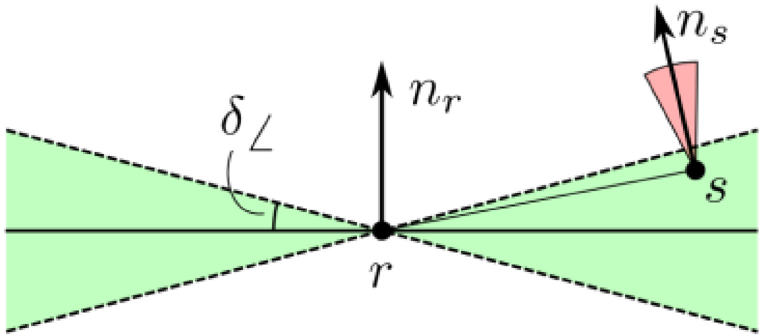


Geometric Primitives: Using Symmetry Information

	Number of parameters		
Shape	**Rigid**	**Local**	**Shape**
Free-form	6	3	0
Plane	3	0	0
Sphere	3	0	1 (radius)
Cylinder	4	1	1 (radius)

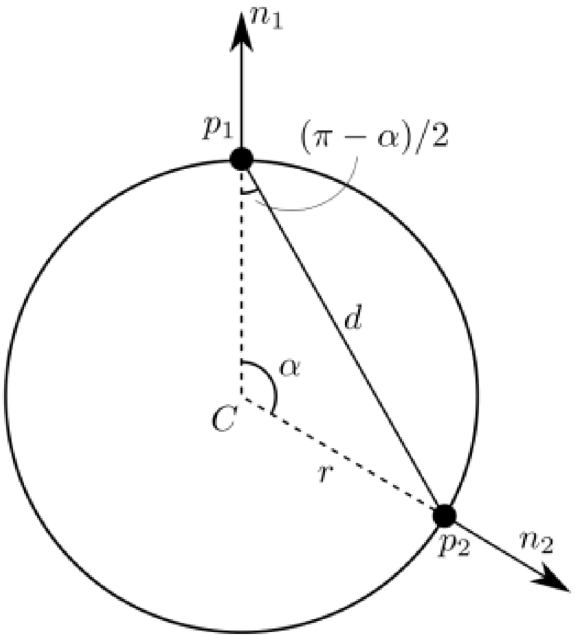
Implicit Point Pairs for Planes

$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) \in \mathbb{R} \times [\pi/2 - \delta_\angle, \pi/2 + \delta_\angle] \times [\pi/2 - \delta_\angle, \pi/2 + \delta_\angle] \times [0, 2\delta_\angle]$$



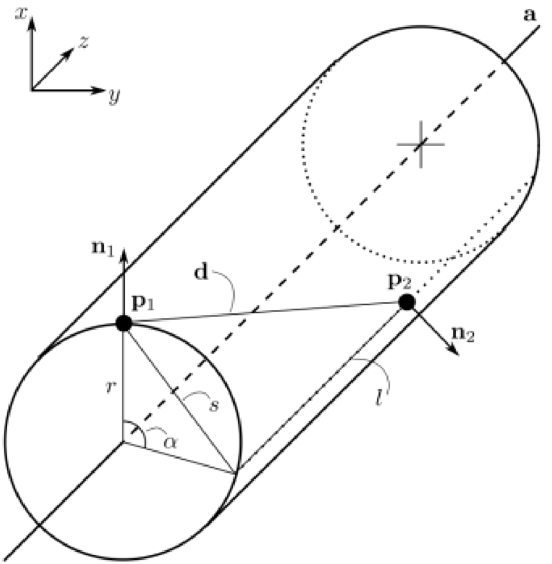
Implicit Point Pairs for Spheres

$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) = (2r\sin(\alpha/2), (\pi - \alpha)/2, (\pi + \alpha)/2, \alpha)$$

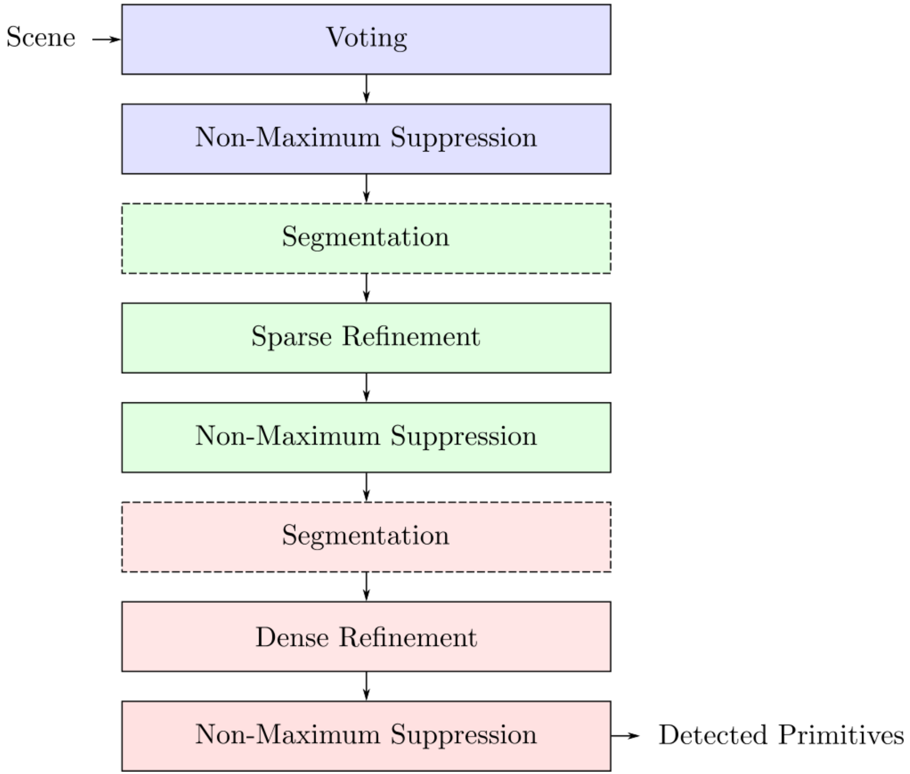


Implicit Point Pairs for Cylinders

$$\mathbf{F}(\mathbf{p}_1, \mathbf{p}_2) = (|\mathbf{d}|, \angle(\mathbf{n}_1, \mathbf{d}), \pi - \mathbf{F}_2, \alpha)$$
$$= (\sqrt{s^2 + l^2}, \angle((1,0,0)^T, (r(1-\cos\alpha), r\sin\alpha, l)^T), \pi - \mathbf{F}_2, \alpha)$$



Pipeline

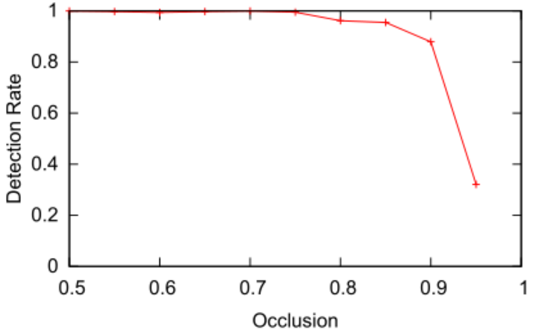


Scene
Voting
Non-Maximum Suppression
Segmentation
Sparse Refinement
Non-Maximum Suppression
Segmentation
Dense Refinement
Non-Maximum Suppression
Detected Primitives

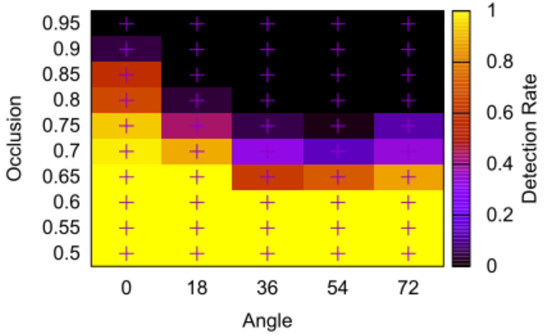
Results on the SegComp ABW Dataset

approach	correct	over	under	missed	noise
USF	12.7 (83.5%)	0.2	0.1	2.1	1.2
WSU	9.7 (63.8%)	0.5	0.2	4.5	2.2
UB	12.8 (84.2%)	0.5	0.1	1.7	2.1
UE	13.4 (88.1%)	0.4	0.2	1.1	0.8
OU	9.8 (64.4%)	0.2	0.4	4.4	3.2
PPU	6.8 (44.7%)	0.1	2.1	3.4	2.0
UA	4.9 (32.2%)	0.3	2.2	3.6	3.2
UFPR	13.0 (85.5%)	0.5	0.1	1.6	1.4
MRPS	11.1 (73.0%)	0.2	0.7	2.2	0.8
ours	12.3 (80.7%)	0.2	0.8	2.6	0.0

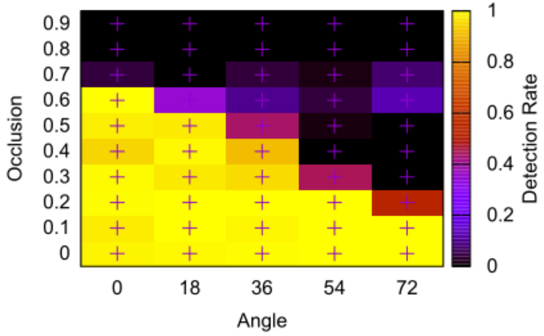
Results on a Synthetic Dataset



Spheres

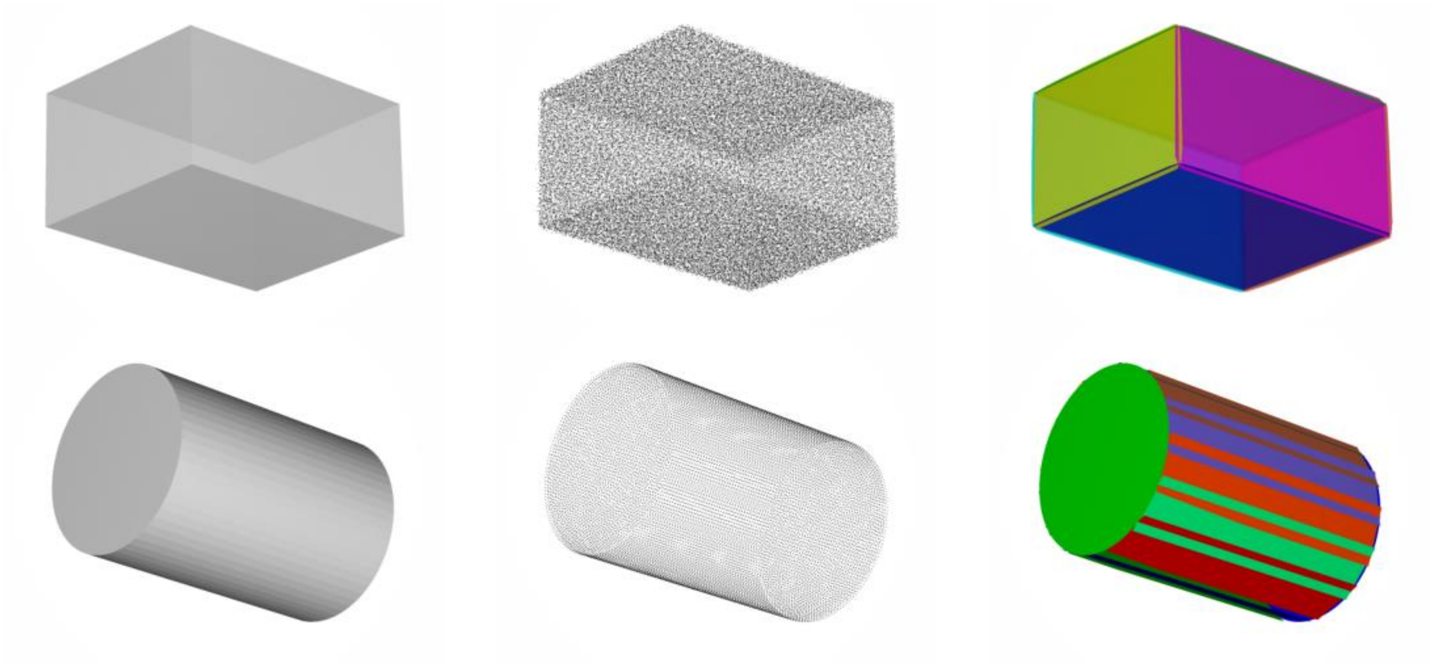


Cylinders

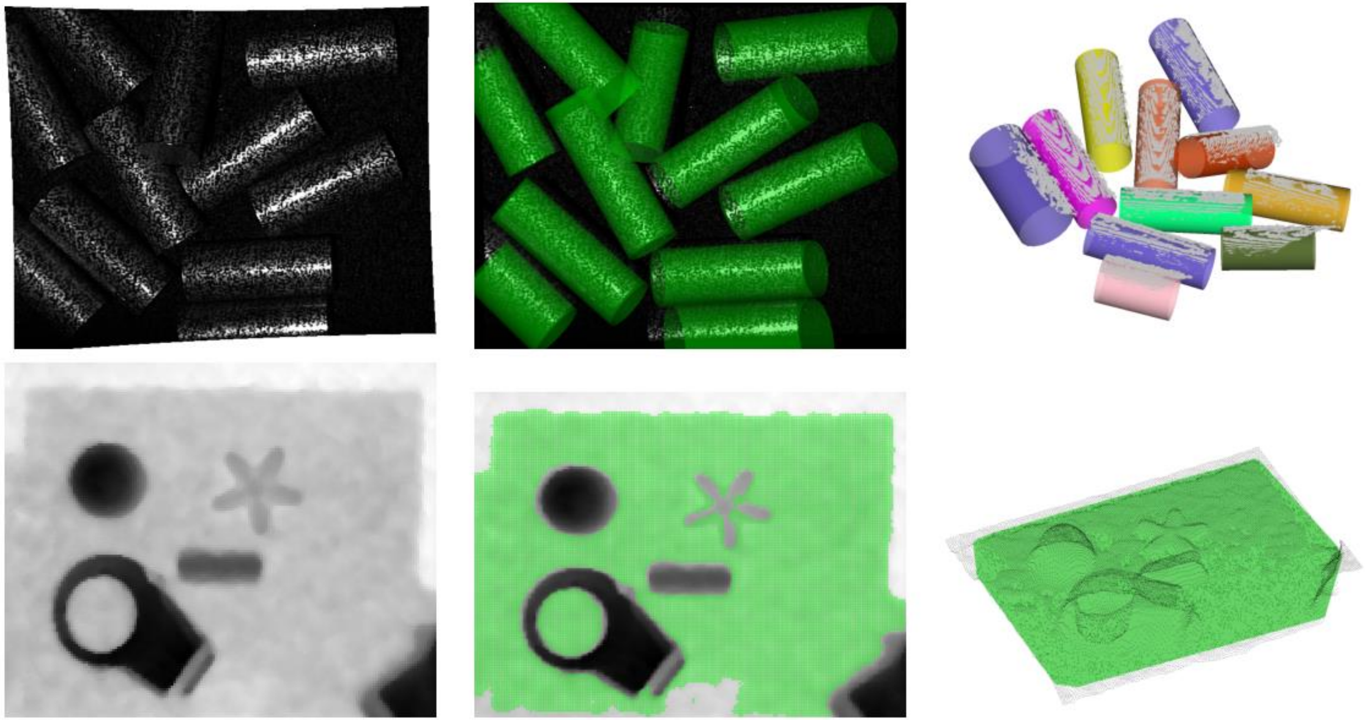


Planes

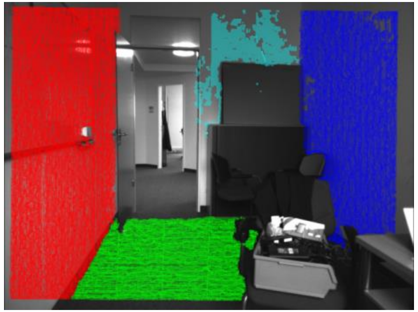
Results on Synthetic Data

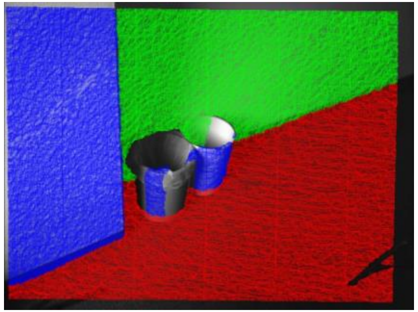


Results on Real Data



Results on Real Data





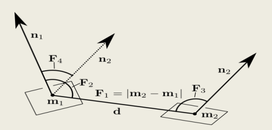
Outlook: Solids of Revolution

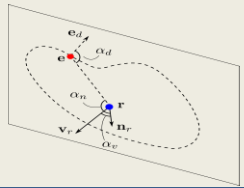
	Number of parameters		
Shape	**Rigid**	**Local**	**Shape**
Free-form	6	3	0
Plane	3	0	0
Sphere	3	0	1 (radius)
Cylinder	4	1	1 (radius)
Solids of revolution	5	2	0
Circular cone	5	2	1 (angle)
3D Boxes	6	3	3 (side lengths)

Iterative Voting though Graph Matching

Feature

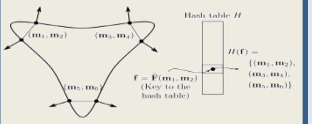
3D Point Pairs





Feature Matching

Implicit Model Description



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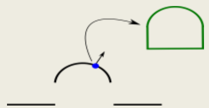
$$\mathbf{F}(\mathbf{p}_1,\mathbf{p}_2) = (2r\sin(\alpha/2),(\pi-\alpha)/2,(\pi+\alpha)/2,\alpha)$$

$$\mathbf{F}(\mathbf{p}_1,\mathbf{p}_2) = (|\mathbf{d}|,\angle(\mathbf{n}_1,\mathbf{d}),\pi-\mathbf{F}_2,\alpha) = (\sqrt{s^2+l^2}, \angle((1,0,0)^T,(r(1-\cos\alpha),r\sin\alpha,l)^T), \pi-\mathbf{F}_2,\alpha)$$

Parameter Space

Local, Data-Driven Parameters



	Number of parameters		
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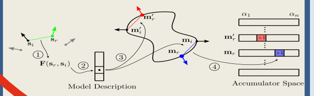
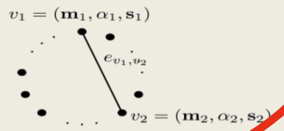
Detection

Voting Scheme





Graph Matching

$$G = (V, E)$$

correspondences between model and scene points

connect **consistent correspondences**

Correct correspondences form a dense subgraph

Duchenne, O., Bach, F., Kweon, I.S., Ponce, J.: *A tensor-based algorithm for high-order graph matching.* PAMI 33(12) (2011)

Graph Matching

$$G = (V, E)$$

correspondences between model and scene points

connect **consistent correspondences**

Correct correspondences form a dense subgraph

Assignment vector: $X \in \{0,1\}^V$

Relax: $X_v \in R^+$

$$X^* = \underset{|X|=1}{\operatorname{argmax}} \sum_{e=(v_i,v_j)\in E} X_{v_i} X_{v_j}$$

Graph Matching

$$G = (V, E)$$

correspondences between model and scene points

connect **consistent correspondences**

Correct correspondences form a dense subgraph

Assignment vector: $X \in \{0,1\}^V$

Relax: $X_v \in R^+$

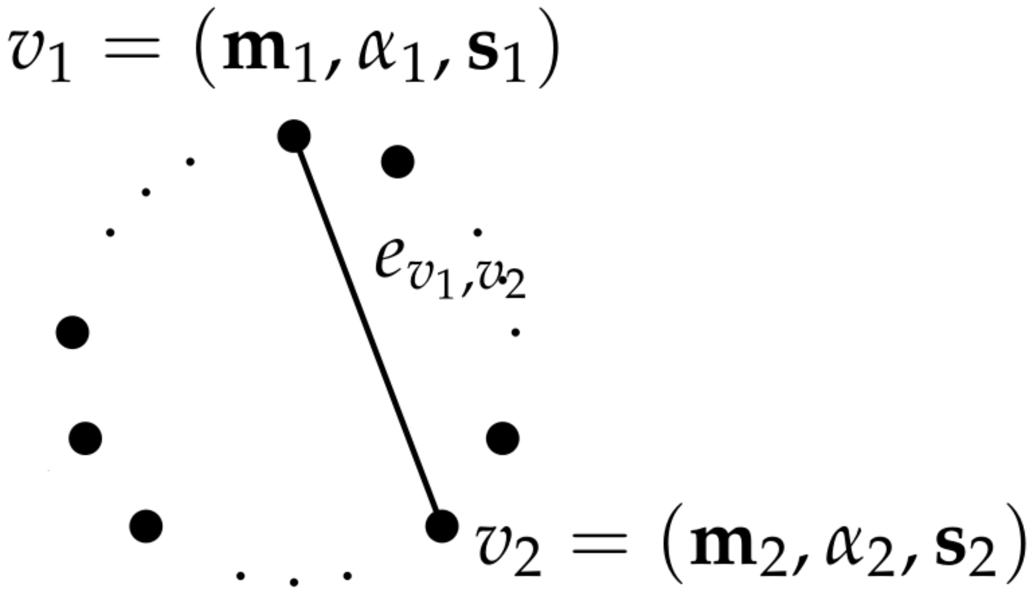
$$X^* = \underset{|X|=1}{\text{argmax}} \sum_{e=(v_i,v_j)\in E} X_{v_i} X_{v_j}$$

Solved using gradient descend: $X^{k+1} = \frac{AX^k}{|AX^k|}$

Equivalent to the power iteration with proven convergence

Equivalent to multiple rounds of voting

Graph Intuition

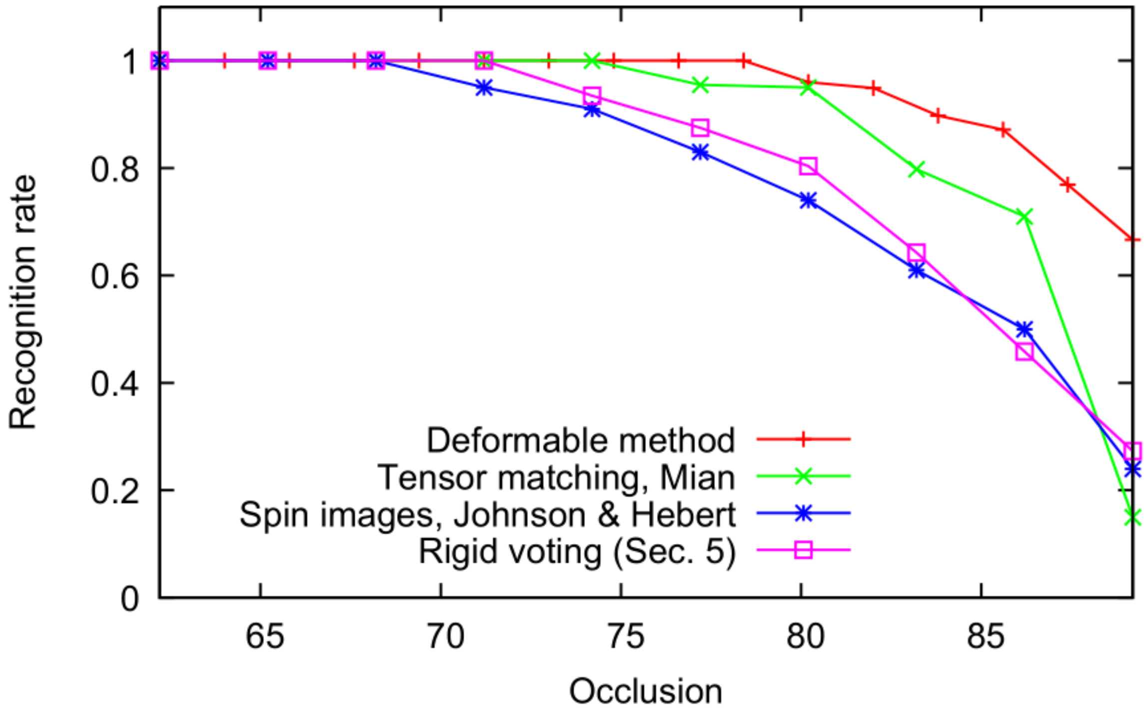


Graph $G = (V, E)$

Graph Pruning

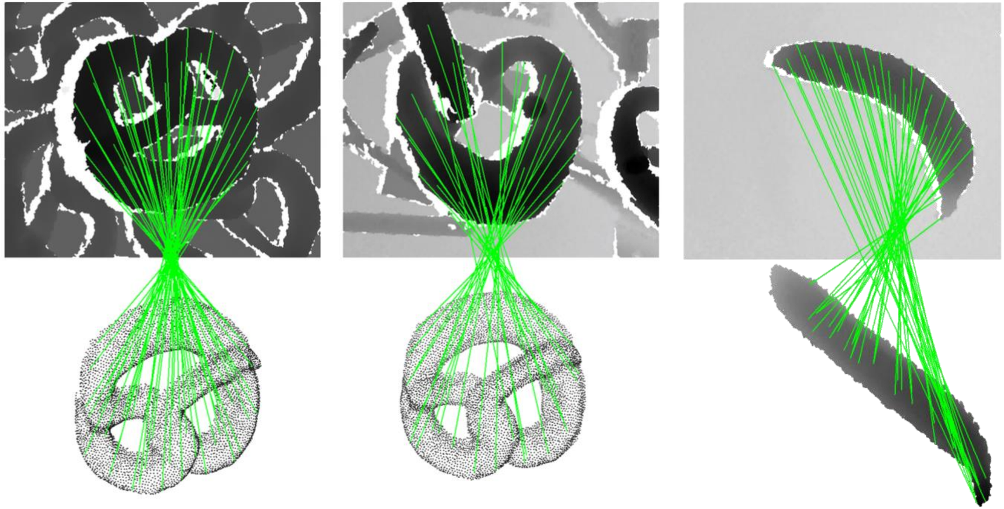
	$\lvert S \rvert$	$\lvert M \rvert$	Vertices $\lvert V \rvert$	Edges $\lvert E \rvert$	Runtime
Dense	13106	300	135.566	98.886.050	1163.6 s
Sparse	13106	300	34.095	42.832	1.1 s

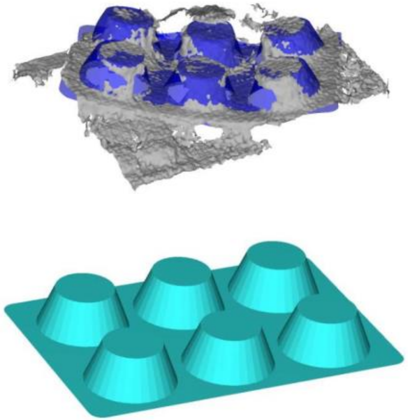
Results



Recognition rate
1
0.8
0.6
0.4
0.2
0
65
70
75
80
85
Occlusion
Deformable method
Tensor matching, Mian
Spin images, Johnson & Hebert
Rigid voting (Sec. 5)

Results





References

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