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YOKOHAMA | JAPAN

Incipient Slip-Based Rotation Measurement via Visuotactile Sensing During In-Hand Object Pivoting

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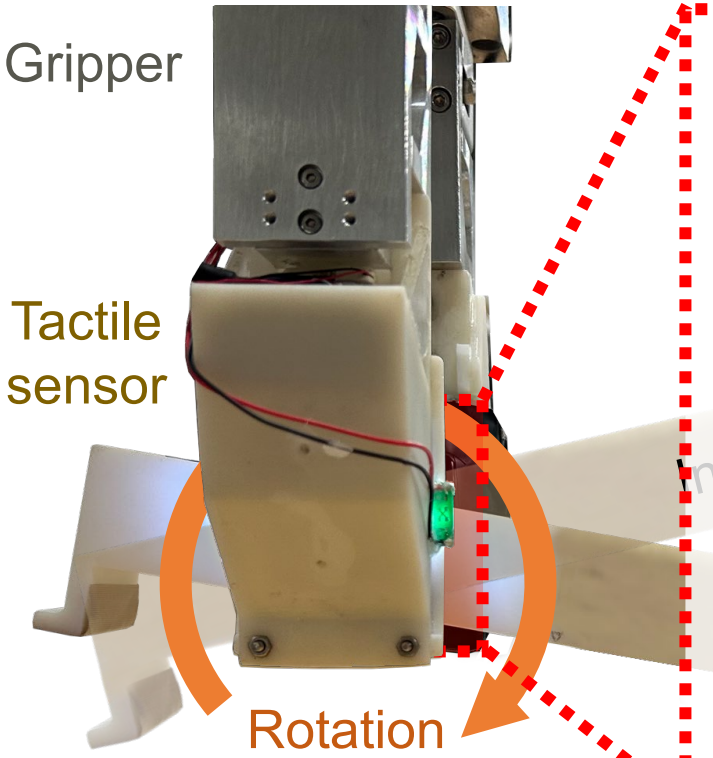
In-Hand Object Pivoting

Background:

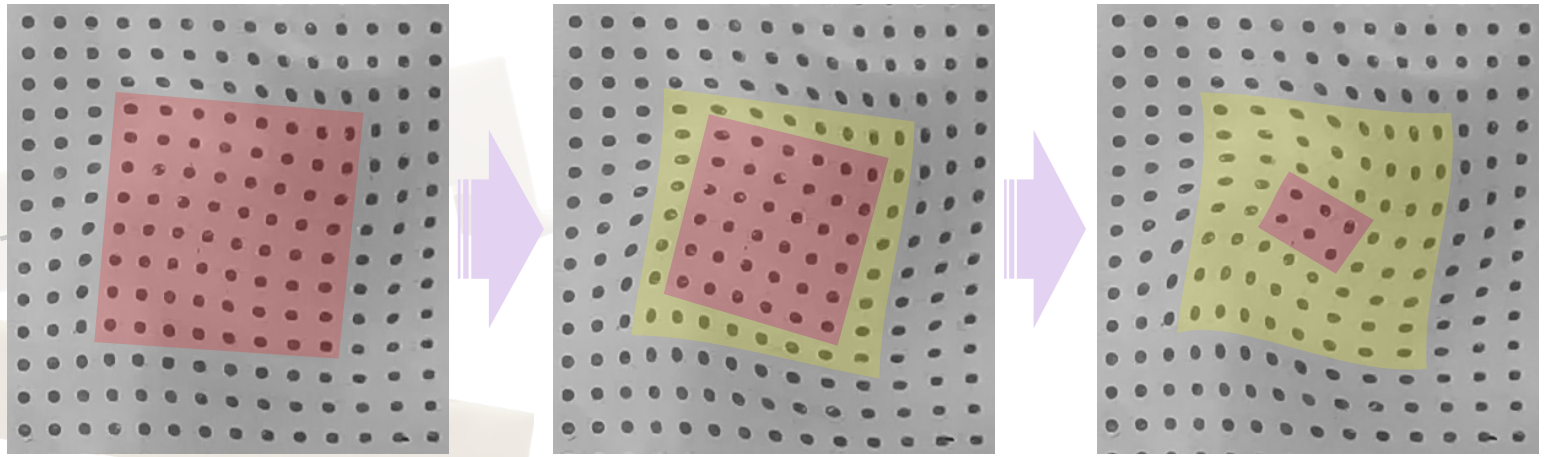
- ✓ **Pivoting:** Re-locating the object to a **specific rotation angle**, to prepare for the manipulation
- ✓ **Aim:** **Measuring the pivoting rotation** to guarantee the **dexterity** and **stability** of robots
- ✓ **Incipient slip:** An individual state between **full stick** and **macro slip** during the pivoting



[An example of **pivoting**]

Incipient Slip Phenomenon in the **contact region**

● : Markers : Stick region : Slip region

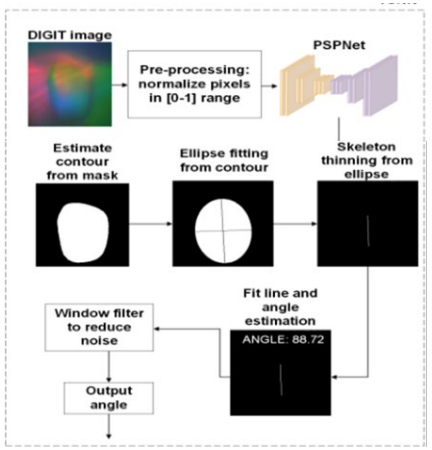


Full stick **Incipient slip** **Near macro slip**

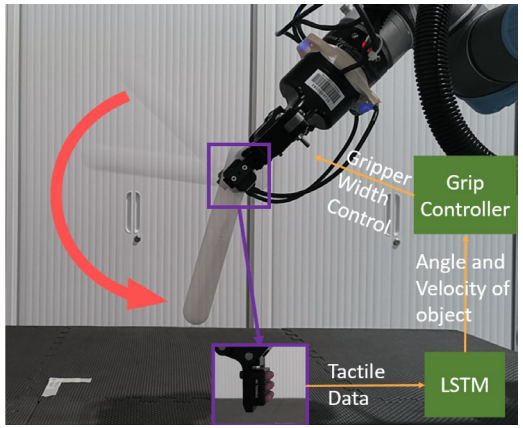
Review and Motivation

Reviewing Rotation Measurement Methods:

- **Rotation relative to the contact surface:**



[1]

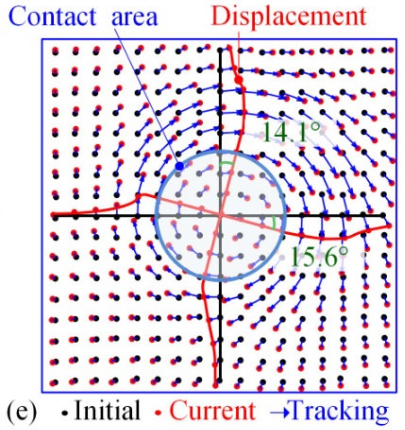


[2]

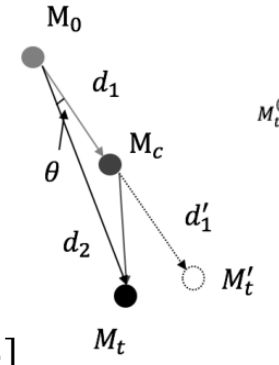
[1] J. Castaño-Amorós *et al.*, IEEE RA-L, vol. 8, no. 8, pp. 4537-4544, 2023
[2] J. Toskov *et al.*, CoRL, pp. 2284–2293, 2023

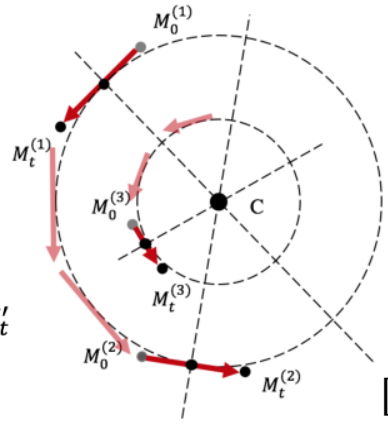
Regard as Macro Slip

- **Rotation of the contact surface per se:**



[3]





[4]

[3] H. Ma *et al.*, IEEE Sensors J., vol. 22, no. 18, pp. 17727-17736, Sep. 2022
[4] R. Kolamuri *et al.*, IROS, 2021, pp. 6809–6816

Regard as Full Stick

Challenge: Ignoring the impact of incipient slip can lead to **measurement errors** and the **overly optimistic estimate** of stable grasping state

Motivation: Incipient Slip-Based Rotation Measurement during pivoting

Conclusion of Contact Modeling

Derived Results:

$$\Delta\boldsymbol{\varphi}_{ij} = -\frac{\boldsymbol{rot}(\Delta \boldsymbol{s}_{ij})}{\boldsymbol{2(k+1)}}$$

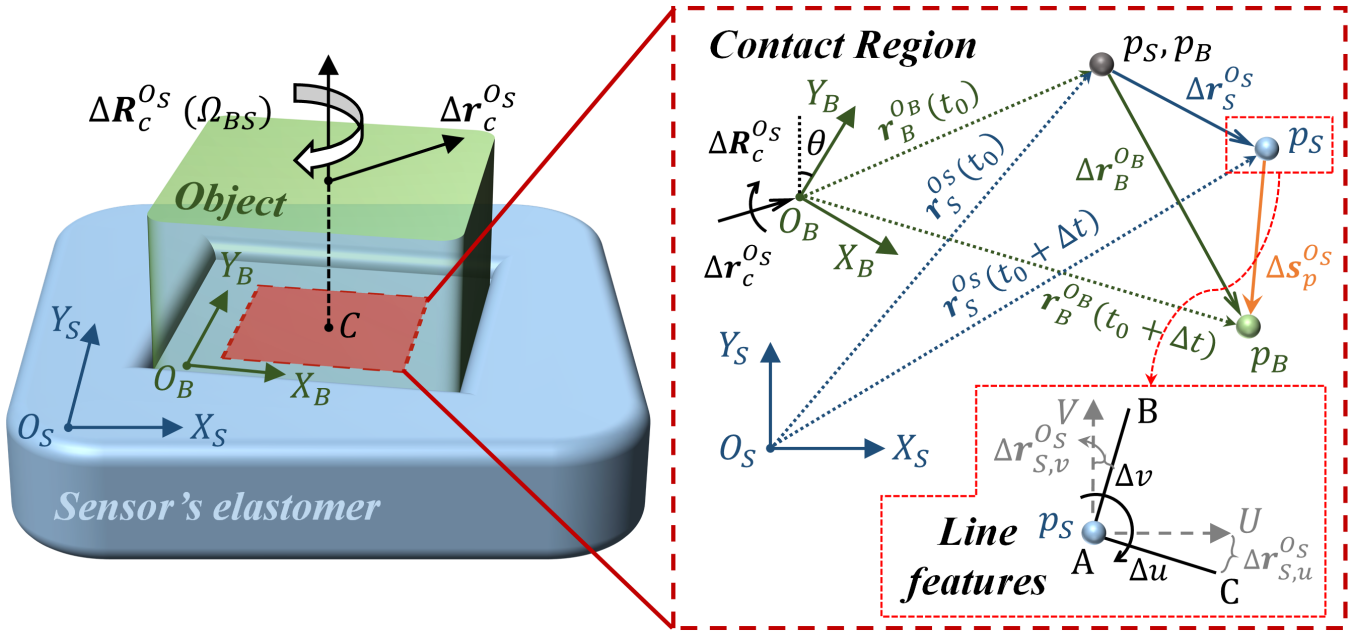
- **Judging the stick region:**
  - ✓ The **stick/slip state** at a certain point on the contact surface can be determined by comparing the **rotation angle of the line feature**

$$\boldsymbol{\theta = -(k+1)\cdot \varphi_i}$$

- **Estimating the rotation:**
  - ✓ The **pivot rotation angle** of an object can be estimated using the **rotation angle of the sticking region** on the contact surface

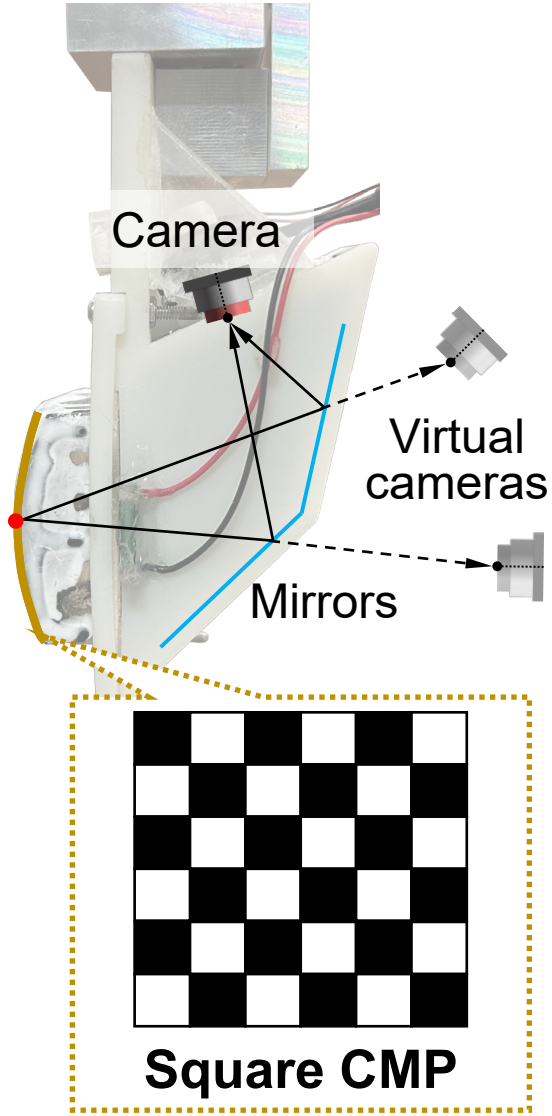
Measuring Rotation:

- ✓ Find some **stick points** on the sensor's contact surface;
- ✓ Detect the **local rotation angle using marked line features** to find the whole stick region;
- ✓ Calculate the **average rotation angle of the stick region** and estimate the pivoting angle.



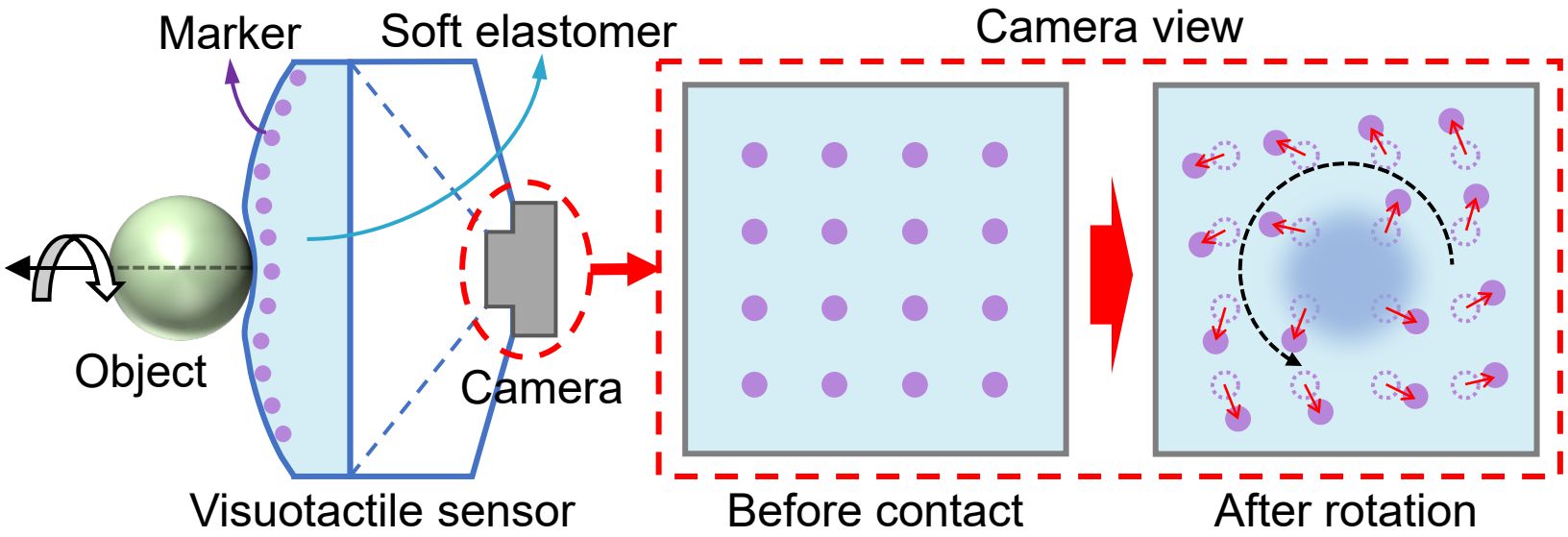
Rotation Measurement Pipeline (1)

Tac3D Sensor

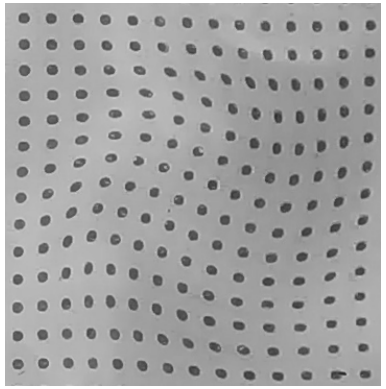


Square CMP

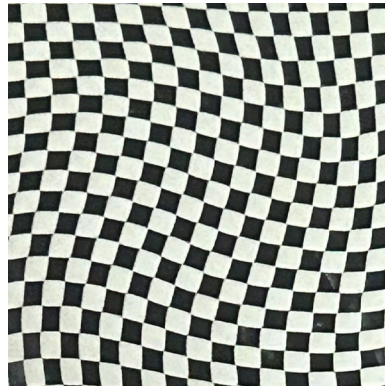
Visuotactile Sensing:



Continuous Marker Pattern (CMP):

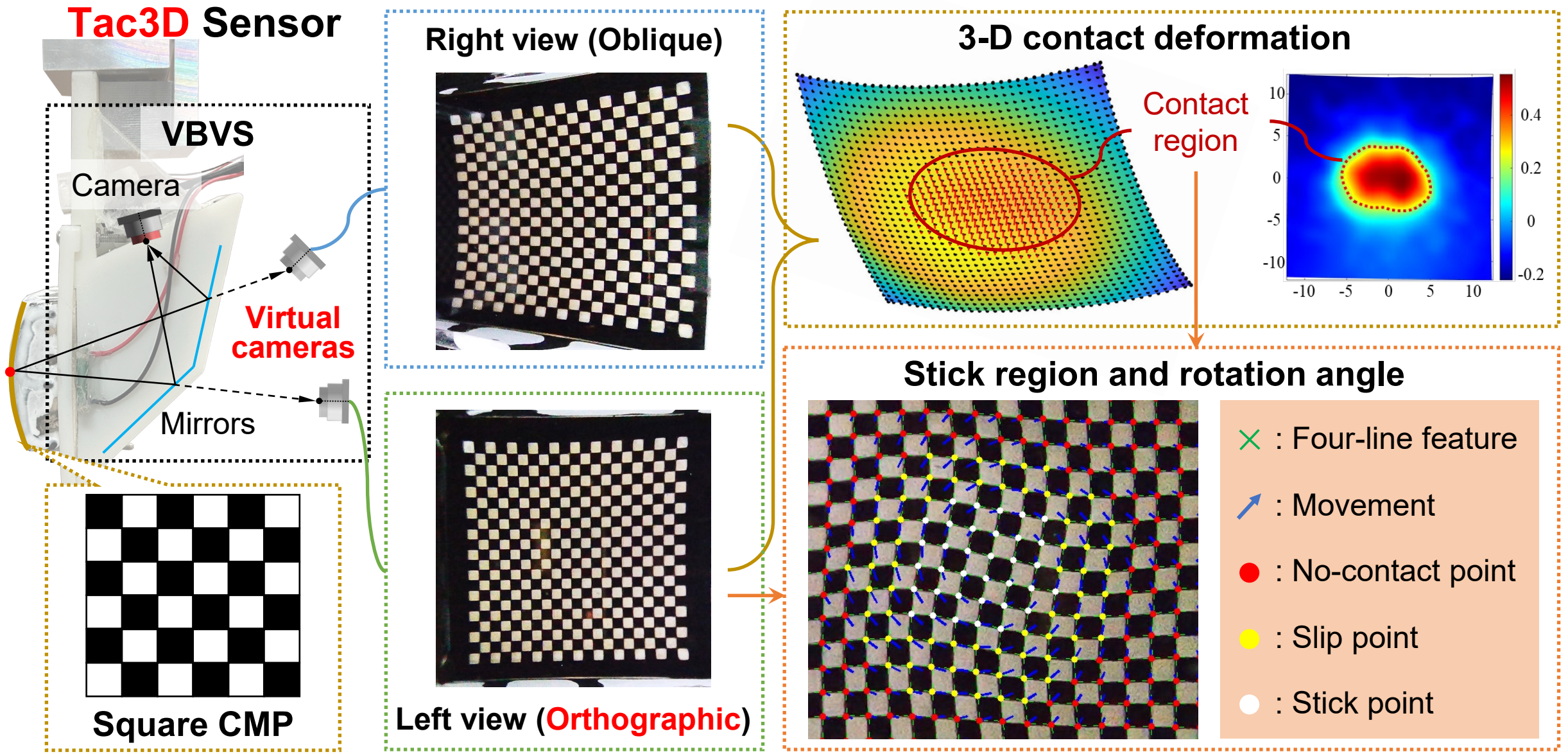


Distributed marker pattern → Continuous marker pattern



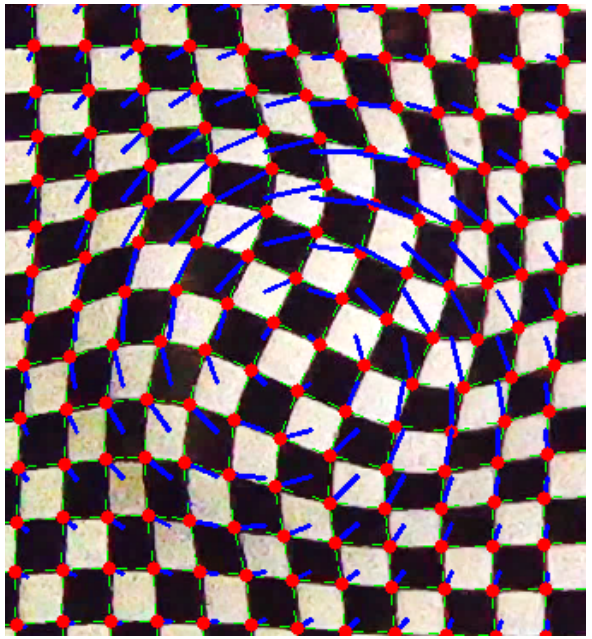
Converting discrete markers into **line features in CMP**: To ensure **high resolution**

Rotation Measurement Pipeline (2)



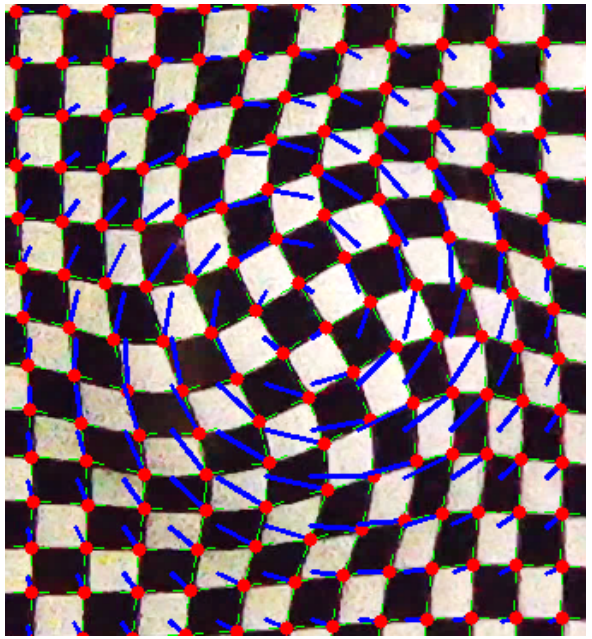
Measurement of Different Rotation Cases

- **Clockwise rotation**



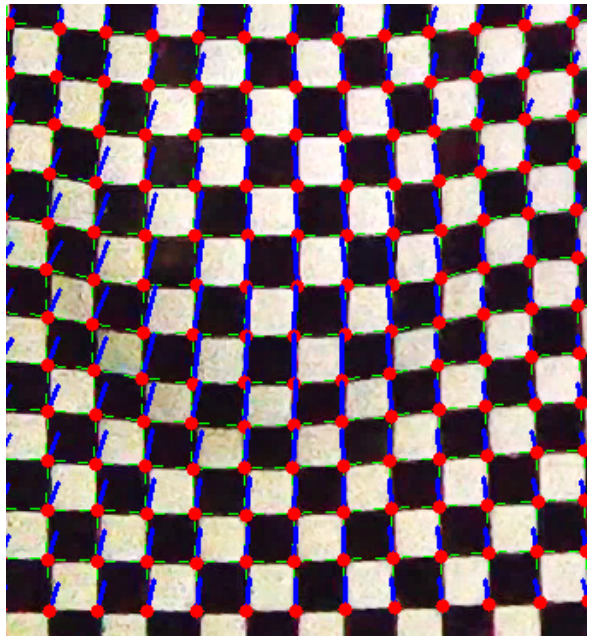
Angle: **22.46°**

- **Counterclockwise rotation**



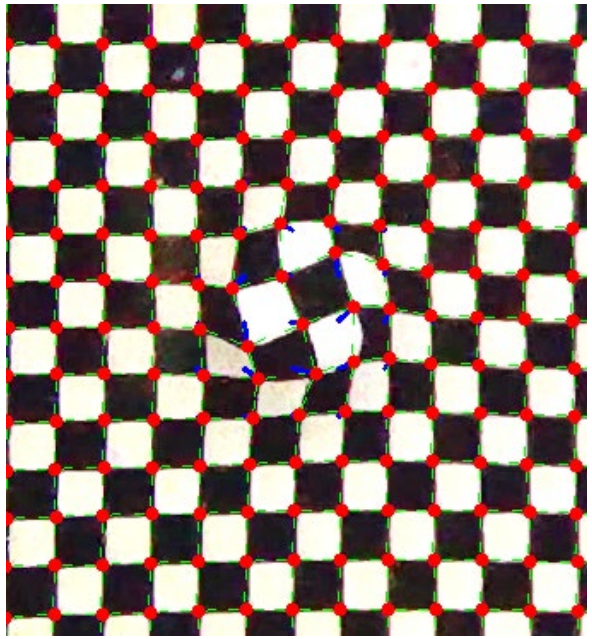
Angle: **-21.95°**

- **Translation (no rotation)**



Angle: **0.017°**

- **Small and round contact area**



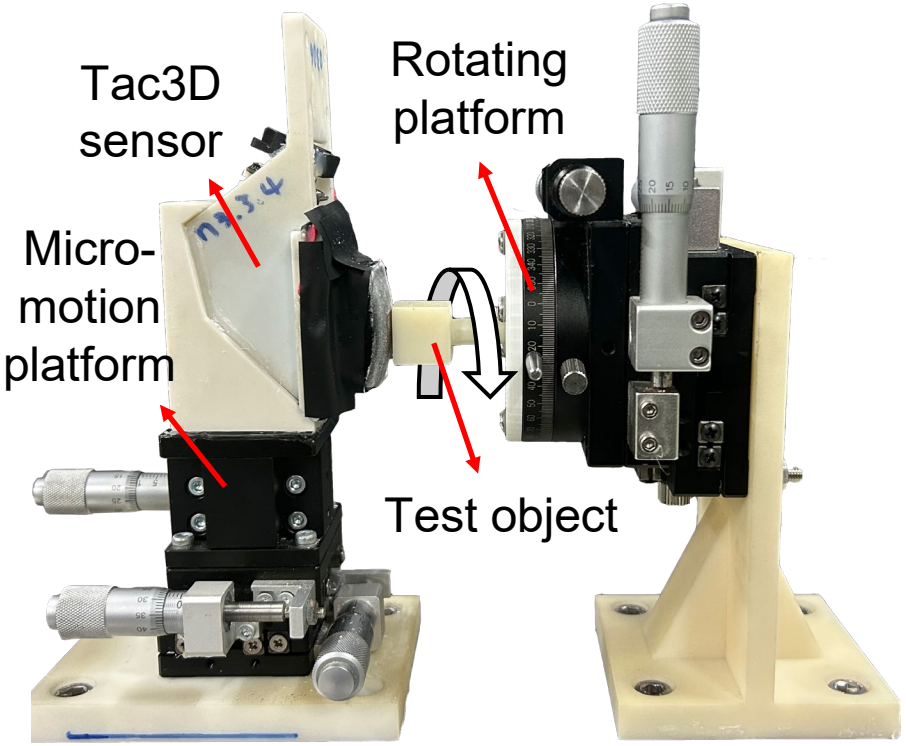
Angle: **-14.61°**

Conclusion:

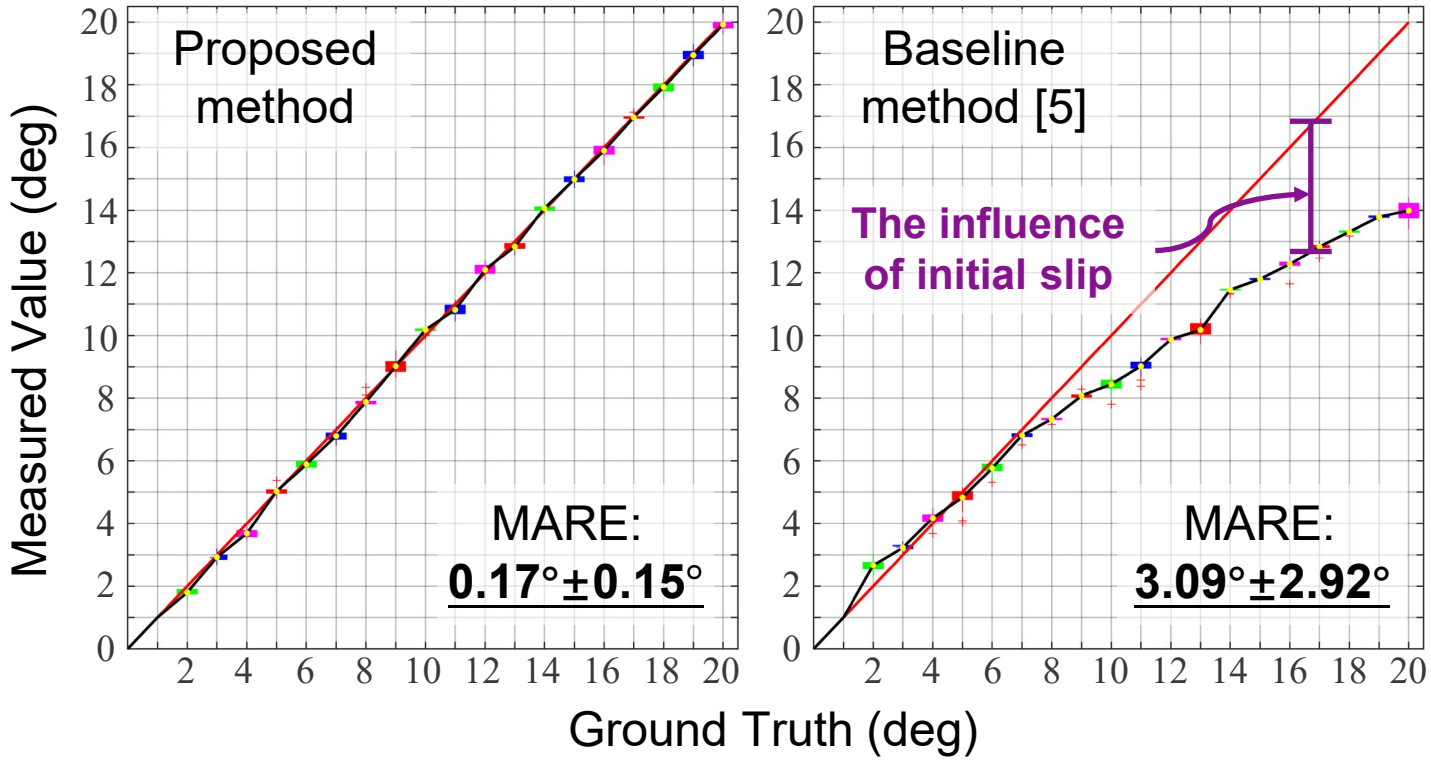
✓ The proposed method can **distinguish between translational and rotational displacements**, and works well while handling special cases like translation and small/round contact areas.

Evaluation of Rotation Measurement

- **Experimental Setup:**



- **Quantitative Comparison with Baseline:**



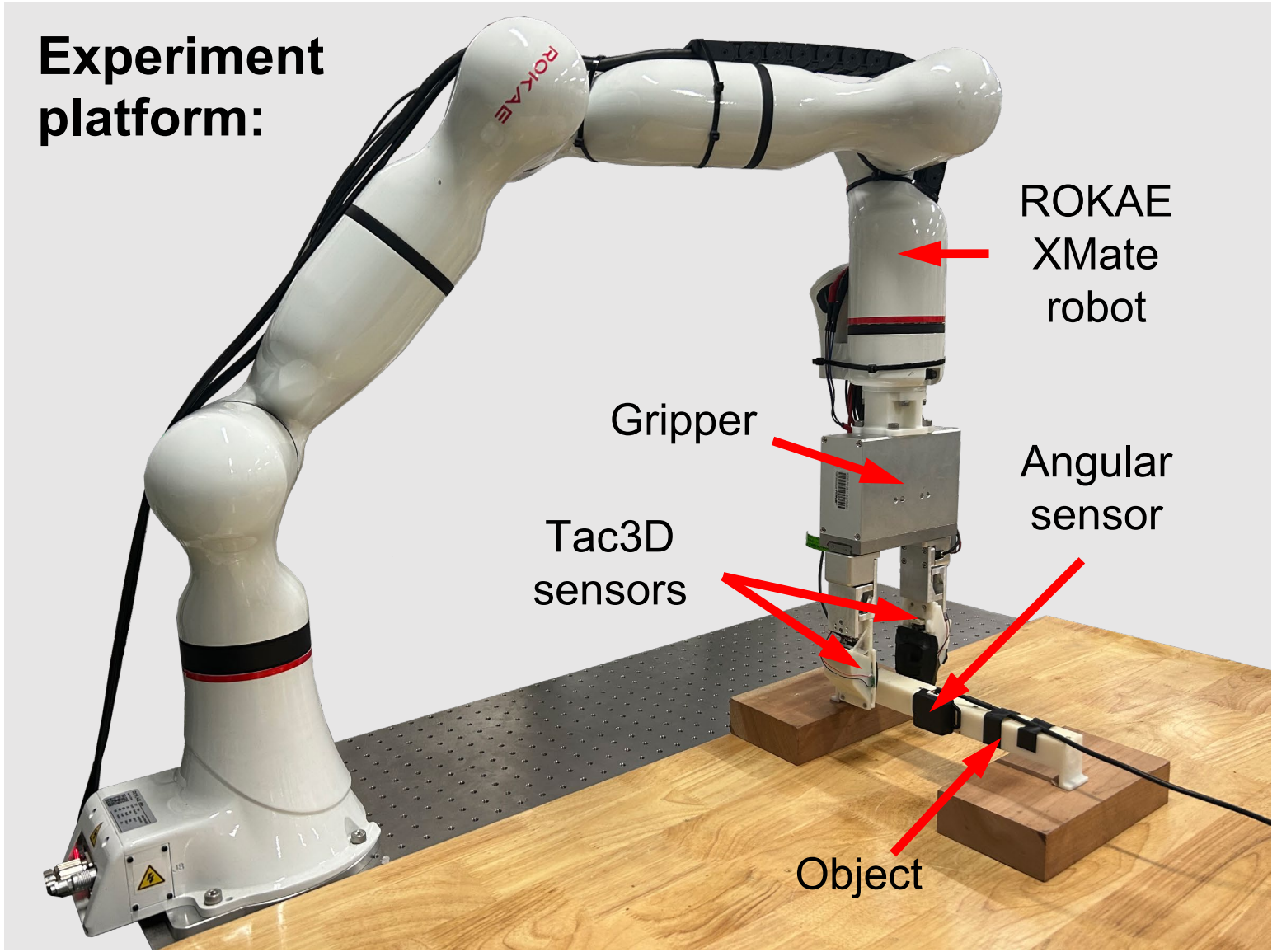
[MARE: The mean absolute rotational error]

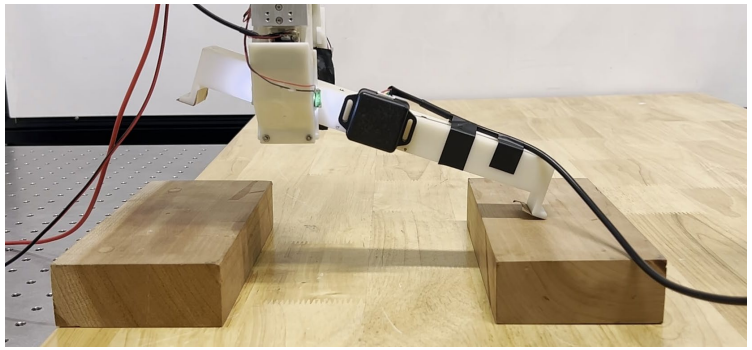
Conclusion:

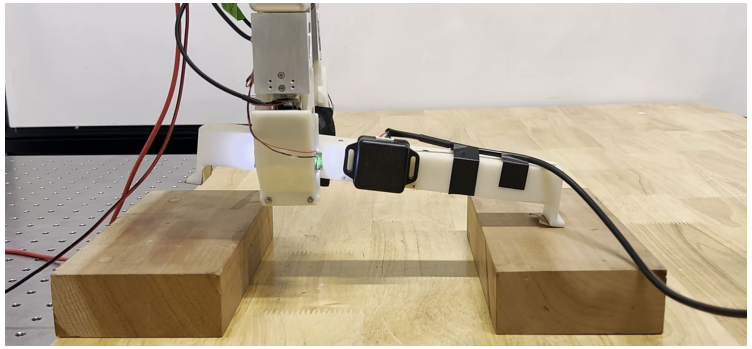
- ✓ The proposed method can **exclude the slip markers** and **utilize only the stick region** for the calculation, thus improving in the measurement accuracy.
- ✓ It achieves a **static MARE of $0.17° \pm 0.15°$ (SOTA)** (Baseline: MARE of $3.09° \pm 2.92°$[5]).

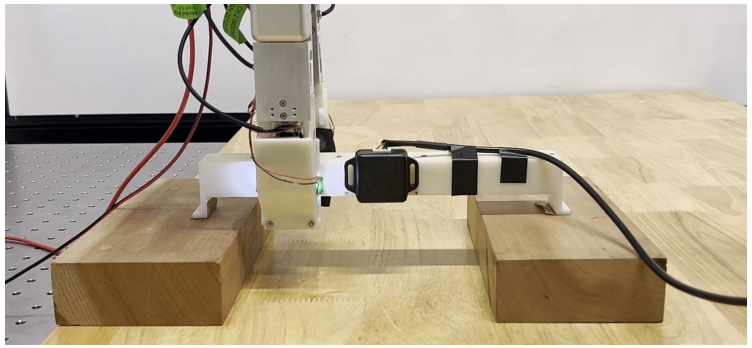
[4] R. Kolamuri *et al.*, "Improving grasp stability with rotation measurement from tactile sensing," 2021 IROS, pp. 6809–6816

Robot Experiment Platform

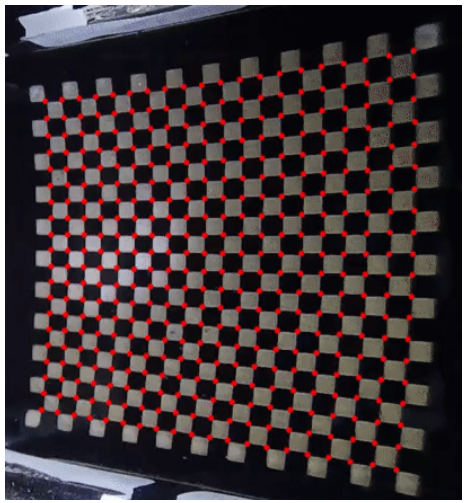




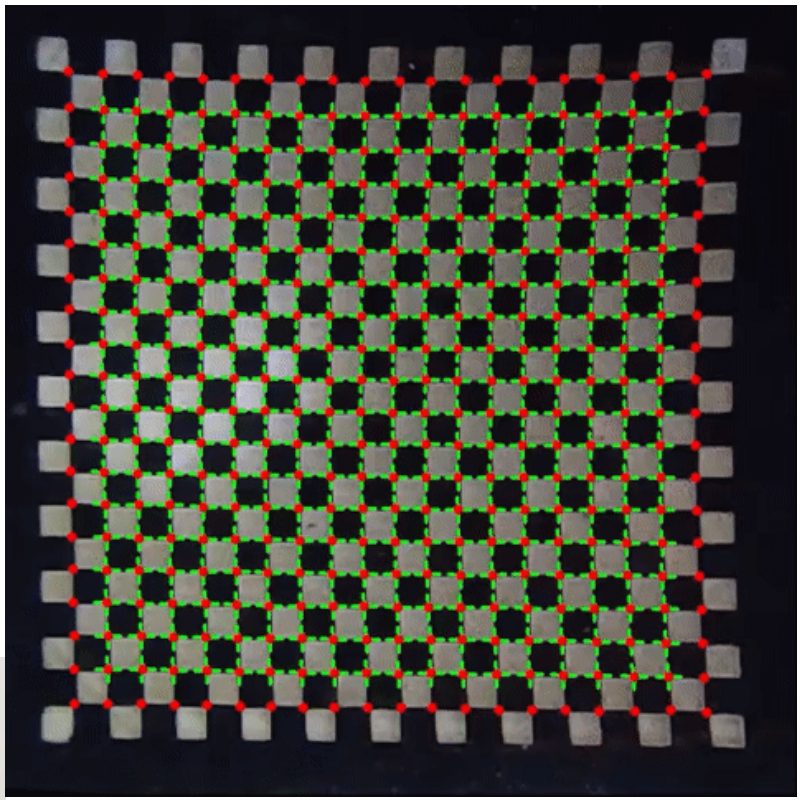




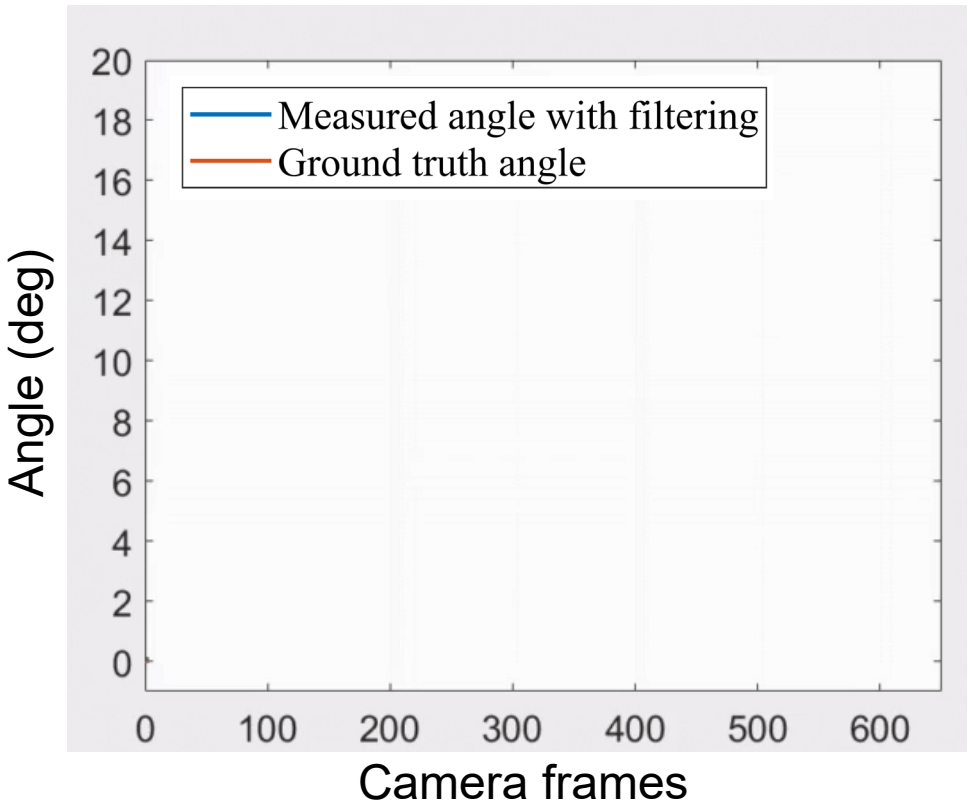
A Demonstration of On-Line Measurement



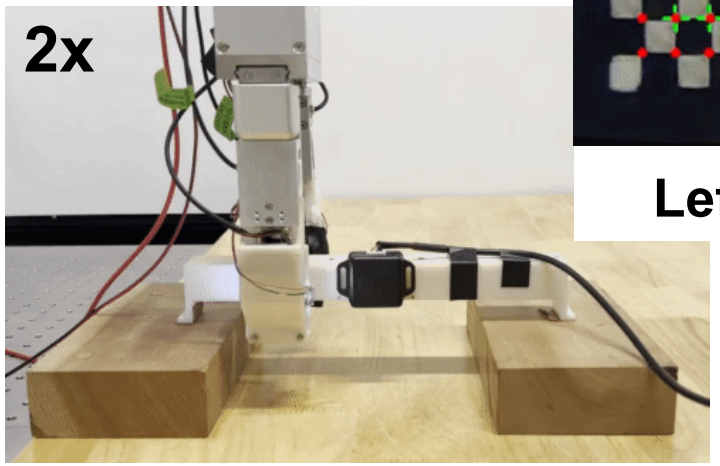
Right view of Tac3D image



Left view of Tac3D image



Measured angle vs Ground truth

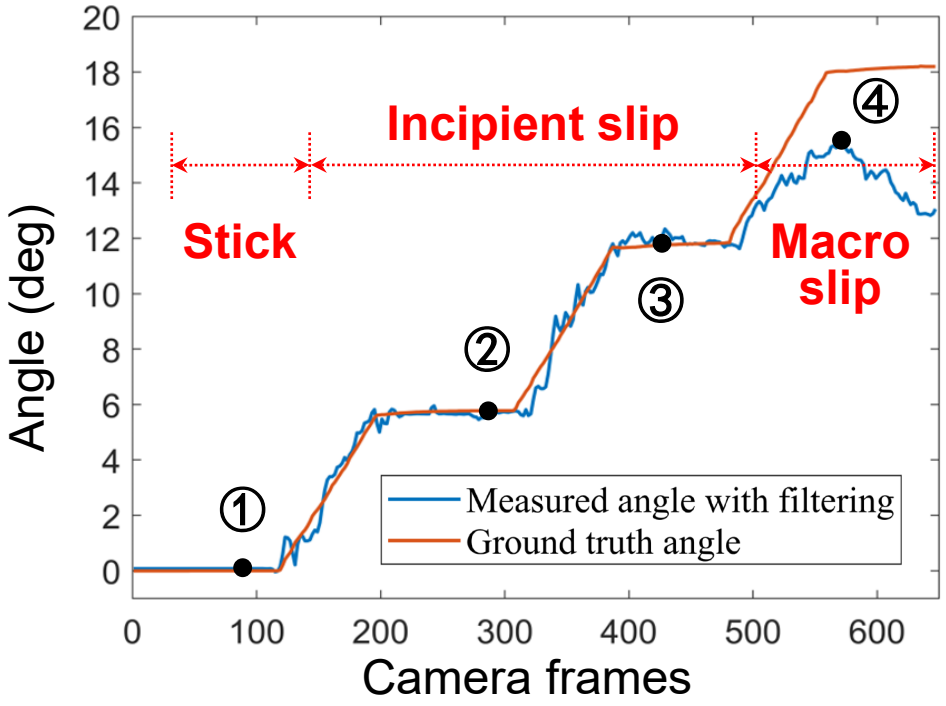


Side View

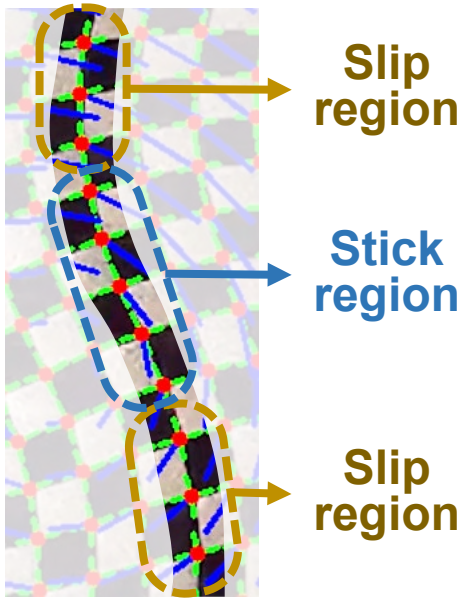
- ✓ The ground truth is provided by the **angular sensor**.
- ✓ The determination of stick region and rotation angle are achieved using the line features provided by **continuous marker patterns**.

Evaluation of Rotation Measurement

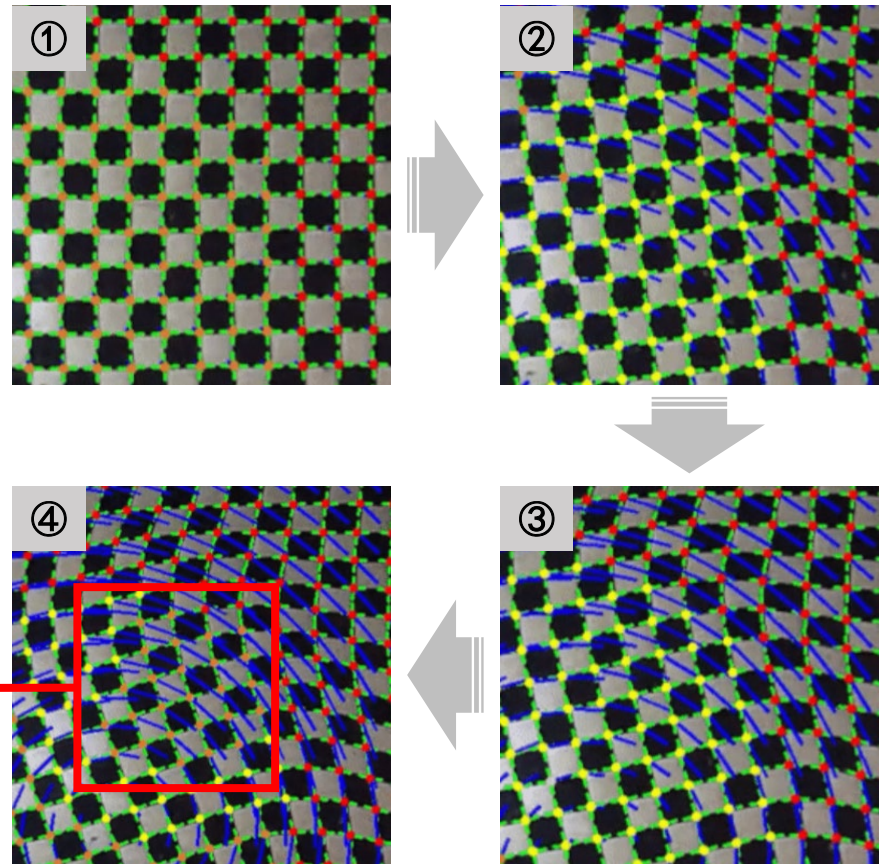
- **Quantitative Evaluation:**



Measured angle vs Ground truth



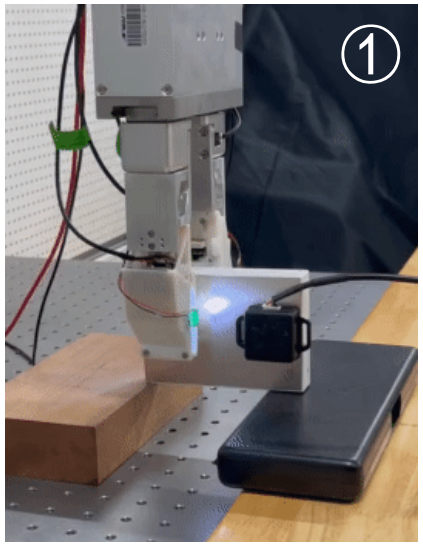
- **Qualitative Evaluation:**

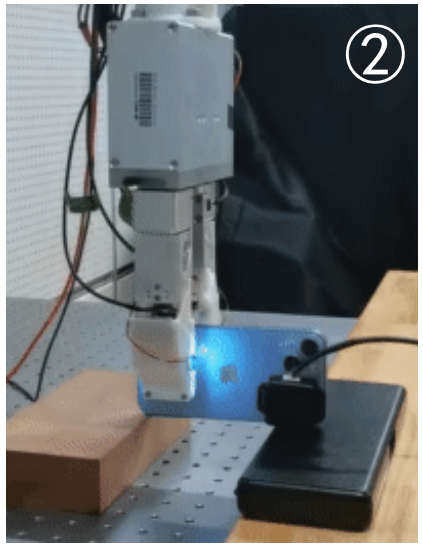


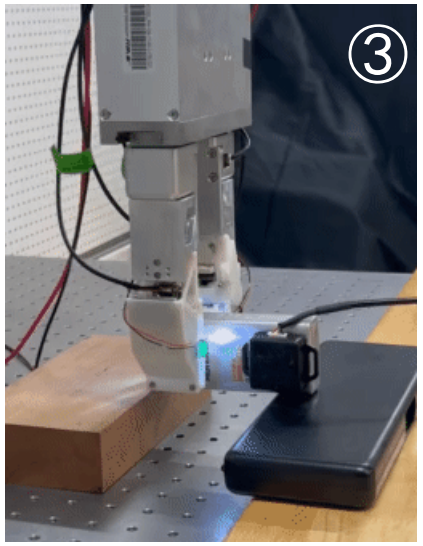
Conclusion:

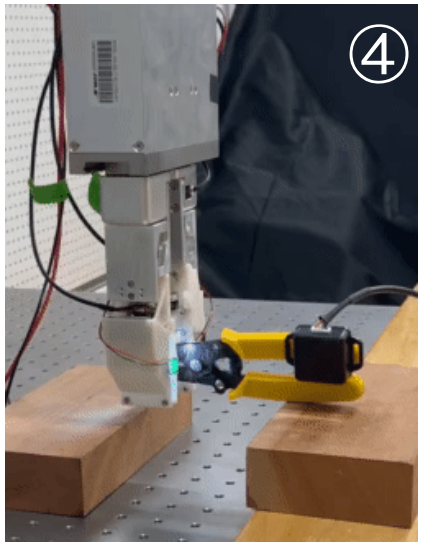
- ✓ The proposed method can **identify the stick and slip points** during the incipient slip process.
- ✓ The **error amplifies** when the rotation increases until the contact state transitions to **macro slip**.

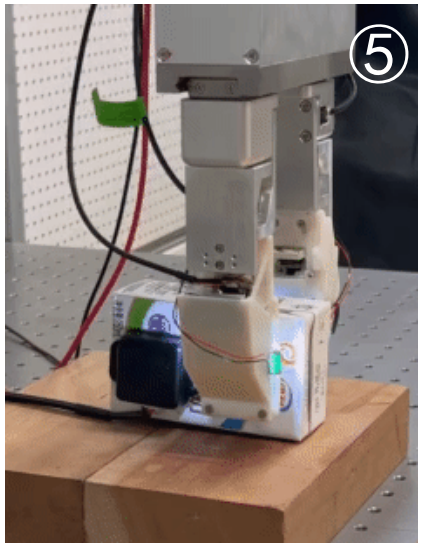
Gripping and Lifting Tasks on Robot

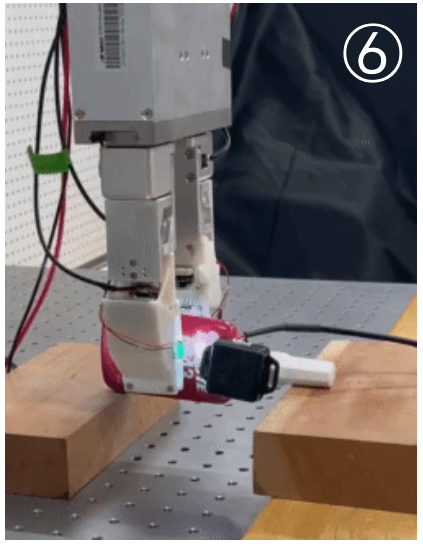


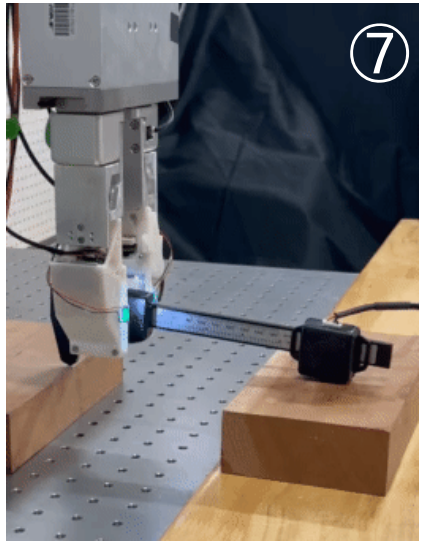


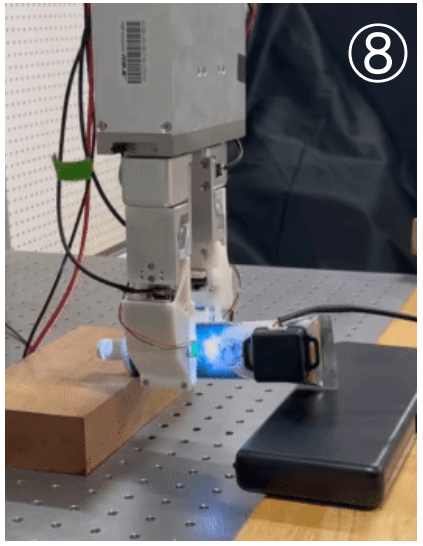


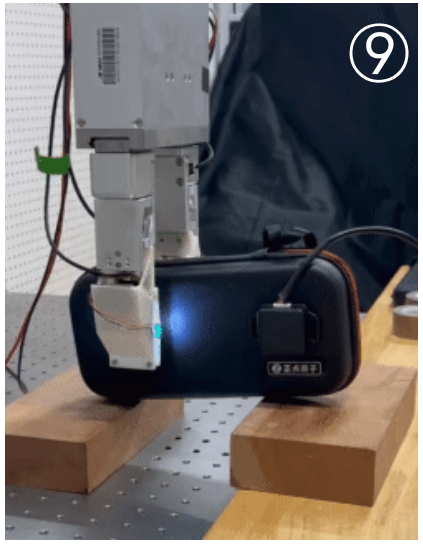


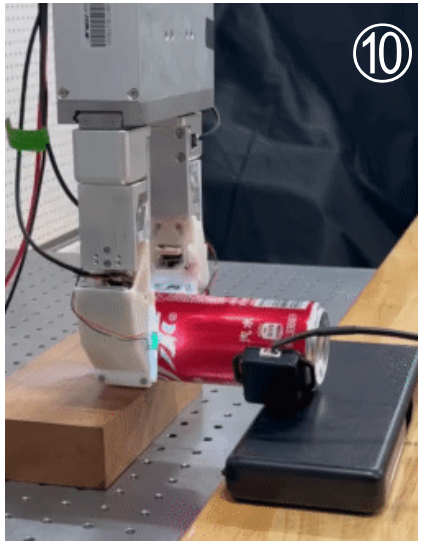










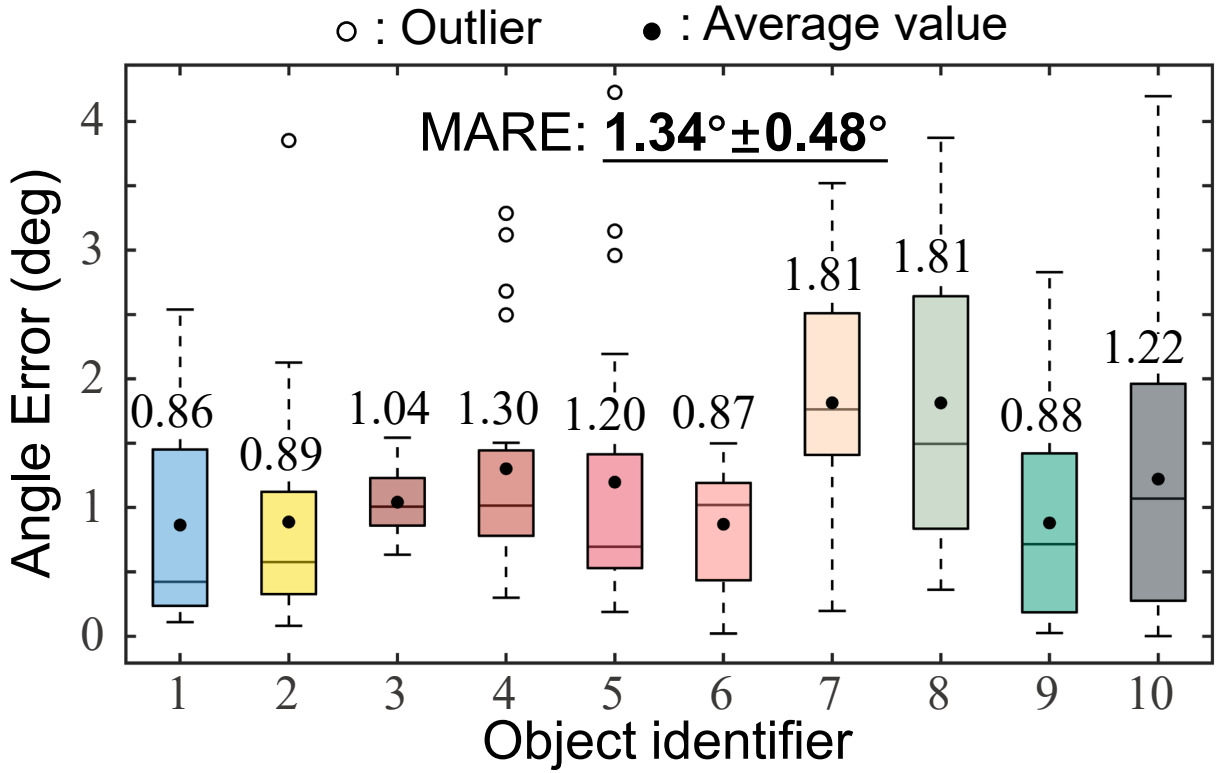


Evaluation of Adaptability to Different Objects

- **Household Objects**

□ : Contact position

- **Measurement Error Evaluation**



Measured angle vs Ground truth

Conclusion:

- ✓ The proposed method is suitable for **typical household objects** of different materials, shapes, and masses **without any prior information**.
- ✓ It achieves a **dynamic MARE of $1.34° \pm 0.48°$ (SOTA)** (Baseline: MARE of $1.85° \pm 0.96°$ [1]).

[1] J. Castaño-Amorós and P. Gil, "Measuring object rotation via visuo-tactile segmentation of grasping region," IEEE RA-L, vol. 8, no. 8, pp. 4537-4544, 2023

Summary

- ✓ This paper describes a generalized 2-d contact model under pivoting, and proposes a rotation measurement method based on the line-features in the stick region.
- ✓ Static measurement error: $0.17° \pm 0.15°$; Dynamic measurement error: $1.34° \pm 0.48°$.
- ✓ Advantages:
  - High precision and accuracy; less affected by contact shape, contact area, and translational displacement.
  - Clear physical meaning; no training dataset required.

Future Directions

- ✓ Can we handle objects with soft structures?
- ✓ Can incipient slip detection be applicable to 3-d rotating objects?
- ✓ In-hand manipulation applications: Peg-on-hole and tool usage.

Thank You Very Much