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

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Abstract

In typical in-hand manipulation tasks represented by **object pivoting**, the real-time measurement of rotational slippage has been proven beneficial for improving the dexterity and stability of robotic hands. We describes a generalized **2-d contact model** under pivoting, and proposes a measurement method of rotation angle based on the line features in the stick region. The proposed method is **training-free**, **physical meaning-clear**, and can achieve the **real-time and accurate measurement on a real robot** with the mean absolute rotational error (MARE) of 0.17°±0.15° (in static measurement) and 1.34°±0.48° (in dynamic measurement).

Theory

Incipient slip during pivoting:

Conclusion: Since the slip region cannot reflect the object's true motion, detecting only macro rotational slip leads to **measurement errors**.

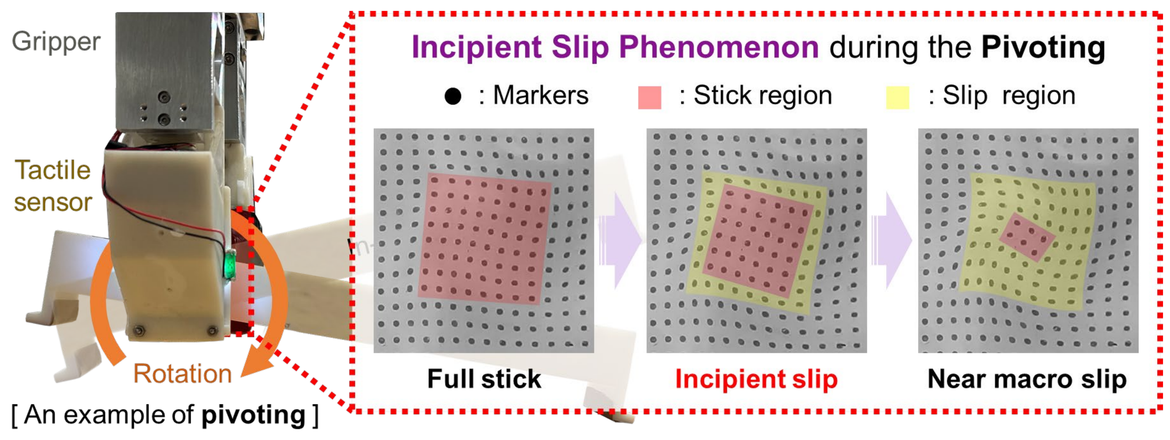

Fig.1. Incipient slip during pivoting. The slip region expands from outside to inside until the stick region disappears.

Contact modeling considering incipient slip:

$$\Delta\varphi_{ij} = -\frac{rot(\Delta s_{ij})}{2(k+1)}$$

Judging the stick region: **Stick/slip state** can be determined by comparing the **line feature rotation**

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

Estimating the rotation: **Pivoting rotation** is in proportion to **rotation angle of the stick region**

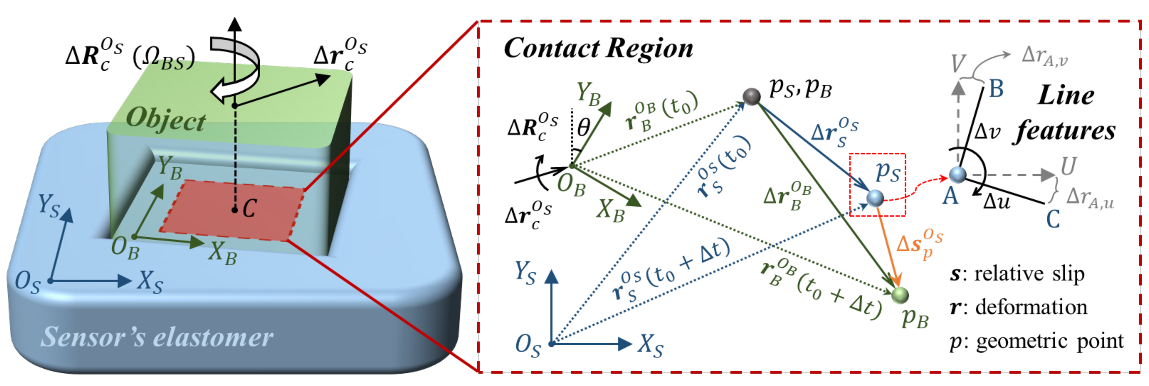

Fig.2. 2-D contact model between a soft object and the sensor's elastomer.

Method

Visuotactile sensing with continuous marker pattern:

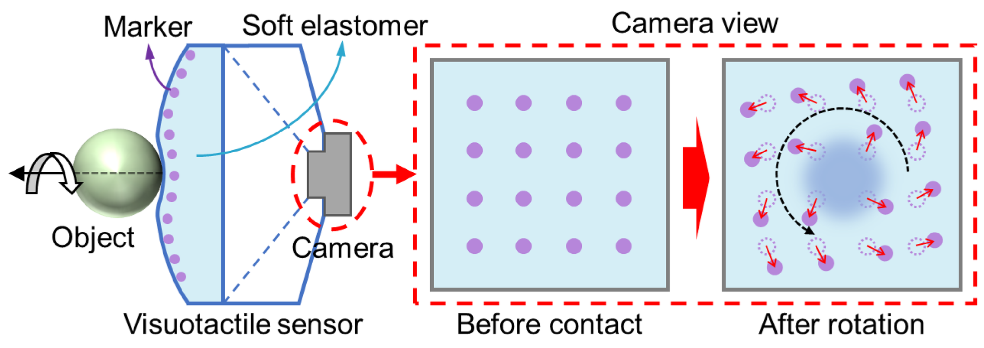

Fig.3. Marker displacement method used in visuotactile sensors can obtain contact deformation using markers.

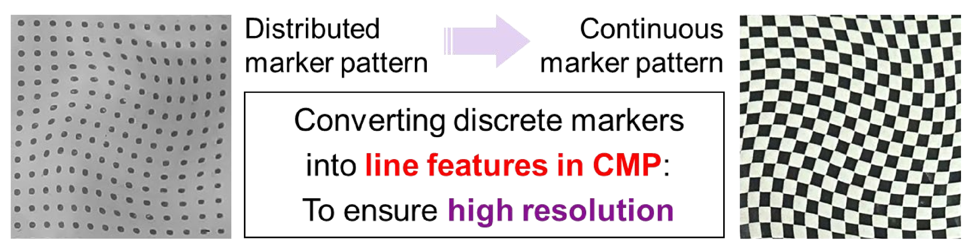

Fig.4. Line-features used in continuous marker patterns can ensure high-resolution presentation of the pivoting information.

Rotation angle measurement pipeline:

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

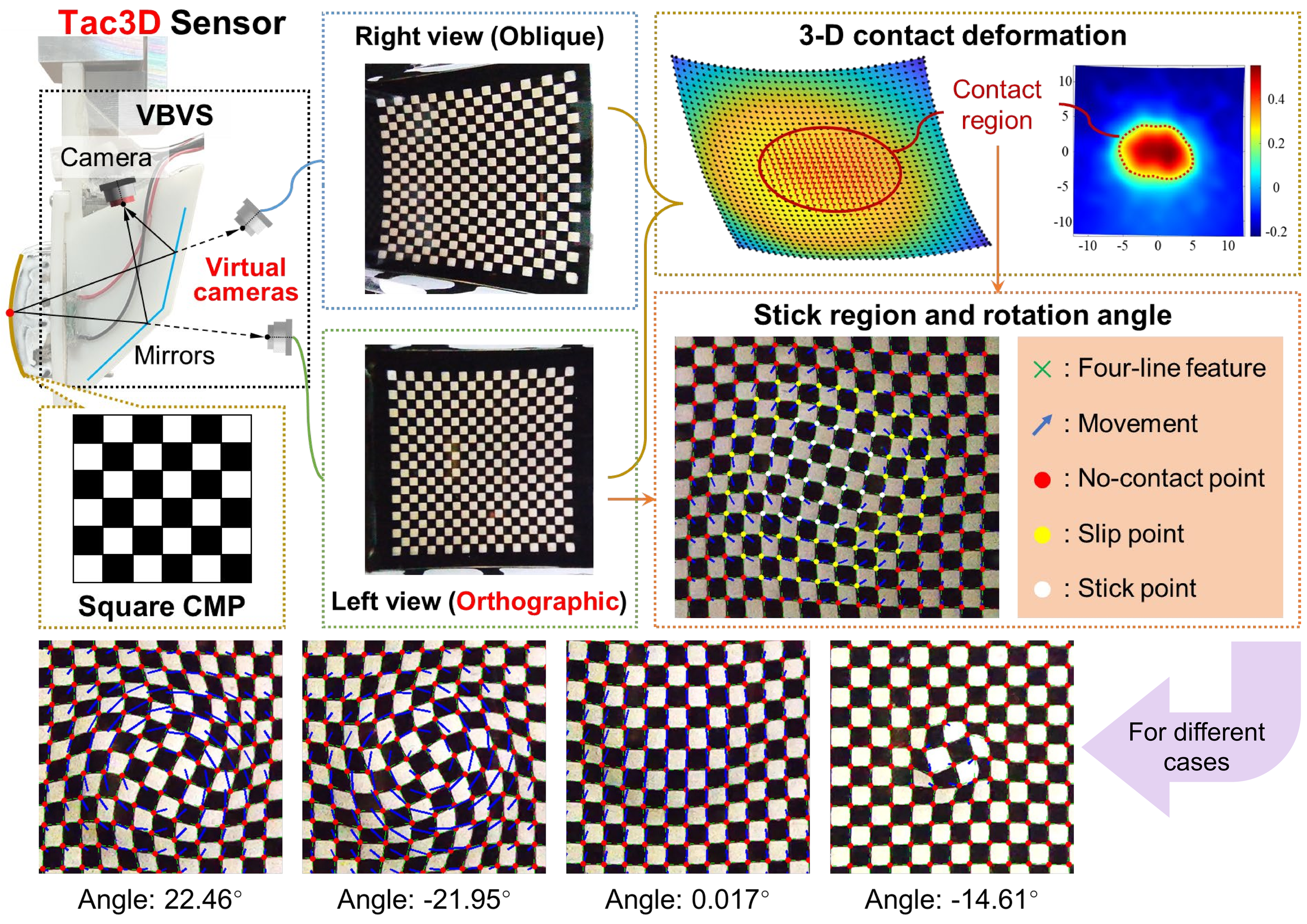

Fig.5. Rotation measurement pipeline using the Tac3D tactile sensor.

Experimental Results

Static measurement evaluation:

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** $0.17° \pm 0.15°$ (Baseline: MARE of $3.09° \pm 2.92°$ [1]).

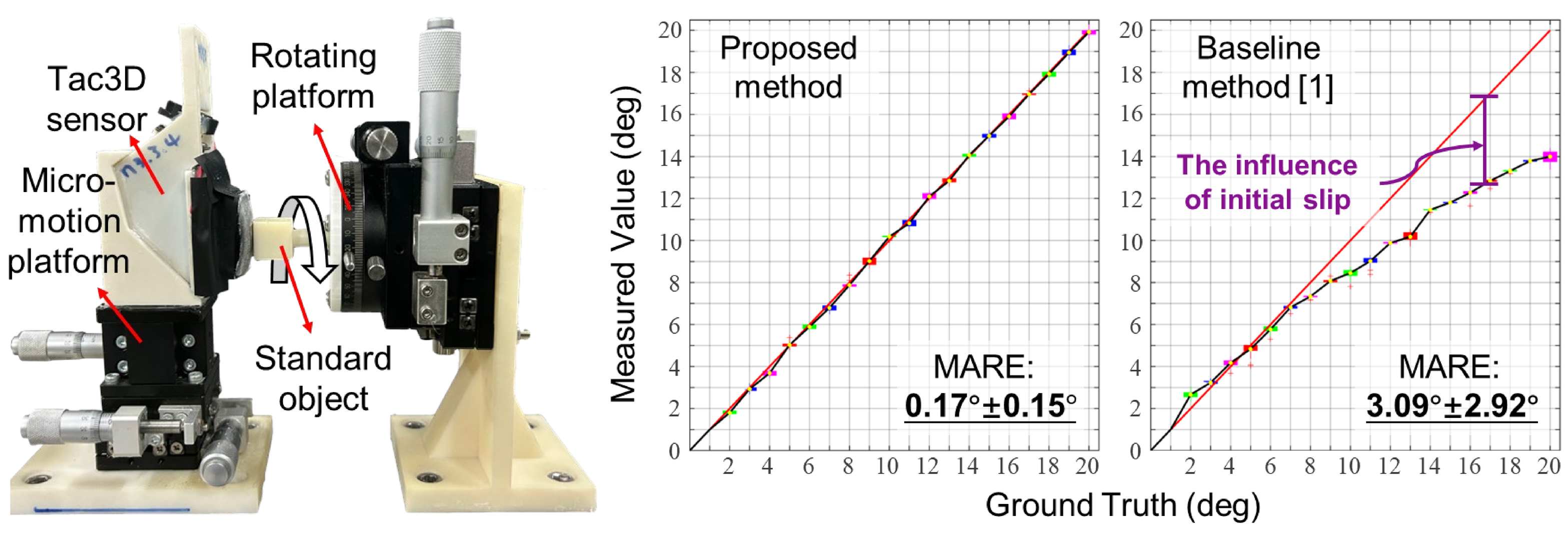

Fig.6. Left: Experimental setup for accuracy evaluation. Right: The red line denotes the ground truth angle, the black line denotes the measurement angle, and the colored boxes denote the discrete distribution of the repeated test results. MARE denotes the mean absolute rotational error introduced in [2].

On-line measurement during pivoting:

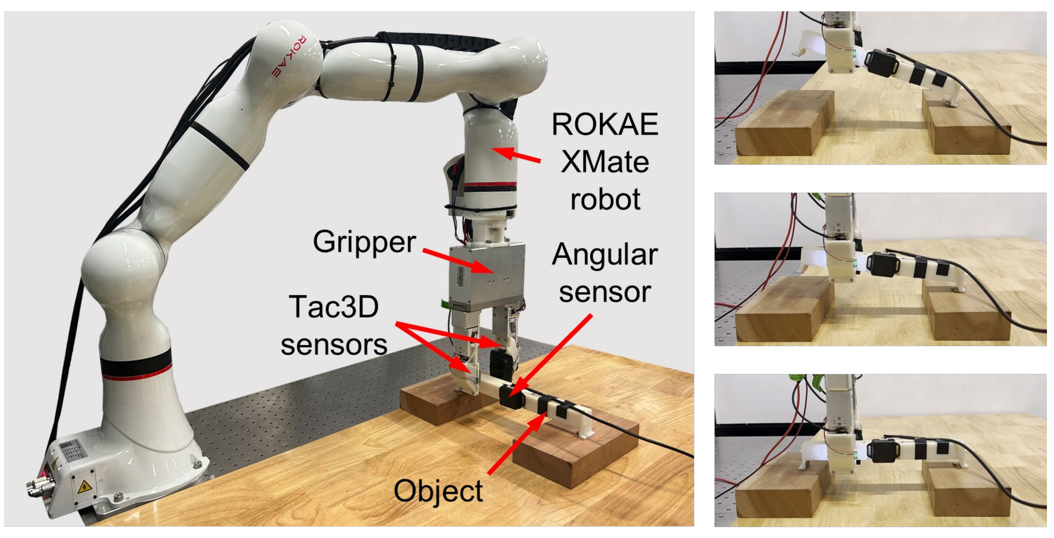

Fig.7. A two-finger parallel gripper on a robot with two Tac3D. Pivoting operation is performed by grasping and lifting in-hand objects. Ground truth is provided by a an angular sensor.

Conclusion: The proposed method can **identify the stick/slip states** during the incipient slip process, and finally fails since the **macro slip occurs**.

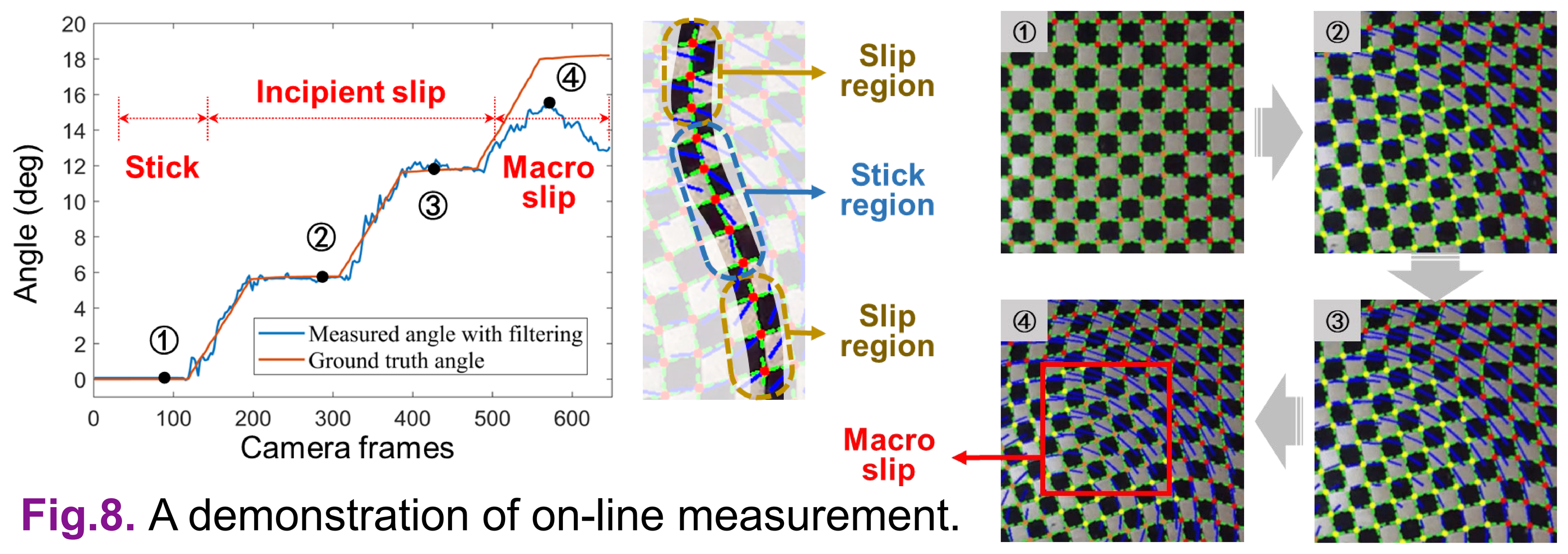

Fig.8. A demonstration of on-line measurement.

Dynamic measurement evaluation:

Conclusion: The proposed method applies to household objects with different materials, shapes, and masses **without any prior information**. It achieves a **dynamic MARE of** $1.34° \pm 0.48°$ (Baseline: MARE of $1.85° \pm 0.96°$ [2]).

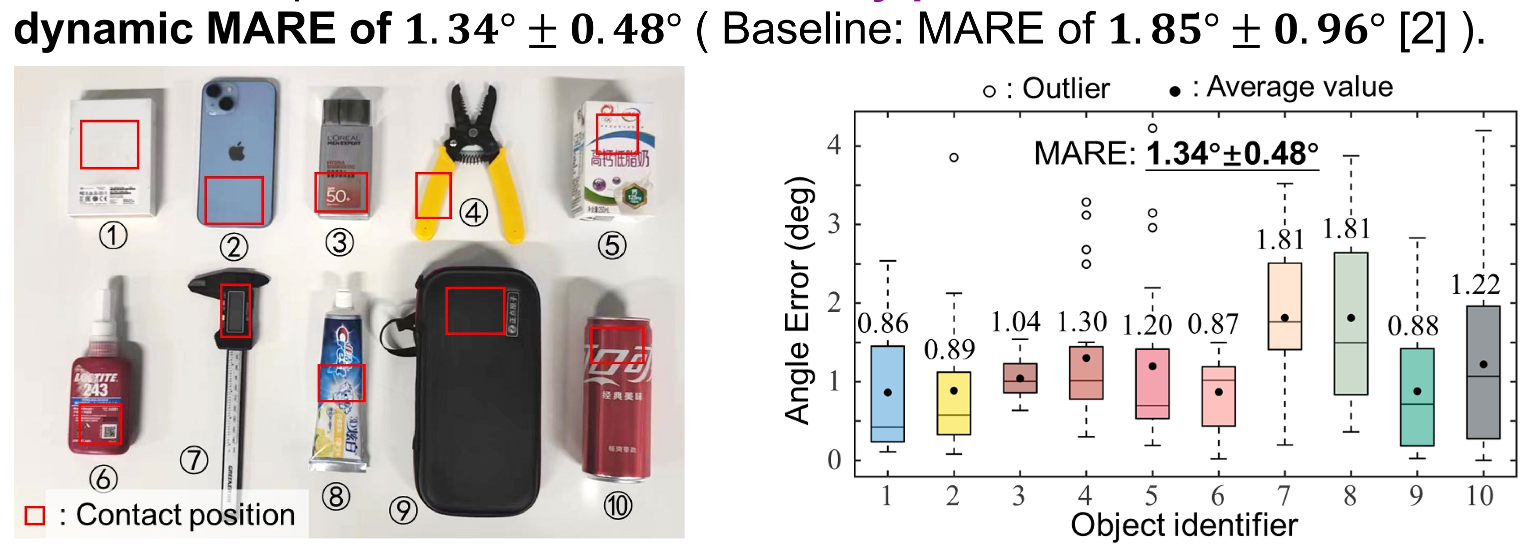

Fig.9. Left: Test objects. Right: Measurement errors for different objects.

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

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

Conclusion

Conclusion: Benefitting from the **effective differentiation of stick/slip states** through contact modeling, this approach achieves the **state-of-the-art result** even compared to related **learning-based techniques**.

Highlight: **High precision and accuracy** in on-line measurement; **Less affected by special cases**, like contact shape, contact area, and translational displacement; Clear physical meaning; **No training dataset required**.

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