From Millimetres to Microns:

Hysteresis Characterization and Compensation of a Cable-Driven Continuum Surgical Robot

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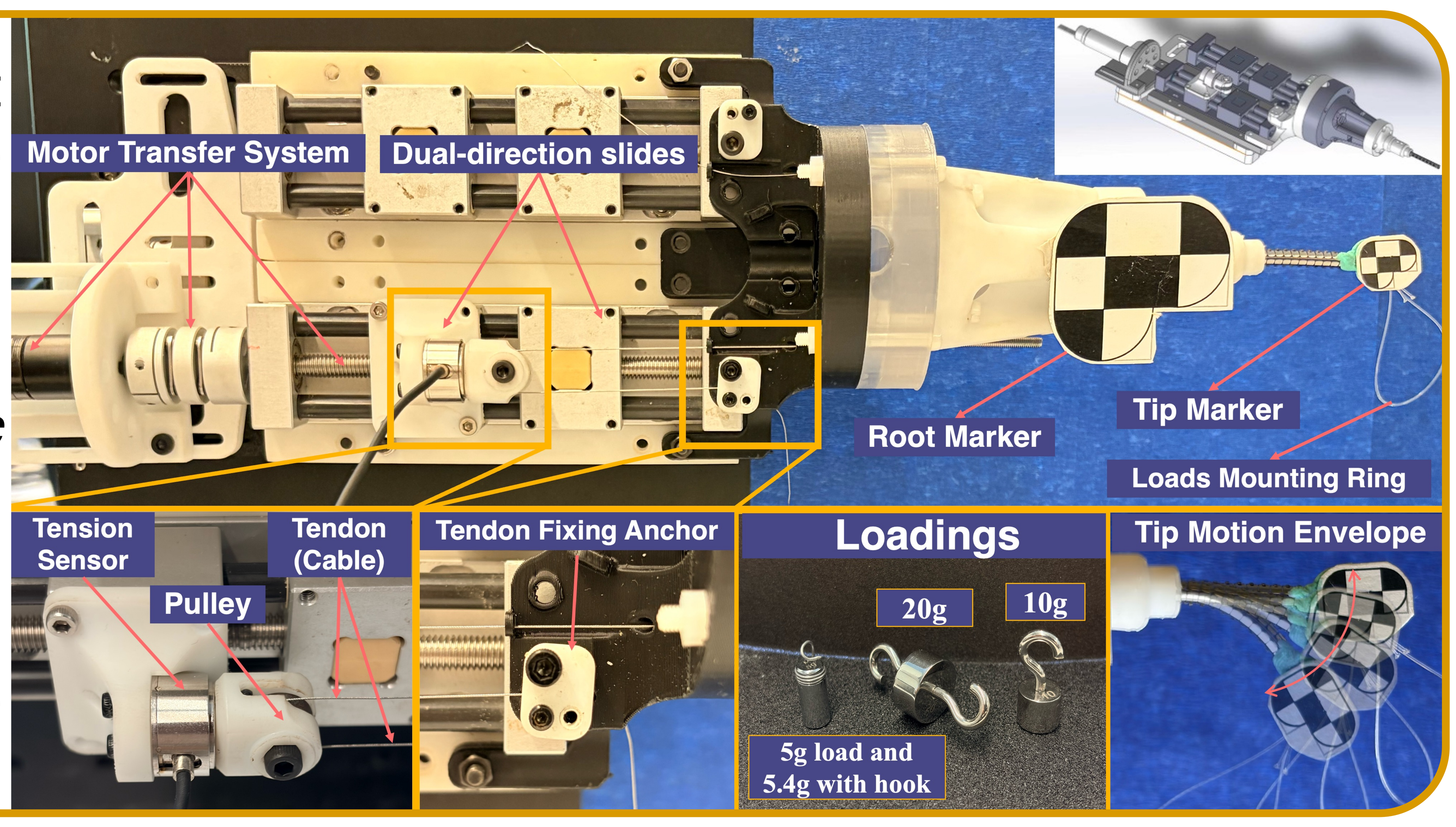
OVERVIEW

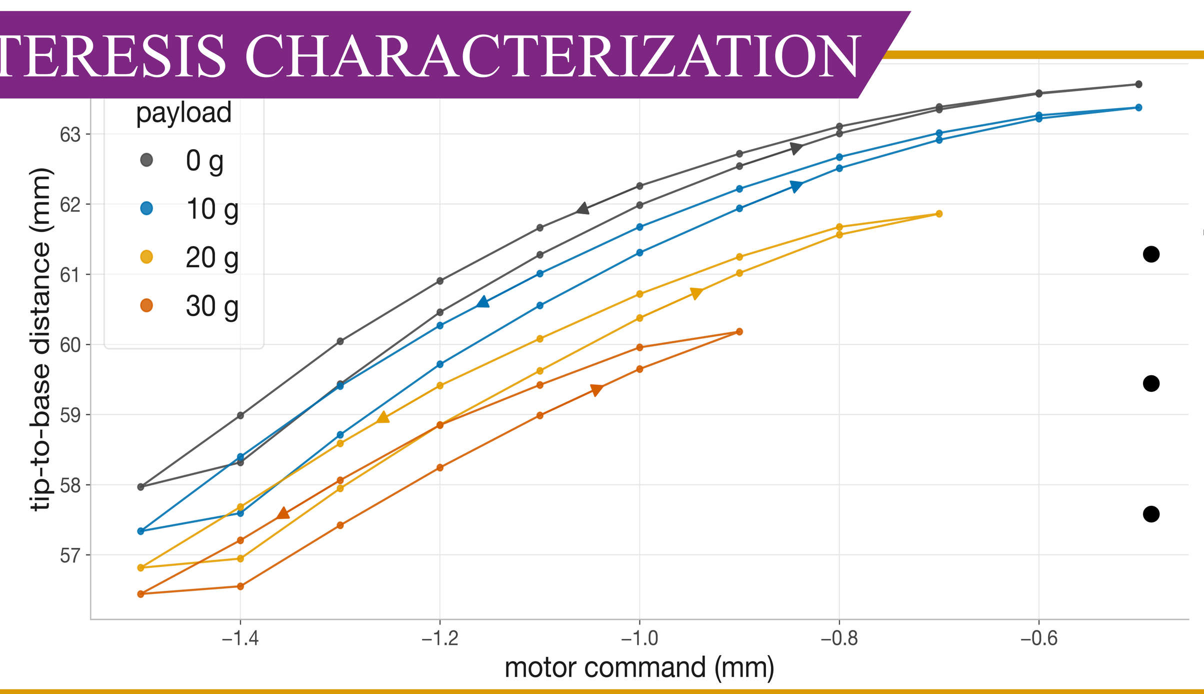
Continuum Robots access sites beyond rigid-instrument reach, but cable friction causes motion-history-dependent **Hysteresis**. On the prototype, tip can miss by **1 mm** under identical commands.

Hysteresis was further characterized under **0–30 g payloads** and three strategies were compared on a 28-target benchmark: the ***static calibration***, a direction-aware ***Compensator*** and ***Iterative Learning***.

The direction-aware *Compensator*, trained on 498 points, reduced RMS error **three-fold** and remained effective over **18 days**, while *Iterative Learning* reached the **repeatability limit (15 μm).**



HYSTERESIS CHARACTERIZATION



- Two branches **remain separated** under all payloads.
- Increasing payload **narrows** the usable range and **widens** the loop.
- Separate compensation maps are used for the **two motion directions**.

METHODOLOGY

Experimental Platform — A 14-notch Cable-Driven Continuum Robot with stereo tip tracking and cable-tension sensing. [5]

- **A | Static Calibration** — A direction-blind isotonic map [1], fitted to binned medians and inverted to generate commands.

$$u = f^{-1}(y_d)$$

- **C | Direction-aware Compensation** — Separate maps for two motion directions capture the two hysteresis branches [2]. After fitting, the maps remain frozen; a 5-min recalibration estimates the session offset.

$$\textit{Compensator}: y = f_{dir}(u) + b_{session} \ ; \ \textit{Command}: u = f_{dir}^{-1}(y_d - \hat{b})$$

- **L | Iterative Learning Control (ILC)** — Per-target command refinement from measured error [3,4] | 3 iterations

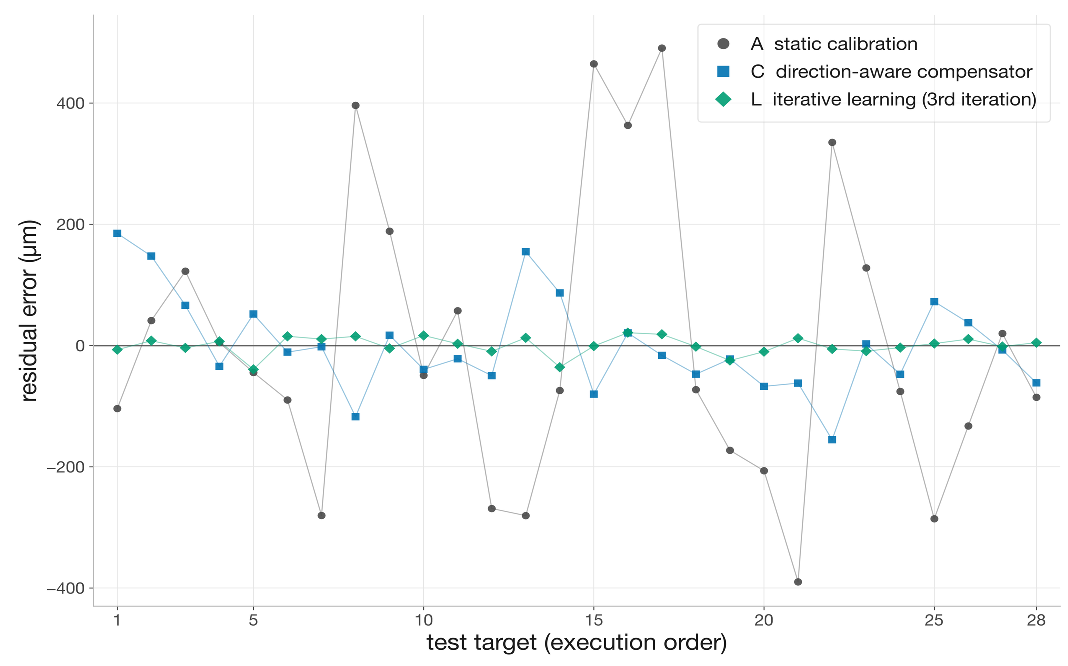
$$u_{j+1}(k) = u_j(k) - 0.7 \cdot e_j(k)/\hat{s}(k)$$

Training & Evaluation — A: 130 samples | C: 498 samples | 28 targets | same measurement correction | RMS Error

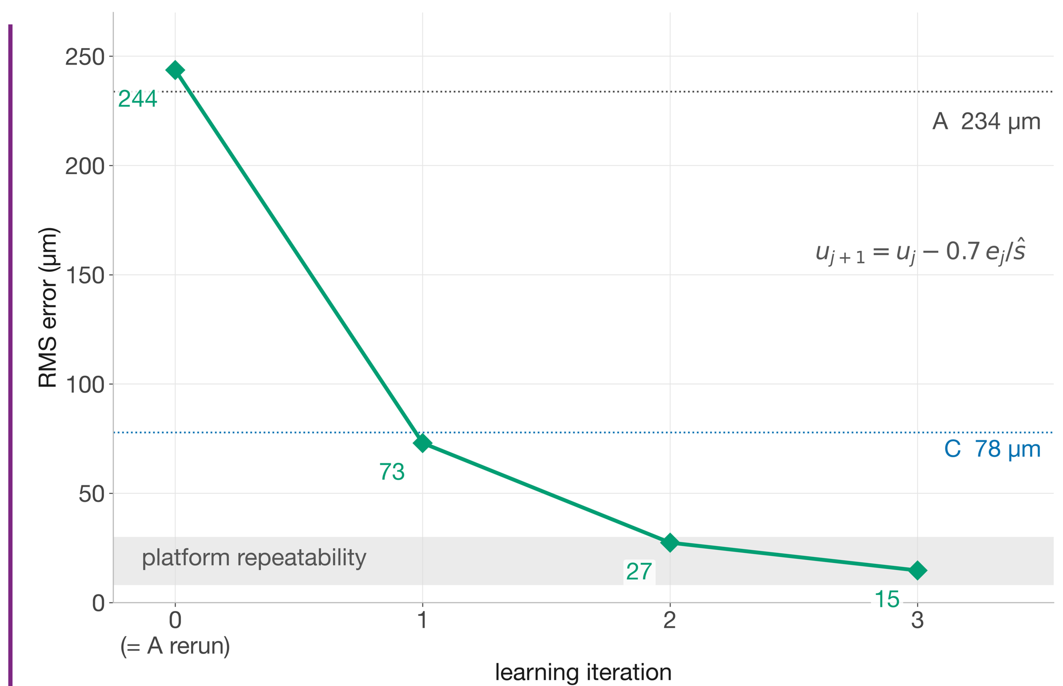
RESULTS

Method	RMS Error (μm)	vs A
A	233.8	—
C	77.8	3.0×
L (3rd iteration)	14.7	15.9×

- **The compensator** was frozen for 18 days after fitting. Its three-fold improvement was maintained across three sessions (3.42×, 3.57×, 3.01×).



- **Direction awareness** reduced the RMS error three-fold



- **ILC** entered the repeatability band after two iterations and reached 15 μm after three.

CONCLUSION

Takeaways

- Hysteresis, not sensor noise, dominates open-loop error on this platform.
- A direction-aware nonparametric compensator recovers a three-fold accuracy gain that persists for weeks with only a 5-min recalibration.
- Iterative learning closes the remaining gap to the repeatability limit.

Outlook

- Evaluate the direction-aware compensator under varying payloads.
- Develop history-aware models using automated multi-session data collection.

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WEBPAGE

yecheng-wang.com/cuhk-surp-2026

[1] R. E. Barlow et al., *Statistical Inference Under Order Restrictions*, Wiley, 1972. [2] T. N. Do et al., "Nonlinear friction modelling and compensation control of hysteresis phenomena for a pair of tendon-sheath actuated surgical robots," *Mech. Syst. Signal Process.* 60–61:770–784, 2015. [3] S. Arimoto et al., "Bettering operation of robots by learning," *J. Robot. Syst.* 1(2):123–140, 1984. [4] D. A. Bristow et al., "A survey of iterative learning control," *IEEE Control Syst. Mag.* 26(3):96–114, 2006. [5] G. Zhang et al., "A general modular framework for modeling cable-driven continuum surgical robots," *Int. J. Mech. Sci.* 318:111521, 2026.

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