In-Hand Following of Deformable Linear Objects Using Dexterous Fingers with Tactile Sensing

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***Abstract*— Most research on deformable linear object (DLO) manipulation assumes rigid grasping. However, beyond rigid grasping and re-grasping, in-hand following is also an essential skill that humans use to dexterously manipulate DLOs, which requires continuously changing the grasp point by in-hand sliding while holding the DLO to prevent it from falling. Achieving such a skill is very challenging for robots without using specially designed but not versatile end-effectors. Previous works have attempted using generic parallel grippers, but their robustness is unsatisfactory owing to the conflict between following and holding, which is hard to balance with a one-degree-of-freedom gripper. In this work, inspired by how humans use fingers to follow DLOs, we explore the usage of a generic dexterous hand with tactile sensing to imitate human skills and achieve robust in-hand DLO following. To enable the hardware system to function in the real world, we develop a framework that includes Cartesian-space arm-hand control, tactile-based in-hand 3-D DLO pose estimation, and task-specific motion design. Experimental results demonstrate the significant superiority of our method over using parallel grippers, as well as its great robustness, generalizability, and efficiency. The full paper and video are available on `https://mingrui-yu.github.io/DLO_following`.**

I. INTRODUCTION

Although robotic manipulation of deformable linear objects (DLOs), such as cables and ropes, has been widely researched [1], most of the existing studies assume rigid grasp of DLOs, e.g., shaping by fixedly grasping the two DLO ends [2]–[7] or planar rearrangement by a series of pick-and-place actions [8]–[10]. However, humans usually do not manipulate DLOs entirely relying on rigid grasp and re-grasp, but involving some dexterous in-hand actions, such as following the DLO towards the other end-tip by in-hand sliding, which is called *DLO Following* [11]. This skill is essential and efficient for many high-level tasks, such as cable routing and wrapping. However, such a task is much more challenging for a robot to handle than tasks with rigid grasp, since the robot has to achieve precise in-hand manipulation, i.e., carefully controlling the gripping motion and force to continuously change the grasp point while holding the DLO to prevent it from falling off.

To ensure holding the DLO during following, a straightforward approach is to design specialized end-effectors whose mechanical structures naturally guarantee holding the DLO between fingers [12]–[14], but then the gripper will lose its versatility and cannot manipulate other objects. Instead, some researchers have tried using generic parallel jaw grippers for DLO following [11]. However, since parallel grippers have only one degree of freedom (DoF), it is challenging to find a proper gripping force for following, as large forces will prevent in-hand sliding while small forces cannot robustly keep the DLO between fingers. As shown in Fig. 1, the parallel gripper can only be horizontally placed owing to the gravity, and frequent re-grasp by another manipulator is unavoidable. Limited by the low dexterity of parallel grippers, these problems are difficult to solve from an algorithmic perspective. Instead, we try to overcome these problems from another perspective: by using dexterous hands with tactile sensors. Dexterous hands are also generic and versatile end-effectors but with much higher DoFs. Beyond the dexterous manipulation of rigid objects, how to use dexterous hands to enhance DLO manipulation is still an open question. In this work, we study how to enable a dexterous hand with tactile sensing to achieve DLO following with much better performance, with no need for collecting offline data and learning dynamical models. We use LEAP Hand [15], an open-sourced hand costing less than 2,000 USD. To the best of our knowledge, we are the first to explore DLO following based on dexterous hands in the real world.

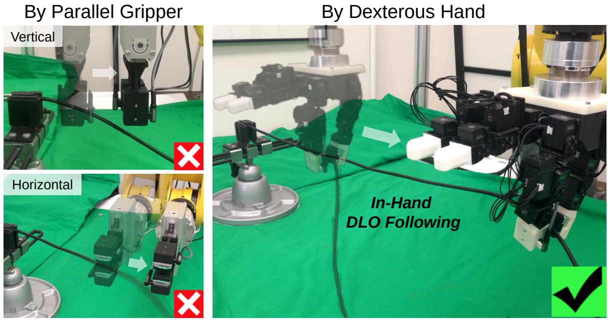

Fig. 1. Task of in-hand DLO following. The goal is to slide along the DLO towards the other end while holding the DLO.

Although dexterous hands and tactile sensors provide the hardware foundation, additional challenges arise due to the high DoFs of the hand and noisy sensing from the tactile sensors. To enable the hardware for deployable manipulation, we propose a framework that mainly includes three parts:

- **Control of the arm-hand system**: we design an optimization-based multi-objective inverse kinematics (IK) solver for the arm-hand system to achieve Cartesian-space control of the fingertips, and a hybrid position/force control method for the position-controlled LEAP Hand to achieve simultaneous control of finger motion and gripping forces.
- **Tactile estimation of in-hand DLO poses**: we propose an adaptive contact region segmentation approach and

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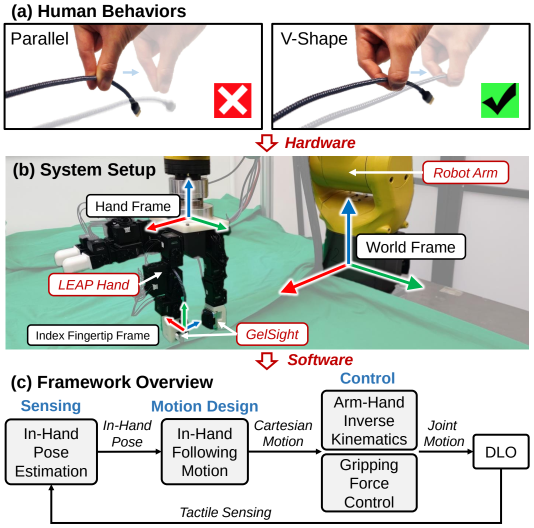

Fig. 2. Overview of this work's inspiration, hardware setup, and algorithm framework. (a) How humans use fingers to follow DLOs. (b) The hardware setup and the defined frames. For each frame, the red, green, and blue arrow refers to the X, Y, and Z axis, respectively. (c) Our algorithm framework that includes generic control, sensing, and task-specific motion design.

an optimization-based 3-D line fitting approach to estimate the in-hand 3-D DLO pose from two GelSight Mini tactile sensors mounted on two fingertips.

- **Motion design for DLO following**: based on the generic sensing and control methods, we design simple but effective robot motions to achieve DLO following with significantly better performance than the existing methods using parallel grippers.

Experimental results demonstrate that our framework successfully enables the dexterous hand with tactile sensing to achieve DLO following with great robustness, generalizability, and efficiency.

II. METHODOLOGY

The key idea for enhancing DLO following by a dexterous hand is inspired by how humans use fingers to follow DLOs. As shown in Fig. 2(a), humans usually form the index and thumb fingers as a V-shape, which ensures holding the DLO without applying large contact forces to the DLO. This work aims to imitate such human skills by a generic dexterous hand with tactile sensing. Fig. 2(b) shows the hardware setup and defined frames. It contains an anthropomorphic LEAP Hand installed on a robot arm and two GelSight Mini [16] tactile sensors mounted on the index and thumb fingertips. In this work, we explore the usage of the index and thumb fingers and keep the other two fingers fixed. We denote the world frame and hand frame as $\mathcal{W}$ and $\mathcal{H}$, respectively. To enable human-like in-hand following of DLOs by the above robot system, we propose an algorithm framework involving generic arm-hand control, tactile sensing, and task-specific motion design, as overviewed in Fig. 2(c). Please refer to the **full paper** for the details.

A. Cartesian-Space Control of the Arm-Hand System

As for the low-level control module, two main objectives need to be achieved: controlling the Cartesian-space motion of fingertips and the gripping forces between fingertips.

1) Optimization-Based IK Solver: In this work, we formulate the IK solving as a constrained optimization problem. The potential Cartesian-space objectives include: the poses of the two fingertips in $\mathcal{W}$ (i.e., ${}^{w}\boldsymbol{P}_{f,i}$), the poses of the two fingertips in $\mathcal{H}$ (i.e., ${}^{h}\boldsymbol{P}_{f,i}$), the relative position between the two fingertips in $\mathcal{H}$ (i.e., ${}^{h}\Delta\boldsymbol{p}_f = {}^{h}\boldsymbol{p}_{f,1} - {}^{h}\boldsymbol{p}_{f,2}$), and the hand pose in $\mathcal{W}$ (i.e., ${}^{w}\boldsymbol{P}_h$). The optimization-based IK solving is formulated as

$$\begin{aligned} \min_{\boldsymbol{q}} \mathcal{C} = & \frac{1}{2}\sum_{i=1}^{2} {}^{w}\tilde{\boldsymbol{P}}_{f,i}^{\mathsf{T}} \boldsymbol{W}_{fw,i} {}^{w}\tilde{\boldsymbol{P}}_{f,i} + \frac{1}{2}\sum_{i=1}^{2} {}^{h}\tilde{\boldsymbol{P}}_{f,i}^{\mathsf{T}} \boldsymbol{W}_{fh,i} {}^{h}\tilde{\boldsymbol{P}}_{f,i} \\ & + \frac{1}{2} {}^{h}\tilde{\Delta\boldsymbol{p}}_f^{\mathsf{T}} \boldsymbol{W}_{rfh} {}^{h}\tilde{\Delta\boldsymbol{p}}_f + \frac{1}{2} {}^{w}\tilde{\boldsymbol{P}}_h^{\mathsf{T}} \boldsymbol{W}_{hw} {}^{w}\tilde{\boldsymbol{P}}_h \\ \text{s.t.} \quad & \boldsymbol{q}_{\mathrm{lb}} \le \boldsymbol{q} \le \boldsymbol{q}_{\mathrm{ub}} \end{aligned} \tag{1}$$

where $\tilde{(\cdot)}$ refers to the error between the desired pose and the current pose. Each objective and each dimension of the objective can be weighted by the weighting matrices $\boldsymbol{W}_{fw}, \boldsymbol{W}_{fh}, \boldsymbol{W}_{rfh}$ and $\boldsymbol{W}_{hw}$. The joint positions are constrained by the lower bound $\boldsymbol{q}_{\mathrm{lb}}$ and upper bound $\boldsymbol{q}_{\mathrm{ub}}$.

2) Hybrid Position/Force Control for LEAP Hand: Controlling the gripping force between the two fingertips is essential for grasping and sliding along the DLO. We design a gripping force control method based on the hand's default position controller.

B. Tactile Sensing of the In-Hand DLO State

The pipeline of our tactile sensing approach is illustrated in Fig. 3(a). Compared with 2-D poses on one tactile sensor, estimating 3-D poses from two sensors is necessary since 1) the 3-D in-hand pose can guide the robot to adjust its 3-D motion for DLO following, and 2) the contact region on only one sensor can be too small for reliable pose estimation (e.g., Fig. 3(b) right).

1) Contact Region Segmentation: We adopt a flexible depth threshold to segment the contact region. We apply the EM algorithm to approximate the distribution of all depth values by a two-component GMM. We assume the Gaussian component $\mathcal{N}(\mu, \sigma)$ with a higher weight represents the non-contact region. Then, the depth threshold for contact segmentation is specified as $D_{\mathrm{thres}} = \mu + 3\sigma$.

2) In-Hand DLO Pose Estimation: After extracting the contact regions, we use the forward kinematics of fingers to transform all contact points from two sensors to the same frame. We define the in-hand DLO pose as a 3-D line in the index fingertip frame, whose distances to all contact points are as close to the DLO radius r as possible. We formulate the estimation of the 3-D line as a constrained nonlinear optimization problem.

C. Motion Design for DLO Following

As illustrated in Fig. 4, it is difficult for parallel grippers to find a proper gripping force to balance following and holding. In contrast, by utilizing the more DoFs of dexterous fingers, the two objectives can be decoupled by forming a "V" shape: for holding, it can apply a large gripping force to keep the

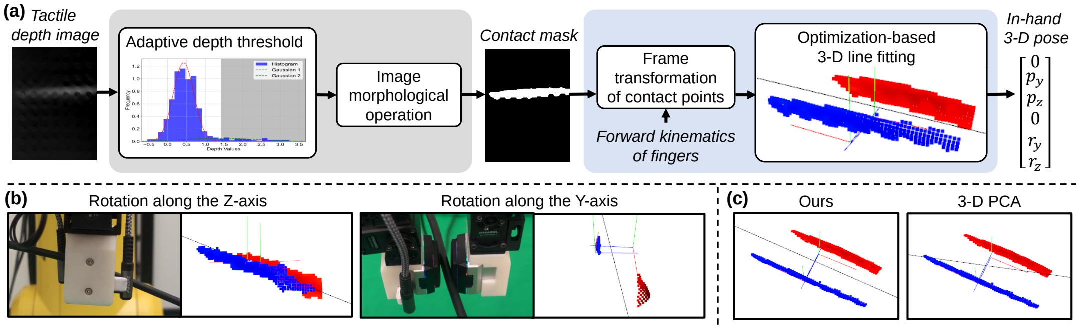

Fig. 3. Tactile sensing of the in-hand DLO pose. (a) Estimation pipeline. (b) Estimation results of the in-hand DLO that rotates along the Z and Y axes of the index fingertip frame. (c) Comparison between our optimization-based 3-D line fitting method and the 3-D PCA method. The blue and red points represent the contact points on the index and thumb GelSight, respectively; the black line represents the estimated DLO axis.

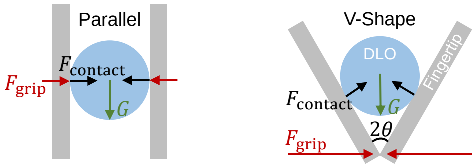

Fig. 4. Superiority of V-shape fingers over parallel fingers.

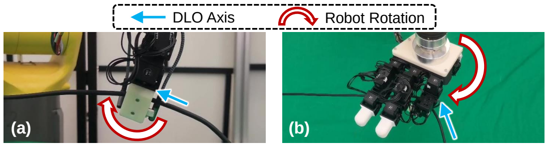

Fig. 5. Orientation adjustment to better match the in-hand DLO pose.

bottom of the two fingertips tightly close; and for following, it can adjust the angle of the V shape (i.e., gripping angle θ) to apply a moderate contact force. Moreover, we find it is necessary to adjust the orientations of the fingertips to match the in-hand 3-D DLO pose during the following. Thus, we adopt a proportional (P) controller to control the rotation of the fingertips along the X and Z axes of $\mathcal{H}$ to better match the estimated in-hand DLO pose (see Fig. 5).

III. Experimental Results

We conduct a series of real-world experiments. Please refer to the **full paper** for the details and other experiments.

A. Following While Holding Task

Unless otherwise stated, the tests are performed on a typical USB cable with the desired following direction being the positive Y-axis of $\mathcal{W}$ and a following speed of 0.025 m/s.

1) Comparison with Parallel Grippers: We first compare the proposed method using a dexterous hand with the conventional approaches using parallel grippers. As shown in Fig. 1, two settings using parallel grippers are tested: 1) the gripper is vertically placed [17] and moves in an open-loop manner; and 2) the gripper is horizontally placed and reactively moves using the approach in [11]. We test the three approaches on a cable with a straight shape and a curved shape, respectively. Each approach and each shape is tested five times, and the results are summarized in Table I. Our approach based on a dexterous hand shows robustness and practicability, as the hand reaches the maximum following length in all tests with no need for deviating from the desired following direction.

TABLE I

Comparison between dexterous hands and parallel grippers.

DLO shape	Metrics	Parallel (vertical)	Parallel (horizontal)	Dexterous hand
Straight	Follow. length (m)[a]↑	0.08	0.98	**1.0**
	Mov. range (m)[b]↓	0	0.21	0
Curved	Follow. length[a](m) ↑	0.07	0.27	**1.0**
	Mov. range (m)[b]↓	0	0.11	0

[a] Ave. following length along the DLO. The max. length is 1.0 m.
[b] Ave. required moving range perpendicular to the following direction.

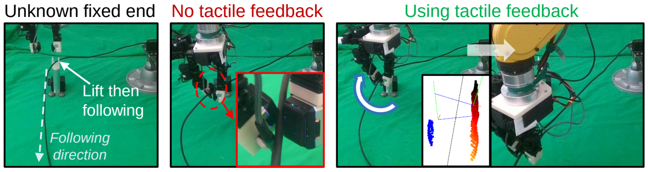

Fig. 6. Comparison between whether using tactile feedback. The task is to lift the DLO and then follow it along the desired following direction, during which the position of the fixed end is unknown.

2) Generalization to Different DLOs and Following Speeds: We validate the proposed approach on five different DLOs. We test five times for each DLO, and we randomly place the DLO on the table in different curved shapes at the beginning of each test. Additionally We test the following speeds of 0.025, 0.05, and 0.10 m/s for five times, respectively. All tests are successful.

3) Comparison Between Whether Using Tactile Feedback: We demonstrate the necessity of in-hand DLO pose estimation during DLO following in the task shown in Fig. 6, whose goal is to lift the DLO and then follow it along the desired following direction, during which the position of the fixed end is unknown. In an open-loop manner without tactile feedback, the orientations of the fingers are fixed, and the two fingers become misaligned quickly owing to the oblique DLO tension force and fail to continue following. In contrast, when using the estimated in-hand 3-D DLO pose as feedback, the fingers can reactively rotate to better match the direction of the in-hand DLO to reduce the impact of in-hand forces, and all five tests finally succeed.

4) Switch Between Grasping and Following: We conduct a cable routing task to show the ability of our approach to switch between rigid grasping and following in high-level tasks. This experiment shows the application prospects of our approach on more complicated high-level tasks.

REFERENCES

[1] J. Zhu, A. Cherubini, C. Dune, D. Navarro-Alarcon, F. Alambeigi, D. Berenson, F. Ficuciello, K. Harada, J. Kober, X. Li *et al.*, “Challenges and outlook in robotic manipulation of deformable objects,” *IEEE Robot. Autom. Mag.*, 2021.

[2] M. Yu, K. Lv, H. Zhong, S. Song, and X. Li, “Global model learning for large deformation control of elastic deformable linear objects: An efficient and adaptive approach,” *IEEE Trans. Robot.*, vol. 39, no. 1, pp. 417–436, 2023.

[3] C. Wang, Y. Zhang, X. Zhang, Z. Wu, X. Zhu, S. Jin, T. Tang, and M. Tomizuka, “Offline-online learning of deformation model for cable manipulation with graph neural networks,” *IEEE Robot. Autom. Lett.*, no. 2, pp. 5544–5551, 2022.

[4] M. Yu, H. Zhong, and X. Li, “Shape control of deformable linear objects with offline and online learning of local linear deformation models,” in *IEEE Int. Conf. Robot. Autom.*, 2022, pp. 1337–1343.

[5] M. Yu, K. Lv, C. Wang, M. Tomizuka, and X. Li, “A coarse-to-fine framework for dual-arm manipulation of deformable linear objects with whole-body obstacle avoidance,” in *IEEE Int. Conf. Robot. Autom.*, 2023, pp. 10 153–10 159.

[6] H. Zhong, Z. Xu, G. Ma, M. Yu, and X. Li, “Regressor-based model adaptation for shaping deformable linear objects with force control,” in *2023 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2023, pp. 1–7.

[7] M. Yu, K. Lv, C. Wang, Y. Jiang, M. Tomizuka, and X. Li, “Generalizable whole-body global manipulation of deformable linear objects by dual-arm robot in 3-d constrained environments,” *arXiv preprint arXiv:2310.09899*, 2023.

[8] X. Huang, D. Chen, Y. Guo, X. Jiang, and Y. Liu, “Untangling multiple deformable linear objects in unknown quantities with complex backgrounds,” *IEEE Trans. Autom. Sci. Eng.*, 2023.

[9] R. Lee, M. Hamaya, T. Murooka, Y. Ijiri, and P. Corke, “Sample-efficient learning of deformable linear object manipulation in the real world through self-supervision,” *IEEE Robot. Autom. Lett.*, vol. 7, no. 1, pp. 573–580, 2022.

[10] S. Jin, W. Lian, C. Wang, M. Tomizuka, and S. Schaal, “Robotic cable routing with spatial representation,” *IEEE Robot. Autom. Lett.*, vol. 7, no. 2, pp. 5687–5694, 2022.

[11] Y. She, S. Wang, S. Dong, N. Sunil, A. Rodriguez, and E. Adelson, “Cable manipulation with a tactile-reactive gripper,” *Int. J. Robot. Res.*, vol. 40, no. 12-14, pp. 1385–1401, 2021.

[12] X. Jiang, Y. Nagaoka, K. Ishii, S. Abiko, T. Tsujita, and M. Uchiyama, “Robotized recognition of a wire harness utilizing tracing operation,” *Robot. Comput. Integr. Manuf.*, vol. 34, pp. 52–61, 2015.

[13] J. Chapman, G. Gorjup, A. Dwivedi, S. Matsunaga, T. Mariyama, B. MacDonald, and M. Liarokapis, “A locally-adaptive, parallel-jaw gripper with clamping and rolling capable, soft fingertips for fine manipulation of flexible flat cables,” in *IEEE Int. Conf. Robot. Autom.*, 2021, pp. 6941–6947.

[14] A. Wilson, H. Jiang, W. Lian, and W. Yuan, “Cable routing and assembly using tactile-driven motion primitives,” in *IEEE Int. Conf. Robot. Autom.*, 2023, pp. 10 408–10 414.

[15] K. Shaw, A. Agarwal, and D. Pathak, “LEAP Hand: Low-cost, efficient, and anthropomorphic hand for robot learning,” *Robotics: Science and Systems (RSS)*, 2023.

[16] GelSight Mini. [Online]. Available: https://www.gelsight.com/gelsightmini/

[17] R. B. Hellman, C. Tekin, M. van der Schaar, and V. J. Santos, “Functional contour-following via haptic perception and reinforcement learning,” *IEEE Trans. Haptics*, vol. 11, no. 1, pp. 61–72, 2017.