Adaptive Cable Manipulation Around Constrained Fixtures with Bi-Manual Slack Control

Osher Azulay*[1], Kavish Kondap*[1], Jaimyn Drake*[1], Shuangyu Xie[1], Hui Li[2], Sachin Chitta[2], Ken Goldberg[1]

***Abstract*— Automated cable routing requires deformable object manipulation in constrained and cluttered environments. However, achieving reliable routing is challenging due to fixture constraints, cable flexibility, and the need for slack management. In this work, we introduce a bi-manual cable routing framework that integrates a learned cable tracer with sliding-based motion planning to achieve desired cable trajectories while ensuring precise slack control. Unlike previous methods that use single-arm manipulation, our approach uses open-loop coordinated bi-manual sliding motions to dynamically adjust the cable configuration to avoid tangling and misrouting. Physical experiments with a modified NIST task board demonstrate 84% average success rate across multiple tiers, significantly outperforming a single-arm approach and underscoring robustness across varied fixture configurations.**

I. INTRODUCTION

Cable routing, the process of guiding one or more thin deformable cables along a specified path around rigid fixtures, is a fundamental challenge in applications such as the installation of wiring for vehicle manufacturing, server networking for data centers, configuration of electronic infrastructure in industrial settings, and other tasks in residential and retail settings. Unlike rigid objects, cables exhibit near-infinite degrees of freedom and complex deformations [1–3]. Robotic cable routing requires planning gripper trajectories to guide a cable along a desired path while adhering to spatial constraints imposed by rigid fixtures. As opposed to free-space manipulation, this involves contact interactions, grasping constraints, and structured motion planning.

To systematically evaluate cable manipulation, we draw inspiration from the NIST Assembly Task Board 4 [4], a standardized benchmark for studying robotic cable routing. The board includes various fixtures, such as C-clips and channels, designed to guide and constrain the cable in specific configurations. We retain the core setup and dimensions of the original NIST board, but introduce additional mounting holes to enable flexible reconfiguration of (as shown in Figure 3). In cable routing, effective slack management is crucial to prevent excessive tension or deformation. In this work, we propose a bi-manual manipulation strategy, where one arm maintains cable tension while the other routes the cable through fixtures, to avoid tangling and incorrect routing in intricate layouts. We modify caging grippers used in previous works [2, 5] to be more suitable for the routing task, enabling controlled sliding and reducing uncertainty in the position of the cable.

[1] AUTOLab at the University of California, Berkeley, [2] Autodesk Research
* Equal contribution

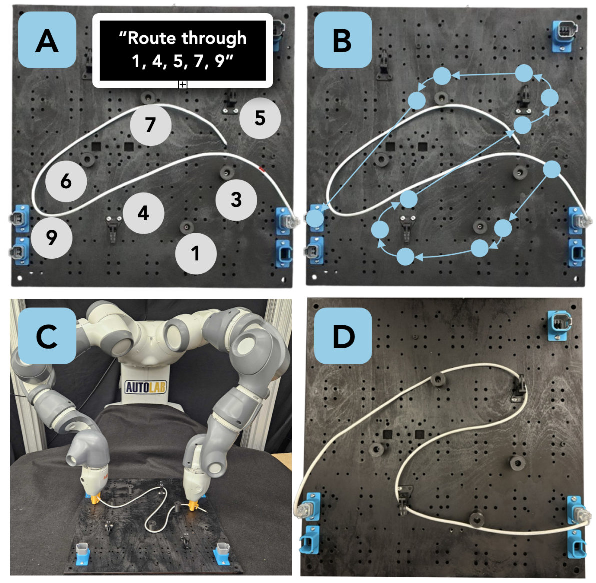

Fig. 1: System overview with four key modules in the cable routing process. (Top-left) User defines the target path. (Top-right) Planner computes valid waypoints and sliding actions. (Bottom-left) Robot executes motions with adaptive strategies. (Bottom-right) Final routed configuration.

Our approach extends previous cable manipulation techniques by integrating a learned cable tracer, cable sliding primitives, and structured slack management. Unlike prior methods that rely on fixed grasping strategies or single-arm manipulation, we use coordinated bi-manual motions to dynamically adjust the cable configuration. Designed for complex scenarios, our system can handle up to 5 fixtures and routing paths featuring up to 4 directional changes with no human intervention by autonomously selecting grasping points and planning sliding actions to guide the cable along the designated path.

This paper makes the following contributions:

1) MOTORCYCLE (Multi-turn Optimized Trajectories for Ordered Routing of Cable Yoking and Cable Loop Execution): A cable routing framework that combines visual learned tracing with bi-manual sliding motions to achieve desired routing configurations.
2) A slide motion planning module that computes spatially valid waypoints and generates a structured sequence of bimanual motion primitives to route the cable while avoiding collision with fixtures.
3) Physical experiments that quantitatively suggest the effectiveness of MOTORCYCLE in routing cables, achieving an 84% average success rate across multiple tiers.

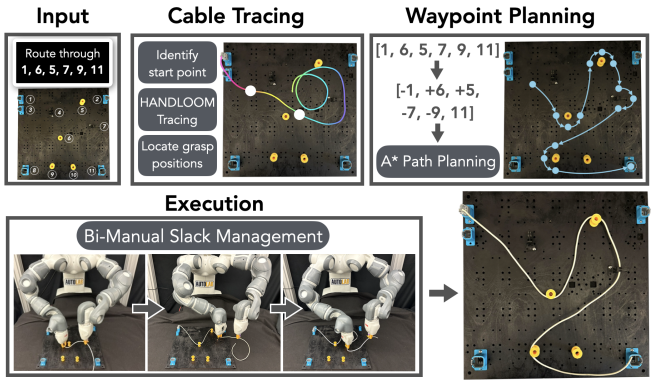

Fig. 2: Overview of MOTORCYCLE. (Top-left) The input route configuration is shown along with the cable tracing pipeline, where the system detects the cable near the connector and uses HANDLOOM tracing to identify two valid grasp locations. (Top-right) Waypoint planning determines a valid spatial route trajectory, utilizing A* to compute collision-free paths. (Bottom-left) Sequential images of the robot executing the routing process using bi-manual slack management, where the following arm alternates between leading and following. (Bottom-right) The final solved configuration.

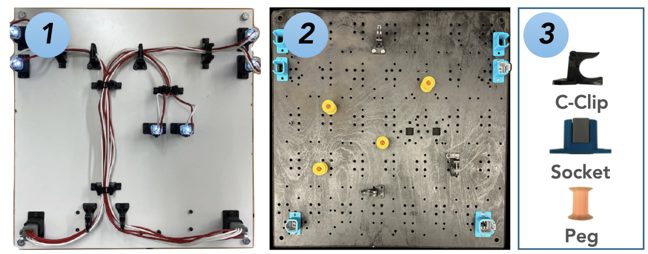

Fig. 3: (1) NIST Task board #4 [4](2) Modified NIST board #4. The setup includes a cable connected to a socket, utilizing different fixture types such as C-clips and cylindrical pegs (3). The board features multiple holes to support various routing and testing scenarios.

II. Method

We present the challenge of routing a deformable cable around a series of fixtures using bi-manual robotic manipulation. It is important to ensure the cable follows the desired path without excessive deformation, slack, or tension. To address this, we propose a cable routing framework that integrates visual learned tracing and bimanual sliding planning to iteratively adjust the cable trajectory while respecting spatial constraints, as illustrated in Figure 2. The objective is to generate a feasible and adaptable routing strategy that ensures the cable follows the designated path while maintaining proper slack and avoiding excessive tension.

A. Problem Formulation

We assume a planar fixture surface with an $n \times n$ grid of mounting holes. We further assume that a fixed socket is rigidly attached to the surface, connected at one end to a cable of length d. Up to N fixtures, either a C-clip or a cylindrical peg, are attached to the surface grid such that the minimum distance between any two fixtures is greater than h. Given the position of the connector and fixtures, a routing configuration specifies a desired path of the cable starting at the connector and going around the fixtures either clockwise $(+)$ or counter-clockwise $(-)$, in a desired ordering.

Let the xy-plane represent the fixture surface with holes at integer intervals, starting with $(0, 0)$ in the lower left. We define a sequence of coordinates, where the first indicates the position of the connector, and subsequent coordinates define the position of the ith fixture. The input consists of a routing configuration $\mathcal{C}$, a sequence of fixture numbers (e.g., $(0, 4, 6)$), and the objective is to determine the corresponding routing configuration, i.e., assigning the correct directions to each fixture. This results in a sequence of signed fixture numbers, e.g., $(0, +4, -6)$, indicating that the cable should go clockwise around fixture 4, and counter-clockwise around fixture 6, without making contact with any other fixtures.

At the beginning of each routing procedure, an overhead RGB camera captures an image observation $\mathbf{I} \in \mathcal{I}$, where $\mathcal{I}$ denotes the image pixel space. Given the observed image $\mathbf{I}$ and a fixture sequence, the task is to arrange the cable into the specified configuration.

We make the following assumptions: (1) the cable is visually distinct from the monochrome background; (2) the cable is untangled, with no knots present; (3) one endpoint of the cable is plugged into a fixed socket, while the other endpoint is unconstrained; (4) the positions of the fixtures on the board are known, but the cable starts in a randomly initialized configuration and, (5) the sliding motion required to reach the goal configuration remains within the feasible joint limits of the bimanual robot.

B. Cable Tracing Algorithm

We determine the cable's starting state using HANDLOOM, an autoregressive cable tracing algorithm [6]. At each iteration, the model generates a dense probability map representing the likelihood of the next cable trace point, selecting the highest-probability point greedily. To initiate tracing, we conduct a pixel search around the starting clip and feed the result into an analytical model, similar to [2], to locate 2 to 4 points on the cable as input for the learned tracer.

C. Slide Planning

We frame cable routing as moving through a series of waypoints to wrap the cable around each fixture. For each fixture $f_i \in \mathcal{C}$, we define candidate waypoints offset at $0°, 90°, 180°$, and $270°$ from the fixture's center.

To select a suitable waypoint sequence, we compute direction vectors between fixtures: $\mathbf{d}_{\text{prev}}$ from the previous fixture to f_i and $\mathbf{d}_{\text{next}}$ from f_i to the next fixture. The resultant vector $\mathbf{r} = \mathbf{d}_{\text{prev}} + \mathbf{d}_{\text{next}}$ guides waypoint selection based on its dominant component for natural routing. The cross product $\mathbf{d}_{\text{prev}} \times \mathbf{d}_{\text{next}}$ ensures correct clockwise or counterclockwise motion around the fixture.

With the waypoint sequence established, we apply the A* algorithm [7] to generate a collision-free trajectory for the gripper, starting from the initial cable state C_0 and avoiding fixture intersections.

D. Slack Management and Sliding Motion

Effective cable slack management is required to ensure sufficient tension, prevent tangling, and maintain stable cable placement [8]. Single-arm manipulation often struggles with complex routing constraints due to its inability to

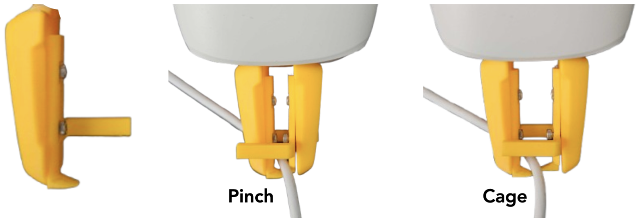

Fig. 4: Modified caging gripper, designed for cable routing tasks. The combination of 3D-printed "toe" and horizontal cantilever facilitates both pinching for stable grasping (left) and sliding for controlled cable manipulation (right).

simultaneously control slack and guide the cable. In contrast, bi-manual strategies enable coordinated movements and constraint-aware adjustments [2].

We implement a bi-manual sliding motion strategy using a caging gripper design. Gripper g_1 slides tangentially along the planned path while gripper g_2 dynamically adjusts to manage slack. The caging gripper features a toothed base to retain the cable and a perpendicular cross-beam to constrain vertical movement (Figure 4). By adjusting the gripper jaw width, the end effector can switch between pinching (for initial cable grasping) or caging (during routing).

Given the waypoints generated by the slide motion planner, g_1 follows the trajectory while maintaining a tangential alignment with the path to ensure smooth motion and reduce the likelihood of the cable getting tangled around the gripper. Simultaneously, g_2 follows a modified trajectory, offset in the direction of the tangent line on each point from the path of g_1. In scenarios where the user-specified routing requires a $180°$ turn, following this tangential offset would lead to the robot arms crossing. Similarly, if g_1 is operating near the edge of the reachable region of the robot, applying this offset would require g_2 to exceed its joint limits. To prevent collision or kinematic failures in such situations, g_2 adapts to closely follow g_1 with a constant offset on the y-axis, while matching the x-coordinate of g_1.

III. Experiments

Hardware Details: The experimental setup features a bi-manual ABB YuMi robot equipped with modified caging grippers, along with an overhead ZED mini camera positioned 1 meter above the workspace. Note that only RGB image data is used as input in our work. A modified NIST Task Board 4 is mounted on a table in workspace of the robot, with a single cable attached to one of the sockets. Additionally, three different cable lengths are used for each tier, enabling adaptable fixture configurations while preserving structured routing constraints.

A. Evaluation

We assess the performance of MOTORCYCLE across varying levels of cable complexity and fixture constraints. We introduce a tiered evaluation system that classifies routing complexity based on the number of fixtures and abrupt directional changes in the workspace.

- **Tier 1**: A simple routing scenario with three fixtures, involving minimal directional changes.
- **Tier 2**: Increased complexity with four fixtures, requiring sharper directional changes while primarily maintaining a forward routing direction.
- **Tier 3**: The most challenging scenario, involving five fixtures, multiple intersections, and significant directional shifts.

TABLE I: Success rate for 120 physical experiments across three tiers for MOTORCYCLE and a single-arm ablation.

Method	**Tier 1**	**Tier 2**	**Tier 3**
Single arm	31.6 %	8.7 %	8.0 %
MOTORCYCLE	90.0 %	82.5 %	79.0 %

For each tier, we randomly sampled four board configurations, each designed to match the tier's difficulty level and goal routing setup. The cable was initially placed in a random graspable configuration. We compare MOTORCYCLE against a single-arm approach to evaluate the advantages of coordinated slack management and enhanced routing stability. Each configuration was executed five times, totaling 60 physical experiments for the bi-manual approach and 60 for the single-arm approach.

Table I shows the success rates across different tiers. The results suggest that the MOTORCYCLE maintains strong performance, with a slight decrease as complexity increases due to additional fixtures and sharper directional changes. In contrast, the single-arm approach has significantly lower success rates, with performance declining sharply in higher tiers, underscoring its limitations in complex routing scenarios. This is primarily due to the cable getting tangled in the fixtures during routing, causing the robot to frequently exceed its torque limits. Additionally, the lack of slack management (e.g. pulling the cable taut between waypoints) often results in the cable passing over fixtures instead of routing through them.

IV. Conclusion

Although successful across multiple tiers of experimental difficulty, MOTORCYCLE has several limitations. In high-curvature regions, cable stretching can increase tension, causing the YuMi to exceed its torque limits. Additionally, since the entire trajectory is planned before execution, the open-loop nature of the system prevents real-time adjustments, limiting potential for regrasping, arm switching and adaptation to occlusions. The method also inherits assumptions from HANDLOOM, requiring planar, visually distinguishable cables. In future work, we will integrate real-time feedback to adjust grasping points and dynamically modify sliding trajectories, improving robustness in complex scenarios.

References

[1] J. Grannen, P. Sundaresan, B. Thananjeyan, J. Ichnowski, A. Balakrishna, M. Hwang, V. Viswanath, M. Laskey, J. E. Gonzalez, and K. Goldberg, "Untangling dense knots by learning task-relevant keypoints," *arXiv preprint arXiv:2011.04999*, 2020.

[2] K. Shivakumar, V. Viswanath, A. Gu, Y. Avigal, J. Kerr, J. Ichnowski, R. Cheng, T. Kollar, and K. Goldberg, "Sgtm 2.0: Autonomously untangling long cables using interactive perception," in *2023 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, 2023, pp. 5837–5843.

[3] J. Luo, C. Xu, X. Geng, G. Feng, K. Fang, L. Tan, S. Schaal, and S. Levine, “Multistage cable routing through hierarchical imitation learning,” *IEEE Transactions on Robotics*, vol. 40, pp. 1476–1491, 2024.

[4] K. Kimble, K. Van Wyk, J. Falco, E. Messina, Y. Sun, M. Shibata, W. Uemura, and Y. Yokokohji, “Benchmarking protocols for evaluating small parts robotic assembly systems,” *IEEE robotics and automation letters*, vol. 5, no. 2, pp. 883–889, 2020.

[5] V. Viswanath, K. Shivakumar, J. Kerr, B. Thananjeyan, E. Novoseller, J. Ichnowski, A. Escontrela, M. Laskey, J. Gonzalez, and K. Goldberg, “Autonomously Untangling Long Cables,” in *Proceedings of Robotics: Science and Systems*, New York City, NY, USA, Jun. 2022.

[6] V. Viswanath, K. Shivakumar, M. Parulekar, J. Ajmera, J. Kerr, J. Ichnowski, R. Cheng, T. Kollar, and K. Goldberg, “Handloom: Learned tracing of one-dimensional objects for inspection and manipulation,” in *Conference on Robot Learning*, PMLR, 2023, pp. 341–357.

[7] P. E. Hart, N. J. Nilsson, and B. Raphael, “A formal basis for the heuristic determination of minimum cost paths,” *IEEE transactions on Systems Science and Cybernetics*, vol. 4, no. 2, pp. 100–107, 1968.

[8] V. Viswanath, J. Grannen, P. Sundaresan, B. Thananjeyan, A. Balakrishna, E. Novoseller, J. Ichnowski, M. Laskey, J. E. Gonzalez, and K. Goldberg, “Disentangling dense multi-cable knots,” in *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, IEEE, 2021, pp. 3731–3738.