Automating Multi-Turn Cable Routing on the NIST Fixture Board with a Bi-Manual Robot and Caging Grippers

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***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.**

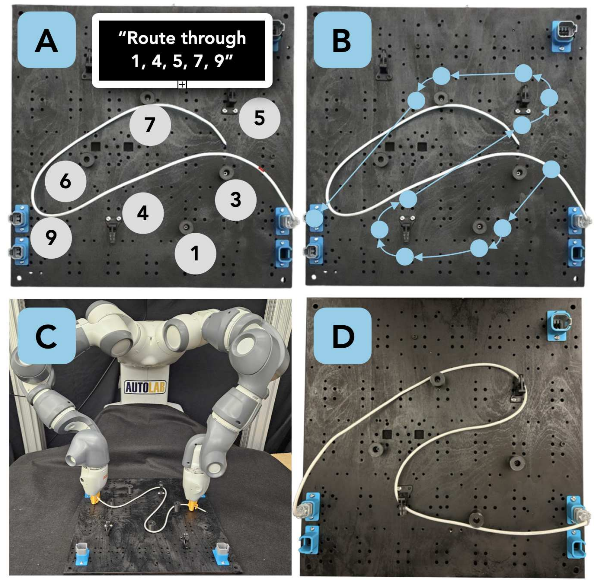

Fig. 1: System overview illustrating the four key modules involved in the cable routing process. (Top-left) The user specifies the target route by defining the desired cable path. (Top-right) The slide motion planning module computes spatially valid waypoints and determines a feasible sequence of bi-manual sliding actions to guide the cable. (Bottom-left) The robot executes the planned motions, adapting its grasping and sliding strategies while caging the cable. (Bottom-right) The solved configuration is displayed.

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. Unlike 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 fixtures (as shown in Figure 3). This modification allows us to test diverse spatial constraints and routing scenarios, providing a more comprehensive evaluation of system adaptability.

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. 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.

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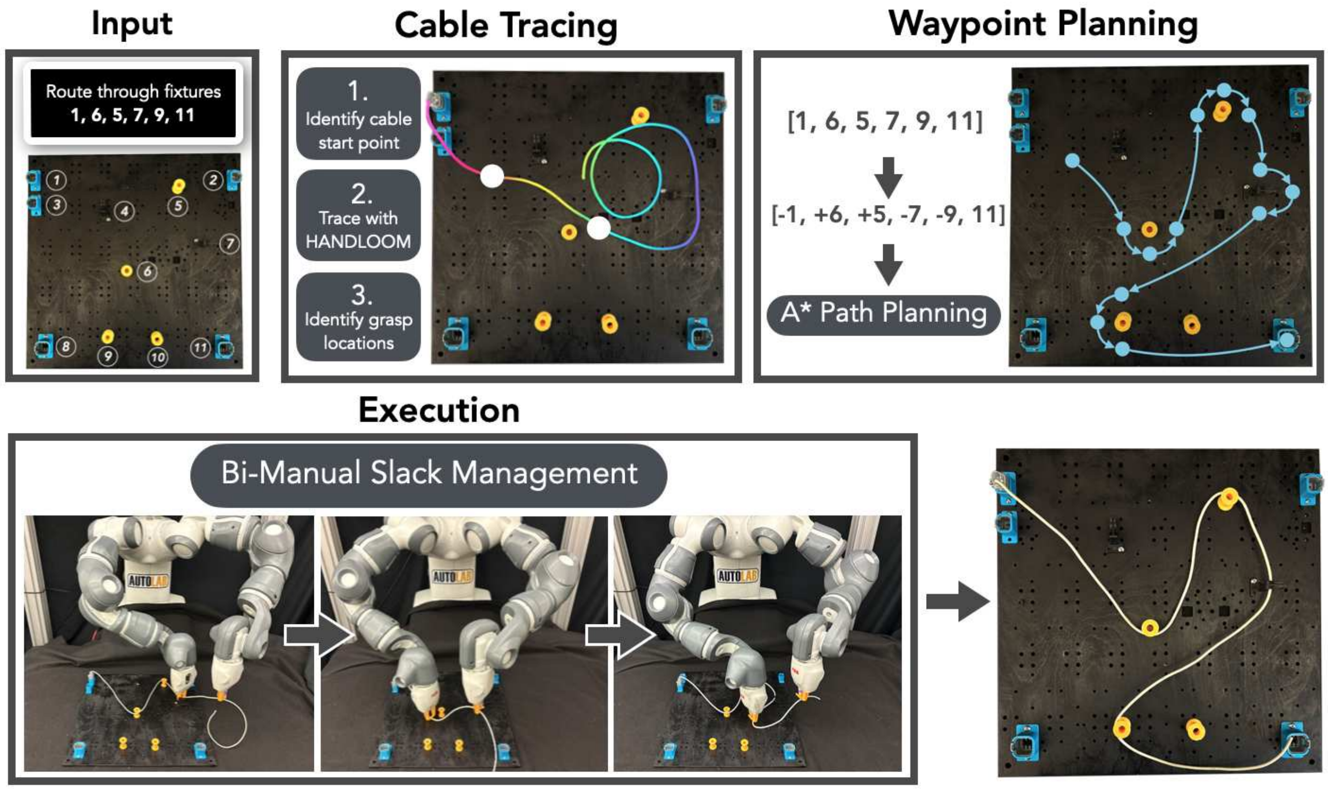

Fig. 2: Overview of MOTORCYCLE. (Top-left) The input route configuration is shown along with the cable tracing pipeline, where the system detects the cable near the connector and uses HANDLOOM tracing to identify two valid grasp locations. (Top-right) Waypoint planning determines a valid spatial route 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.

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.

II. Related Work

Manipulation of deformable objects has been a long-standing challenge in robotics, including tasks such as knot untangling [6], cable tracing with interactive perception [7, 8], and gasket assembly [9]. Various methods have been developed to manipulate cables, including motion planning techniques that optimize minimal-energy trajectories [10, 11] and, roadmap-based planners that rely on predefined motion primitives [12]. While these methods have been effective in structured settings, they often assume minimal environmental constraints and unrestricted object movement, making them less suitable for cable routing tasks, which require precise interactions with multiple rigid fixtures.

Cable routing introduces additional challenges, as cables must be guided through a series of constrained paths while maintaining control over tension and slack. Existing approaches rely on various strategies, such as heuristic-based planners [13] or optimization techniques like genetic algorithms [14] and tactile sensing to infer internal cable properties for better manipulation [15]. More recently, learning-based methods have improved adaptability by leveraging human demonstrations, with some approaches focusing only on training low-level manipulation primitives [16], while others also learn high-level routing policies to plan feasible paths based on spatial relationships with fixtures [3].

Despite these advances, most methods are evaluated in simplified setups with a limited number of fixtures or limited directional change, restricting their generalization to more complex routing scenarios. Our work addresses these limitations by introducing a structured routing framework that demonstrates generalization across multiple scenarios by generating feasible routing plans, even in intricate environments with many fixtures.

III. 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

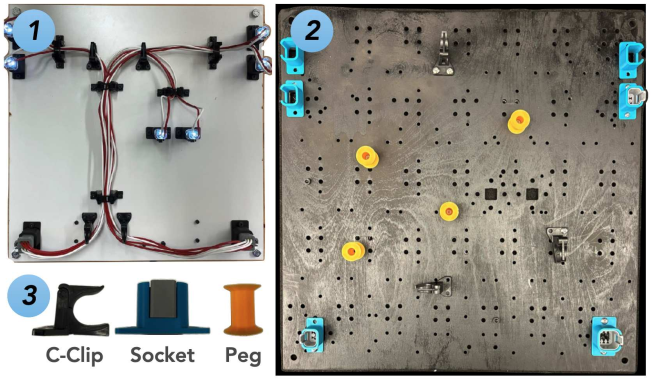

Fig. 3: (1) NIST Task board #4 [4](2) Modified NIST board #4. The setup includes a cable connected to a socket, utilizing different fixture types such as C-clips and cylindrical pegs (3). The board features multiple holes to support various routing and testing scenarios.

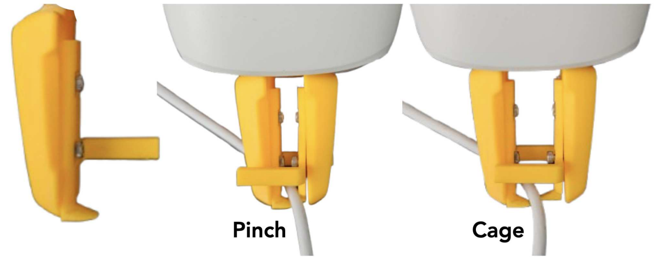

Fig. 4: Modified caging gripper, designed for cable routing tasks. The combination of 3D-printed "toe" and horizontal cantilever facilitates both pinching for stable grasping (left) and sliding for controlled cable manipulation (right).

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 from the connector, 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 while deriving the sliding motion for both arms to ensure precise manipulation and alignment, while actively managing slack to prevent excessive tension or entanglement, enabling smooth and controlled adjustments.

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

To determine the starting state of the cable, we use HANDLOOM, an autoregressive cable tracing algorithm [7]. At each iteration, the model generates a dense probability map, where each pixel represents the likelihood of being the next cable trace point; using this prediction, the next cable point is selected greedily based on the highest probability. To initiate tracing, similar to [2], we use an analytical model to locate between 2 and 4 points on the cable, which serve as input for the learned tracer. This heuristic tracer requires a single start point, which we identify using a pixel search around the starting fixture in the routing sequence, allowing tracing to be conducted with no human intervention. Since our focus is on bi-manual cable routing with sliding, the tracer generates a sufficient cable trace for determining the two grasp points. Grasp points for each arm are determined by locating points on the cable trace that are sufficiently far from any fixtures and within an acceptable distance of the starting fixture. During grasping, each gripper is oriented perpendicular to the cable's path to enable sliding.

C. Slide Planning

We frame the task of routing as moving through a series of waypoints to wrap the cable around each fixture. To determine

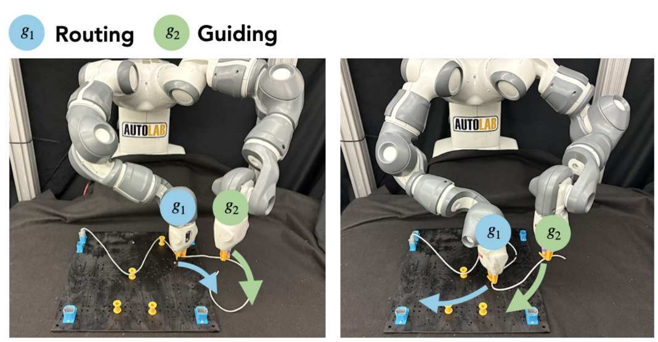

Fig. 5: Bi-manual arm coordination: On the left, g_2 leads with a tangential offset, while on the right, it follows g_1 to prevent collisions and joint limit violations, dynamically adjusting its trajectory for smooth cable routing.

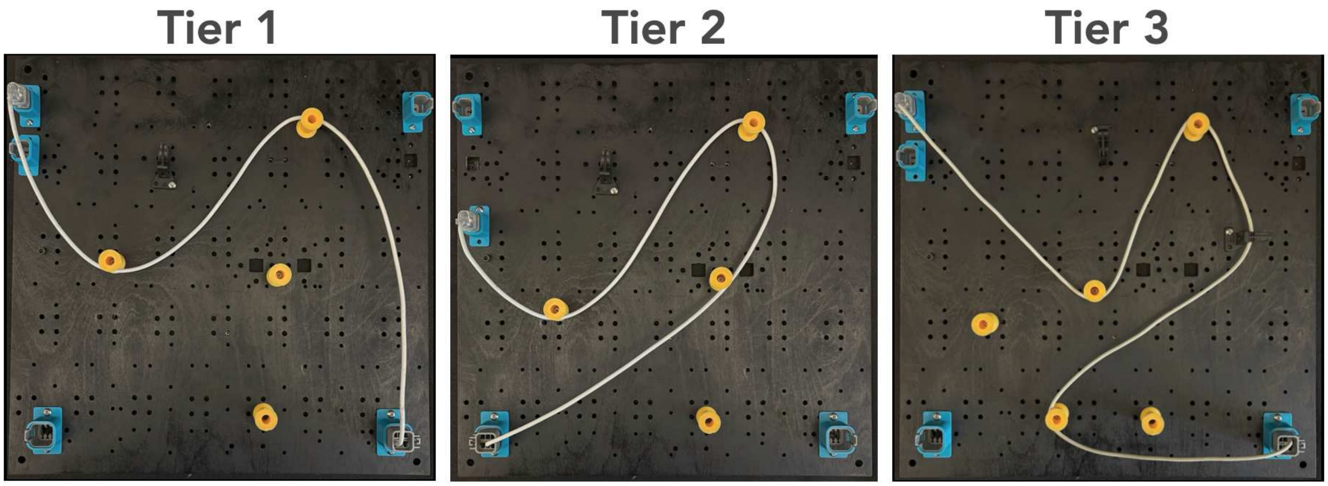

Fig. 6: Examples of solved configurations for each tier, demonstrating increasing complexity with more fixtures and greater directional changes. Once the robot completes the routing, the user manually inserts the cable tip into the socket.

the correct path to follow for every fixture in the routing configuration, $f_i \in \mathcal{C}$, we define a set of candidate waypoints, representing possible entry and exit directions relative to the fixture's position. Specifically, these waypoints are offset by a constant distance from the fixture center pose at angles of $0°, 90°, 180°$, and $270°$. To determine a suitable waypoint sequence, we compute direction vectors between consecutive fixtures. Let $\mathbf{d}_{\text{prev}}$ be the direction from the previous fixture to f_i, and $\mathbf{d}_{\text{next}}$ be the direction from f_i to the next fixture. We obtain a resultant direction vector: $\mathbf{r} = \mathbf{d}_{\text{prev}} + \mathbf{d}_{\text{next}}$. The intermediate waypoint for f_i is selected based on the dominant component of $\mathbf{r}$, ensuring that the cable follows a natural routing direction. The cross product $\mathbf{d}_{\text{prev}} \times \mathbf{d}_{\text{next}}$ confirms that the cable will follow a clockwise or counterclockwise motion around the fixture.

Once the waypoint sequence is established, we use the A* algorithm [17] to generate a collision-free trajectory for the gripper between consecutive waypoints. Given an initial cable state C_0, A* searches for a feasible path in the workspace while avoiding intersections with other fixtures.

D. Slack Management and Sliding Motion

Effective cable slack management is required to ensure sufficient cable tension, avoid tangling, and ensure stable cable placement, reducing the risk of damage or operational failures [18]. Single-arm manipulation may struggle with complex routing constraints due to its inability to simultaneously control slack and guide the cable, whereas bi-manual strategies can enable coordinated movements and constraint-aware adjustments [2]. Building on this, we implement a bi-manual sliding motion strategy while caging the cable, where robot gripper g_1 slides tangentially along the planned path while gripper g_2 dynamically adjusts to manage slack. Instead of using tactile sensing, we introduce a caging gripper with a toothed base to retain the cable and a perpendicular cross-beam to constrain vertical movement (Figure 4). This design enables controlled sliding through fixtures without the need for active force control or tactile sensing. By varying the width of the gripper jaws, the end effector can switch between pinching (while initially grasping the cable) 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, as illustrated in Figure 5.

E. Cable Routing

Given the desired routing configuration $\mathcal{C}$, MOTORCYCLE selects which gripper will slide and which gripper will manage the slack. First, the system receives an image observation $\mathbf{I}_t$ and uses HANDLOOM to extract a partial cable trace starting from the known connector endpoint. Once the cable trace is partially established, the system selects the grasping positions for the robotic arms, where the first gripper grasps the cable near the connector endpoint while avoiding collisions, and the second gripper is positioned at a predefined distance along the traced cable. Next, the system computes a feasible routing sequence through the designated fixtures following the pipeline introduced in Section D.

IV. 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 (Figure 7). Note that only RGB

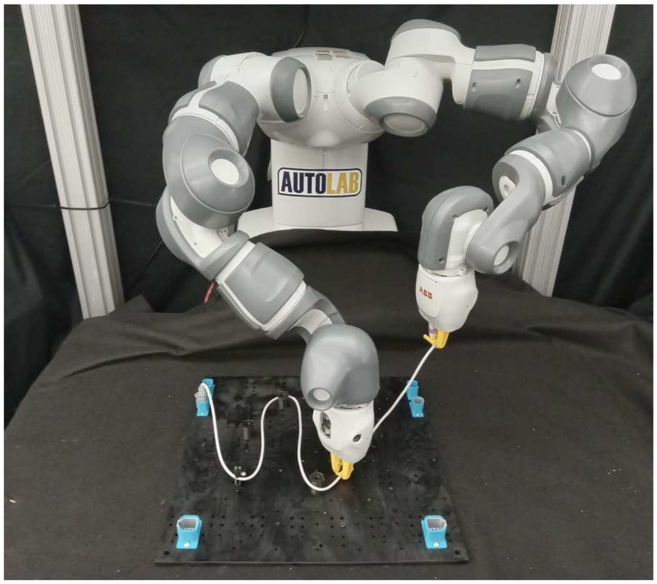

Fig. 7: The experimental setup consists of a bi-manual ABB YuMi robot equipped with caging grippers, an overhead RGB camera positioned 1 meter above the workspace, a modified NIST Task Board 4 with multiple fixtures, and a single cable used for routing experiments across different configurations.

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 %

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. Figure 6 illustrates a solved example from each tier.

- **Tier 1**: A simple routing scenario with three fixtures, involving minimal directional changes.
- **Tier 2**: Increased complexity with four fixtures, requiring sharper directional changes. This setup demands more precise cable placement while primarily maintaining a forward routing direction.
- **Tier 3**: The most challenging scenario, involving five fixtures, multiple intersections, and significant directional shifts. The routing path includes substantial reversals in direction, necessitating careful slack management and adaptive routing strategies.

For each tier, we randomly sampled four board configurations, each designed to match the tier's difficulty level and goal routing setup. The cable's initial position was randomized while ensuring sufficient space for both arms to grasp it. 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, resulting in 120 experiments overall.

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.

V. LIMITATIONS

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. Variations in thickness, elasticity, or reflectance may affect heatmap predictions. Furthermore, the monocular overhead camera restricts depth perception, making it difficult to detect slightly elevated cables, which can lead to initial grasping errors.

VI. FUTURE WORK

In future work, we will integrate real-time feedback to adjust grasping points and dynamically modify sliding trajectories, improving robustness in complex scenarios. Another key direction we plan to explore is refining arm coordination. Implementing adaptive role-switching between arms based on cable slack, fixture constraints, and grasping stability could also enhance efficiency, especially in high-curvature regions where precise slack management is essential. Furthermore, extending the method to accommodate a wider range of cable properties, such as varying thickness, stiffness, and material compliance, would improve generalizability. Training policies on diverse cables and integrating adaptive grasping strategies could enable more reliable manipulation in real-world applications.

VII. Acknowledgements

This research was performed at the AUTOLAB at UC Berkeley in affiliation with the Berkeley AI Research (BAIR) Lab.

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