Generalizable Whole-Body Global Manipulation of Deformable Linear Objects by Dual-Arm Robot in 3-D Constrained Environments

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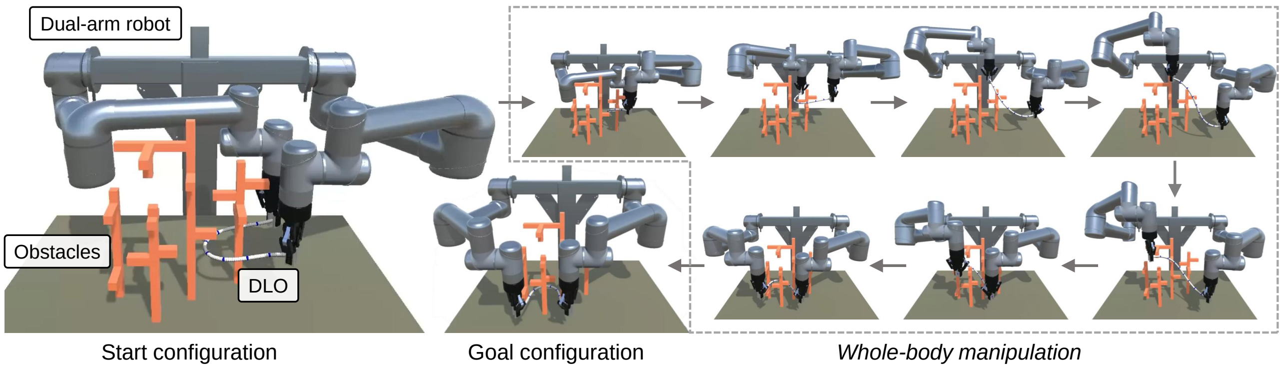

Fig. 1. Illustration of the task: whole-body global manipulation of DLOs by a dual-arm robot in 3-D constrained environments. Given the environment and goal configuration, the proposed approach achieves collision-free moving and shaping of the DLO from start to goal configuration, during which the whole body of the DLO and robot is considered.

***Abstract*— Constrained environments are common in practical applications of manipulating deformable linear objects (DLOs). This task is high-dimensional and highly constrained owing to the highly deformable DLOs, dual-arm robots with high degrees of freedom, and 3-D complex environments. Furthermore, accurate DLO models needed by planning are often unavailable, resulting in unreliable planned paths. This article focuses on the global moving and shaping of DLOs in constrained environments by dual-arm robots. The main objectives are 1) to efficiently and accurately accomplish this task, and 2) to achieve generalizable and robust manipulation of various DLOs. To this end, we propose a complementary framework with whole-body planning and control using appropriate DLO model representations. Experiments demonstrate that our framework can accomplish considerably more complicated tasks than existing works, with significantly higher efficiency, generalizability, and reliability. The full paper and video are available on https://mingrui-yu.github.io/DLO_planning_2.**

I. Introduction

Deformable linear objects (DLOs), such as cables, wires, ropes, and rods, are prevalent in various everyday scenarios [1]. Many research works have been devoted to robotic manipulation of DLOs [2], [3], but most of them are designed for unobstructed environments without other objects [4]–[13]. This article focuses on DLO manipulation in constrained environments. Figure 1 illustrates an example of the manipulation task considered in this article, which constitutes a general problem in DLO manipulation, i.e., the task of a dual-arm robot manipulating a DLO from a start configuration to a desired (goal) configuration in a complex constrained environment with non-convex obstacles. This task involves both moving and shaping of the DLO by the robot, necessitating both accurate final manipulation results and collision-free moving paths for the DLO and robot body.

This task is high-dimensional and highly constrained owing to the deformable nature of DLOs, high degrees of freedom (DoFs) of dual-arm robots, 3-D complex environment, underactuated nature of the system, and requirement of long-distance movements. Consequently, global planning becomes indispensable but also extremely challenging. Some previous works have tried this task by offline planning and open-loop executions. The most critical issue is that it is difficult to obtain accurate DLO models needed by planning in practical applications, given the significant diversity and nonlinearity of DLOs. Thus, directly executing planned paths may fail owing to the inevitable DLO modeling errors. However, most works assumed the acquisition of sufficiently accurate DLO models either through analytical modeling [14]–[18] or learning from pre-collected data [19], taking no account of adaptability to new DLOs. Furthermore, previous works usually simplified the challenging planning problem or only partially addressed it, for example, by regarding the end-effectors as floating grippers without considering arm bodies [14]–[17], relying on time-consuming physical engines [17] or pre-built roadmaps [18], or over-simplifying the representations of DLOs [20].

This article proposes a novel framework for global whole-body collision-free manipulation of DLOs in constrained environments. We aim to address two key questions:

1) How to both efficiently and accurately accomplish this high-dimensional task subject to multiple constraints, such as the stable deformation, overstretch prevention, closed-chain movements, and collision avoidance?
2) How to enhance the robustness and generalizability of the proposed approach to various real-world DLOs for which accurate models are difficult to obtain?

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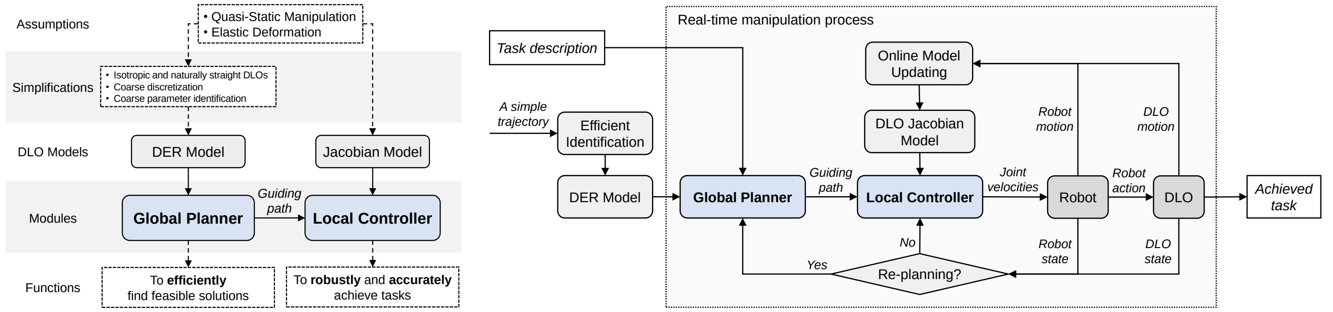

(a) (b)

Fig. 2. Overview of the framework. (a) Relationships between the global planner, local controller, and their corresponding DLO models in the proposed complementary framework. (b) The proposed manipulation framework with whole-body global planning and closed-loop executions.

Our solution is a complementary framework that integrates whole-body global planning and local control (see Fig. 2): the former efficiently finds feasible (but imperfect) solutions and the latter improves the robustness and accuracy of manipulations. The contributions are highlighted as follows:

1) We establish an efficient path planning algorithm for global collision-free manipulation of DLOs by dual-arm robots, which considers the full state space of both the DLO and arms and guarantees the satisfaction of all necessary constraints.
2) We implement an MPC for smoothly tracking DLO and robot paths, which includes hard constraints for local obstacle avoidance and overstretch prevention in general 3-D environments.
3) We propose a complementary framework combining global planning and local control, in which the planner relies on a simplified DLO model to efficiently find feasible solutions, and the controller uses real-time feedback to closed-loop compensate for planning errors during tracking. It achieves robust, accurate, and collision-free manipulation of various DLOs in complex constrained environments.

We carry out exhaustive simulations and real-world experiments to demonstrate that our framework can effectively address the open challenges in dual-arm manipulation of DLOs in constrained environments, such as those pertaining to high dimensionality, multiple constraints, long-distance movements, and generalization on various DLOs. To the best of our knowledge, this study is the first successful attempt at achieving whole-body collision-free manipulation of various types of DLOs in real-world 3-D constrained environments. The proposed approach achieves a 100% planning success rate among thousands of trials with an average time cost of less than 15 second (such as the simulated task in Fig. 1), and a 100% manipulation success rate among 135 real-world 3-D tests on five DLOs of different properties with an average execution time of less than 1 minute.

This work is an extension of our previous work [21]. The improvements include: 1) employing a new DLO energy model, the discrete elastic rod model, to account for twist energy and gravity effects; 2) further optimizing the planning algorithm to improve the success rate, efficiency, and path quality; 3) extending the controller to a long-horizon MPC with hard constraints for obstacle avoidance; and 4) conducting more comprehensive simulation studies and 3-D real-world experiments.

II. Overview of the Framework

In this section, we briefly overview the proposed framework. Please refer to the **full paper** for the details. Our core concept is to use a moderately coarse DLO model to plan a path that closely approximates real-world conditions without significantly increasing the time cost. Subsequently, we use closed-loop control with an adaptive DLO motion model to compensate for the residual modeling errors.

Global planning: During the planning phase, we consider all constraints of configurations based on the assumed DLO model, including the stable DLO configuration constraint, closed-chain constraint, and collision-free constraint. We use a rapidly-exploring random tree (RRT) framework for this high-dimensional planning problem, in which we use projection and rejection methods to ensure all constraints are satisfied. We employ the discrete elastic rod (DER) model [22] for planning rather than data-driven forward predictive models of DLOs, such as [19], since the latter may suffer from accumulated errors. To generalize to various types of DLOs, we use a simplified model that assumes naturally straight and isotropic DLOs in planning. Such a model involves only three scalar parameters, and we design an efficient strategy to coarsely identify them through a simple trajectory. This simplification also helps improve the planning efficiency.

Local control: During the planning phase, the following simplifications are made in exchange for realizability and high efficiency: 1) we use a simplified DER model for isotropic and naturally straight DLOs; 2) the discretization of the DLO is coarse; and 3) the identification of the model parameters is coarse. Thus, if the planned robot path is directly executed in an open-loop manner, the DLO may not move exactly as expected, potentially failing to reach the goal configuration owing to collisions or deviations. Consequently, we use closed-loop control to compensate for the residual modeling errors and achieve robust and accurate manipulation. We apply our previously proposed DLO Jacobian model [23] for control. This data-driven model only assumes the elasticity of the DLO and quasi-static manipulation, so the controller is more general and locally precise compared with

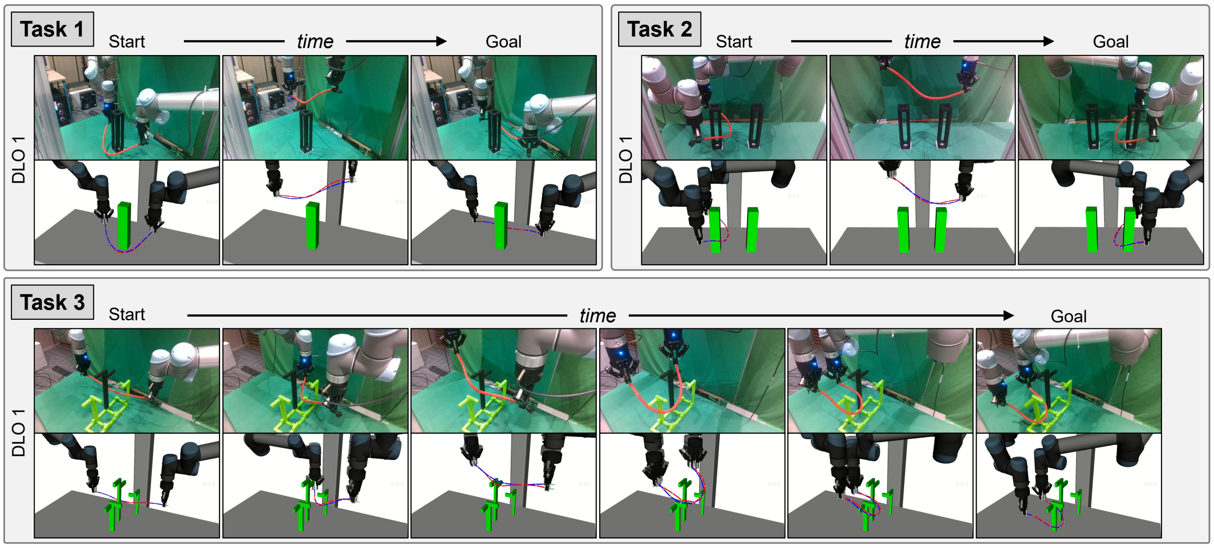

Fig. 3. Task 1, 2, 3 in the real-world experiments, and corresponding manipulation processes using the proposed method. For each task, the pictures in the second row are visualizations by the Rviz, in which the blue lines and translucent robots indicate the planned waypoints, and the red lines and non-translucent robots indicate the real-time configurations. We test on five different DLOs. Here we only show the tests for DLO 1.

TABLE I

PERFORMANCE OF THE PROPOSED MANIPULATION METHOD IN THE REAL-WORLD EXPERIMENTS.

Task	Planning time (s)	Manipulation mode	Success rate	Final task error (mm)	Collision time (s)	Execution time (s)
1	0.90 $\pm$ 0.83	Open-loop	43/45	16.15 $\pm$ 9.68	0.51 $\pm$ 0.78	41.31 $\pm$ 2.85
		Closed-loop	45/45	9.44 $\pm$ 5.03	0.0 $\pm$ 0.0	
2	0.83 $\pm$ 0.46	Open-loop	45/45	21.77 $\pm$ 10.06	1.58 $\pm$ 4.18	42.79 $\pm$ 4.41
		Closed-loop	45/45	10.38 $\pm$ 4.34	0.0 $\pm$ 0.0	
3	3.82 $\pm$ 3.04	Open-loop	39/45	14.46 $\pm$ 8.07	2.22 $\pm$ 2.31	53.12 $\pm$ 6.07
		Closed-loop	45/45	9.52 $\pm$ 4.45	0.004 $\pm$ 0.029	

the planner. The complementary relationship between the planner and controller is illustrated in Fig. 2(a). We formulate the controller as an MPC with hard collision constraints to track the planned path as guidance and locally avoid obstacles. Other constraints, such as the overstretch and robot DoFs constraints, can also be easily incorporated. The overall manipulation process is illustrated in Fig. 2(b).

III. RESULTS

We conduct simulations and real-world experiments to demonstrate that our method can efficiently, robustly, and accurately accomplish tasks that the existing works cannot realize. Please refer to the **full paper** for all results.

Simulation: We design four tasks with different obstacles, start/goal configurations, and DLO properties for exhaustive quantitative testing. The results demonstrate that 1) our global planner is highly robust, as the planning success rate is 100% for all 800 trials; 2) the planner is highly efficient, as the average time for finding a feasible path is about 1 to 3 s for Tasks 1 to 3 and about 10 s for the challenging Task 4. 3) our method can robustly and precisely accomplish such global manipulation tasks, as all 400 tests are successful and the final task errors are less than 0.5 mm; 4) our method can effectively avoid collision when using imprecise DLO models, as collision is minimal with an average collision time of less than 0.05 s; and 5) the replanning module is invoked only once among all 400 tests.

Real-world experiments: We test on five different DLOs with lengths ranging from 0.32 m to 0.72 m, diameters ranging from 7 mm to 11 mm, and material stiffnesses ranging from stiff (TPU elastic) to soft (hemp rope). Before manipulation, the DER parameters of the DLOs are coarsely identified. We design three 3-D tasks for evaluation, as shown in Fig. 3. The results are summarized in Table I, which indicate that 1) the planning is efficient, as the average time for finding a feasible path is only 3.82 s in the most challenging Task 3; 2) the proposed closed-loop manipulation framework is robust, as the manipulation success rate of the closed-loop manner is 135/135, while that of the open-loop manner is 127/135; 3) the closed-loop manner improves the final task precision (reducing the average error over the three tasks from 17.46 to 9.78 mm), as the real DLOs exhibit elastoplastic deformation during manipulations and may not reach exactly the same configuration between different open-loop executions; 4) the closed-loop manner effectively avoids unexpected collisions, as collision occurs only once (0.2 s) during all closed-loop manipulations, while the average collision time of open-loop manipulations in Task 3 is 2.22 s. Additionally, no replanning is invoked in any of the manipulations. The average execution time of Task 3 is 53.12 s.

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