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Dual-Armed Manipulation Planning for Tethered Tools

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Abstract— **The present paper details our manipulation planning-based approach to tethered tool manipulation for dual-armed robots. Our approach is aimed at preventing entanglements and cable collisions during tethered tool manipulation tasks that require tool re-grasping and handover. Our framework implements constraints and bi-manual simultaneous tool-cable manipulation to avoid excess bending and cable collisions. Simulations and real-world experiments help validate our approaches.**

I. INTRODUCTION

The ever increasing implementation of robots in industrial settings is aimed at increasing productivity and safety, reducing costs and achieving performing tasks with superior precision and efficiency, when compared to human workers. Robots have also led to a decrease in required human workforce to complete certain industrial tasks. An often overlooked challenge and shortcoming in robotics and robotic manipulation planning is the manipulation of elastic and deformable objects such as cables and ropes. In particular, the behaviour of cables is difficult to predict, and they can cause the failure of a motion planning task, especially when a tool cable gets entangled around the robot or an element of its workspace.

Several strategies have been proposed to solve cable manipulation problems. For example, a study on quasi-static manipulation of a planar kinematic chain is presented in [1]. A control solution, for the manipulation of a fire hose, was shown in [2]. A planner for manipulation of interlinked deformable linear objects for aircraft assembly was shown in [3]. A planning method for knotting/unknotting of deformable linear objects [4], and a motion planner to manipulate deformable linear objects is described in [5].

However, said work do not address the problem of maneuvering both, a tool and its cable simultaneously. In this paper, we present a motion planning framework for tethered tool manipulation based on our previous research on object manipulation [6]. Our approach is characterized by three key aspects:

1) Our motion planner deals with a tool and its cable during manipulation tasks. The focus of the manipulation task is placed on completing a task using a given tool. The cable is treated as a dynamic obstacle that changes shapes/state according to the tool position, the location of the cable source, and the history of previous cable states.

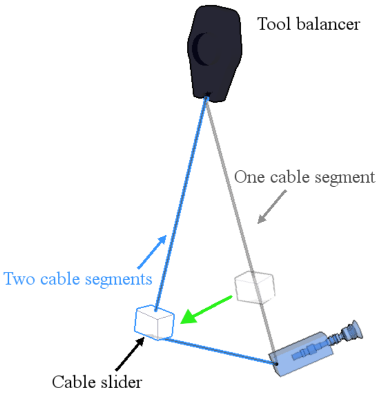

Fig. 1. The tension induced by the tool balancer straightens the tool cable to a straight line segment connecting a tool to the balancer, which facilitates cable shape and trajectory prediction during motion planning. The addition of a cable slider (used in our second approach) adds a control point for the robot to grasp and pull the cable, which can be represented by two straight lines that connect the balancer to the slider and the slider to the tool. We make use of both, cable straightening and a cable slider in our proposed methods.

2) Our framework seeks to simplify a tool cable behaviour by directly controlling its state. Cable state control is done by both, by making the robot grasp and pull the cable to modify its state with the help of a cable slider tool, shown in Fig. 1, and the use of a tool balancer mechanism to control cable tension, as shown in Fig. 1 and 2. The simplified cable behaviour is easy to predict during motion planning.
3) The simplified cable behaviour allows for the implementation of collision constraints that prevent the tool cable from getting entangled. Furthermore, our framework limits maximum expected bending of the tool cable, potentially reducing stress on the cable.

Especially, we present two distinct approaches to tethered tool manipulation: a constraints-based approach that limits the robot actions, based on the cable expected behaviour, to avoid cable collisions and entanglements, and a bi-manual tool-cable manipulation planning approach that generates a motion sequence to control both the tool and the cable motions during manipulation. Both approaches use the aid of a mechanical tool, a tool balancer, to simplify the tool cable shape and predict its movement during manipulation.

II. CABLE STATE PREDICTION

Our approach for tethered tool manipulation uses cable tension to simplify the tool cable shape. To maintain a constant tension on the tool cable, we make use of a tool balancer, shown in Fig. 2. The tension provided by the balancer, helps straighten the tool cable, which can then

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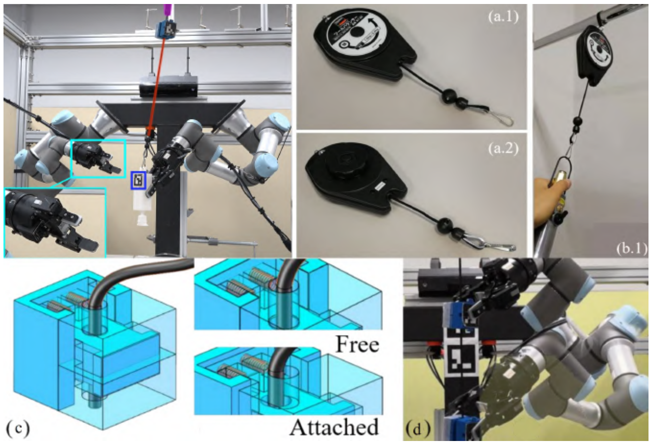

Fig. 2. (**Upper Left**) The robot workspace. Our robot consists of two UR3 robotic arms attached to a metal frame; the robot uses its hand-mounted cameras (light blue) to detect the position of a 3D printed tool. The tool possesses an AR marker (blue square) for pose detection. The tool is suspended by a tool balancer (purple). ((**a.1-2**)) Front and back view of a tool balancer. (**b.1**) The cable of the tool balancer presents a constant pulling force that simplifies the cable deformation into a straight line. ((**c**)) The cable slider model. (c-Free) The slider in its free state. When the robot gripper grasps the slider, the gripper overcomes the spring forces and pushes the two slider internal circular holes to a concentric state, allowing for the free movement of the cable through both holes. (c-Attach) The slider in its attached state. When it is not being manipulated, its internal springs apply a constant force, constraining the cable. (**d**) The robot manipulating the slider in its free state.

be approximated as a straight line connecting the tool to a cable source point (the balancer). Since the tool balancer remains fixed in the robot workspace, the cable shape is usually determined by the tool pose. Hand-mounted cameras are used to detect the tool the initial pose of the tool before grasping it and our planner predicts the future states of the tool cable, based on the planned tool movement.

For our tool-cable manipulation planning approach, we introduce a cable slider to the tool-cable-balancer system. The cable slider is a 3D-printed tool for cable manipulation. The slider adds an additional point of control for the cable, which can now be divided into two straight segments, one connecting the tool to the slider and other connecting the slider to the cable source point. By controlling the slider pose, our robot directly modifies the cable shape and trajectory to evade collisions. Fig. 1 shows how the cable tension and the slider can be used to simplify the cable shape.

III. CONSTRAINTS-BASED TETHERED PLANNING

Our constraints-based approach [7], [8] uses a constrained manipulation planner for dual-armed tethered tool manipulation. The planner predicts the simplified cable states during manipulation and restricts the robot motions in order to avoid cable entanglements and collisions while performing tool re-posing tasks. The planner is capable of performing tool re-posing by using handover-based regrasping, making use of both of our robot arms.

To address cable entanglements, we use a method to predict the magnitude of cable "snarling" or cable angle accumulation around a robot arm during simulation [8]. By measuring the angle accumulation of every robot state during the planning stage and preventing the accumulation from surpassing a given threshold, it is possible to create entanglement-free motion sequences for tool manipulation.

The concept of angle accumulation, described in [8], represents the degree of rotation or movement of the tool cable around the robot arm. For simplicity, our planner uses polar coordinates in the tool reference frame to quantify the movement of the cable. The angle accumulation is measured by computing the azimuthal and polar rotations of the cable within an "accumulation region". The accumulation region is determined by the polar angle used by the robot hand to grasp the tool ϕ_H and the azimuthal positioning of the robot hand, as shown in Fig. 3.

Our planner measures the angle accumulation of every robot state during motion planning. If a certain robot or tool pose is found to surpass a user-given angle accumulation threshold, the planner uses RRT exploration to generate an alternative path for the robot.

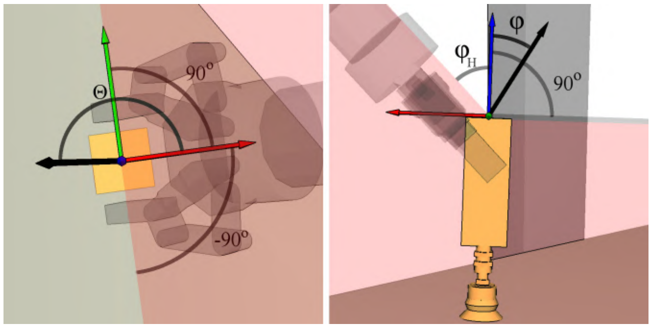

Fig. 3. Sideways views of the robot holding a tethered tool in simulation. The tool reference frame, represented by the red, green and blue arrows (x, y and z axes in the tool reference frame) are used to measure the polar and azimuthal angles of the cable, represented by ϕ and Θ respectively. The grasp used by the robot determines the entanglement region (in red): the orientation with which the robot holds the tool ϕ_H (right image) and the octants in which the hand is located (left image) define the region. If the cable vector (black arrow) crosses the entanglement (red) region, the planner counts how much the cable rotates in said region. The total rotation is called angle accumulation.

The Fig. 4 shows a comparison between our approach and a regular state-of-the-art motion planner shows how the angle accumulation constraints help the robot avoid entanglements caused by a tool cable. By using RRT exploration and setting a maximum threshold for angle accumulation, our planner creates an alternative path for the robot to avoid cable entanglement. More experiment results and metrics to evaluate the stress of the cable on the robot using out method can be found in [8].

IV. CABLE MANEUVERING-BASED PLANNING

The inclusion of angle accumulation constraints can limit the amount of feasible manipulation tasks. In cases where

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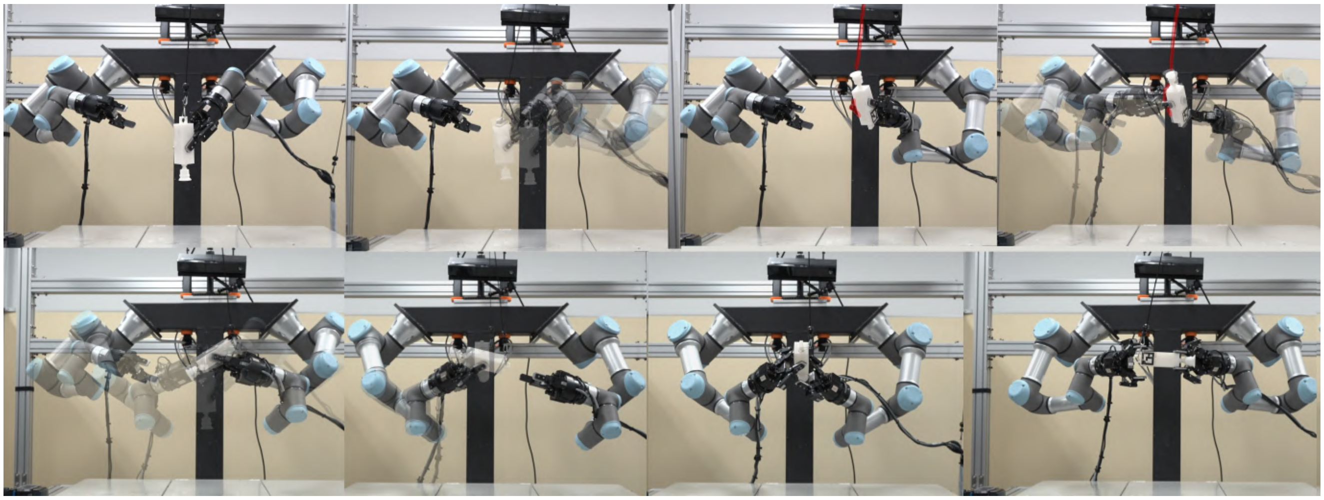

Fig. 4. Comparison between the constrained and unconstrained planner. The upper motion sequence, computed with the unconstrained planner, shows the robot getting entangled with the tool cable (red), making it fail the manipulation task. The lower sequence, computed by our proposed planner, shows the robot taking an alternative motion path to preserve angle accumulation and cable bending below the given thresholds. The result is a complete motion sequence without entanglement-related accidents or excess cable bending.

handover-based regrasping is not necessary to complete a tool manipulation task, it can be more advantageous for our dual-armed robot to perform regular manipulation planning to handle a tool using one robot arm and then use its free robot arm to handle the tool cable and avoid collisions.

In said cases, our framework also presents a solution for tethered tool manipulation which involves cable maneuvering [9]. Robot cable maneuvering is accomplished by making the robot pull the tool cable with its non-tool holding arm. The robot uses the cable slider shown in Fig. 5 to place the tool cable in pre-planned positions. The Figure also shows how the tool cable shape is determined by the positions of the tool, the cable slider, and the tool balancer. The tool balancer position is constant throughout the manipulation task, it is fixed on the robot workspace. The tool balancer position is placed between both robot arms to maximize the manipulability at the tool and the cable slider positions. Our planner generates motion seuqences to control both, the tool and the cable slider to move the cable.

Essentially, the planner generates a two motion sequences to complete the tool manipulation task. The first motion sequence, the Object Manipulation Motion Sequence (OMMS), uses one of the robot arms to grasp and handle the tethered tool. The second motion sequence, the Cable Manipulation Motion Sequence (CMMS), makes the robot use its free hand to grasp the cable slider and pull the tool cable to a position located directly behind the tool. Each tool slider goal position during the manipulation task is directly defined by the corresponding tool pose. By pulling the cable slider, the robot directly controls and modifies the cable shape. Collision avoidance during the simulation stage is used to avoid collisions and entanglements between the modified cable shape and its environment.

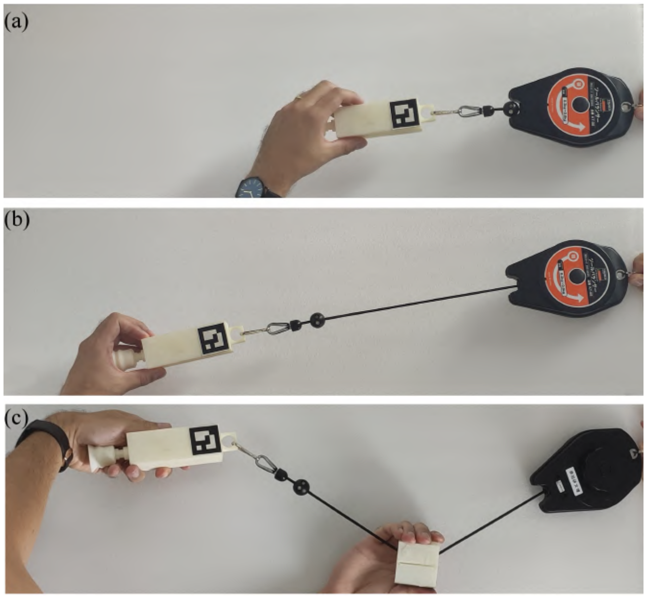

Fig. 5. (a) The tool balancer provides a cable with tension that retracts when it is not being pulled. (b) The tension on the cable straightens it. The straight cable shape is approximated as a straight line in our planner, which eases collision avoidance. (c) The addition of a cable slider (white cube with a through hole) represents a control of grasping point for the cable. The robot pulls the slider to control and modify the cable shape during manipulation.

Real-world experiments for our cable maneuvering approach not only test the planner using the aforementioned tool balancer, but also explored the possibility of using the cable slider to control other type of cables and make the robot modify the cable trajectory, avoiding obstacles and accidents. Fig. 6 shows some experimental results.

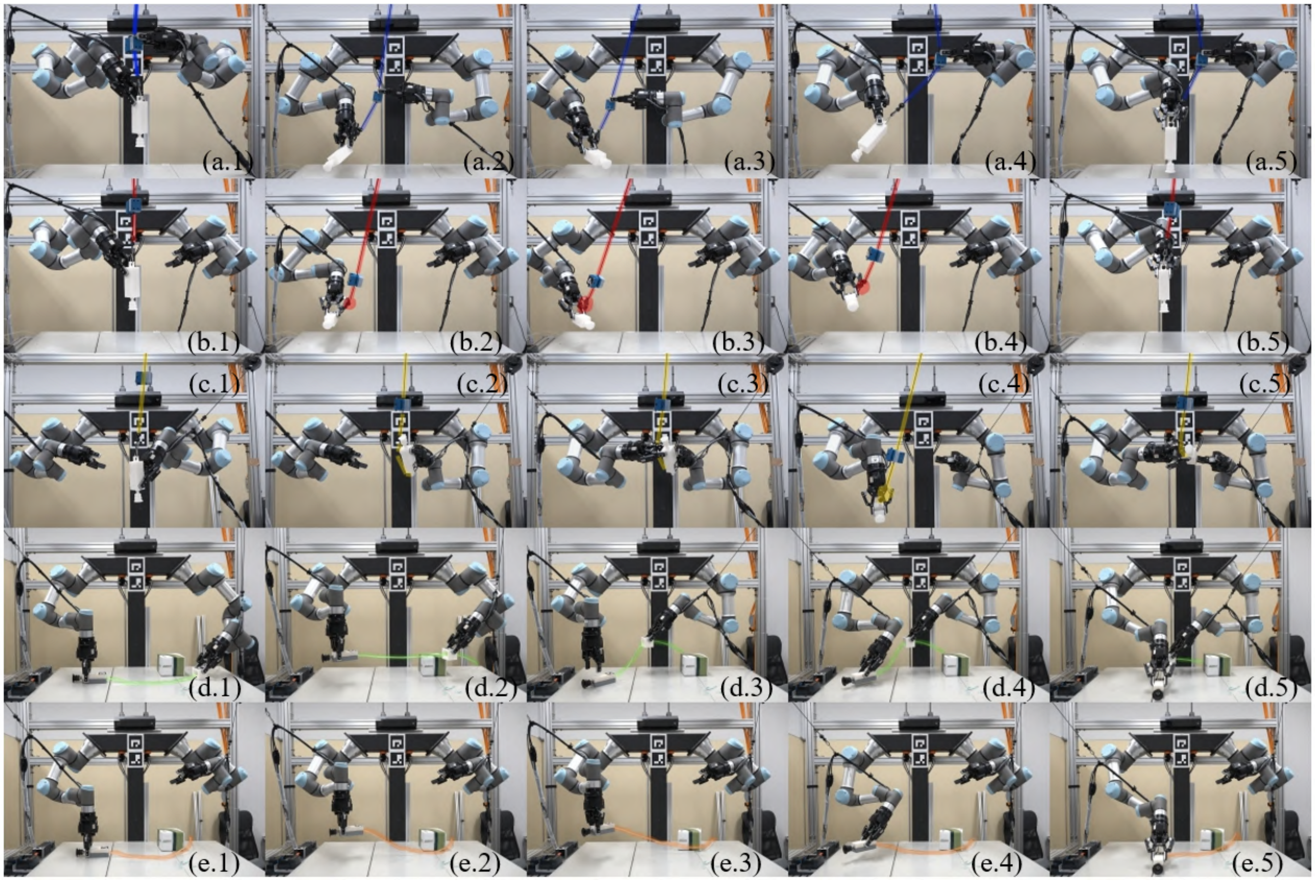

Fig. 6. Real-world implementations. The first row shows the OMMS+CMMS motion sequences – The robot completes its task with cable maneuvering. The second row shows the OMMS-only sequence, from the second to the fourth image we can observe the excess bending on the cable. The third row shows a part of the planner solution involving handover. In this case, the cable gets snarled around the robot end-effector when the robot performs the handover motion. Rows four and five show the OMMS+CMMS and OMMS-only solutions respectively. In the OMMS+CMMS solution, the robot successfully maneuvers the cable and avoids the obstacle by lifting it above the box. The OMMS-only solution, on the other hand, does not consider the box or the cable and results in a cable-box collision.

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