Tactile based robotic skills for cable routing operations

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Tactile based robotic skills for cable routing operations

Andrea Monguzzi[1], Martina Pelosi[1], Andrea Maria Zanchettin[1], Paolo Rocco[1]

***Abstract*— This paper proposes a set of tactile based skills to perform robotic cable routing operations for deformable linear objects (DLOs) characterized by considerable stiffness and constrained at both ends. In particular, tactile data are exploited to reconstruct the shape of the grasped portion of the DLO and to estimate the future local one. This information is exploited to obtain a grasping configuration aligned to the local shape of the DLO, starting from a rough initial grasping pose, and to follow the DLO's contour in the three-dimensional space. Taking into account the distance travelled along the arc length of the DLO, the robot can detect the cable segments that must be firmly grasped and inserted in intermediate clips, continuing then to slide along the contour until the next DLO's portion, that has to be clipped, is reached. The proposed skills are experimentally validated with an industrial robot on different DLOs in several configurations and on a cable routing use case.**

I. INTRODUCTION

Deformable linear objects (DLOs) are elements such as cables, tubes, wires, and ropes having one dimension, the length, substantially bigger than the other two and can be clustered in two groups based on their mechanical properties, [1]. The first one comprises objects that do not exhibit compression strength (e.g. ropes), while the second one contains elements that present large strain when manipulated, including DLOs typically involved in industrial tasks (e.g. the oil hose of a braking system). DLOs manipulation is widespread in several tasks, both industrial and not, as specified in [1], [2]. In particular, in fields like automotive and aerospace, DLOs are involved in several applications, such as wiring and wire harness assembly. However, DLOs manipulation is often the bottleneck of such applications due to the issues in automating this task, as explained in [3]. Robotic manipulation of DLOs remains indeed an open challenge characterized by highly non-linear dynamics, non-trivial state representations, and deformation sensing.

In this work, we propose a set of tactile based robotic skills (see [4]) to perform cable routing operations for DLOs characterized by large strain during the manipulation and constrained at both ends as shown in Figure 1, in a framework that could be extended to wire harness assembly operations, [5]. In particular, we define a strategy to first align the gripper to the local shape of the DLO, roughly known, grasp it and then follow its contour in the 3D space. In doing this, the robot keeps track of the travelled distance along the DLO to identify and insert predefined portions of cable in intermediate clips, whose poses are known.

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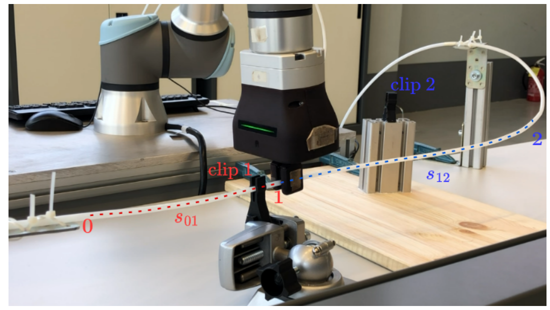


Fig. 1: Setup with a DLO constrained at both ends. Two intermediate clips are highlighted together with the corresponding distances (s_{01}, s_{12}) along the arc length of the DLO, identifying the portions of cable (1 and 2) that have to be clipped. 0 corresponds to the initial grasping point.

DLO contour following is challenging as the cable's shape varies dynamically while the robot is following its profile. The proposed skills rely on tactile sensors (see Figure 2a) mounted on the fingertips of the gripper. Tactile perception allows indeed to reconstruct the local shape of the grasped DLO and to compute an estimate of the future local shape: this information can be exploited to manipulate the DLO without the need to estimate its entire shape. Moreover, we avoid specialized end effectors as we use a parallel pneumatic gripper (see Figure 2b) equipped with proportional regulators and an encoder, allowing to control the fingers opening and closure in position. The remainder of this work is organised as follows. Section II contains a review of relevant state-of-the-art methods and emphasises the main contributions of our work. Sections III and IV contain respectively details on the used tactile sensor and on the formalization of the skills. The experimental validation of the skills applied to different DLOs in several configurations is discussed in Section V, together with the analysis of the performed cable routing operation. Finally, Section VI draws the conclusions.

II. RELATED WORKS AND CONTRIBUTIONS

As detailed in [6], several kinds of tactile sensors have been developed based on different technologies such as optical [7], piezoelectric [8], capacitive [9], and optoelectronic [10] technologies. The tactile sensors presented in [10] are used to estimate the local shape of the grasped DLO, approximating it with a linear, [11], or a quadratic function, [12]. [11] and [13] propose a strategy to insert the final part of an electric wire, assuming that the robot grasps the DLO at a predefined distance from its end. In both works, tactile data are exploited to estimate the wire shape and to re-orient the gripper to accomplish the insertion. The authors of [14] estimate the grasping pose of the wire thanks to a vision algorithm and perform the insertion by combining data from tactile and vision sensors. To execute an operation involving a DLO, it is often assumed that the DLO is grasped in a predefined pose or that a vision sensor is exploited to determine the grasping pose. DLO contour following can represent a strategy to avoid the use of vision sensors and relax the assumption of grasping the DLO in a known point, allowing to trace its contour and reach one end, starting from the other one. In the literature, few works deal with DLO contour following. [15] deals with the task of closing a ziplock bag using reinforcement learning and exploiting data from tactile sensors. The learned policy is also tested on wires and ropes, experiencing, however, loss of contact. [16] addresses the contour following problem exploiting a specialized gripper with four rollers in the jaws. In particular, contour following is performed based on force measures during the sliding motion. This methodology is suitable for cables with large diameters and stiffness. However it needs a complex gripper and it would be difficult to generalize for smaller and less stiff DLOs. The most similar work to ours is the one presented in [17], where authors deal with the problem of manipulating a free moving cable. In particular, the authors consider a setup where a fixed gripper holds the DLO from one end in a predefined pose while the other gripper, mounted on the robot, follows the cable contour until the other end, aiming to detect the connector that can be then inserted. The grippers' fingertips are equipped with a vision-based optical tactile sensor [18], allowing the estimation of the cable pose and of the friction force pulling from the fingertips, that are exploited to keep the cable centered in the fingertips. However, the authors model the interaction between the DLO and the gripper as a planar pulling problem: the cable contour is hence followed in a plane. Moreover, the methodology proposed in [17] is designed to manipulate thin and not too stiff cables.

As said in Section I, cable routing is one of the most relevant operation involving DLOs. [19] proposes a vision based strategy to define the motion of a dual arm robot to grasp a DLO and perform cable routing. Notice that the methodology relies on the assumption that the manipulated DLO is characterised by a low compression strength (as a rope), being then not suitable for stiffer cables. Another strategy that exploits a vision sensor is presented in [20], that describes a method to perform routing operations of DLO with low stiffness around pegs exploiting the contact with the environment. Differently from our work, the methodology presented in [20] exploits two robotic arms with specialized end effectors and does not deal with the grasping phase. Finally, in [21], the tactile sensor presented in [10] is used to execute a cable routing operation for an electric wire with a free end. [21] proposes a methodology that generates motion trajectories according to an expected path, ensuring a proper tensioning of the cable during the operation. In contrast with the strategy proposed in our work, in the setup considered in [21], the robot begins the operation with the cable already grasped, and it does not follow its contour since the robot pulls the wire, which is characterized by a low stiffness.

With respect to the previous works, the main contributions of our methodology are the following:

1) We deal with the contour following of DLOs connected at both ends and characterized by a considerable stiffness, in contrast with the setup and kinds of DLOs addressed in [17], where the robot follows the free end cable contour in a two-dimensional plane, straightening it. Instead, our method enables to follow the cable contour in three dimensions: stiff DLOs constrained at both ends are characterized by considerable curvatures that make the shape not planar and not easily predictable. A situation where the robot has to follow the contour of a DLO characterized by low stiffness (as the one used in [17]) and constrained at both ends by two fixtures would not be scientifically relevant. Indeed, in this case, the cable shape can be approximated with a straight line connecting the two fixtures and with a slightly downwards curvature due to the gravity effect.

2) We propose skills for a grasping strategy that allows the gripper to completely align in the space (and not only planarly) to the local shape of the DLO, centering the DLO in the fingertips. The only information required is a very rough pose of the portion of DLO to be grasped.

3) Our strategy exploits capacitive tactile sensors, differently from the previously mentioned works that use optical based tactile sensors, and does not require multiple robotic arms, specialized grippers, and force or vision sensors. Vision based DLOs state estimation is indeed challenging since the shape of cables varies dynamically and can be occluded. Moreover, DLOs can be thin and made of translucent and/or reflecting material, being difficult to detect.

III. Capacitive tactile sensor

The exploited tactile sensors are based on the capacitive technology described in [9]. The sensor relies on the same working principle of a capacitor and consists of two main elements, depicted in Figure 2c, upper part. The first element is a matrix of taxels embedded into the flexible printed circuit board (FPCB), representing the lower plate of the capacitor. The second element is composed of the external skin, made of a soft dielectric layer directly in contact with the FPCB, and of a soft upper conductive layer, used as the other plate of the capacitor. The output of each taxel is a measurement of the capacitance (in fF) depending on the distance w between the layer of taxels and the external skin surface. In the undeformed condition, corresponding to the dielectric thickness w_0, each taxel outputs an almost constant value Δc_0. When an external object touches the conductive layer of the skin, the soft dielectric is deformed due to the pressure applied during the contact: the sensed capacitance Δc tends to increase as the distance between the conductive layer w is reduced (see Figure 2c, lower part). Figure 2a shows the reference frame for each fingertip positioned in

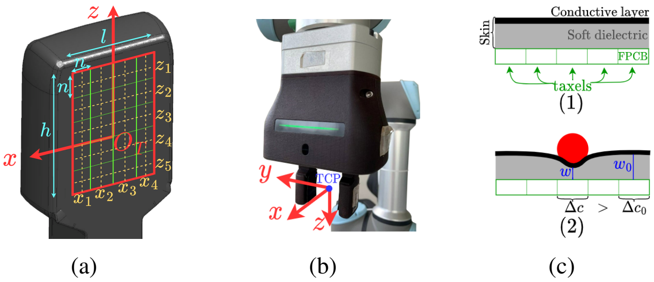


Fig. 2: (a) Scheme of a tactile sensor and reference frame of a finger. (b) UR5e robot equipped with the Camozzi Smart Gripper having a tactile sensor mounted on each fingertip. The tool reference frame is highlighted. (c) Capacitive tactile sensor structure (1) and its operating principle (2).

the middle of the finger. When the gripper fully closes, the origins O_T of the fingertips frames coincide with the tool center point (TCP) (see Figure 2b). For each finger, the taxels are arranged in a 5×4 matrix bordered in red in Figure 2a: rows and columns are separated by green lines. We carried out some analysis about the noise characterizing the taxels. In particular, the signal-to-noise ratio for each taxel has been evaluated by acquiring tactile data without any object touching the finger. The average value of the signal-to-noise ratio among all taxels is $6.8\mathrm{e}^7$ fF, while the maximum noise root mean square value among all taxels is 17.9 fF.

IV. Skills for spatial alignment for DLO grasping, contour following and cable routing

This Section contains the formalization of the skills to optimally grasp the considered DLO, follow its contour, and inserting it in N intermediate clips. The information needed to perform the cable routing operation is the initial grasping pose (a rough pose of the portion of DLO exiting from the fixture constraining one of its ends), and some details about the intermediate clips. In particular, the cable routing operation is defined by i clips, with $i \in I = \{1, \dots, N\}$, and by the distances between the DLO's portions that must be clipped, measured along the arc length of the cable. These distances are defined as s_{ab}, with $a = 0, \dots, N-1$ and $b = a+1$. Figure 1 shows a setup with two intermediate clips ($N = 2$) and the corresponding s_{ab}. The pose of each intermediate clip i and the related s_{ab} are considered known. Figure 3 shows the flowchart defined for the cable routing operation. Since a non-zero offset characterizes the sensors, it must be computed before performing any skill and subtracted from the data collected afterwards. In particular, 20 values for each taxel are acquired with the gripper fully open, and the offset for each taxel is defined as the average value of these data. The TCP is then moved to the initial grasping pose and, thanks to the *axial alignment* and the *planar alignment* skills, the fingertips are aligned to the local shape of the cable. In particular, these skills allow grasping the DLO along the x axis of the fingertips reference frame, ensuring the best starting condition to perform the *contour following* skill. The robot then wires the cable clipping it in the intermediate clips and continuing to follow its contour after each insertion.

A. DLO grasping strategy and diameter estimation

The *axial alignment* skill (flowchart in Figure 5) consists in estimating and compensating the angle β, shown in Figure 4b. The fingers, controlled in position, are closed progressively of 2.5 mm: to determine β, the two tactile sensors must touch the DLO with the two columns of taxels at opposite ends, numbered as 1 and 4 in Figure 4b. The mentioned contact between the k-th finger ($k = 1, 2$) and the DLO is reached when at least one taxel measurement, belonging to the mentioned columns, exceeds a user-defined limit value T_a: $\Delta c_{ij}^k > T_a$ for at least one $i = 1, \dots, 5$ and $j = 1, 4$, where Δc_{ij}^k is the output capacitance of the taxel at the i-th row and j-th column of the k-th finger. In this case, $\beta = \arctan(d/l)$, where d is the current distance between the fingertips and l the longitudinal size of the sensor (see Figure 2a). The mentioned configuration can be obtained only if the DLO passes through the TCP. However, it could happen that only one finger contacts the DLO with only one column, as shown in Figure 4a in green. In this case, the position of the TCP must be adjusted in the direction of the side in contact along the x axis of $l/2$ and along the y axis of $d/2$. Instead, if only the first and fourth column of a single finger contacts the DLO, the TCP is moved of $d/2$ along the y axis towards the finger in contact. After the misalignment has been estimated, a rotation of β around the z axis of the tool frame is performed if the columns in contact are the fourth on finger 1 and the first on finger 2. In the opposite case, a rotation of $-\beta$ is performed instead.
Once the *axial alignment* is completed, the shape of the DLO could present a mismatch in the $x - z$ plane of the tool frame: approximating the DLO local shape with a straight line, the misalignment is represented by the angle α, linked to the inclination angle m, and by the intercept q in the z direction (see Figure 4c). These parameters are computed exploiting the least square method, to fit with a straight line the estimated pressure centre of each column of both sensors. In particular, the fingers are entirely closed on the grasped DLO, and tactile data are acquired. The pressure centre of each sensor's column is computed if, for both fingers, at least one taxel i on each column j is in contact with the DLO: $\Delta c_{ij}^k > T_p$, where T_p is a user-defined threshold. It may happen that the grasping pose obtained after the *axial alignment* does not allow all four columns of taxels to be in contact with the DLO since it is grasped at the higher or lower end of the sensor, preventing a correct estimation of the shape. Therefore, before computing α and q, a recovery strategy is applied to adjust the TCP position, moving it upwards or downwards of n mm according to the region where the DLO is sensed (n is the taxel size, see Figure 2a). New tactile data are then acquired to estimate the shape appropriately. The pressure centres are computed as:

$$z_j^{c^k} = \frac{\sum_{i=1}^{5} z_i \Delta c_{ij}^k}{\sum_{i=1}^{5} \Delta c_{ij}^k} \tag{1}$$

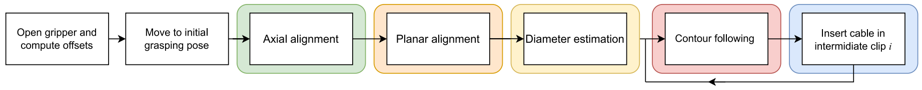
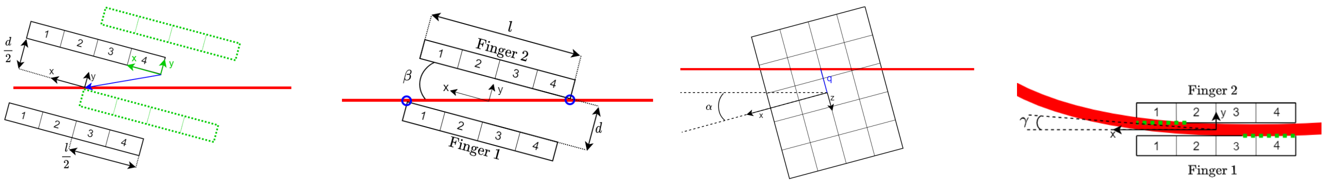


Fig. 3: Skills flowchart for the execution of the cable routing operation.



(a) Translation for *axial alignment* (b) *Axial alignment* for grasping (c) Parameters for *planar alignment* (d) Angle γ in *contour following*

Fig. 4: Schematic representations of several configurations of the DLO (in red) and the fingertips equipped with tactile sensors. The x, y and z axes reported belong to the tool reference frame.

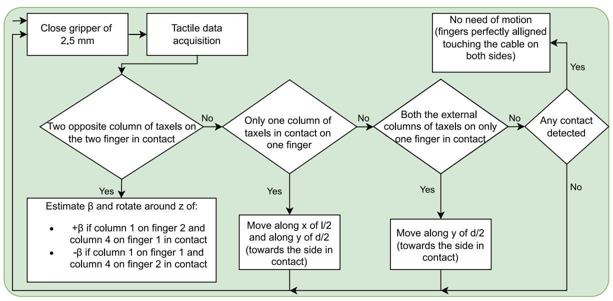


Fig. 5: Flowchart of the *axial alignment* skill.

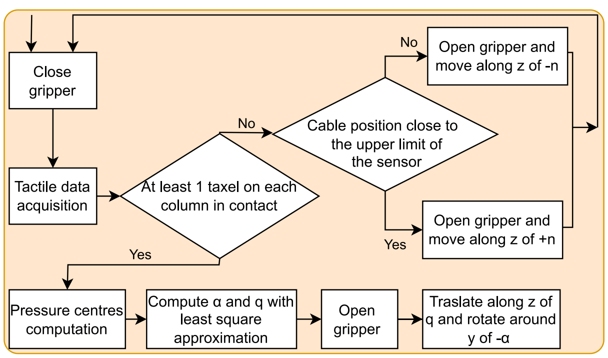


Fig. 6: Flowchart of the *planar alignment* skill.

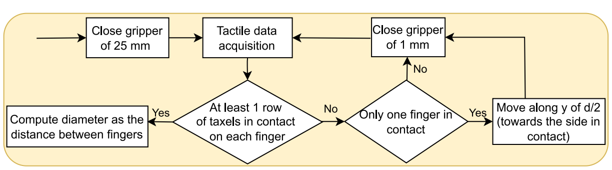


Fig. 7: Flowchart of the *diameter estimation* skill.

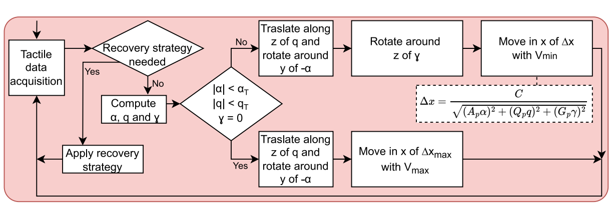


Fig. 8: Flowchart of the *contour following* skill.

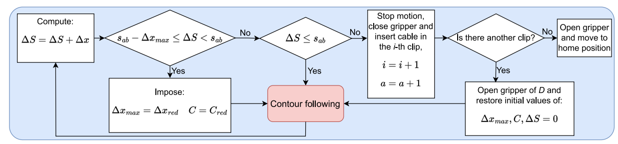


Fig. 9: Flowchart of the *cable routing* skill.

with $k = 1, 2$, $j = 1, \ldots, 4$ and z_i representing the z coordinate of the i-th row of taxels with respect to the finger frame (see Figure 2a). The coordinates of the positions of the four pressure centres with respect to the tool reference frame for the k-th finger are (x_j^k,$z_j^{c^k}$) for $j = 1, \ldots, 4$, where the values of x_j^k represent the taxels positions along the x axis of the finger reference frame. The grasped portion of the DLO is approximated with a straight line $z_j^{c^k} = m x_j^k + q$ written as $z_j^{c^k} = \phi_j^k \theta$ with $\phi_j^k = [x_j^k \quad 1]$ and $\theta = [m \quad q]^\top$. Exploiting the eight coordinates of the positions of the pressure centres, we can define:

$$\Sigma = [z_1^{c^1} \quad z_2^{c^1} \quad z_3^{c^1} \quad z_4^{c^1} \quad z_1^{c^2} \quad z_2^{c^2} \quad z_3^{c^2} \quad z_4^{c^2}] \tag{2a}$$

$$\Phi = [\phi_1^1 \quad \phi_2^1 \quad \phi_3^1 \quad \phi_4^1 \quad \phi_1^2 \quad \phi_2^2 \quad \phi_3^2 \quad \phi_4^2]^\top \tag{2b}$$

Finally, the parameters of the straight line can be computed as $\theta = \Phi^\dagger \ \Sigma$, where $\Phi^\dagger$ is the pseudo inverse of Φ, and the angle α is obtained as $\alpha = \arctan(m)$. The *planar alignment* skill (flowchart in Figure 6) involves, after the opening of the fingers, a translation of q along the z axis and a rotation of $-\alpha$ around the y axis of the tool frame. This sequence of movements aligns the fingertips x axis with the DLO shape, centering the cable in the fingertips. The proposed grasping strategy can be exploited in different setups involving DLOs characterized by several stiffnesses, with a portion laying in the free space where they must be grasped. Our method allows to robustly center the DLO in the fingertips, both planarly and axially without the risk of dragging the DLO while closing the gripper. This strategy can also be exploited for operations as terminal insertion or disconnection.

Once the DLO has been properly grasped, its diameter D is estimated (flowchart in Figure 7). This skill consists of gradually closing the fingers of 1 mm at each step until both the fingertips touch the cable identifying the distance D between the two sides. A fingertip is considered in contact with the DLO if at least one row of taxels in its matrix touches the cable: the i-th row is defined as in contact if $\frac{\sum_{j=1}^{4}\Delta C_{ij}}{4} > T_d, i = 1, ..., 5$ where T_d is a user-defined threshold. Due to approximations in the estimation of the previous parameters, an offset between the TCP and the position of the DLO along the y axis of the tool frame could be present before the *diameter estimation* skill is executed: if only one finger contacts the DLO, the TCP is moved of $d/2$ along the y axis in the direction of the touched side.

B. Skills for contour following and cable routing

Once the diameter is estimated, the *contour following skill* (flowchart in Figure 8) is achieved by keeping the gripper open for a quantity D. Thanks to the low friction force generated on the DLO during the motion, it is possible to slide along it, allowing the taxels to sense its profile properly. To follow the contour in $3D$, the robot has to move along the DLO locally aligning to its shape. The presented *planar alignment* skill can be used to compensate the misalignment on the $x - z$ plane. However, stiff DLOs constrained at both ends can exhibit a considerable curvature γ in the $x - y$ plane of the tool reference frame (see Figure 4d) that must be estimated and then accommodated. An attempt has been made to physically characterize γ as a function of the obtained pressure differences between the two fingers, looking at the tactile data acquired enforcing seven different values of γ among 0° and 30°. Analysing the differences of the acquired taxels values between the fingers, defined as $\Delta c_{ij}^{2-1} = \Delta c_{ij}^{2} - \Delta c_{ij}^{1}$ for $i = 1, \ldots, 5$, and $j = 1, \ldots, 4$, it is noted that a variation of γ affects more the external columns $1, 4$ as the DLO presses against the first column of the internal finger and the last one on the opposite side. In particular, we can define:

$$\Delta c_1^{2-1} = \max_i |\Delta c_{i1}^{2-1}| \cdot \mathrm{sign}(\Delta c_{\bar{i}1}^{2-1}) \tag{3a}$$

$$\Delta c_4^{2-1} = \max_i |\Delta c_{i4}^{2-1}| \cdot \mathrm{sign}(\Delta c_{\bar{i}4}^{2-1}) \tag{3b}$$

where $\Delta c_{\bar{i}1}^{2-1}$ and $\Delta c_{\bar{i}4}^{2-1}$ are the values returned by the *max* operators. In general, as it can be deduced by Figure 4d, Δc_1^{2-1} increases and Δc_4^{2-1} decreases if γ increases. It follows that the magnitude and the sign of γ could be estimated analysing the values of Δc_1^{2-1} and Δc_4^{2-1}. However, due to the hardware realization of the adopted fingertips, the module of Δc_1^{2-1} does not increase continuously with γ since, in the presence of a sharp angle ($\gamma > 10°$), the cable touches the finger plastic shell, protecting the sensor body, reducing the pressure perceived by the taxels. Therefore, in the proposed skill, the estimate of γ can assume just two values: 0 and $\bar{\gamma}$, with $\bar{\gamma} < 10°$. The value of γ is computed as follow:

$$\text{if} \quad \Delta c_1^{2-1} > T_{g1} \land \Delta c_4^{2-1} < -T_{g4}, \quad \gamma = \bar{\gamma} \tag{4a}$$

$$\text{if} \quad \Delta c_1^{2-1} < -T_{g1} \land \Delta c_4^{2-1} > T_{g4}, \quad \gamma = -\bar{\gamma} \tag{4b}$$

otherwise $\gamma = 0$ rad (T_{g1}, T_{g4} are user-defined thresholds). The robot moves to compensate for the estimated DLO misalignment in the space, advancing then along the x axis of the tool frame, now aligned to the grasped DLO. In particular, if $|\alpha| < \alpha_T$, $|q| < q_T$, $\gamma = 0$ (where α_T, q_T are user-defined thresholds) the robot moves of $\Delta x = \Delta x_{max}$ at v_{max} as the future local estimated shape of the DLO is straight; otherwise the velocity is set to v_{min} and Δx is:

$$\Delta x = \frac{C}{\sqrt{A_p\alpha^2 + Q_p q^2 + G_p\gamma^2}} \tag{5}$$

where C, A_p, Q_p, G_p are user-defined weights. The robot motion along the DLO is hence adaptively modified depending on the estimated parameters: the more relevant the misalignment is, the less the robot will move since the future local shape could substantially vary. The weight G_p must be greater than the others since γ represents the most critical misalignment: the shape of the DLO could significantly change even within a few centimetres in the presence of curvature. In this way, the robot can follow the contour of a DLO presenting a considerable curvature since it compensates of $\bar{\gamma}$ and moves slowly and of a restrained quantity, repeating then this procedure all along the curve.
Finally, the *cable routing* operation (flowchart in Figure 9) is performed. Starting from the initial grasping pose ($a = 0$), the robot keeps track of the travelled distance ΔS along the arc length of the cable: after compensating for the misalignment of the DLO and moving of Δx, ΔS is incremented of Δx. As soon as a distance s_{ab} is reached, the robot stops, closes the gripper, approaches the clip and inserts the grasped portion of the DLO into the corresponding intermediate clip, continuing then to follow the DLO contour. Close to the cable segments that have to be clipped ($s_{ab} - \Delta x_{max} \leq \Delta S \leq s_{ab}$) the motion along the x axis of the tool frame is restrained exploiting the parameters Δx_{red} and C_{red} instead of Δx_{max} and C in the contour following procedure, to reach precisely s_{ab}. After the insertion, the original values of Δx_{max} and C are restored, $\Delta S = 0$ is set and the procedure is repeated for the next clip ($i = i + 1$, $a = a + 1$). The points where the DLO has to be clipped can be successfully identified since the cable is considered as inextensible: plastic deformation is an undesirable phenomenon that must be avoided.

V. EXPERIMENTAL VALIDATION AND USE CASE

Table I contains the user-defined values of parameters and thresholds used in the skills, selected according to the sensors noise analysis results (Section III), the study about γ, and preliminary analysis of data sensed while interacting with a DLO. The robot used is a UR5e equipped with the Smart Gripper manufactured by Camozzi. Figure 10 shows the experiments performed with the corresponding success rates. In these experiments air hoses are used as DLOs. We tested the *axial* and *planar* alignment skills as well as the *diameter estimation* imposing 15 initial grasping poses. We analyzed the success rate of the *contour following* skill in several configurations of the DLOs: each test is considered successful if the robot follows the contour starting from one end and reaching the other. In particular, some basic configurations are tested (straight, with slope and curved) together with a complex configuration that combines a significant slope and

T_a	T_p	T_d	T_{g1}	T_{g4}	α_T	q_T	$\tilde{\gamma}$	Δx_{max}	v_{max}	v_{min}	C	A_p	Q_p	G_p
20 fF	30 fF	25 fF	100 fF	150 fF	0.1 rad	4 mm	0.1 rad	7 cm	250 mm/s	125 mm/s	80 cm	0.4 rad^{-1}	0.2 mm^{-1}	0.8 rad^{-1}

TABLE I: User-defined thresholds and parameters used in the skills for DLO grasping and contour following.

curvature. Finally, the considered use case consists in the execution of cable routing operations with two intermediate clips, starting from the DLO complex configuration. All the tests have been carried out for two different hoses (Hose 1 and Hose 2) of PA12 material with external diameters of $D_1 = 8$ mm and $D_2 = 6$ mm. Moreover, the cable routing use case is tested also with one hose of TPC SH 98 (Hose 3), characterized by the same diameter of Hose 1 and lower stiffness than the other two hoses. The lengths of the DLOs between the fixtures ranges from 90 cm to 120 cm depending on the configuration. The accompanying video shows some of the performed experiments.

Axial and *planar* alignments are evaluated together, being both necessary for grasping. The failures in the *axial alignment* are linked to errors generated by an excessive angle β (greater than 50°), causing contacts between the DLO and the shell of the fingers and generating incorrect taxels reading. However, in industrial setups, a bounded uncertainty on the initial grasping pose can be assumed, thus reducing the error rate. The *planar alignment* skill obtains better success rates: only one experiment failed due to an excessive error in the shape estimation. This issue is particularly related to the DLOs with larger diameters since it is more complex to accurate estimate the local shape due to the higher ratio between the taxel dimension and the DLO's diameter. The *diameter estimation* has a success rate of 100%. In the "straight" configuration, the success rate of the *contour following* skill is high since only one experiment failed for a wrong estimation, while for the "slope" configuration, the skill sometimes fails as the grasp of the DLO is lost. The loss of contact usually happens due to a minimal initial axial misalignment, insignificant at the beginning, which however becomes relevant during the motion, bringing the DLO to be laterally dragged due to the strain generated during contour following. This issue is the leading cause of failure for tests involving Hose 2: in the case of larger diameter and hence greater stiffness, an axial misalignment related to γ can be more easily sensed and compensated. For the same reason, in the "curved" configuration, the success rate is lower for Hose 2 due to the higher flexibility: the gripper may drag the DLO instead to follow it since γ is not sensed correctly, while higher success rates characterize the tests on Hose 1. However, although the profile of larger cables has an intrinsic curvature, the proposed skill can fail for DLOs with diameters greater than twice the dimension of a taxel ($n = 5$mm). In this case, especially for sharper curvatures, the tactile sensors cannot sense the curvature if it is so large that the cable touches the plastic shell of a finger from both sides. The complex configuration tests and the cable routing ones share the same DLOs shape. However, the success rate is higher in the second case since the loss of contact with

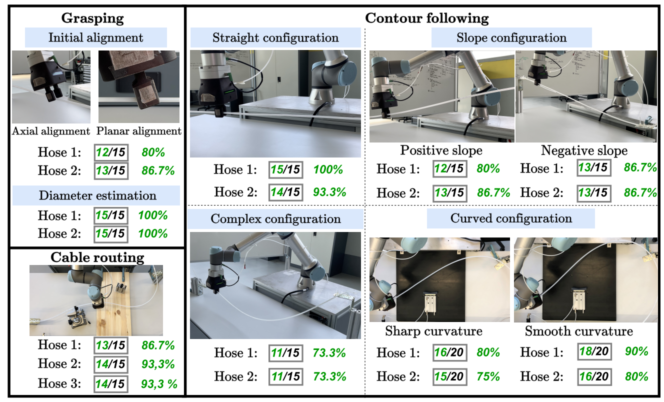


Fig. 10: Success rates of the skills in the performed tests.

the DLO during contour following is highly reduced: this is due to the two intermediate clips that constrain the DLO once inserted in them, making it less flexible and reducing the difficulty in the manipulation. The cable routing tests are carried out on two different setups: the first used for Hose 2 ($s_{01} = 30$ cm, $s_{12} = 32$ cm) and the other for Hose 1 and 3 ($s_{01} = 27$ cm, $s_{12} = 41$ cm). For all the tests we used $\Delta x_{red} = 2$ cm and $C_{red} = 20$ cm. The tests performed on Hose 3 reveal that the DLO's material does not affect the success rates relevantly as the robot slides along the DLO keeping the gripper open of a quantity equal to the estimated diameter. The friction force is never excessive due to the soft skin composing the tactile sensors (see [9]). Finally, the contour following procedure is realized with an average speed of 4.36 cm/s, computed by averaging the speeds obtained in the several configurations, while the cable routing operation has an average execution time of 48 s.

VI. Conclusions

We propose a method to perform cable routing operations for DLO characterized by considerable stiffness constrained at both ends. We introduce a set of skills based on tactile data that allows grasping the cable optimally, following its contour in the 3D space and realizing the cable routing operation. Experimental results show satisfying success rates for tests involving three different DLOs in several configurations. Future works can enhance the *contour following* skill, dealing with obstacles and adding a strategy to geometrically estimate the future local 3D shape of the DLO based on the traced contour.

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